# X REALITY NETWORKED PERFORMANCE:

## MESSAGE BASED DISTRIBUTED SYSTEMS FOR CONTROLLING AND PRESENTING MULTIPLE REALITIES

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For Jana

Thanks always to Mum, Nan & Pop

Eileen Alenka, The European Union & Small Bears

# Abstract

X reality networked performances connect physical, fictional and computer generated realities in a new world of performance, one that is without geographical bounds and that can include many physical locations—with their own performers and audience members—within a single event. They explore a unique medium while drawing on historical and contemporary performing arts practices that normally occur within the confines of a single physical location.

Such performances present a special set of requirements on the system that supports them. They need to access and integrate all the systems that are typically found in the physical place of the performance (such as theatre lighting) with those that are unique to the medium, such as network technologies and environments for the delivery of computer generated realities. Yet, no suitable systems or frameworks have been developed to support them. Technologies are available (such as LoLA and UltraGrid) that support individual aspects—like audio/video streaming—but which do not address the wider requirements of controlling and synchronising, of integrating all these technologies into a system of systems for X reality networked performance.

Therefore, this research investigates the creation of a systems framework whereby existing hardware and software components can be continuously integrated with bespoke components to provide a platform for the delivery of X reality networked performances. The methodological approach to this investigation is through the lens of the author's previous experience in other fields of complex systems integration, including, approaches employed in the design and integration of avionics systems.

Specifically, it tests if a systems integration approach to providing a technical platform for X reality networked performances, one that employs strongly-defined interfaces and communication protocols, and that is based on open and industry standards, delivers an elegant platform that can be characterised as: deterministic, reliable, extendable, scalable, reconfigurable, testable and cost effective.

The platform for X reality networked performance has been developed iteratively—using the results of a framework investigation—and tested in four different performance projects over a period of 24-months, in ten different venues, across five countries. The research concludes that the enabling framework is well suited to the delivery of X reality networked performances. Also, that the approaches employed could equally be applied to the needs of other arts practitioners who rely on complex technical systems for the creation and delivery of their work.

# Table of Contents

# Table of Figures

# Appendices

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Appendix B contains complete lists of credits for each project that forms a part of my research and arts practice discussed in this thesis but I will make some special mentions, also for some that were not directly involved in these projects.

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Unless otherwise noted, all illustrations and video material are by the author.

# 1. INTRODUCTION

This research is centred on the artistic and technical practice of **networked performance**, which I define[1] as: an artistic performance[2] that occurs simultaneously across physically distributed spaces, which by means of a communications network allows the participants to collaborate in a single event.

Specifically, it involves my own practice in **X reality networked performance**, that which I define as: a network of simultaneous realities across the nodes of a networked performance, where X represents the variable superset of the combinations of realities on the reality-virtuality continuum, fictional realities, the interactions with and between them, and between the objects existing therein (including physical and virtual performers, and the audience)[3].

As there are no previously defined technical frameworks or integrated systems to support X reality networked performance, this research investigates solutions to address this need. Specifically, it questions the use of a systems integration approach to providing a technical platform for X reality networked performances, one that employs strongly-defined interfaces and communication protocols, and that is based on open and industry standards.

The aim of the research is therefore:

- The creation of a systems framework whereby existing hardware and software components can be continuously integrated with bespoke components to provide an elegant[4] platform for the delivery of X reality networked performances.

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[1] Other definitions of 'networked performance' exist, as discussed in section: 1.1

[2] "an artistic performance is one that takes place in the context of those established practices that we think of as 'performing arts' [including] - theatre, music, and dance" (Davies, 2011, p. 5).

[3] The 'reality-virtuality continuum' and the basis for my definition of X reality networked performance is discussed in detail in section: 1.3.4

[4] The definition of 'elegant' used is "pleasingly ingenious and simple [as a] solution to a problem" (OED, 2018) the relevance of 'elegant' in systems design is discussed in detail in section: 1.5.2

The aim of the research will be accomplished through the realisation of the following objectives:

- Definition of the system requirements, architecture and framework for the realisation of X reality networked performances;
- Exploration of a message-based approach for the communication between widely distributed systems components within an X reality networked performance environment;
- Creation and delivery of a series of X reality networked performances in which capabilities of the systems architecture and message-based communications approach are explored and tested technically within the objective of enabling new performative constructs.

The systems required to deliver X Reality Networked Performances ("XR networked performance" or "XRNP" hereinafter) present a technical and logistical challenge. As XR networked performance is a developing medium and practice, it is the responsibility of pioneers to assemble the components necessary and configure them in an appropriate architecture to support the artistic vision, and for the reliable delivery of the performance. The distributed nature of networked performances results in the need to coordinate and interact with technological and human components of the system across wide geographies. Systems are available that fulfil some of the technical and operational requirements for XRNP, such as audio and video streaming platforms, but they are not integrated with other elements required to support a performance, such as lighting, video switching, video effects, projection mapping, and environments for the development and delivery of computer generated realities.

Many of the other systems components needed to deliver aspects of XR networked performances can be sourced (such as solutions for video mixing, real-time video composition, lighting, and platforms for the creation and delivery of virtual or augmented realities) but they have not been specifically engineered for use in XRNP. Furthermore, because XRNP is an emerging practice, and networked performances of any variety have not yet been mainstreamed or commercialised, there are no integrated systems solutions available for this type of practice. Apart from audio/video streaming solutions, there are in fact no published frameworks for systems enabling networked performance that incorporate control and synchronisation of elements such as virtual worlds, video compositing, and lighting.

In this opening Chapter, I investigate the medium of networked performance and its historical context, proceeding to investigate the question of computer generated realities and their applications in the performing arts. A review of contemporary practice in networked performance is framed by my definitions of networked performance and XR networked performance; it also details some of the technical approaches and technologies employed by other practitioners. Through the lens of my background in the design and integration of complex distributed system, especially in the avionics industry, I explore some examples of best practice and consider how these could be applied to developing a systems framework for XR networked performance. The Chapter concludes by detailing the methodological approach taken in this research.

Chapter 2 introduces my own practice and relevant projects in which I was a significant collaborator. The projects include my first solo productions in networked performance (*Here, Not Here, Where,* and *Bridge to Everywhere: 234*) where I began to develop a deeper vision for my arts practice. In these projects, I also experimented with different technical approaches and commenced development of what the requirements would be for a system to support XR networked performance.

Chapter 3 builds on the outcomes of my early projects and the desire to develop the practice of networked performance incorporating computer generated realities. It presents the functional requirements of a systems framework for XR networked performance, and considers my typology of networked performances. It investigates the different technical solutions and standards for integration and communication between sub-system technologies in the performing arts, and draws conclusions as to the most appropriate solutions to support the practice of XRNP.

Chapter 4 presents the four XR networked performance projects I developed that were used to examine the systems framework presented in the previous Chapter. The artistic concept for each project is presented together with the technical research objectives, implementation and outcomes.

The final Chapter (5) provides a summary and reflection on the research and its findings, details the contributions to knowledge, and provides some thoughts as to the direction of future research on this topic.

This research encompasses my practice in arts and technology, it also draws on skills, knowledge and activities across several fields:

- **Performing Arts** - the use of traditional and contemporary practices from theatre, music and dance;
- **Visual Arts** - the creation of still and moving image by means such as: drawing, painting, photography, videography and animation;
- **Distributed Systems** - the design and integration of complex systems that are a combination of hardware and software components, and other systems, specifically, it draws on prior practice in the avionics industry;
- **Digitally Mediated Realities** - the creation and use of realities which are not purely physical, such as augmented and virtual realities;
- **Networks** - the use of networks to connect disparate technologies and humans across distributed locations.

## 1.1. The field of networked performance

### 1.1.1. Space

Performing arts have traditionally been constrained to a stage or similarly defined area of space which is dedicated to the performers. Exceptions may exist, such as in site-specific projects or in immersive theatre productions, where performers and audiences may inhabit common ground with softer borders, as opposed to the more clearly outlined areas which demark the zones of audience and performers in what might be considered more 'traditional' performance venues.

A networked performance can include the gamut of the performing arts[5], nevertheless, in my exploration of space I use terminology from the theatre. Not because I am primarily interested in the theatre as a genre in networked performance but because it has the most suitable set of definitions to explain space and the use of space in performance.

Llewellyn-Jones (2002) provides a useful introduction to theatre space:

> *"Live performance takes place in a three-dimensional space. The study of any period of theatre history will reveal that there has always been a constructed evolution of theatre space, both formal and informal. In all cases, the audience member, the spectator, becomes part of the performance, and is therefore an integral part of the space itself; for contemporary performances, the theatre space and the spectator's relationship to that space can range from a strictly formalized proscenium-arch stage to a make-shift performance space in a busy street or in an abandoned warehouse."*

He further identifies these constituent spaces as: **dramatic** - "an abstract space of the imagination"; **stage** - "the physical space of the stage"; **gestural** - "the actors and their movements"; and **theatre** - "the area occupied by the audience and the actors during the period of the performance".

In *The Potentials of Space*, Oddey and White (2006) present for consideration some additional spaces. Outside the theatre as a dedicated performance venue they consider **creative space** and the notion of **found space**. Ariane Mnouchkine (co-founder of Théâtre du Soleil) termed found space to mean "a site that has some particular properties, that either fits a performance or which suggests performance to be made for the site" (Kristiansen, 2015).

Oddey and White describe creative space as "buildings and spaces [that have] existing character, ambience and dramatic potential, which were and are exciting, offering a creative space very different from that of the traditional theatre building". They introduce also **architectural space** in which "scenography is no longer ornamentation, but rather the body,

[5] I take 'performing arts' as: "forms of creative activity that are performed in front of an audience, such as drama, music, and dance" (OED, 2017).

which is intrinsic to the media of theatre culture". And, **performing space** in which the "potentials of spaces for performance are necessarily spaces where the reality and illusion are both a simulation of the material world but also, and simultaneously, real".

Regardless the permeability of the borders and size of the performance area, the space that is allocated to the performers still has its boundaries, its frontier. Through time, directors, scenographers, visual artists, composers and choreographers have employed myriad techniques to take their performance and the audience's perceptions beyond what is directly portrayed in the performance space.

In *Space in Performance: making meaning in the theatre* (McAuley, 2000, p. 126) surmises a theatrical performance: "whatever its genre, is a physical event occupying a certain space and a certain duration…A traditional theatrical performance creates and presents a fictional world[6] or worlds and a series of events occurring in these fictional worlds…"

Liina Unt (2002, p. 364), as a designer and scenographer, introduces the concept that a network of places come together in stage space: places that contain characters in the **fictional space**, the places created by the design of the set, and the places that are within the real space. With the term 'real space' Unt is referencing Arlander (1988, p. 57), who defines this as "an actual **physical place** where the performance is given, either in the theatre building or in the found space".

In the digital age, the performance space has been injected with video projection and audio enhancement, it has been digitally mediated (Coniglio, 2006), creating new visual layers and worlds within the performance space, surrounding the audience with images and sounds that endeavour to move them beyond the place of performance. Yet, outside of the field of networked performance the performance space remains that which is singular and contained within the place of performance, and bound to a singular audience that is physically present in the same venue (with exception of live streaming to remote audiences that do not have any co-located experience, see: 1.1.4.).

[6] The term 'fictional' is discussed further in Chapter 1.3.4.

Oddey and White (2006, p.21) also discuss **cyberspace,** which they see as challenging the very meaning of [theatrical] space:

> *"Cyberspace presents the interaction of digital codes and human desire and it is entirely dependent on technological equipment, a performance alliance of digital technologies, which enables the expansion of potential space as well as geometric space and can alter the dimension of time or the duration of the performance. Cyberspace very concretely creates a new spatiality, through the scenography of this media and mediated space. The environments, worlds and architectures are all spaces of potential performance. Again, the spaces of the sites that are real and the speed of communication in a live performance arena becomes part of that aesthetic, not simply a way the future is celebrated but in the way that it conditions and it pursues the aesthetics of disappearance and reappearance."*

Though their presentation of cyberspace may not have been addressing networked performance the idea that "environments, worlds and architectures are all spaces of potential performance" is an attractive proposition in this context. However, in networked performance, cyberspace is more than a virtual environment that is then mediated e.g. through projection as part of the scenography of a singular space of performance or as the environment in which all the performance takes place. It is the potential of cyberspace as a connective element between multiple physical spaces of performance—even as a notional construct—that promotes investigation.

The virtual, overlapping and collaborative spaces that are afforded by the infrastructure of the internet or created in the cloud, the performances that take place there, have been coined using a range of terms by artists active in the field. The term '**third space**' has been adopted by Randall Packer to represent "the fusion of the physical (first space) and the remote (second space) into a networked place that can be inhabited by multiple remote users simultaneously or asynchronously (third space)" (Packer, 2014). Packer's own practice tends to be conducted more online, employing web-based technologies and with participants and audience connecting using a browser, rather than events that incorporate co-located audience members in performance venues.

Networked performances afford an extension of the singular performance space to a multiple of all the spaces within as many venues that are involved in that performance instance. Further, it not only breaks the frontiers of the traditional performance space, but offers new avenues through which the meaning of space and community can be actively explored within the performative act; through the affordances[7] it brings to the writer, the composer, the choreographer, the performer and the audience.

Moreover, a networked performance offers an engagement with physically collocated audiences at multiple venues, each of which may also be co-present with one part of the 'global' stage that comprises the networked performance space. It breaks with the traditional relationships in the performing arts: that between performance space, audience space and venue[8]. (A typology for networked performance is presented in 1.4.1).

I propose that a networked performance world comprises supersets of spaces in: 1) real space – the spaces that are manifested in a physical place; and 2) cyberspace - as a notional connective element between the physical spaces of performance, that can also be a container for the realities which are not physically manifest. The affordances of space in networked performance can be likened to those of 3D chess, compared with those in non-networked performance (those which take place in a single location) which are more like a 2D board game. In 3D chess, where the board is segmented and layered across several vertical levels, the player must consider moves and relationships in three-dimensional space. A similar shift in creative thinking and spatial logic is required to address the opportunities and challenges that are offered by this new set of affordances in a networked performance.

[7] The term 'affordance' is regularly traced in original definition to Gibson as "the affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill" (Gibson, 1979). Examples of things that have affordances include stairs for climbing up/down, a chair for sitting on, a handle for turning. However, Gibson's theory of affordances encompasses much more than just the affordances of physical things, telling us that "Affordances are properties taken with reference to the observer. They are neither physical nor phenomenal" (1979, p.144). The idea of affordances has been widely used in the design of objects, in the everyday, and especially in the field of human-computer interaction (HCI). Arguably, less so in theatre and the performing arts. Through the affordances of the networked performance environment, objects (including the performers) within any one physical space have what could be deemed a set of local affordances (actionable by the physically present performers and audience) and a set of global affordances, those which are actionable to the remote performers and audience.

[8] I take 'venue' to be "the place where something happens, especially an organized event such as a concert, conference, or sports competition" (OED, 2019).

### 1.1.2. Nomenclatures of networked performance

Helen Varley Jamieson may have been the first to have used '**cyberperformance**' as a compound of 'cyberspace' and 'performance' to mean a "live performance by players using internet technologies" (Abrahams and Varley Jamieson, 2014). Varley's definition does not specifically include or preclude the possibility that a cyberperformance be purely conducted on the web or if it might extend to physical places of performance and audience co-location.

However, some (Ubik et al, 2016) have used 'cyberperformance' as a nomenclature for performances which are primarily between physical locations and with audiences across two or more nodes of the performance. In this context, I suggest that the use of this portmanteau naming is inappropriate for what I call networked performance because cyberspace is defined as "a notional environment in which communication over computer networks occurs" (OED, 2019). Therefore, a 'cyberperformance' cannot be conducted in cyberspace. It may be facilitated by this notional construct for the purposes of networked communications, but cyberspace is neither a virtual environment nor a space composed by meeting of physical locations.

Cyberspace as a component within a networked performance becomes interesting when it is an "arena for science fiction" (*William Gibson | LIVE from the NYPL*, 2013) that allows us to create fictional realities within a performance that are beyond or between the physical places of the performance. Gibson comments that in his origination of the term it "meant absolutely nothing", he wanted a space in which "he could specify the rules for the arena".

Others have adopted names or phrases to reflect their view on - or a practice area related to - networked performance, such as Janet Murray '**Cyberdrama**' (Murray, 1997) "a reinvention of storytelling for the digital medium", and Christina Papagiannouli 'Etheatre' (Papagiannouli, 2016) who wanted "to name the phenomenon of online theatre [while] ignoring at the time the existing terms used to define [those] practices". The term '**networked performance'** itself has been used by Michelle Riel, whose definition in 2004 was "networked performance is real-time, embodied practice within digital environments and networks; it is, embodied transmission" (Chatzichristodoulou, 2012, p. 4) and more recently, Riel has defined networked performance as "real-time, embodied practice within digital environments and networks; it is, embodied transmission" (ibid).

Others have used the term '**telematic**' to describe their networked activities, such as Gigs and Warburton (2010) in their project Lubricious Transfer; Oliveros, Weaver, Dresser, Pitcher, Braasch and Chafe (2009) in their respective networked music practices; and by Paul Sermon (2000) in his often-cited piece *Telematic Dreaming*, which rather than a performance, is what I would term a 'telepresence experience' or 'networked interactive installation'. In a similar vein, is Atau Tanaka's *Global String* (Tanaka and Bongers, 2001) of 1998-2000.

### 1.1.3. Definition of networked performance

In my own practice, I found that the definitions given for 'networked performance', or for alternatives, such as 'telematic' or 'cyberperformance', were lacking or inappropriate, and did not adequately or correctly describe my vision and understanding of the field. Though the term '**real-time**' is often used in definitions of networked performances, it is not always an appropriate use of the term. As 'real-time'—in the computer use of the word—is defined as "relating to a system in which input data is processed within milliseconds so that it is available virtually immediately as feedback to the process from which it is coming" (OED, 2019), there may be an intent of achieving real-time, but in fact 'near real-time' or 'real-time when necessary / possible' would often be more appropriate. Therefore, I do not use the term in my own definition but employ it when relevant to describe specific aspects of the system. Existing definitions of networked performance, including the alternatives, also lack in their reference to the physical spaces of performance; they often allude to a performance that could be entirely online, with no inclusion of physical spaces: for me these are best termed as 'online performance'. In my own practice, the inclusion of physical space, physical performers and co-located audiences, are all essential components of a networked performance. Though the virtual, or the idea that elements of a performance may exist in 'cyberspace', are artistically interesting elements for construction of the performance world, I employ them in my practice in combination with the physical space.

For the purposes of my research and practice I therefore delineated the term '**networked performance**' as: **an artistic performance that occurs simultaneously across physically distributed spaces, which by means of a communications network allows the participants to collaborate in a single event**.

The definition of X reality networked performance, as a layering of my definition of networked performance, is disused in section: 1.3.4 and presented in section: 1.3.5.

### 1.1.4. The medium of networked performance

Whatever the name, it is arguable that each of the practitioners is approaching their ‘networked performance’ as a new medium, informed by their practice or interests outside of network enabled performance. An historical parallel being the script writers, directors and producers who migrated their craft from the cinema to the television as technologies such as radio transmission, cathode ray tubes and valves enabled the television as a new medium with its own affordances.

McLuhan (1964) suggests that the ‘content’ of any medium is always another medium”. While it is true, for example, in the case of films developed for cinema later being transmitted by radio waves to the television, it does not devalue the unique agency and affordances of the newer medium. Nor does it reduce the likelihood that a new medium can and will inspire its own medium specific content that could not have lived by any other medium. There may be common elements of the content that can be developed and delivered through networked performance as a medium—spoken word, music, visual art, performative movement —but there are also opportunities for entirely new forms of content. In any case, all media are—arguably—hybrids of human foundational capabilities (the ability to make a sound, a mark or a movement in space and time) and the desires to communicate and inform or perform from the earliest stages of our intellectual and emotional development.

Conversely, one might argue that networked performance is merely an extension of work in existing media (theatre, dance, music, etc.) rather than a new medium itself, such as when surround sound and digital projection were introduced into the cinema. This is, however, not a notion I subscribe to herein.

Dworkin (2013) takes this argument to a different approach: “that there is no medium, understood in isolation, but only and always a plurality of media: interpretive activities taking place in socially inscribed space”.

A theatre production may include the medium of visual art, of text, of voice, of music, of movement, of fashion, and more. The scenography within the production may incorporate the medium of paint, of textiles, of wood.  And, the lighting of a production, electricity, the "electric media" (McLuhan, 1994, p.7) which also fuels all the digital media (be they electronic or photonic). Theatre is at the juncture of many media and mediated art forms, including that of "social media" (Hadley, 2017) and the digital arts, that which Graham (2007) defines as any "art made with, and for, digital media, including, the internet, digital imaging, or computer controlled installations".

We can argue that not only are all media a hybrid (or a mix) of other media but they are also mutable, especially with the effects of technology; the current transference of nearly all analogue media of one form or another to the medium of the digital. Murray (2012) believes that "All things made with electronic bits and computer code belong to a single new medium, the digital medium, with its own unique affordances". Many media are now digitally enabled, broadcast or consumed and therefore, effectively, part of that "digital medium" collective but that does not make them any less their own medium: television, cinema, opera.

2006 marked the first **streaming of a live performance** from New York's Metropolitan Opera (The Met) when Mozart's *The Magic Flute* was beamed to digital cinemas via a satellite link (McClintock, 2014), in a medium that Heyer (2008) has called "Digital Broadcast Cinema".  Other performing arts venues have subsequently followed on this path, including the likes of the Royal Shakespeare Company's theatre in Stratford-upon-Avon, London's Royal Opera House and the Bolshoi and Paris Opera. In 2009, Digital Theatre (www.digitaltheatre.com) launched their online service; an on-demand library of films of what were "live" performances.

Digital Theatre position cameras and microphones within the set of the performance to obtain video footage from angles that the co-present audience would not normally be privileged to. These intimate views, along with video shot from a regular audience perspective, are edited to produce an audio-visual record of the performance that are then available for on-demand viewing. This is the medium of theatre, mediated using digital audio/video technology, delivered through the medium of streaming media. The Times

(Cavendish, 2009) reported the launch as “a new online theatre site [that] will break boundaries in the experience of theatre - bringing the stage to you” and that “Theatre is the new mass medium”. The idea that theatre only now has the possibility of becoming a “mass medium”, when it was for centuries one of the main form of communicating to the masses, is an arguable perspective on media history.

If we consider the streaming of “live” performances to remote audiences, this does not create any new affordances for the writers, composers, choreographers and performers, other than financial. The conditions are the same as with a non-broadcast performance. The performance has been developed for a single stage with a single co-present audience. The various technological implants of the stage and venue required to capture and relay the “live” event as a stream are hidden to the greatest extent possible to minimise any distraction of the physical performers and physically present audience. The objective is to cause minimal or no change in the actions or experience of the performance in the physical first space.

It might seem that in a networked performance, the situation is not dissimilar to that of digital broadcast cinema, because the performers who are not physically present in the same node are only seen remotely. But, the key difference in a networked performance is that the audience, in addition to viewing the performers at other nodes through their digital representation at the networked stage, are also experiencing the physical presence of the performers in their own node. The performance experience at each node is a combination of, and the interactions between, the total members of the networked cast, those that are both physically and digitally manifested in the local. Furthermore, unlike unidirectional broadcasts of theatre, ballet or opera to e.g. a cinema audience, a networked performance comprises broadcasts from each node in the event world, which reach all the other nodes in that world; and each broadcast provides the medium for the opportunity of a multidirectional exchange between performers and audience at any node.

In a networked performance, the intervention of the “other” can be celebrated for all of the new affordances it brings to the creative team and to the audience. These opportunities are born of the challenge in addressing: the physically present audience members at more than one location of “live” performance (the networked audience); the interaction between the performers at all of the locations (the networked performers); and the space which extends beyond the boundaries of each location's physical stage to encompass the space of all stages and the cyberspace that lays between and connects them (the networked performance space).

By any accepted meaning or interpretation of a definition, networked performance can be considered a medium; a member of other media sets, such as digital (Murray, 2012) and multimedia (Klich and Scheer, 2012); and for its ability to mediate the performing arts. Its role in the spectrum of media is determined depending on the intent within each production and the focus of content development.

To conclude, rather that attempting to justify a medium's uniqueness by the content it employs or generates, or its innovative technological underpinning, it is more useful to understand the affordances of a hybrid medium such as networked performance. That it is the unique combination of spatial types in a networked performance, how they are addressed dramaturgically and performatively, that defines its very uniqueness as a performance medium, rather than the content and its source: pre-existing, hybridised or new.

## 1.2. Historical context

The following paragraphs investigate the origins of networked performance, using technologies which predate the general availability of the internet[9] for public use, up until around 1990. Section 1.4 then examines the contemporary field of networked performance, from c.1990. The examples given are indicative; they are not intended to represent a comprehensive review of the practices that employed communications to connect locations of a performance pre-internet.

[9] The internet has its roots in the Advanced Research Projects Agency Network (ARPANET) of the late 1960's, originally funded by the Department of Defense (USA), and which adopted TCP/IP in 1983 as the standard protocol suite (Davidson, 2013, p. 2). The internet as we know it today, and as a workable transport for networked performance, did not really emerge until the development of world wide web technologies (Berners-Lee and Fischetti, 2008) in 1990, and the subsequent growth in connectivity and availability of higher-speed internet access: the 1990's in research and academia; the 2000's for commercial broadband access using technologies such as ADSL (Asymmetric Digital Subscriber Line), coaxial cable, and then fibre.

We can consider that the earliest form of what might be deemed ‘networked performance’ was the use of drums for communication, such as the African talking drums (Ong, 1977). Drumming was an important component in communicating ceremonies between villages, ones that also had a performative aspect.

The advent of communications systems employing electrical circuits (the telegraph and then the telephone) led to experimental projects, artistic and business initiatives at the intersection of communications and music. In 1880, a Zurich concert was transmitted by telephone circuits 50 miles to Basel (Chanan, 1995, p. 26), and in 1884, a company in London offered a telephone system based service, where: “for an annual charge of £10, four pairs of headsets through which subscribers would be connected to theatres, concerts, lectures and church services” (ibid).

The Telharmonium, invented by Thaddeus Cahill, considered to be the first “electronic musical instrument capable of synthesising various instrumental sounds” (Riis, 2016, p. 177), was the subject of some early experiments in music ‘streaming’. In 1902, Cahill demonstrated the Telharmonium by sending music over a telephone line to the house of George Westinghouse (the engineer and entrepreneur), and in 1906, several performances were transmitted from Cahill’s home–over a distance of one mile–to the ballroom of the Hamilton Hotel in Holyoke, Massachusetts (Holmes, 2012, p. 10).

Though these projects were pioneering activities, they were more a harbinger of what we now call ‘streaming’ than they might be termed ‘networked performance’ in the context of this research. Once radio (and then television) became widely available, this was the medium of broadcasting, not the telephone system. In 1910, the Metropolitan Opera were already experimenting with radio broadcast (Heyer, 2008, p. 592) and would proceed to routinely broadcast performances by radio from 1931.

The introduction of the satellite[10] as a means of global communication, predating the internet and fibre optic links but surpassing the capabilities of the telephone system at that time, led to opportunities for artists to explore this new form of global communication

[10] Geostationary communications satellites, first proposed by Arthur C. Clarke in 1945 (Clarke, 1945) became a reality with the launch and entry into operational service of Telstar 1 in 1962 (Dalgleish, 1989, p. 3).

system. The *Satellite Arts ‘77* project, *A Space With No Geographical Boundaries* (*Satellite Arts Project '77*, n.d.) by artists Kit Galloway and Sherrie Rabinowitz, created “an immersive space for embodied interaction, and modelled a new technologically enabled way of being in the world” (Paulsen, 2013). With the support of the National Aeronautics and Space Agency (NASA) Galloway & Rabinowitz used satellite links to implement a bidirectional analogue television link between locations on each coast of the USA. In initial experiments, dancers in each location appeared on either side of a split-screen monitor at each location. In a later experiment, they attempted to create what they called “an immersive global real-time environment” (Chandler, 2005) wherein (clearly using some form of chromakeying) the two dancers in each location were collaged to a common background image of a grass field surrounded by trees.

Galloway & Rabinowitz were also responsible for a 1980 experiment, a “public communication sculpture” (*Hole in Space ’80*, n.d.), also described as a “streetscape portal” (Foth et al, 2011, p. 412), in which the public interacted in a two-city network. In *Hole-In-Space* (Harrison, 2009, p. 10) a two-way satellite link—between New York City’s Lincoln Center for the Performing Arts and a Broadway department store in Los Angeles—connected a large video screen, camera, speakers and microphones at each location, providing a sort of pre-skype, group interaction, communications gateway between the two cities. The early work of Galloway and Rabinowitz was interesting in the way it looked to experiment with what the medium and media of networked performance could be, rather than attempt to graft them onto existing formats. They do not specifically set out to make a performance from script or score, but look to understand what it is to coexist within the realms of a networked environment: conceptually, artistically, performatively and technically.

The high cost of using satellite links and the lack of suitable low-cost supporting technology meant that long-distance, high-bandwidth networked performance did not emerge as a possibility for more artists to explore until the creation of the world wide web. The web spurred a massive growth in affordable and accessible internet access in the 1990s. Even then, the limitations of commercial internet provider’s connections, cost and available technology (at suitable functionality/price points) meant that there were only a few experiments in low latency networked performance that could incorporate high-resolution and high-quality video until the beginning of the 21st century.

One way in which networked performance did develop in the 1980s was through point-to-point connections or dial-up servers, both using modems. In 1986, the Hub was formed by the League of Automatic Music Composers, a collective who had already been performing music with various computing devices connected by RS-232 serial interfaces (Gresham-Lancaster, 1998, p. 40) in the same room. In 1987, the Hub made a networked performance in New York using 300-baud modems to share performance data between two venues, each with three performers (ibid, p. 41).

Though first performed in 1995—post the introduction of the world wide web—Stockhausen's *Helikopter-Streichquartett* (Helicopter String Quartet) used individual radio links between each helicopter and a ground station, from which the sounds of the circling helicopters with string-instrument players on board were delivered to the audience PA on the ground (Connor, 2009, p. 62).  However, this is more a case of a 'network' being used to enable the performance (as with contemporary groups that use a LAN to share data between computers in a 'laptop orchestra') rather than a networked performance.

This section has reviewed some notable projects in the early development of the field of networked performance. Section 1.4 details contemporary practice in networked performance and discusses some of the practitioners and reference projects from the 1990's to date. As this research specifically addresses the different types of reality—especially digitally mediated realities—that can be incorporated within the networked performance framework, a foundation discussion of these realities is presented first in the following section.

## 1.3. A question of realities

In 1972, when asked by an 11-year old girl to give a one-sentence definition of reality, the author Philip K. Dick replied: “Reality is that which, when you stop believing in it, doesn't go away” (Flux, 2017).

The use of digitally mediated realities is a necessity within networked performance practice, due to the need to present what is physical in the remote in some form in the local. The most common methods for this local manifestation of the remote are the use of a sound system, computer display or projection. However, the consideration of realities that are not physically formed, those that are purely of virtual origin (for which no physical basis exists at any node of the networked performance), that are manifested in the nodes of performance through means of augmentation or overlay, are less commonly considered in networked performance practice to date. Examples of practitioners who have started to actively consider these purely virtual constructions as elements within the performance are mentioned in section 1.4. This discussion of realities provides a background to the implementation of different realities within the practice of networked performance. It concludes with a definition of X reality networked performance that fully addresses the inclusion and use of different realities within the networked performance world.

### 1.3.1. Virtual reality

The popular perception of virtual reality (VR) is one where the user (most typically in a game playing scenario) enters an immersive experience though the use of a head mounted display (HMD) and proceeds to explore an immersive fantasy world: travelling through space, riding a roller coaster, or as a cowboy shooting from the hip.

Virtual reality, a term popularised by Jaron Lanier (Rubin, 2017) in the early 1980’s, encapsulates the work of computer scientists up to that point—such as Ivan Sutherland (Earnshaw et al, 1993, p. 52) and Morton Heilig (Laurel, 1993, p. 51)—in working to create hardware and software based systems that would allow a user to experience a simulated environment that was different from the physical environment in which they were situated. Though not VR as we might encounter it contemporarily, the creation of devices which attempt to create partially simulated realities during the $19^{th}$ and $20^{th}$ centuries, included the likes of stereoscopic viewers and mechanical flight simulators. Lanier also encapsulated the experimental and optimistic mood of technologists around the first evolution of computer systems for the creation and experience of VR that occurred in the late-1980 and early 1990s. While the development and use of computer systems for VR has continued throughout the intermediate period, it has only been the last few years (since around 2014) that have been marked by what might be considered the second evolution of VR. From a wider public perspective—especially for those that did not see the movie *The Lawnmower Man* (Kirby, 2009, p.197) in 1992—it might also be understood as the birth of something entirely new technologically.

One of the turning points in this new awareness of VR was the development and introduction, later the acquisition by Facebook (Dredge, 2014), of the Oculus Rift HMD (Desai et al, 2014). The Oculus Rift was important in the development and acceptance of VR by the public (especially in the case of gamers) because it was the first HMD that provided acceptable visuals (1080p video), field of view (100 degrees) and refresh rate (75 Hz). Critically, it also incorporated head tracking (using gyroscope, accelerometers, magnetometers and cameras) so that the views to the VR world rendered for each user were contextual to their movement, and it was marketed at a price which was acceptable to the consumer.

While VR, most commonly, is understood as am immersive experience (at least visually), non-immersive environments can also be used, such as through a “window-on-the world” or “desktop VR” (Robertson et al, 1997), where the view—not the VR model—is from the computer monitor or projected display, and navigation is typically using a mouse rather than the movement of a person wearing an HMD equipped with motion sensors.

### 1.3.2. Augmented reality

Whereas VR may be experienced using an immersive HMD, augmented reality (AR) overlays information into the physical space of the user. AR augments their surroundings with contextual information taken from a model that is aware of the physical space and potentially also the movements of the user in that space. In visual AR, the augmented information might be viewed in the physical space using one of several technologies:

- Projection mapping (Pejsa et al, 2016);
- A non-immersive HMD (or “smart glasses”), one which allows the user to directly view the physical world but that also presents additional visual information using optical see-through glasses that employ technologies such as waveguides or combiners (Aukstakalnis, 2016, p.136), or retinal projection (Azuma et al, 2001, p.35; Jang et al, 2017);
- A mobile handheld display - such as that of a mobile phone – which employs the device’s camera to view the physical world, and based on its internal position and motion sensors or use of image recognition, presents to the user a view on the display that is a composite of the physical world and the virtual. Examples include: the AR game *Pokémon Go* (Paavilainen et al, 2017, p. 2493), and the AR mobile application available to the audience during U2’s *Experience + Innocence* tour (Gilmore, 2018: Hitti, 2018; *Bono and The Edge: Why U2 is embracing AR tech on tour*, 2018, 2:05).

### 1.3.3. Virtual and augmented reality in the performing arts

Use of the VR type of HMDs for experimental work in the performing arts is increasing: artists such as Maria Júdová and Andrej Boleslavský in *Dust* (Smith, 2018, p. 205; *DUST Trailer*, 2017), AΦE's in the physical theatre cum installation piece *Whist* (Fromell, 2018; *WHIST Trailer*, 2017) and Compagnie Voix with *EVE* (*Eve*, 2019) are using them in performances to engage with small groups or selected audience members.

Nevertheless, the wearing of immersive HMDs by audience members who are physically present in the place of performance results in a completely different experience, one which likely isolates them from the traditional model of direct observance of the performers and the space (see: 1.4.2) which they occupy. Such a scenario also has the potential to interrupt the social concourse of the audience in the place of performance. Even though, in the case of a networked audience, one that is not physically present but is e.g. at home, the use of an immersive HMD might present an opportunity for deeper engagement with the performance than currently experienced with the live streaming of theatre to remote cinemas (Heyer, 2008). Conversely, the use of AR implemented as projections into the physical space of the performance, offers the ability for the artist to develop rich mediated environments that can be equally shared by all members of the audience without interrupting the sense of occasion that is created by the audience cohort in the place of performance. AR glasses that do not occlude or remove the feeling of presence of the surrounding audience members or the direct view of the performance space, might provide visual overlays that are unique to each audience member as opposed to projected AR where the augmentation of the physical space of performance is shared by all audience members. Microsoft have supported one such experimental dance project at Chase University in 2016 (*Dancing with holograms*, 2016) where early versions of their HoloLens AR glasses were used by the audience at *Imagined Odyssey* to see augmented imagery in the space of the physical dance performers. AR glasses are also being used to provide personal subtitles and description of dialogue to audience members who have e.g. hearing difficulties or need language translation in live performance (Boyle, 2017).

In an XRNP scenario, such as in *The Spaces Within* and *A Short Journey into Folded Space* (see: Chapter 4) virtual environments are used as the source for visual scenes that are then rendered into the physical space of the user (audience or performer) using projection mapping, resulting in an augmented reality environment. Components of that same physical environment are then used to augment the source virtual environment, as augmented virtuality (AV). In this example, the question as to which computer generated reality technology is dominant is raised; this is why we have terms for scenarios which employ different techniques for generating and using such realities.

### 1.3.4. Mixed, cross, X and fictional reality

To address hybrids of VR, AR, AV and physical space, the concept of a "reality-virtuality continuum" was suggested (Milgram and Kishino, 1994) along which the blend of objects laying somewhere on a spectrum between the "real environment" and the "virtual environment" could be considered as constituting to a "mixed reality" (MR). Furthermore, the exchange of information or media between real and virtual world systems has been termed "cross-reality" or "X-reality" (Coleman, 2009), sometimes as 'extended reality'. Mann et al (2018) consider "X" as a "mathematical variable that can assume any quantity" along the reality-virtuality continuum". Whereas Milgram and Kishino were primarily considering the visual aspects of a reality-virtuality continuum in their "taxonomy of mixed reality visual displays", cross reality has been considered as a "ubiquitous mixed reality environment" (Paradiso and Landay, 2009) that incorporates displays, sensors and actuators, and which are "social environments, populated with human-driven avatars and other representations of residents and sensor data... not restricted to head-worn or other wearable/mobile devices". Simões et al (2018, p. 2) argue that the "concept of XR is more extensive than virtual reality (VR), augmented reality (AR) and mixed reality (MR). XR technology mixes the perceived reality as MR does, but it is also capable of directly modifying real components… [it] refers to all real-and-virtual combined environments and human–machine interactions generated by computer technology".

While these studies investigate the definition and application of computer generated realities, they focus on their technical construction and realisation, their relationship to and dependency on each other, and that of the physical space in which they are manifested or experienced: they do not address e.g. the fictional realities of theatre. The "actions on stage [that] forge what we call a convention, an unspoken agreement between actor and audience concerning a fictional reality" (Mitchell and Hayford, 2014, p. 14). And, the realities that the authors may attempt to create in the space of the performance: the perception of those realities by each audience member within the place of performance or at a site of remote consumption.

Contrarily, if we consider the proposition of Philip K. Dick, it is unlikely that most members of the audience will continue to believe in the various realities (computer generated or otherwise) of the performance on its termination, so, it might be questioned if any should be termed "reality".

I summarise my investigation of realities (see: 0) as follows:

- There are established terms for different types of computer generated realities, including: virtual reality (VR) and augmented reality (AR);
- Applications involving combinations of AR, VR and the physical environment, at some point on the reality-virtuality continuum, can be termed mixed reality (MR);

- "X" can be a variable that indicates a moveable "quantity" on the reality-virtuality continuum;
- Cross reality or X reality (XR) are proposed as a superset of MR, which encompass all the realities that are computer generated and physically present, and that support interactions with them by humans, sensors and actuators;
- In the performing arts, there is the potential for fictional realities which are separate from those of the physical world and those that are computer generated.

#### 1.3.5. X reality networked performance

My definition of X reality networked performance is **a network of simultaneous realities across the nodes of a networked performance, where X represents the variable superset of the combinations of realities on the reality-virtuality continuum, fictional realities, the interactions with and between them, and between the objects existing therein (including physical and virtual performers, and the audience).**

Because X reality networked performances are essentially distributed systems, they are also **distributed realities**. As such, there is the potential, depending on the typology (see: 1.4.1) and design of a performance, that at any node of the performance, the local value of X on the reality-virtuality continuum might be different to that at another node of the performance. Therefore, **X also represents a variable which is the number of reality sets that might be experienced across the XRNP world at any one moment during the performance.**

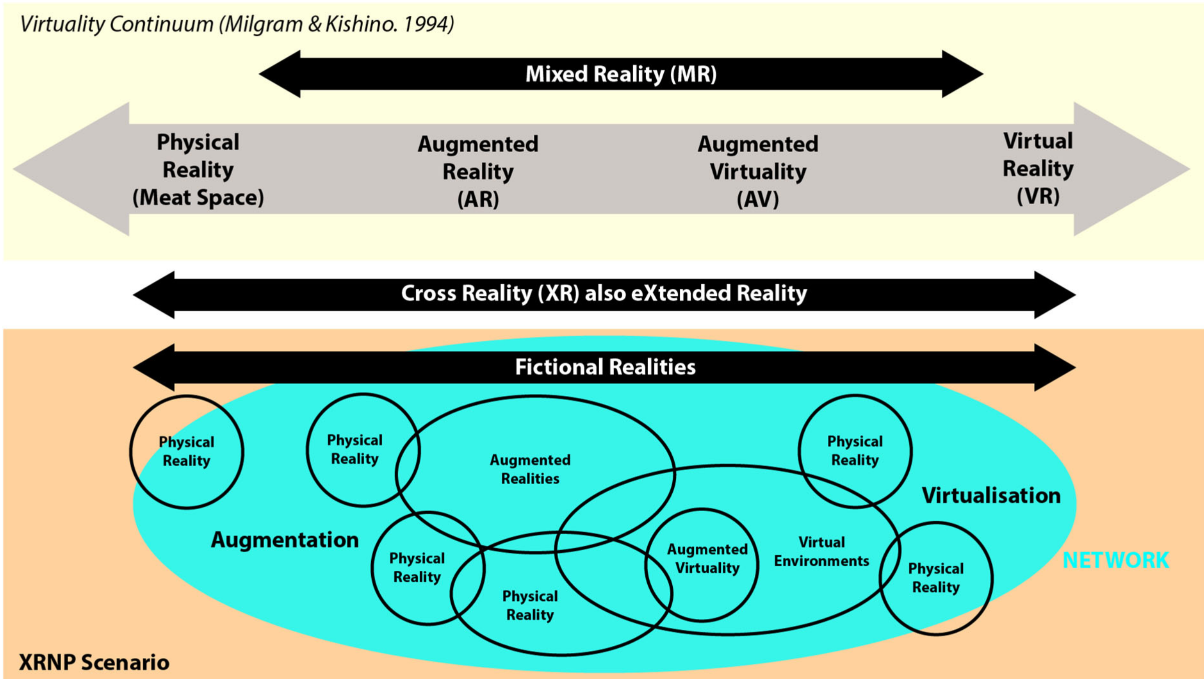


Figure 1: An example of a multi-nodal XRNP scenario that demonstrates the relationships with the Virtuality Continuum, and the relative scopes of Mixed Reality and Cross Reality.

## 1.4. Networked performance: contemporary practice and technologies

This section examines the field of contemporary networked performance, which I consider to be that which evolved from the greater availability of the internet for public use, broadband internet access, and the introduction of the world wide web (WWW) in 1991. The projects discussed are selected from what I consider to be important progressions in the field of networked performance, that have taken technical approaches which are relevant to the discussion of a framework for XR networked performance, or that have investigated themes of networked realities. Details of the contemporary technologies available for networked performance—those used most frequently by practitioners—are discussed in Chapter 2 as part of the investigation into a systems framework for XR networked performance. Reference to literature and practice in the field of systems engineering, design and integration are discussed in Systems design and integration: a theoretical framework for XRNP (see: 1.5).

In the subsequent period, much of the innovation in networked performance has taken place within the confines of academic research environments or facilitated by the national providers of academic networks, notably: Internet2 in the USA, Janet in the UK, CESNET in Czech Republic, GARR in Italy, CSUC in Catalonia and ACOnet in Austria). This is perhaps not surprising when one considers that academic institutions were the first to have access to each new generation of high-speed internet access (then 1Gbps, now 10Gbps or more). Similarly, academic research institutions have tended to be considerably less constrained by commercial concerns.

Contemporary practice in networked performance has tended to develop along the traditional performing arts genres of music, theatre and dance, with a sphere of technologists and arts practitioners developing around each of these specialisms as they have explored the unique affordances of the network in performance.

In parallel, forms of alternative practice have emerged, ones that were developed around the specific qualities of the internet, the web and the availability of low cost or free (but typically low-quality) audio/video streaming, or video conferencing platforms. Many of these practices exist in a form that is purely online, that is, they are not intended for, nor do they seek to or cater for, offline audiences and the type of audience environments found in conventional venues for the performing arts. For example, the Hamnet Players performing Hamlet in text using Internet Relay Chat (Danet, 1994); as noted by Varley Jamieson (2008) the online theatre platform UpStage (n.d.) used by Avatar Body Collision (n.d.); and performances in the virtual world of Second Life (n.d.) by the likes of the Metaverse Shakespeare Company (n.d.), Twelfth Night in a virtual Globe Theatre (Hirsch and Craig, 2008), and dance performance Senses Place (Gomes, 2012, p. 31) by Ballet Pixelle (n.d.).

Elena Perez's (2014) opinion on the contemporary state of activities in networked or "telematic" performance is that "there are typically two versions: high-tech and low-tech. Hi-tech telematic performance has been criticised for focusing on developing the technical and dismissing the aesthetic, by merely displaying the telematic connection in a theatrical manner". Perez builds her case that "low-tech" can produce outcomes which are more artistically focused:

> *"…scientists use performance to further develop technologies, planting their technologies in social aspects of human activity while also researching ways of commodifying these technologies. Artists, on the other hand, use technology as a means of experimenting with innovative machinery to pioneer the development and modernisation of the performance field."*

The position that the performing arts are being used to further research that is primarily technological, or that performances have been used primarily to demonstrate new technology, is not one I subscribe to in my practice, where artistic outcomes are a two-way trade with technology. The better that the supporting or inspiring technology is contextually integrated into the practice, the greater the possibility for it to dissolve from the consciousness of the audience and of the performers, so that a focus on the artistic idea and aesthetic quality is prominent. I would argue, that whereas Perez claims the artistic high ground for "low-tech" approaches to networked performance, these practices often lack in their presentation, with poor image quality, sub-standard audio, and a lack of thought regarding the integration of the technology for networking into the space and place of performance.

As the field of artistic experimentation and development of the performing arts in networked performance have been well documented in other resources, I focus herein on those that are relevant to my own practice and that relate to the research topic. Steve Dixon (2007), in his *Digital Performance* compendium that covers activities in the field of digital performing arts practices up to the mid-2000's, provides an excellent account of networked performances, the use of streaming, webcams and communications technologies in networked and related performance types. Staines and Boddington (2010) provide a companion to Dixon, through a series of interviews with artists involved in "virtual mobility", many of whom have created some form of networked performance or telematic practice.

The technical focus of musicians working in networked music performance tends to be on latency, audio quality, and what the network might offer as an extra dimension in performance, such as with embracing delay. Latency, noise, echo and bandwidth all have a significant impact on what can be performed in a networked music scenario. Video has also become important, with the realisation of the benefits it brings to networked performance and distance education, with its ability to enhance the networked relationship of musicians in performance and with the audience. The availability of higher bandwidth connections has also led to more opportunities to use video as a part of networked music performance. The use by musicians of data communications in networked music performance—to send musical data, instrument control and synchronisation signals is accomplished through some form of MIDI operating over LAN (Local Area Network) or across the Internet. For example, RTP-MIDI (Lazzaro et al, 2004), or more commonly by use of OSC (Wright, 2005). In the case of the Yamaha Disklavier – a piano with MIDI interface, keys with sensors, and that is equipped with servo-motors for computer controlled play – a proprietary protocol (Teeter and Dobrian, 2004) running over UDP (User Datagram Protocol) is used to achieve operation over a LAN or via the Internet. Though video manipulation, use of animations, and the control of lighting may have formed a supplementary aspect to some networked music performances, it is not a feature that is highly reflected in the research and practice originating in the networked music community.

The primary tools[11] of musicians working in the networked performance arena have been jacktrip (Cáceres and Chafe, 2010) and LoLa (Drioli et al, 2013). Jacktrip only provides audio streaming capabilities but is a flexible solution with support for multiple channels, tightly integrated with the Jack (2009) audio server. Jacktrip is a software only solution, it does not have a framework that extends to include specified microphones or sound reproducing devices. In contrast, LoLa is a tightly integrated system framework for audio and video streaming, one which specifies (*LoLa Suggested Hardware*, n.d.; *Low Latency Audio Visual Streaming System*, 2017) the supported video cameras, and recommends network devices, displays and projectors that should be employed to maximise the benefits of LoLa's design for low latency end-to-end operation.

Numerous alternatives are, or have been, available for networked music performance, rehearsals and distance learning. A comprehensive review of such solutions for networked

[11] There are a wide variety of other solutions—that have been or still are available—for networked music activities but they do not provide the functionality for networked performance as defined herein. For example, software for use in connecting Digital Audio Workstations (DAWs) and studios are primarily intended for collaborative recording and may only work with a single software environment, such as: Steinberg VST Connect Pro (n.d.) which supports audio streams, MIDI and video chat but only for use with Steinberg's Cubase DAW; the server based NINJAM (What is NINJAM?, n.d.) which provides online jamming capability for users of Reaper (n.d.) using compressed audio streams; Source Elements' Source–Connect (n.d.) an internet audio streaming solution to replace traditional ISDN connections in the recording industry; and the Ableton Link (n.d.) functionality to synchronise between computers on a LAN but which does not transmit audio, video or MIDI data.

music performance is provided by Rottondi et al (2016, p. 8835) in which “frameworks” for audio, and audio/video networked music performance are discussed. Use of MIDI for musical instrument data exchange and synchronisation is considered but no discussion is given as to the control and communication with other elements that may comprise a networked music performance, such as that for video cameras, video processing, lighting and systems of display.

In the networked practice of choreographers and theatre makers we find diverse approaches that often blur the borders of what might be uniquely classified as dance or theatre practice. Although he studied music, Mark Coniglio is most known for his work in Troika Ranch (*Troika Ranch - About The Company*, n.d.), as a co-producer with choreographer Dawn Stoppiello of multimedia dance performances, and as the developer of Isadora (*Troikatronix*, n.d.). Troika Ranch’s 1996 performance *The Electronic Disturbance* used ISDN (Integrated Services Digital Network) connections for communication between sites of the performance, in New York, San Francisco and Sante Fe. Sensors were also employed; the lighting in New York was “modulated by the vocal inflections of the singer in Sante Fe” (Dixon, 2007, p.423). Coniglio developed the software application Isadora as a module based visual environment for the creation of interactive visuals in live performance (deLahunta, 2005). Although Isadora is not a tool for audio/video streaming it has subsequently been used as a component in networked performances by other artists, such as in Santana’s *Versus* (Santana, 2014b, p.9), and in the research project *Choreographic Morphologies* (Bailey et al, 2008, p.13).

In *The UBU Project*, the Gertrude Stein Repertory Theatre (GSRT) used IBM’s Person-to-Person video conferencing to enable experimental performances (which included puppetry) between New York, St. Petersburg and Tokyo (Dixon, 2007, p.422). Elements of some of the performances (Faver, 2001) were projections of models created in VRML (Virtual Reality Modelling Language).

Both Lisa Naugle (working with technical collaborator and artist John Crawford) and Susan Kozel used the CU-SeeMe videoconferencing software (*CU-SeeMe*, n.d.) for experimentation and performance, such as with Naugle’s *Janus/Ghost Stories* (Naugle, 2002) between University of California and Arizona State University, and Kozel’s *Ghosts and Astronauts*

(Dodds, 2005, p.15) in 1997 between Riverside Studios and The Place Theatre in London. Kozel (2008) referred to the CU-SeeMe software as “the grainiest, most delayed, and pixelated option”, though there were not that many better, low-bandwidth and free options in the late-1990’s.

Two projects in the USA in 2001, *Technophobe and the Madman* (Rowe and Rolnick, 2004) and *Songs of Sorrow, Songs of Hope* (Naugle and Crawford, 2014) used a hardware approach to streaming. In both cases, the Vbrick (*Vbrick MPEG CODEC*, n.d.) MPEG-1 hardware video compression unit was employed. The USA’s academic network Internet2 provided the network connections.

Brazilian choreographer and dance researcher Ivani Santana has worked with the Arthron (Santana, 2014, p.134) streaming software application—developed by LAVID at the Universidade Federal da Paraíba (de Melo et al, 2010) in Brazil—to facilitate several networked dance performances over a period of 10 years, in North and South America, and with Europe. In *Versus*—the first networked dance performance in Brazil, in 2006, between Salvador and Brasilia—Santana manipulated video in Isadora to play with the scale of the performer projected at the remote locations (Santana, 2014a, p.133). In 2009, Santana, as part of the work group GTMDA, collaborated with Kònic Thtr on the project *e-pormundos afeto*. Involving more than 20 technicians (Santana, 2010), *e-pormundos afeto* connected dancers in Brazil and Barcelona while remote audience members, accessing the performance via a web interface, were presented as simple avatars on the screens in the spaces at each physical venue of the performance (Santana, 2014b).

Kònic Thtr, a multimedia arts and technology practice based in Barcelona, have also participated in networked performances, such as the 2$^{nd}$ and 3$^{rd}$ editions of *Near in the Distance*, an initiative of the Austrian national academic network ACOnet.  The 3$^{rd}$ edition of the performance in 2017 was a music and dance project with the audience in Linz, Austria; contributing musicians and dancers were in Barcelona, Prague, Rome, Mumbai, and Hailutoto, Finland (*review - near in the distance 3*, n.d.). It employed both LoLa and UltraGrid for streaming, running over networks with bandwidths of 1 to 10 Gbps, and employed a video aesthetic that could best be described as 1980’s pop video. Details of the project

*Similarities*, to which Konic contributed as one of the remote nodes of a Copenhagen centred performance, are discussed in Chapter 2.

In the UK, Pauline Brooks, at Liverpool John Moores University, has been involved with several networked dance and choreographic research initiatives.  In collaboration with Luke Kahlich at Temple University in Philadelphia, USA, between 2007 and 2012, they explored the possibilities of networked activity in dance education (Brooks, 2014). They used the Adobe web conferencing products (*What is Adobe Connect?,* n.d.) Macromedia Breeze, Adobe Connect and Connect Pro for the research and performances (Brooks, 2010). There was no experimentation in networked performance technologies beyond the use of audio and video for streaming. A follow up project “Making Connections Through the Fifth Wall: A New Creative Place for Performing Arts and Pedagogy in Higher Education” (Brooks et al 2015) in collaboration with the music department of Edinburgh Napier University and Nova Southeastern University, Fort Lauderdale, used the VisiMeet video conferencing software, supported by the UK national academic network Janet.

*The Adding Machine* (Brown and Hauck, 2008), a 2007 theatrical performance at Bradley University, with remote nodes at The University of Central Florida and The University of Waterloo, used a system which was a combination of the DVTS (*Digital Video Transport System*, n.d.) streaming software running on Windows, the commercial Polycom (n.d.) videoconferencing system, video mixers and Isadora software.

In 2015, *Ultraorbism*, the one venture of Catalan artist Marcel·lí Antúnez Roca into networked performance, a combination of theatrical performance, dance and multimedia, in which I participated, is discussed in Chapter 2.

Funded by the Culture Fund of the European Union, the research project “European Tele-Plateaus - Transnational Sites of Encounter and Co-production” was a collaboration in 2009-10 between partners in Madrid, Norrköping, and Prague, led by the Trans-Media-Akadamie Hellerau in Dresden (*ETP - European Tele-Plateaus*, 2010). The project attempted to create spaces for physical interaction in the four cities which “connect through the internet in order to generate a common interactive audio-visual environment for interactive dance performances and installations” (*Networked Bodies: ETP European Tele-plateaus*, 2010). The project did not send video between the test sites but rather audio, and data, using OSC as the messaging format. The research outcomes are not well documented (except in videos) but the team used tools such as Max/MSP (*Rehearsal Excerpts from European Tele-Plateau*, 2009, 2.32) to gather, manipulate and transmit data between sites. For example, the movements of a participant using motion capture in one location could be used to generate projected patterns in another location.

For the Vietnam Science and Technology Day in 2014, a networked performance using avatars was presented by the Daejeon based School of Culture and Technology in the Republic of Korea (Hee Soh and Goo, 2014). Avatars of dancers at venues in Korea and Malaysia "were created by obtaining the dataset of dancer's skeleton using Kinect and then from those data generating a graphic in the form of a human body using Max/MSP program". The avatar skeleton data from each remote venue was sent to Vietnam where the avatars were projected behind a stage to accompany the dancers physically present there. The approach of using avatars for remote visual representation of the physical performers in a networked performance has been proposed by the same group, as a possible solution to latency and reduction of bandwidth requirements in networked performances (Park et al, 2013). Sending the data required to produce a remote avatar is significantly less than if the video of the physical performer were communicated. The processing overhead is also lower due to less time being required to process motion capture data when compared to acquiring, processing, compressing and transmitting video streams. However, the approach reduces the potential for the networked performers to connect as their only visual connection is through a representative avatar: facilitating a working relationship between performers in networked performances is always a challenge, so reducing the performers remote manifestation to that of a skeleton tends to magnify this challenge. Furthermore, the latest generation of commercial computing solutions, powered by CPUs such as Intel i9 and AMD Ryzen Threadripper series of CPUs, combined with the increasing availability of affordable, high-bandwidth networks, means that any advantages of networking avatars rather than video is insignificant in most cases, especially so, when one considers the artistic and aesthetic advantages of video.

*Worlds* (2015) is one of the few networked performance projects to have employed a live VR environment, using the Unreal 4 software platform (*Unreal Engine*, n.d.). Pepper's

Ghost, a Canadian arts organisation, produced the collaborative research project which was demonstrated as ISEA 2015, between Vancouver and Montreal. Control of virtual world elements inside Unreal 4 could be managed by an external controller using OSC messaging (Lantin et al, 2017).

*The Infinite Bridge (*2015*)* a "multimedia symphony" was developed by a team starting out from the Royal College of Music (RCM), London. Thought not originally devised as a networked performance, it was adapted to include networked performance elements to fit with its premiere during the NPAPW 2015 conference in London. The audience and majority of the performers were at the RCM. Remote performers contributed to the performance from Barcelona (dancers), Copenhagen and Helsinki (musicians). Streams were sent to London using Polycom (*Royal College of Music students*…, 2015). A sharkstooth scrim [12] positioned mid-stage was used as the projection surface in the Britten Theatre at the RCM. Resolume was used as a video server for digital animation files.

In 2018, TwinLab, a research collaboration between the University of Zurich and the City University of Hong Kong, used motion capture and the Unity[13] (*Unity for all*, n.d.) games engine to create avatars of the dancers at each end of the performance, in their project *The Hidden Formula &The Heavenly Palace (TwinLab Performance,* 2018*)*. UltraGrid was used to send video streams of the dancers (Liška, 2018), which were then composited with the avatars from Unity using the AR video mapping software SPARCK (*SPARCK Introduction*, n.d.). Motion capture data from the Optitrack motion capture system was sent to the remote location using Optitrack's own NatNet protocol (*NatNet SDK*, n.d.) running over UDP.

[12] A sharkstooth scrim is an open weave net that is frequently used in the theatre as a projection surface and for special effects. Depending on the lighting conditions, the scrim can appear to the audience as transparent or opaque. When lit from behind, the audience will be able to see those elements that are upstage of the scrim. When there is no light behind the scrim, then depending on the light in front (downstage) of the scrim, it can appear opaque and conceal what lays upstage. When scrim is used as projection surface, it can also help in giving the perception of depth or a three-dimensional feel to the image. The sharkstooth scrim is also known in European theatre as 'sharkstooth gauze' or 'tulle'.

[13] Unity is a software application that provides development tools and runtime environments for the production and execution of games on different target platforms. As the games which can be developed in Unity are real-time, can be visually complex, and support virtual and augmented reality environments, Unity also lends itself to the development of other types of applications which might not necessarily be classed as 'games'.

### 1.4.1. Typologies of networked performance

Reflecting on the projects discussed and referenced, and in consideration of my own practice, I have established a few key typologies for organisation, operation and performer/audience distribution in networked performances, namely:

- **Centric** - performances that revolve around one key location, and in which the audience are all at that one central location. The remote locations in the performance serve only to contribute artistic elements, music, dance, other action or site specifity, which is then transmitted to the environment of the key location. One would normally also expect that there are physically present performers in the central location. The transmission of audio, video or other data from the central location to the outlying nodes of the performance is purely to coordinate and synchronise the performance;

- **Off-Centric** - as with centric but in which there are some audience members, or other interaction with the performance (e.g. observers of the process), at locations other than the central node (where most of the audience are physically located), and for which viewpoint the dramaturgy is optimised, and the complete work is most coherent;

- **Asymmetric** - a networked performance in which all the nodes of the performance provide a near-equal level of engagement with the performance for the benefit of the audience members sited at each physical location. The viewpoint and experience at each node of the performance may be different but the level of engagement offered to the audience should be equally rewarding;

- **Symmetric** - a networked performance in which all the nodes of the performance, as regards performative actions, audience experience and any audience interactions, are near-identical. The level of audience experience and engagement at each node is near-identical, as is the mise en scène, save for the difference in venue and associated scale of stage or setup, and that the combination of performers that are physical and remote at each node are unique.

It should be noted that it is also possible that a performance with more than two nodes may be a hybrid of two or more of the networked performance typologies outlined above. For example, a performance that was of the symmetric typology between two nodes of the performance might have a third node which was purely a satellite, and which provided a location for performers but not for an audience. This third node would be more of the type found as a satellite node in a centric typology.  Although the performance is ostensibly of the symmetric type it also has attributes of the centric type.

For many reasons, the majority of networked performances have tended be of types centric or off-centric. This may be because of issues surrounding the availability of suitable venues (two or more normally being required on the same dates), project funding, audience development, availability and capabilities of partners with which to develop and operate networked performances, a low level of interest in or understanding of networked performance, technical and logistic aspects.

### 1.4.2. On venues for networked performance

Today, networked performances typically take place in academic or research friendly environments.  There is as yet little, if any, developed market for networked performance as an art form, and that is even more the case if we are to consider performances taking place on a commercial basis.

The result of this undeveloped market for networked performance has resulted in performances where one venue is often the primary venue (with an audience) and the other venues are providing locations for remote performers, perhaps with a small observational audience. *Opravdoví* (see: 4.3) is likely the first instance of a symmetric, independent, commercial, designed for touring, networked performance offering.

Although the projects discussed in this analysis of my networked performance practice are primarily of the type where a single venue has the greatest mass, the work has always been created with a mind to exploring the fullness of networked performance as a multi-venue distributed activity that involves both audiences and performers at each node of the performance. The supporting technical developments have also been so considered, even when they were only required, in-part, to incorporate and service the remote venues of a performance where one node was the primary place of audience.

### 1.4.3. Summary of technical components for networked performance

From an analysis of the referenced network performances, at least for those where technical details have been published, I summarise the technical approaches taken under the following categories:

- **Streaming** - from the review of current practice (and my direct observations of networked performances over the past decade) we can note that LoLa and UltraGrid are the low latency audio/video streaming solutions being used most frequently in contemporary networked performances in Europe and North America. In the case of networked music performances, jacktrip is a popular solution, sometimes being used in conjunction with a separate solution for the video streaming element of the performance. The Arthron application has also been popular in South America, and DVTS in Asia/Pacific, although the number of documented networked performances in these regions are far less than in Europe and North America. At the "low-tech" end of technical approaches to networked performance, and in some cases where the preferred "high-tech" solutions are not workable due to the likes of limited bandwidth and firewall issues, there is no one single preferred solution. The market for capable and low cost video conferencing solutions is a commercially volatile one, so practitioners have tended to use whatever is most popular in that period, or simply the one that they are familiar with. The commercial hardware and software video conferencing solutions produced by Polycom are also popular in networked performance and distance learning applications;

- **Data communication** - networked music performances have (in the experience of the author) most commonly used OSC, or less frequently, some form of MIDI over network solution, to transmit instrument and synchronisation data between nodes. The use of these protocols being to convey e.g. note on/off or note velocity information as opposed to digitally encoded audio streams. The use of data, as an adjunct to video and audio streaming, is much less common in other genres of networked performance, and where it has been used it is most likely to be OSC or some custom protocol running over UDP;

- **Toolbox applications** - Max/MSP, including its Jitter video tools, is the most commonly employed software application when processing, control and video manipulation functions are required to supplement audio/video streaming. Pure Data (n.d.) is a free alternative—an application with some of the same functionality and user approach as Max/MSP—has also been used (Naveda and Santana, 2014). As discussed, Isadora has been used in several networked performances to accomplish some of the same tasks. Tools such as VVVV (*vvvv - a multipurpose toolkit*, n.d.) have also been used (Rebelo and King, 2010);

- **Augmented and virtual reality** - VRML was used in a few projects, especially late 90s and early 2000's, for creation of avatars to be displayed or overlaid on streamed video. The very limited number of projects that have so far embraced the use of VR/AR platforms (such as Unity and Unreal) have used them to generate visuals or for hosting rigged avatars that are driven by motion capture data from live performers. I found no examples of such VR / games engines being used for placement and 3D real-time compositing of live video streams from nodes of a networked performance;

- **Video processing and presentation** - tools such as Max/MSP/Jitter, Isadora and Resolume have been used for manipulation and composition of video streams, with other streams, with pre-recorded video/animations or with live animations. Such tools have also been used for managing multiple displays in the physical performance space, and for projection mapping;

- **Distributed cue management** - the process by which cues for performers, video camera control, video switching, video manipulation, stream selection, video output, projection mapping, virtual and augmented reality, lighting, audio, instruments, sensors and actuators are managed and synchronised across the nodes of a networked performance. As most networked performances have been of type Centric, there has been relatively little need for a cue system which works across all the nodes of the performance; the central node in this typology then being operated by a group of technicians, depending on the complexity of the performance. Audio back channels, and video conferencing software, especially skype, appear to have been used most frequently for coordination and management of cues between technicians across nodes of the performances. Some performances have built cue management functions in Max/MSP, used custom software applications, or the cue sheet function in Isadora. Apart from some limited use of OSC for remote coordination, there is little in the way of documented approaches to this aspect of managing a networked performance, especially with respect to those of types Asymmetric and Symmetric;

- **Network infrastructure** - performances normally have to work with whatever network installation exists at the venue, yet little documentation is available about what has and hasn't worked, or what issues were encountered. In many cases, there will be a need to use a dedicated router, or additional switches to connect multiple items of equipment required to support the performance. Some recommendations of switches to avoid are provided in the LoLa system documentation but that is about all that is published as regards details of network components for use in networked performance;

- **System frameworks** - There are no published system frameworks or system integration guidelines for assembling the distributed systems to support networked performances. However, it might be argued that many networked performance projects use only simple audio or video streaming, do not require the use of additional technologies, or can employ larger teams of technicians to operate peripheral aspects, such as lighting and video, at each node of the performance, and therefore do not need to automate these. One exception is the detailed systems framework provided to configure the LoLa audio/video streaming solution. One networked music project that is fully documented in terms of its complete systems approach is the *Online Orchestra*, discussed in Chapter 4.

Whereas networked performances that are routed in theatre practice have extended their thinking from the networked realm to better encompass the space and affordances of the theatre environment as place, they have mostly continued to rely on the same technical setup within the venue that would be the case for non-networked performances. The technical focus has been on the streaming of video and audio, and the presentation of video within the physical performance space, not on the integration, synchronisation and automation of the systems of contemporary theatre (such as lighting) across the venues of the performance. In the few cases that computer generated realities haven been incorporated within the networked performance, these have tended to be for the sake of technical research rather than for an aesthetic value that is contextual to the dialogue, dramaturgy or choreography of the performance.

#### 1.4.4. The need for an integrated systems approach in networked performance

The need for a more integrated systems approach—one that gives the flexibility to support different types of networked performance—becomes essential when a practitioner moves out of the protected research environment and into 'commercial' performing arts venues, with their tight schedules for get-in and get-out, and a focus on reliable delivery and repeatability that is driven by a paying audience. In an academic or research scenario, there may be days or weeks available for setup, systems test and in-situ rehearsal in an environment where the supporting technologies and infrastructure are known to the practitioner, the technicians and performers. On entering the world of 'commercial' performing arts venues, when trying to operate a tour of such a technically complex performance, we lose the luxuries and securities that are, perhaps, taken for granted in the academic situation. In the commercial or touring environment, there is also the issue of cost, especially regarding the number of technicians required to operate a performance that is technically complex and that will occur in at least two geographically separated locations on each outing of the performance. It is not necessarily practical to have audio, lighting, video and network technicians at each node of the networked performance. An elegant systems framework for networked performance—especially for symmetric types and those that employ computer generated realities—needs to address the artistic, technical, financial and logistical challenges.

Though elements of the solution required to address these real-world needs is found in parts of the literature and practice review, I found no conclusive systems framework. In fact, most of the systems only fulfil the needs of limited areas of the functionality required, and typically, were assembled in 'safe' working environments, and for a one-off performance.

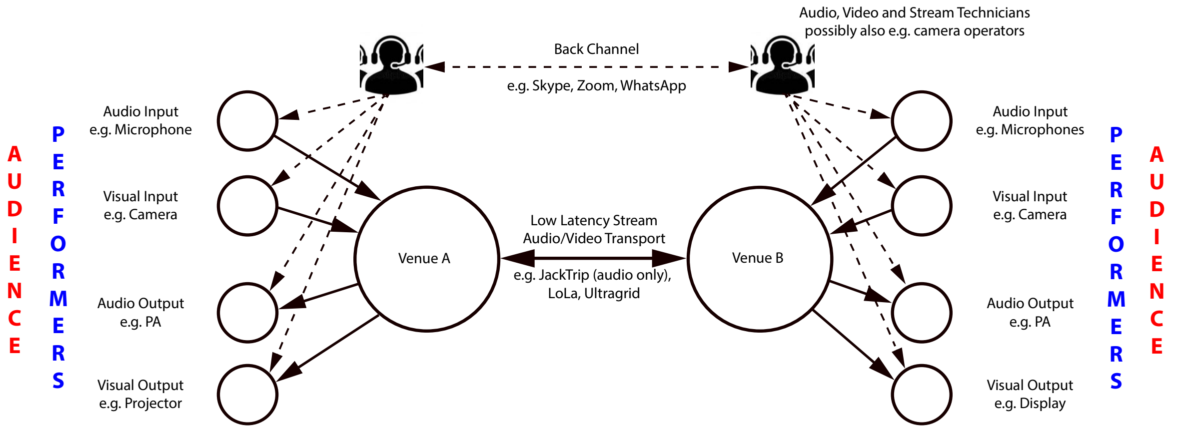


Figure 2: Example configuration of a symmetric networked performance – compare this to the more typical example of a centric networked performance (Figure 3) and that of a symmetric XR networked performance (Figure. 21).

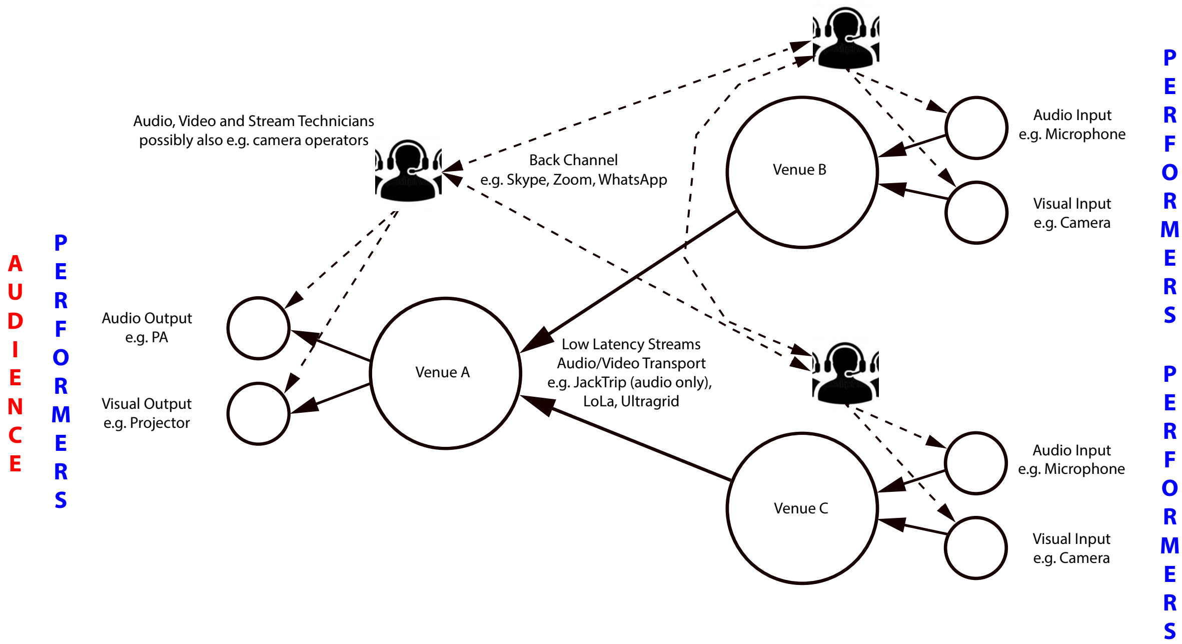


Figure 3: Example configuration of a centric networked performance – the more commonly encountered typology in contemporary networked performances.

## 1.5. Systems design and integration: a theoretical framework for XRNP

A theoretical framework for systems supporting the development and operation of XR networked performances is explored; it draws on my background in the development of similar complex distributed systems in the avionics industry.

### 1.5.1. Important factors for systems supporting arts practice

The design of systems incorporating contemporary technologies to support arts practice will likely involve unique processes; be—by its nature as an artistic activity—experimental; and expect or be open to unusual outcomes. By comparison, the tasks of complex systems design and integration in fields such as aerospace, automotive and power generation, tend to follow a more defined iterative process with clear requirements in mind at the outset. In these industries, the desire is normally for one of a rigorously specified design that will be embodied in a specific product (e.g. aeroplane, car, power station) with a clearly defined functionality and an expected lifespan where little or no changes will be required to the original product. This is not to say that in these fields of systems engineering there will not be changes once the product has been completed, just that change, and especially frequent and experimental changes with potentially undefined outcomes, are not expected or planned for as a regular activity within its lifecycle (with the exception of software updates, which are increasingly common). Though design rigour should be an integral feature of systems design for arts practice, I consider that there are some key differences:

- **Flexible** - systems of technology assembled for arts practice may be for a one-off event or tour, the lifecycle of which might be measured in days or weeks;
- **Reusable and modifiable** - the need for systems to be reusable, further developed or easily modified to support ongoing arts practice;
- **Experimental** - the potential for straightforward experimentation—even for unexpected outcomes that can spark new artistic concepts—is also desirable;

- **Cost effective** - whereas in most other fields of systems engineering the product either has a high volume (over which design costs can be shared) or an expected life cycle of tens-of-years (over which the design costs can be amortized) this is unlikely to be the situation with arts practice.

Additionally, in the case of a system for XR networked performances, I considered the distributed nature of the system that is required to support the multiple nodes of the performance. Though aeroplanes, cars and power stations do not operate alone in a vacuum (aeroplanes share airspace and communicate using radio or satellite; cars share roads, and increasingly will be equipped with systems to better cohabit them with other vehicles; and power stations operate as part of an electricity grid where loads must be balanced), a system for XRNP is an intrinsically distributed system of systems (see: Nielsen et al, 2015 for discussion regarding "Systems of Systems Engineering") that requires each node of the performance to operate independently and in unison in order to deliver the performance.

An approach to addressing these issues when building systems for arts practice is through the use of existing systems and component technologies, that is, ones that have already been developed and proven in other applications. The design focus then becomes one of identifying the available systems and components that can meet the overall systems requirement, and creating a design methodology in which they can be formed into a system of systems solution. To aid the integration process, the various systems components should have a common means of communication: to interface with each other, to collaborate and exchange information, or to receive commands. We also need this logic to satisfy our desires for a system architecture that supports flexibility in configuration: the ability to easily integrate new components that facilitate new artistic expressions, and to reduce the costs and complexity of integrating new components.

What approaches and frameworks can we take from the practice of systems design and systems integration in other fields?

### 1.5.2. The aerospace industry as an example of systems integration through which to examine systems approaches for the performing arts

The lack of an integrated systems approach—or of a systems framework—for the practice of networked performance (see: 1.4.4 ) led me to draw on my prior experience in other fields, where complex systems challenges are common and approaches have been developed. Especially, in the aerospace and defence sectors, the rigorous implementation of systems design and integration methods is common practice. Therefore, I examined the possibilities for applying my experience of system integration in other fields to that of my practice in networked performance. The results of this consideration were then used to develop a theoretical framework for the research into networked performance (especially X reality networked performance), and against which its practical application could be tested.

For 20 years, before I began my journey into arts practice, I was involved in the development of complex distributed systems for use in the process control, aerospace and mobile communications industries. In the world of aerospace, rigorous systems engineering is practiced at all levels of design and development. In the case of a commercial aeroplane, we are also looking at a system of systems, but one that is primarily confined to the fuselage. The aeroplane as a system, comprises many sub-systems, each of which is its own system. All the systems of the aeroplane need to work in a unified manner for the aeroplane to successfully transport passengers and goods from a to b. For an aeroplane, successful also means: safely, reliably and efficiently. Examples of the individual systems that make up the aeroplane, include hydraulics, fuel, avionics and environmental systems. The individual systems may be common (or similar) to many types of aeroplane or can be unique to one specific model. The avionics system—being a set of networked computers possessing the different functions required to operate the aeroplane, integrated using defined processes and interfaces—is the system that will be employed as an analogy for the investigation of our framework for the system to support XR networked performances. The avionics system in an aeroplane is also a system of systems, where systems, such as the flight management system, navigation system, and entertainment system, form part of the overall solution.

Systems design is the process of interpreting the requirements for a system and from that producing a design to fulfil those requirements, including the definition of architecture, components and interfaces. Systems integration is the process of configuring the sub-systems and components required to implement the design (see Houser, 2011, p.2). Systems engineering is the umbrella term for all aspects of design and integration. NASA (National Aeronautics and Space Administration), a designer and integrator of some of the most complex systems imaginable, states the function of systems engineering as "to integrate engineering disciplines in an elegant manner" (Watson, 2017, p.7)., and proposes that an elegant system is one "that is robust in application, fully meeting specified and adumbrated intent, is well structured, and is graceful in operation" (Watson, 2018, p.3).

Watson (2017, p.11) further comments on the importance of future intent, that is, the idea that the system's design should include consideration for future growth or adaption:

> *"there is a deep understanding of the system application in meeting intent without full specification in advance. This connotes the idea that in meeting the intent of the system, there are aspects of the system capabilities where one can naturally extend or configure to meet application needs not well defined during system development. Thus, working from options that meet the current system intent, one makes design choices that support natural extension or configuration of the system for future applications not fully known. The evolution of Apple iPods to iPhones to iPads is an example of a system design that supported expanding capabilities not clearly seen at the beginning of the development. The idea of what they could do was there, but the specifics of how these would work in future applications were not fully clear".*

The idea that systems design, as a process, might embody the requirements of an evolving solution that is not fully understood when design commences, echoes the desire of systems for artistic practice. One where a system that was developed purely around the genesis requirements, that lacked the ability to easily adapt and grow, is likely to stymie artistic development and exploration.

The two processes (design and integration) are closely related and, in many cases, performed by the same organisation. For example, large aeroplane manufacturers, such as Boeing and Airbus, produce the design for the aeroplane and perform the systems integration role as one of their key business differentiators. On such large scale, complex projects, the suppliers of major sub-systems, such as the flight control system or the engine management system, will also manage a design and system integration process at the sub-system level, as a supplier to the aeroplane designer. These will be part of an integrated systems design and integration approach flowed-down from the customer (e.g. Boeing) or developed in partnership with them. To aid in the successful integration of these major sub-systems, the avionics are designed around agreed international standards that define, for example, the physical and logical interfaces between the systems components. This approach is beneficial in terms of supplier choice: sub-systems as functional components, which to some extent can be more easily replaced by alternative components. And, for breaking down the overall system into logical sub-systems that can be tested and verified as such before being “mated” with the other sub-systems to complete the objective systems solution: the avionics system for the aeroplane.

To understand what we can draw on from the world of aerospace and avionics systems, I examined the factors and design choices in consideration of that field and that of the performing arts.

In the aerospace industry, there are specific organisations that coordinate standards for systems and interoperability at an international level. In the world of commercial aerospace, the dominant standards body for avionics is ARINC (Aeronautical Radio, Incorporated). Manufacturers of avionics systems and the major aeroplane manufacturers are all involved in the development of new standards, and though they sometimes use proprietary systems and interfaces, they do, in the majority, collaborate to agree on standards. This process is also clearly in the interests of the commercial airline operators who want the least variety of avionics standards as possible to deal with, especially as they will often operate aeroplanes from more than one manufacture in their fleet. For example, the current generation of major aeroplanes from Boeing and Airbus (such as B787 and A350) have harmonised on using the AFDX (Avionics Full-Duplex Switched Ethernet) data network standard, documented as ARINC specification 664 (Schuster and Verma, 2008, p. 1.D.1-5). It is based on Ethernet (the IEEE 802.3 series of standards) with additions to guarantee deterministic behaviour and bandwidth availability. The core avionics systems on these aircraft then talk to each other over the same network, so if the flight management system needs information from the engine management system, it is available on the network.  Having common interfaces also means that when testing and integrating these sub-systems it is not necessary to have all the other sub-systems completed, or even in the same location, because they can be emulated by, for example, a computer with a compatible interface. This type of design therefore supports continuous integration. The AFDX aircraft data network is based on parts of the IEEE-802.3 standard (as used for Ethernet) but for reasons, such as redundancy and requirements for determinism without any jitter, that are essential in applications such as fly-by-wire, uses a custom protocol and switching architecture. However, the important aspect for our comparison is that, regardless of functionality, all sub-systems can communicate using a common physical interface and communications protocol.

In the world of the performing arts—in theatres, concert halls and venues for dance—there is no equivalent overriding industry body that aids in the specification, or produces standards, of the type or scope that are present in the aerospace industry. Although there are a wide range of standards for systems and interfaces for the equipment used in such venues, each type of equipment (audio, lighting, video) uses standards from a different industry body, or proprietary interfaces and communication protocols.  For example, audio and instrument systems may have a MIDI interface or other standardised functionality that has been developed and agreed by the music industry; lighting systems may have DMX and Art-Net interfaces which have been agreed by the lighting industry; remote controlled cameras use VISCA or other proprietary protocols, such as that from Blackmagic Design which operates over SDI;  projector control is normally proprietary to each major brand; and digital video switchers and digital video recorders may be equipped with Ethernet interfaces but will typically use different protocols (sometimes not easily accessible by third- party applications) to control them from external applications.

One can consider that historically, the different systems in performing arts venues did not necessarily need to communicate or be tightly integrated to deliver a performance. That is, until the arrival of performances that increasingly use multimedia and require synchronised operation of lights, audio, video, etc. There has also been a tradition of employing dedicated technicians for the operation of lights and audio, and now frequently also for video. In XR networked performances, where we look to coordinate the operation of all these elements—not just within an individual venue but across all the venues within the performance—this approach presents additional problems, especially as regards :synchronisation, the number of technicians that would be required (cost and availability) and how they would communicate efficiently during a performance.

Where software music, light and video applications are concerned, these are normally running on a Windows or Mac-based system and have access to an Ethernet network connection. Historically, some of these applications have been provided with a MIDI interface even though they were not music related applications. This practice has resulted in some often-curious mappings of MIDI parameters to non-music functions within the application. Increasingly, such applications are now also provided with an interface that supports the Open Sound Control (OSC) message format. OSC is a relatively simple message format: one that that can run over different physical layers and between software applications. It can utilise different communications protocols, though most commonly this is UDP/IP (User Datagram Protocol/Internet Protocol) or TCP/IP (Transmission Control Protocol/Internet Protocol). OSC is discussed in Chapter 3 as the message format that has been selected to facilitate the continuous integration and operation of systems for XR networked performance.

The field of avionics systems design and integration, with its use of standardised interfaces and protocols across sub-systems that implement a wide range of different functionality, provides an exemplar for what is missing in the world of integrated solutions for the performing arts. However, the world of aerospace is one with significantly higher complexity —especially as regards safety and redundancy—and therefore one that requires more rigorous design strategies (also, therefore, much higher costs) than are practical in the performing arts.

Systems design and integration activity does clearly take place in the word of performing art. However, it is on a much less formal basis and with no similar oversight organisation to maintain standards that work across all the types of technical sub-systems required in contemporary, digitally mediated performances.

Historically, the process of systems integration was often performed on the basis of what is now referred to as ‘big bang’ (Ibrahim and Pyster, 2004, p. 47), in which the integration process only commenced once all the modules or sub-systems were completed and assembled in one location to commence integration. The contemporary approach is one of “continuous integration” (Houser, 2011, p. 5), where integration is performed as an ongoing process during the development cycle: a continuous process of building, integrating and testing. This approach is particularly common in software development (Duvall et al, 2007) where daily builds of code from members of a development team are tested. The primary advantage of continuous integration over big bang integration is that the risks of integration, and potential issues arising from that process, are spread over the development cycle and risks are mitigated as they are identified as part of the development process.

An evolution of the continuous integration process is the introduction of "continuous delivery" (Humble and Farley, 2010). This is primarily relevant to software aspects of the system, and relates to the rapid release of new functionality, opportune as a result of the continuous integration process of new features as they are developed. Examples of this practice are the automatic upgrade processes we now experience with the likes of Windows 10, and with iOS and Android mobile devices. As an upside in these examples, it means customers get the latest functionality as soon as possible. As a downside, instabilities can be quickly released into the product if sufficient testing has not been performed during the continuous integration and delivery process; it can also lead to a loss of configuration control and stability which can be critical for those who use these products within larger systems.

It has been shown, from this discussion of system engineering in other fields, that there exists in continuous integration a process whereby sub-systems can be integrated as they are developed, and released to service on the basis of continuous delivery. This approach serves the requirements of a systems platform for arts practice, fulfilling the need to integrate existing systems components in a flexible way that supports changing needs and experimentation.

An important aspect to the success of the continuous integration process is that sub-systems and components are implemented with a well-defined set of interfaces and protocols. As such, the need for a systems design approach that utilises a common means of communication between sub-systems is considered a critical factor in the development of systems to support XR networked performance.

### 1.5.3. Criteria for XRNP systems framework

The theoretical framework for this research addresses the need to examine a systems integration approach to the provision of systems for XR networked performance, one that likely employs a limited set of strongly-defined interfaces and communication protocols that are based on open and industry standards. Specifically, the framework should consider if the research outcome meets the following criteria:

- **ELEGANT[14] - provides a solution—one that is ingenious and simple—for the continuous integration and delivery of the sub-systems and functionality required for XR networked performances**. An elegant solution will likely facilitate the delivery of other requirements in this framework and provide the ease with which changes to the system functionality are accomplished;

- **DETERMINISTIC - delivers a system that is deterministic within the bounds required by XR networked performances**. The successful implementation of an XRNP requires that the underlying system is deterministic, especially so, in its ability to support repeatability in the artistic constructs of the performance that relate to time. There is not one time-measure of determinism, or percentage of acceptable jitter, that can be defined as the standard rule for an XRNP system. It is the ability to have a system designed so that determinism can be understood, and that events can be deterministically repeated given the same set of circumstances across multiple occurrences;

- **RELIABLE - provides a system that is reliable within the bounds required to deliver and tour such performances**. The level of reliability required is not comparable with that expected, say, in aerospace or automotive applications where lives may depend on the reliability of the systems concerned. However, the reliability should be such that a performance would not ordinarily be cancelled or negatively impacted by the reliability of the system. Though it may not be financially prudent to have redundant systems to enhance the reliability, attention to design detail, selection of

[14] Madni, (2014) defines 'elegant' in a systems design context as one that "offers required functionality with minimum structural complexity. It is cost-effective and exhibits predictable behaviour". See also: 1.5.2

appropriate technologies, the ruggedness of integration, and the possibility for inclusion of manual backups or overrides of systems functions where appropriate, can all aid in increasing reliability. The solution should also support an efficient and timely get-in and get-out process at performance venues without sacrificing reliability. To take XRNP projects out of the 'protective' environment of research and academia, and into more 'commercial' performing constructs, it is necessary that the systems supporting performances are reliable (to a greater extent than that which might be acceptable in a non-commercial, research environment) in addition to fulfilling the artistic and technical requirements.;

- **EXTENDABLE - ensures that the sub-systems to support the different technical and operational requirements—both now and in the future—can be easily integrated and will be able to collaborate with existing components of the system.** As a wide range of technologies are necessary to meet the functional and artistic requirements of XR networked performances, the systems design and architecture should support the integration of new components when needed. The ease with which such new functionality can be incorporated into the framework will also have an impact on the time and costs involved in their integration;

- **SCALABLE - successfully operates at all scales of a performance, regardless of its complexity: the number of nodes and the resources that might be required to deliver it.** XR networked performances can vary widely in their complexity, such as in the number of nodes in a performance, and in the functionality required to deliver the artistic vision. The system design should therefore be one that scales across the nodes of an XRNP without sacrificing reliability or determinism;

- **RECONFIGURABLE - is flexible in terms of its ability to support different modes of operation and variations in its configuration.** XR networked performances require different levels of systems functionality depending on the artistic constructs and configuration of each project. As such, it should not be necessary to rely on one single system configuration for all use cases. This requirement relates to factors including: cost of the system, complexity vs reliability, and the 'tourability'[15] of a project, that, where the amount of equipment to be transported can impact the options for touring. To support opportune availability of equipment and optimise the amount of systems hardware required for a specific project, software sub-systems should ideally be capable of executing on different platforms (such as macOS and Windows). In cases where collaboration is required between software sub-systems, such exchanges can be achieved regardless as to if the applications are hosted on the same host or across a network of computers. The reconfigurability of system hardware and software also supports the optimisation of resources and their deployment. The ease by which new configurations of the system can be accomplished also supports the desire for experimentation.

- **TESTABLE - is designed and implemented so that testing can easily be conducted during integration and to support the process of fault or problem identification.** To enable the process of continuous integration, reconfigurability, scalability and reliability, a modular system, one that incorporates many sub-systems, should be capable of being broken-down into functional components for the purposes of testing. A complex system of systems that does not provide for test at the module (sub-system) level will be inherently one in which it is hard to isolate faults or determine weaknesses during the integration process.

- **COST-EFFECTIVE - this most likely being achieved by the ability to easily incorporate existing sub-systems from commercial or open-source suppliers, supporting the use of alternatives and reducing the need for the development of proprietary sub-system solutions or components**. Systems for XRNP are necessarily complex and may require the use of technologies which are not so commonly used in other performing arts practices. The costs of providing such systems to be measured against the opportunities they provide and in consideration of generally limited financial support. The prudent selection of technologies and component sub-systems available from existing sources—rather than developing solutions

[15] Tourability: the ease and ability with which an artistic production and set of supporting equipment can be toured. See: (Oppermann et al, 2011, p. 233) for example of use.

completely from scratch—can significantly aid in controlling costs. The government, aerospace and defence sectors often refer to such products (Baron, 2006) as COTS (Commercial Off-The-Shelf). A second category of available products, that can be useful when considering outsourced components, are those classed as MOTS (Modifiable Off-The-Shelf) technologies. Such MOTS components might include commercial or open-source software that includes the source code and can therefore be modified and updated to meet changing requirements.

## 1.6. Methodology

In my own practice, it is sometimes difficult to say whether a technical problem that needed to be addressed led to an artistic possibility, or whether it was an artistic concept that produced the need for a technical solution through which to deliver it. It would certainly be true, however, to say that my practice is in a constant state of flux between the worlds of art and technology: I am equally excited to investigate the possibilities of new technologies as I am by artistic concepts developed outside the bounds of technology. With this in mind, the technical discoveries and system implementations discussed in this thesis are written as a dialogue between the artistic concept and the outcome for which they were conceived.

The research methodology is therefore grounded in the arts practice that it supports and by which it is tested. Though the artistic outcome, the reaction by the audience and peers to each new work, is of course of interest to me as an arts practitioner, it is the performance of the supporting technical system which provides the basis on which the research question can be evaluated. Furthermore, has the performance established the adequacy of the proposed solution when tested against the systems framework that this research proposes? That being: the use of a systems integration approach to provide a technical platform for X reality networked performances, one that employs strongly-defined interfaces and communication protocols, and that is based on open and industry standards.

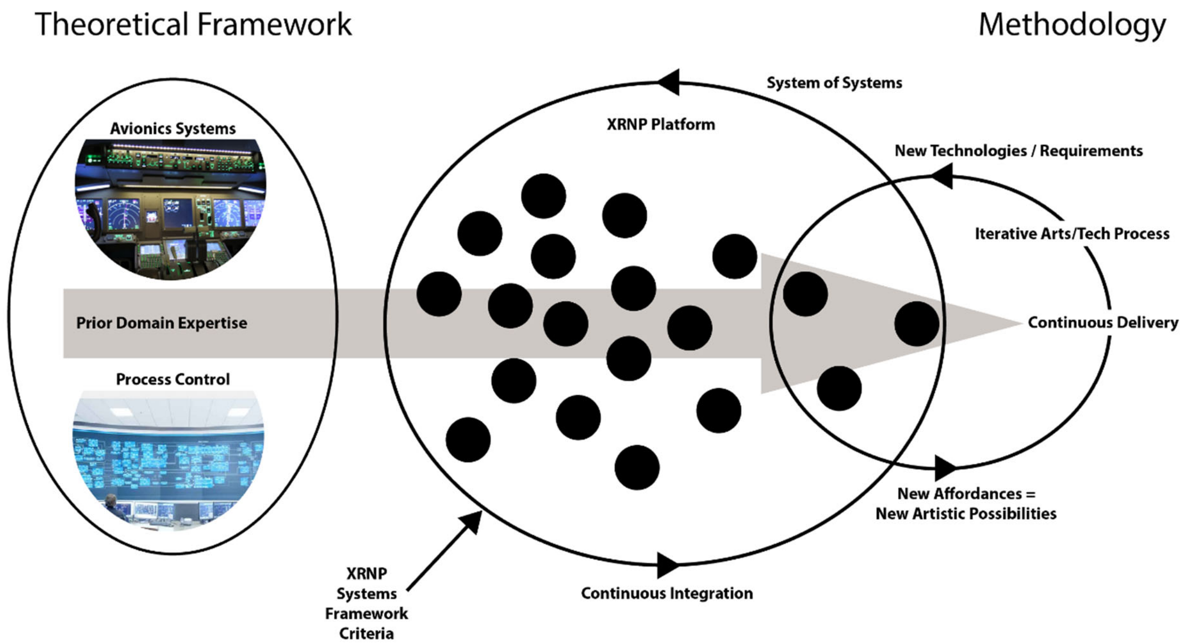


Figure 4: Mapping of methodology and theoretical framework as employed in this research.

The methodology also draws on my prior experience in systems design external to the world of the performing arts, especially from the domain of aerospace and avionics (as outlined in 1.5.2). It is based on the practice of continuous integration and delivery: where new functionality is incrementally[16] integrated into the systems platform as part of an iterative[17] process of artistic and technical exploration, tested within the act of performance. This practice is also common in the wider software development industry, such as in the Agile[18] approach.

The integration of new functionality can arise from an identified artistic need, or the availability of a new technology or component sub-system that might provide new artistic opportunities or improve the use and operation of the platform. Each iteration of the platform benefits from these new technologies and the artistic affordances they provide. In

[16] An incremental approach is one where the design of an expandable system can be delivered or commissioned in stages and wherein each stage provides additional capability (Paul et al. 1989).
[17] An iterative process within software and systems development has been defined by NASA (2014) as "the application of a process to the same product or set of products to correct a discovered discrepancy or other variation of requirements".
[18] Agile is a set of umbrella methodologies that recommended best practices for software development and that includes recommendations such as continuous integration, delivery and improvement. The approach was first outlined in the *Agile Manifesto* (Fowler and Highsmith, 2001).

some cases, technological components may also be removed or replaced: if they have proven unreliable; because an improvement is available, or potentially because no interesting artistic affordances were seen to be derived from the inclusion of that functionality.

The projects conducted for this research have followed my personal interest in the potential of XR networked performance. While projects were artistically led, I used technology to enable the development and realisation of new artistic concepts and performative constructs. It was a process of testing the systems framework. One, where the progression in evolution of each new performance has not been driven purely by the need to test new technical functionality. Each performance presented a real need for the system functionality: additions to the technical system were required to enable each iteration of performance development and to deliver the artistic outcome. This art-technology practice tested the question as to whether the message-based approach to communication and systems integration is a suitable one: not purely from a pre-envisioned timetable of engineering tests but from a set of artistic challenges.

Though artistic and technical concepts were formed during the early stages of the research, there are four core projects (conceived, produced and delivered between 2017 and 2019) that have been used to conduct and test the research. The four performance projects are detailed in Chapter 4. For each of these projects, a detailed description of the artistic concept, realisation, technical evolution, and outcomes is provided.

The outcomes of the projects are summarised in conclusion in the final Chapter of this thesis.

# 2. ESTABLISHING A PRACTICE IN NETWORKED PERFORMANCE

In this Chapter I explore some of the projects that introduced me to networked performance and through which I started to develop a concept for my own practice. They also contributed to the realisation of the need for a systems framework through which to support that activity. Details of the projects in which I commenced the process of experimentation with some of the technologies and methods of working, and which I would later adapt as core practice, are also described. The first two networked performance projects I produced (*Here, Not Here, Where?* and *Bridge To Everywhere: 234*) are also described in this Chapter; although they made significant contributions to the formation of this research and my practice, they were not the vehicles through which the systems framework was tested. The networked performance projects which were used to iteratively explore and developed the framework for XR networked performance practice are detailed in Chapter 4.

## 2.1. Arriving at networked performance

In 2012, I developed a project with a fellow student at Falmouth University, Lucy Frears, which I titled ***The Garden of Collected Consciousness*** and which Frears had titled *The Secrets Garden* (Frears, 2016, p. 135). In reality, the project had a different focus for each of its collaborators. For Frears, it was an opportunity to test her ongoing developments of a locative media application. For me, the work was effectively a very high-latency (a delay of hours between acquisition and presentation) networked performance, albeit one in which the audience and the information moved between the two spaces of the performance: the walled garden and the studio space. The work was situated at the segue of my research into cognitive environments and my interest in developing work in an artistic practice that investigated the relationship of technological networks and art, of connections across space and time. The *Garden of Collected Consciousness*—through the mobile application being developed as part of Frears research—presented a series of prompts and questions to strollers in a walled garden on the campus. The responses to these prompts were anonymised, specifically, because we expected that some of the responses would be extremely personal in nature due to the matter of the questions given. In an adjacent studio space, I had created a projection mapped, surround-visual that attempted to recreate the feeling of the walled garden. At random intervals, on small parts of the walls, in the cracks of the derelict glasshouse, across the grass, were displayed the text of the messages that the strollers in the physical walled garden had previously entered via their mobiles. On entering the studio, the same people are presented with their collective responses to the experience of walking in the real walled garden earlier that day.

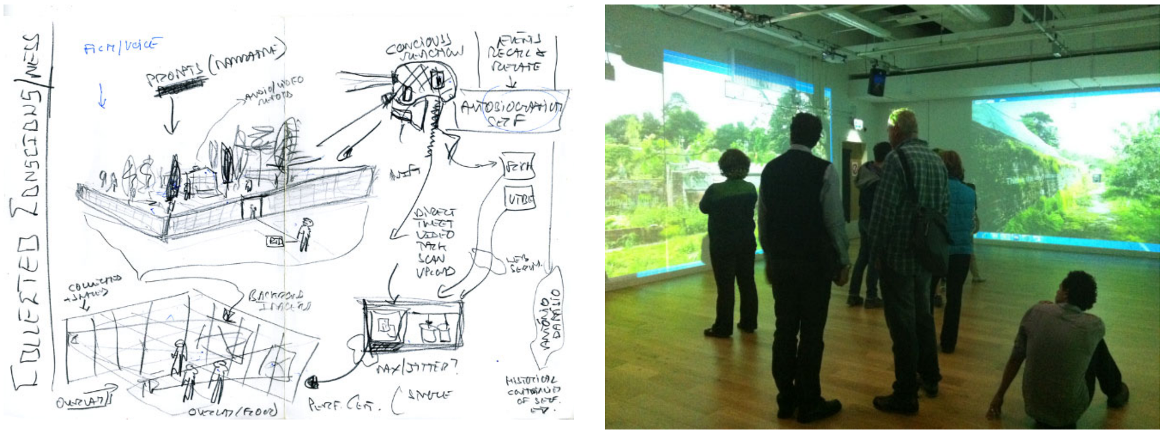

Figure 5: *The Garden of Collected Consciousness* (2012) concept sketch (left) and view of projection mapped installation of virtual garden (right).

The project was my first foray into multi-projector mapping and use of Max/MSP for visual programming. A serendipitous outcome of this project was an invitation by Professor Phil Stenton of Falmouth University to assist in a research project. ***Vconect***, an EU funded research programme that involved a partnership between Falmouth University and several leading telecommunications and research institutes across Europe, was conducting research into new forms of video conferencing, primarily aimed at the business community.

The *Vconect* programme (Ursu et al, 2014) went beyond point-to-point streaming in that it was exploring the use of “cloud” based video routers that would be able to route video between multiple nodes in a conference. It included the development of components for audio/video capture, composition, network optimisation and orchestration (Weiss et al, 2014).

The first initiative in this new collaboration (working with Erik Geelhoed from Falmouth University) was to take the multi-projector system designed for *The Garden of Collected Consciousness* and develop a simple CAVE (Cave Automatic Virtual Environment) like environment in which we could test the idea of a more immersive telepresence environment for dance education. Normally, the "CAVE" acronym is used to describe an environment where three or more surrounding surfaces are formed of displays (projected, flat panel or other methods) and the user wears a head tracking mechanism, so that the projections on the inside of the CAVE can be adjusted for the perspective of the user (Cruz et al, 1992). The addition of stereoscopic shutter glasses allows for projection frames to be synchronised with alternate left/right-eye viewing so as to enhance the perception of depth in the virtual environment. Although we were not attempting to create a virtual environment, we felt that the use of the same acronym was not irregular. Our objective—however crude at this point—was to create a displaced simulacrum of one location inside another location, that shared similar physical dimensions and physical properties. A form of augmented reality, wherein the augmentation of one physical environment was not virtually created, but that was that of another physical reality and the objects (teacher, dance students, etc.). that inhabited that other, remote, physical reality.

Initially, we linked adjacent dance studios back-to-back. There was no networking involved; we simply connected the output of cameras in one studio to the projectors in the other studio using long HDMI cables, and vice versa. Microphones and speakers were similarly connected using long audio cables between audio desks in each studio. On each of three-walls in each studio there was a projection of a view of the camera from the same position in the adjacent studio. The setup was tested in a scenario of remote dance education, with a dance lecturer in one studio and students of dance in the second studio (*Superfast Broadband Vconect on-line CAVEs*, 2013).

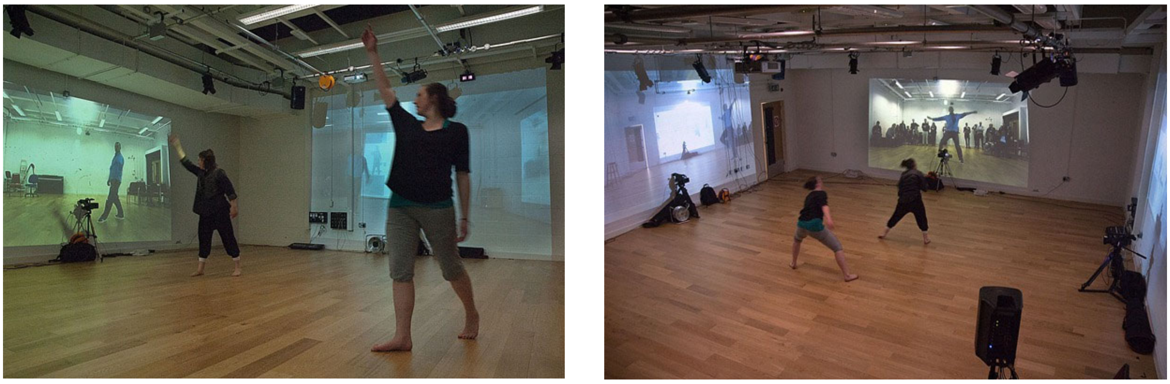

Figure 6: Projected CAVE-like environment for networked dance at
Falmouth University (2012).

In the next step, I produced a patch in Max/MSP that ran on a Windows PC in each of the studios. The mix of three video streams from each studio was then sent over a 1 Gbps direct Ethernet link to the PC in the adjacent studio. The Max patch used the *jit.net.send* and *jit.net.rcv* components, which basically send a complete uncompressed jitter matrix via TCP in each frame.  Other functions within the patch managed camera selection, projector output, scaling and remote control of the other node.

As a further experiment, we tested this approach in 2013 using Falmouth University's campus network, on the occasion of a visit by the HRH Earl of Wessex (*Cornwall's University Campus welcomes His Royal Highness The Earl of Wessex*, 2013).  On this occasion, we again used one of the dance studios in the Performance Centre building, and for the second node, set up a temporary performance space in the AIR (Academy for Innovation & Research) building, at the other end of the campus, approximately 400 m distant.

The demonstration was successful but the inadequacies of using the Jitter components of Max/MSP for streaming audio and video—even across a campus VLAN—were evident.  With the three video streams, each-way operating at low resolutions (640x480) we were using a full 1 Gbps of bandwidth in each direction; close to the limits of the campus network infrastructure at that time. The video streams exhibited quite high latency at times; though we did not make precise measurements this was evident from the sometimes-strained interaction between the dance lecturer in the remote dance studio and the dance student in the temporary "CAVE" space within the AIR building.

Apart from the challenges of high network loads and the inefficiencies of standard Max/MSP objects for video streaming (the understanding of which itself was a valuable learning outcome) we could show the usefulness of the general concept and learnt a lot about camera and projector positioning, lighting and human factors in telepresence education, during these formative tests.

Following these purely 'in-house' experiments, conducted as an adjunct to the core *Vconect* programme, and in which we had not yet tapped into the full technical resources of the *Vconect* team, we then took the projector, video camera system, workstations and knowledge, and grafted this onto the *Vconect* platform. The objective of this activity was to run a series of experiments as a part of the "Performance Use Case" (Ursu et al, 2014, p.2) within the *Vconect* programme. These experiments would investigate "Smart Video Communication to Support Innovative Multi-Site Theatrical Performances" using the *Vconect* technology demonstrator.

The first small test was in support of a *Vconect* technology demonstration between Falmouth University and an exhibition booth at the ICT 2013 Exhibition in Vilnius, Lithuania (*An Introduction to Vconect*, 2014, 0:40). This was also the first test of the working relationship with Miracle Theatre, a Cornish based theatre maker who had agreed to collaborate with the *Vconect* project in support of the performance use cases. The test involved an actor in a small studio in Falmouth, and a second actor at the exhibition booth in Vilnius, performing extracts from Beckett's ***Waiting for Godot.*** The short performances did not make significant contributions to either art or technology in the context of network performance. However, it was an opportunity to promote, and a learning experience in the use of Shakespeare's plays as networked performance scripts that was to be employed later in the project.

The second networked performance project working with the *Vconect* platform came about as an adjunct to another project that had been planned at Falmouth University. Jim Aitchison had composed a new score based on his analysis of ten paintings by the artist Gerhard Richter (*Richter scales: my musical response to the paintings of a great artist*, 2014). The piece ***Portraits for a Study*** was to be performed on a network of four Yamaha Disklaviers (*Disklavier™,* n.d.): pianos that can be controlled remotely through MIDI data, either locally or sent over an internet connection. The four nodes for the performance were: Falmouth University in Cornwall, the offices of Yamaha music in London, the Royal Academy of Music in London, and Goldsmiths University in London. In the first part of the performance, the pianos in the three London locations were coordinated by the piano in Falmouth, which was played by a physically present pianist. In the second part of the performance, a string quartet located in the Royal Academy of Music was broadcast to the other nodes.

Unfortunately, the challenges of the limited internet connections at some of the London nodes, some miscommunications as regards audio/video setup, coupled with the fact that aspects of the *Vconect* video router platform were still in development, led to some limitations within the performance itself. The Disklavier element worked perfectly but there were some difficult moments with the video, and especially the audio streaming using *Vconect*. The project also showed the potential risks of using a technology research platform in a public performance, especially where many of the audience were likely unaware of that condition. From this experience alone, I concluded the imperative that expectations of an audience in such "experimental" situations should be tempered as to the probability of failure. There were also important lessons regarding the provision of better back-channels for technicians to communicate across the nodes of a networked performance; ones which are not reliant on the same channel used for the performance streaming.

The final performance use case demonstration with *Vconect* was the staging of a two-node performance of Shakespeare's ***The Tempest*** (Geelhoed et al, 2014*)*. The performance was developed by Miracle Theatre as a re-staging of Shakespeare's original, designed so that the Island setting of the play was in one location and a setting for Prospero's "lair" was in the other. The audience was split across the two nodes. For reasons of practicality in running the experimental performance, it was decided that the two locations would be in separate venues, only a few hundred metres from each other in Falmouth. Though the locations were physically close, the streaming connections were still via the *Vconect* video conferencing platform routers in London.

For most of the duration of the performance, the audience in each node also received a view from the other audience onto their local stage. The performance used the *Vconect* platform for audio/video streaming. In each location there were 3 cameras. Each of these cameras could be remotely controlled from the PC in each node, but not across the network from the other node. A scripting tool allowed for the recall of specific camera shots (pan/tilt/zoom) and settings required in each scene. The video camera control was achieved using the VISCA[19] protocol with RS422 as the physical interface.

The *Vconect* programme had not originally been focused on the development of a platform for networked performance but it worked adequately in support of the "The Digital Tempest" project. Especially so, as regards video streaming, support for multiple cameras and displays, and experiments in video orchestration: the management of video sources and their distribution to different display devices.

Unfortunately, the experimental, and sometimes proprietary nature of some core components provided by the team members, meant that the core platform was not available for the likes of open-sourcing or easy commercialisation at the completion of the programme. If the technology had been open-sourced, then it would have been a useful addition to the technologies available for implementing the streaming component of networked performances. Tools such as UltraGrid and LoLa (discussed later) currently provide better solutions for the audio/video streaming functions within an overall networked performance systems architecture.

In these early days of my emerging practice in networked performance, there is one final project that is important to mention, one that came about as an indirect result of my participation in the *Vconect* program. In November, 2014, Erik Geelhoed and I were invited to make a presentation at the *Cocreation, distributed performances and alternative content for the big screen* workshop (2014) in Barcelona. During this conference, we met with Catalan artist and co-founder of the collective La Fura dels Baus, Marcel·lí Antúnez Roca.

He was embarking on a project, which was to be a performance as part of the EU funded SPECIFI (*Smart Platform Enabling the Creative Industries for the Future*, n.d.) and RICHES

[19] VISCA is a communications protocol for the remote control of digital video cameras, particularly those that have Pan Tilt Zoom (PTZ) capability. VISCA was originally designed to use either the RS232 or RS422 serial interface at the physical layer. Some manufacturers have subsequently implemented VISCA protocol running over UDP/IP for use with cameras that are equipped with an Ethernet interface, while some have implemented VISCA operating over the Universal Serial Bus (USB).

(*Renewal, Innovation and Change: Heritage and European Society*, n.d.) projects. The requirement was not unlike that for the performance use cases of *Vconect*, in that the project would also be an opportunity to showcase the audio/video streaming solution developed by Catalan research organisation i2cat. Since the project participants and Marcel·lí had been unable to find a technical partner with a suitable venue in which to locate the second node of the networked performance they had started to plan, we offered a space at Falmouth University, along with our expertise in such projects. The agreement to develop a networked performance between Cornwall and Barcelona was made: the project ***Ultraorbism*** (n.d.).

Though this was Marcel-li's first networked performance (or "Distributed Performance" as he and the projects partners would refer to it), he came with a rich background in performance, art and technologies, especially due to the use of computers and mechatronics in his own projects.  Marcel-li even has his own term for the dramaturgical use of computers in performance "Systematurgy" (*Systematurgy, Method and Examples of the Dramaturgies of Computational Systems*, n.d.). The project was realised as a multimedia performance (*Ultraorbism all Performance*, 2015) with actors and dancers; Marcel-li's interpretation of the *True Histories* by Lucian of Samosata. The project is relevant to the system and technical approaches to networked performance research discussed herein, as Marcel-li's technical team had developed—over many years—a systems approach to enable the sort of works he normally produced, involving mechatronics, projection and augmented reality. Their own platform *POL* was built partly around commercial equipment and partly on proprietary software, communications protocols and embedded electronics (Antúnez, 2016). For *Ultraorbism*, elements of the POL platform were coupled with the audio/video streaming solution provided by i2cat to enable the distributed technical platform for the performance.

## 2.2. Foundation projects

The two projects discussed in this section were at the early phases of my research and artistic practice in networked performance. They represent my first two solo projects, in which I originated the artistic concepts, designed and built the technical platform, and assembled a supporting team of collaborators that were necessary to implement the project. They draw on my own artistic interests and background in systems design, and on previous work in projects such as *Vconect*.

In each project, I looked to investigate a new artistic concept in networked performance and investigated new technical solutions through which to implement them. The outcomes of these two projects led to the decision to implement a coherent systems framework for future projects: one that built on the successes, from an understanding of the limitations of the technical approaches used in these projects, and one that would enable me to explore more complex artistic propositions.

### 2.2.1. Research objectives in foundation projects

In *Here, Not Here, Where?* many of the applications and hardware components I used were new to me. They were selected based on a review of the requirements, drawing on my background in systems design and integration, and a knowledge of products that might support the functionality I needed to implement a networked performance.

The key objectives as regards the technical platform for delivery of the performance, were therefore:

- Evaluation and selection of a software environment that could take a mixture of video streams and pre-recorded visuals, and under external program control, support the mapping of the composition to one or more projection surfaces;

- Evaluation and selection of an audio/video streaming solution, one that would support the connection of external cameras (either via HDMI or SDI interface) and with the ability that the video output from the receiver could be streamed into another application for compositing and projection mapping, rather than just displayed to a monitor;

For *The Bridge To Everywhere: 234*, the technical plan was to build on the successful elements employed in delivering *Here, Not Here, Where?* while the artistic ambition was developing, mutating and growing throughout the realisation of the project. The technical objectives in *The Bridge To Everywhere: 234* were primarily ones of investigating the scalability of the basic system developed for *Here, Not Here, Where?* and of testing its usefulness in a different artistic scenario. I also anticipated that I would use a live green-screen process as a part of the performance, so this meant that either the existing solution would need to support this, or that a new component would be required to provide that functionality.

### 2.2.2. Here, Not Here, Where?

In 2014, the UK's national research and education network (NREN) Janet (subsequently renamed as part of the Jisc organisation) had awarded me a research grant to pursue an Immersive Telepresence Environment for real-time interactive performances. The work to be conducted, primarily, at Falmouth University but also in conjunction with a remote partner: Contact Theatre in Manchester. One of the core objectives of my proposal was to demonstrate how—with sufficient bandwidth and use of Janet's high quality network—we could create an immersive networked performance environment. One, where rather than relying on a single screen image of the remote performers, the streams of the remote performers would be projected into different regions of the performance space. I had originally intended to make use of the streaming platform from the *Vconect* project (see: 2.1) but due to the lack of availability and complexity of the *Vconect* research platform, an alternative commercial solution Vsee (2015) was substituted as the audio/video streaming component. Vsee has been developed and marketed primarily as a video solution for telemedicine. As such, it has been developed with a flexible set of features and designed for use in situations where the latest network technology or high-bandwidth solutions are not necessarily available.

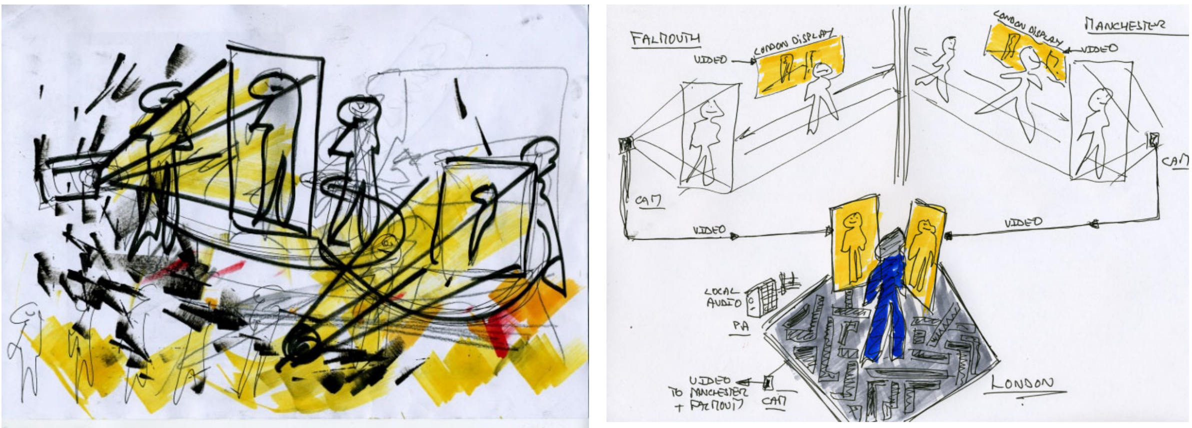


Figure 7: *Here, Not Here, Where?* (2015) concept sketches.

While Vsee is not billed as a low latency solution, it has proven to be a flexible option where latency is not key to the success of the networked performance. Vsee is especially useful where the ability to shape the network path is limited, such as the need to get through firewalls, or having no dedicated public IP address available for the project.

A series of teaching and experimental performances were conducted between Falmouth University and Contact Theatre, Manchester during development of the project, supported by Jason Crouch (2018) who worked at Contact. One agreed outcome for the project with Jisc was that a networked performance would be included in the 2015 edition of the Network Performing Arts Production Workshop (NPAPW), to be hosted by the Royal College of Music in London, in May of that year.

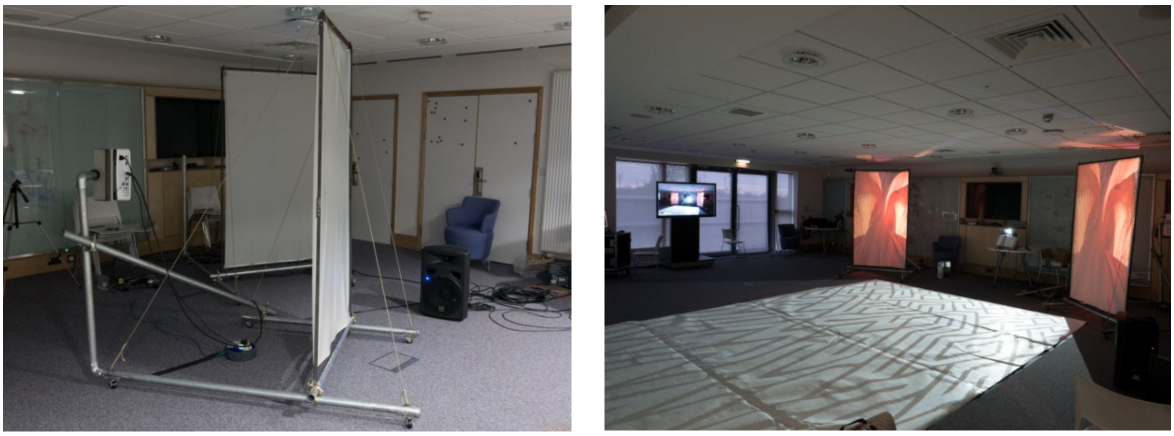

Figure 8: *Here, Not Here, Where?* (2015) in development at Falmouth University.

The concept for this performance was to take sounds and movements that were rooted in their local origin (Falmouth, Cornwall and Manchester) and project these into the performance space at the Royal College of Music (RCM). In London, there was another performer that represented the view from London and responded to the remote performances. So, this was a project that looked to mesh the site-specificity of the remote locations into the primary audience node at the RCM.

The venue for the performance at the RCM was the organ room of the Parry Rooms: a set of historic wooden-panelled and floored rooms at the very top of the building, tucked into the roof space, reached by spiral staircase, and facing the Royal Albert Hall. It had no capability for rigging and nothing could be attached to the surfaces of this listed building. With some difficulty, a portable free-standing truss was erected inside the room so that a projector could be mounted at sufficient height to illuminate the floor, which was covered with dance-matt flooring. A Falmouth-based fabricator was commissioned to construct two welded-steel frames with wheels and outriggers, which were designed to be disassembled for transport. These wheeled frames provided mountings for a vertical projection screen and back projector. The original intent had been that the performer in London would be able to move them around the floor during the performance. In reality, they were too heavy and the performance space inside the RCM was too small to achieve this objective.

In the performance, which was accompanied by sounds of textile machinery (Manchester) and mining machinery (Cornwall), the remote performers initially appeared separately on one of the mobile screens (video: *Here, Not Here, Where? - full performance*, 2015, 00:04:00 and 00:07:02). As the piece progressed, they moved to the floor where they connected in a group floorwork of two remote dancers and one physically present dancer (video: *Here, Not Here, Where? - full performance*, 2015, 00:10:55). The backgrounds of the video streams were effectively but crudely removed as the use of green screen and chroma keying was not possible in this project. The processed streams were then composited with pre-composed animations (which had been created in the arts programming environment Processing (2015)) using the commercial video software Resolume Arena (2015). Cueing of streams, audio and animations was all performed manually.

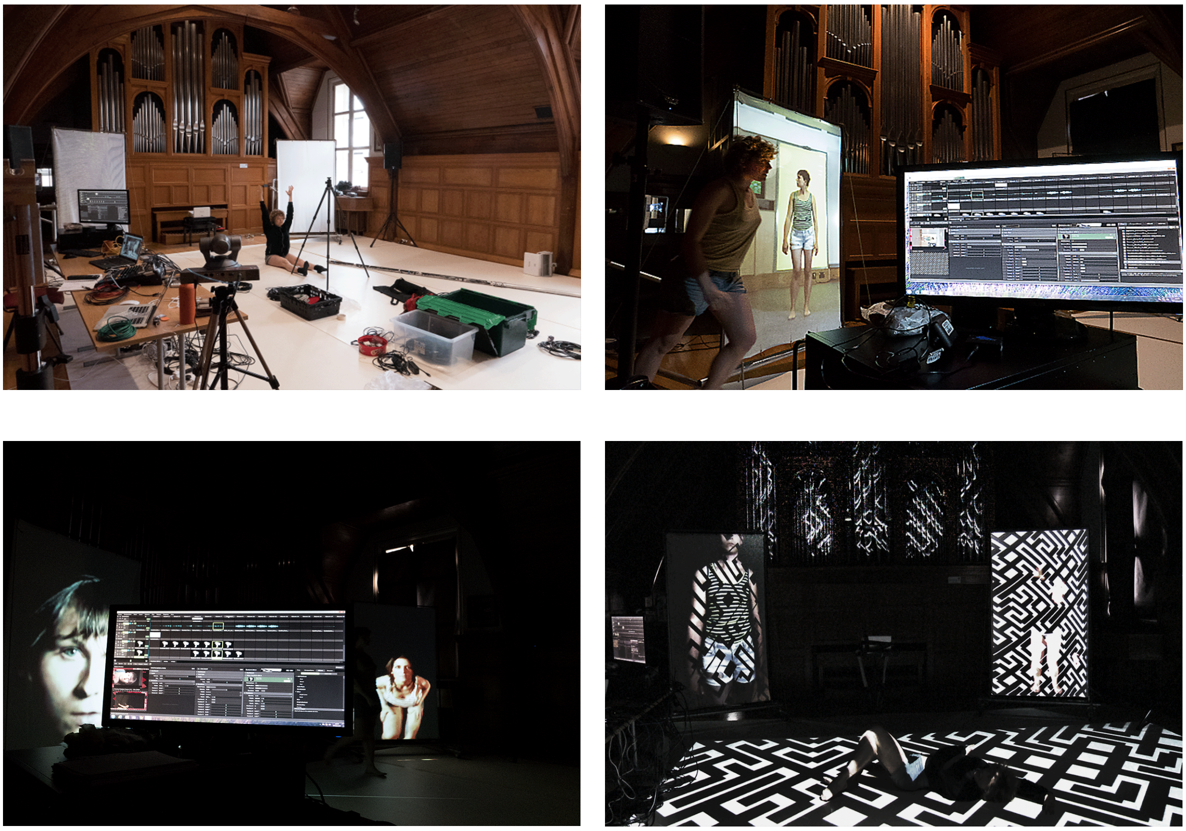

Figure 9: *Here, Not Here, Where* (2015) setup, rehearsal and performance in the Parry Rooms at the Royal College of Music, London, during NPAPW15.

The performance was well received by the London audience. There were two showings due to the limited space for an audience in the confines of the RCM's organ room.

A key learning outcome was that I would need solutions for reliable low latency audio/video streaming that had a greater ability to be integrated with other components and sub-systems, especially as regards exchanges of streamed video. I was aware of the initiatives of the Italian NREN, Garr and the Music Conservatory of Trieste with LoLa, and of the Czech NREN, Cesnet with UltraGrid (Holub et al, 2012), but felt they did not yet fulfil those needs. In any case, LoLa is optimised for networked music performances, and as such requires very specific hardware and only supports point-to-point operation: it is not suitable for multiple-camera setups, or where there are more than two nodes in a networked performance. In subsequent projects (detailed later in this Chapter and in Chapter 4), I have used UltraGrid extensively, as it has been developed over time to provide more functionality that supports integration into larger systems. I have also used LoLa, but in the specific cases where very low latency audio streaming was required as part of an audio/visual connection.


Figure 10: Covers of project overview for *Bridge To Everywhere: 234* (2016).

### 2.2.3. Bridge To Everywhere: 234

*Bridge To Everywhere: 234* marks an important point in my practice, artistically and conceptually, as a creator and producer of networked performances, but less so from a technical perspective. Although the technical challenge was high, the artistic, and especially the logistic challenges, were far greater on this first international solo project. It was *Bridge To Everywhere* that delivered on many artistic concepts I had been formulating for networked performance, since my first involvement with projects such as those in *Vconect*. Notably, the project also clearly established for me what the technical requirements were for future systems integrations to meet more advanced forms of networked performance, especially those where multiple nodes might be treated equally as regards their performative and audience propositions.

Having presented *Here, Not Here, Where?* at the 2015 edition of the NPAPW in London, I had subsequently proposed a more ambitious project for the next event in Miami, in 2016. The New World Symphony (NWS) in Miami Beach, Florida were to be the hosts. NWS along with Internet 2 (the primary academic internet provider in the US) had founded the NPAPW in 2003, with the NWS hosting the event for the first few years, and on a biannual basis until 2018. Since completion in 2011, the NWS have been housed in the Frank Gehry designed New World Center (Etherington, 2011), in Miami Beach, a few hundred metres from the beach front. This was therefore the venue for NPAPW 2016. The building is equipped with a comprehensive suite of audio and video technologies. Systems like LoLa are used daily for remote teaching and collaborations with music conservatories around the world. I was also attracted to the possibility of using their Wallcast system, a 650m$^2$ projection surface on the front of the building, illuminated by four 35,000 lumen HD projectors.

> *"Bridge to Everywhere (working title) - a telepresence theatre work that examines the cultural ties formed by immigrants between their adopted home and their place of origin; the links that are established virtually between these places and peoples through the Internet. Physical actors in Miami, multiple remote actors, maybe in several countries. Can also be additional cast members in/around Miami" Text of original proposal to NPAPW organising committee. In email (Biscoe, I., 2015, personal communication, 7 October).*

The artistic proposition was based around Miami being a relatively new city and one that has been formed by large immigrant communities. Immigrants from elsewhere in the United States but especially by those of Hispanic origin, mostly from South America, the largest percentage of which being Cuban. The proposal that the networked performance would be between Cuba and Miami was therefore agreed and set as the highlight performance of NPAPW 2016.

The core artistic concept for the performance was based around people who were born in Cuba but who now lived in Miami, the struggle to communicate with those friends and family members that remained behind in Cuba. I wanted to use imagery and music connected with Cuba but without some of the gloss that might form something of a typical tourist's view of Cuba. Specifically, I looked to create a networked dance performance where the dancers in Miami were of Cuban origin and the dancers in Havana were friends or fellow students from the time the Miami dancers still resided in Cuba. For the performance, we were fortunate to work with two dancers in Miami who knew the dancers in Havana; a third Miami performer was of Cuban ancestry but born in Florida.

The title *Bridge To Everywhere: 234* was a reflection on the seemingly unstoppable reach of the internet and the public's ability to access it, except where politics and geographies seek to prevent this. The title was also inspired by the bridges of Henry Flagler's Overseas Railroad (Standiford, 2002) which ran from mainland Florida to Key West, just 106 miles from Havana; no longer in use but which I had explored around 2003. 234, is the distance in miles between the New World Center in Miami Beach and central Havana.

With only three-months for development of the project, trying to find ways to work with Cuba, to establish a connection with collaborators, and find a communication link I could use to stream between Cuba and Miami, time was really in short supply and the logistical task was truly complex. Cuba has only two fibre optic connections to the outside world, one is through Venezuela (Frank, 2013), controlled by the Cuban Government. The second connection is from the Guantánamo Bay Naval Base to the US mainland (McCammon, 2015); this, clearly not being an option due to the security issues and that Guantánamo is effectively a US zone within Cuba that is completely isolated from the rest of Cuba and surrounded by minefields. Although the relationship between the US and Cuba had begun to thaw a little in the previous year—due to the presidency of Barack Obama—it was difficult to see how I would be able to get access to the required quality of internet connection in Cuba for the performance.

In 2016, the only public internet access was via a series of Wi-Fi hotspots in city streets, some state run cafes and hotel lounges. Use of the Internet was easily monitored as everyone had to be in the street to use it. Skype and many international websites were blocked. If a Cuban national was lucky and not seen as a "threat" then after some years of applying they might be able to get a home internet connection, but this was typically limited to just 64Kbps. To gain access to the public Wi-Fi it was necessary to cue at outlets of ETECSA (The Cuban state telecommunications monopoly), show proof of identity and pay around 1 CUC (around 1 USD at the time) for one hour of Internet access. Though not expensive to a foreign visitor, this amount is quite high considering that the average monthly salary is equivalent to 25 USD, though the actual unofficial amount may be closer to between 100 and 200 USD (Whitefield, 2016).

I tried to obtain official access to the "Internet" in Cuba for the project, many emails being exchanged with the Cuban NREN RedNet, and with the support of Internet2 (the US version of an NREN). Despite the technical possibility of the RedNet option, I was thwarted by the reality that it would take at least 3-4 months to get through Cuban government red-tape and also the unlikely possibility I would be successful due to no university Dean being prepared to risk sponsoring such an activity with the US mainland.

I also investigated satellite links (though not ideal for networked performance due to the much higher latency compared to terrestrial fibre links) but it was impractical logistically, and also from a customs perspective: bringing a suitable VSAT (Very-Small-Aperture-Terminal) device into the country likely leading to an arrest.

Figure 11: Development of *Bridge To Everywhere: 234* (2016) in Havana, Cuba with the dancers of the Rosario Cardenas Danza Combinatoria company. Right: a first experience of green screen for the Cuban dancers.

I then looked to the few Havana hotels that might be prepared to let us use their business conference rooms, several of which had 1-2Mbps internet connections that could be used by foreign guests, though not strictly for a networked performance with the US. This became our main hope in obtaining a performance link with Cuba, but just a few weeks before the NPAPW performance in mid-March, Barack Obama announced (Smith, 2016) that he would be the first US President to visit Cuba since 1928, the date of his visit to be the 21$^{st}$ March, the very week our performance would take place. The situation as to the possibility of using a Havana hotel business room for the performance immediately changed as all hotels announced they would close for that period and would only accept Cuban state endorsed visitors, members of the foreign press, and similar approved officials as guests. I managed to establish communication with the US Embassy in Havana (as they have their own internet connection) to see if they would help or if I could use a room in the embassy. Despite some sympathy and interest in the project they, understandably, expected to be overrun with work the week of the presidential visit.

Before arriving in Havana in March, I had managed to obtain the services of a local “fixer”, an agreement to work with dancers of the Rosario Cardenas Company, and some other potential locations and contacts who might be able to assist with providing an internet connection with Miami for the performance. In a little over one week in Cuba we had developed a choreography with the Havana dancers, trained our local Cuban crew in the use of streaming software and green-screens, and captured background video that would be used in the performance in Miami Beach.

However, despite meetings with several semi-state media organisations and museums—all of whom had some form of higher quality internet access available—I was not able to secure a suitable venue in Havana for the performance. On departing for Miami, the only solution remaining was to attempt to run the performance in Havana on the street, using a public Wi-Fi hotspot for connectivity; the possibility that this approach would have resulted in an interruption by the police was quite high.

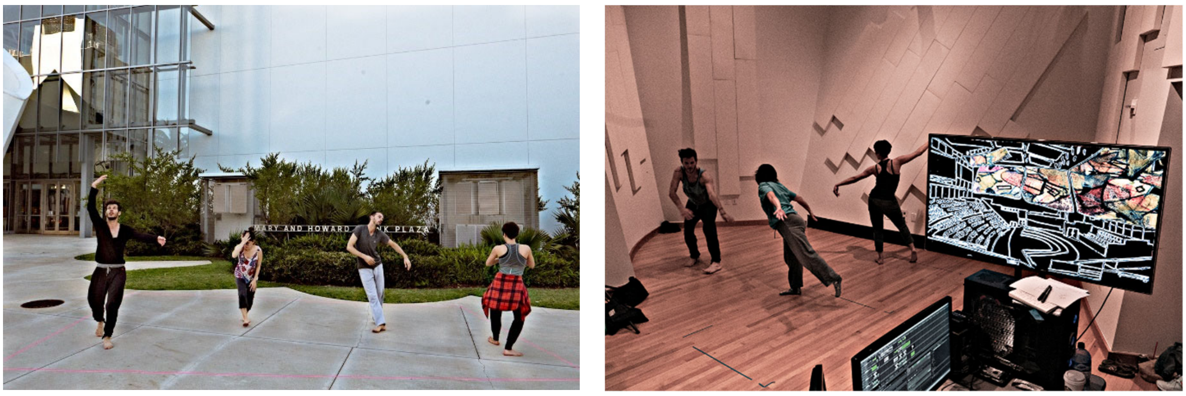

Figure 12: Development of *Bridge To Everywhere: 234* (2016) at the New World Center in Miami Beach. Left: the dancers (three of which are Cuban) rehearse in SoundScape Park. Right: the dancers rehearse inside one of the studios while I work on video compositions for the final scene.

The choreography for the performance was developed by Jana Bitterová, who ably built on the artistic concept and produced a work that incorporated the thematic of connections and breaks in connections: human and technological.

Music for the performance comprised a mix of Cuban traditional drumming; tracks from Cuban contemporary electronic music producers Nacional Electrónica; and a remix of some of their work by Miami musician and producer, DJ Le Spam. I felt Nacional Electrónica were particularly appropriate for the project, given that they had built their image from “old socialist propaganda magazines of the ‘70’s” (*Nacional Electrónica*, n.d.)  and were a complete counter-culture to the afro-Cuban or salsa styles that would might typify the music scene in Cuba. The complete playlist, acquisition of recordings and remixes, was accomplished while on the road, in Havana and in Miami at the studios of DJ Le Spam. The drummers, both from Cuba, were contracted to the project during a very late night meeting at a club in the Little Havana neighbourhood of Miami. Video and audio of the drummers was streamed live to the New World Center from the third-node of the networked performance, at Miami Light Project, a contemporary arts venue in the Wynwood district of Miami.

Serendipitously, the problem with lack of suitable internet access in Cuba was resolved just the day before the performance due to the unexpected assistance of a contact I made in Miami. Our Havana crew were therefore able to use a meeting room in a hotel some miles outside of the city of Havana, which had a 1 Mbps internet connection. On the night of the event, the dancers and crew travelled out of Havana city, locking themselves into the hotel's conference room for the period of the performance with Miami. I first saw the live video stream from Cuba about 20 minutes before the performance started.

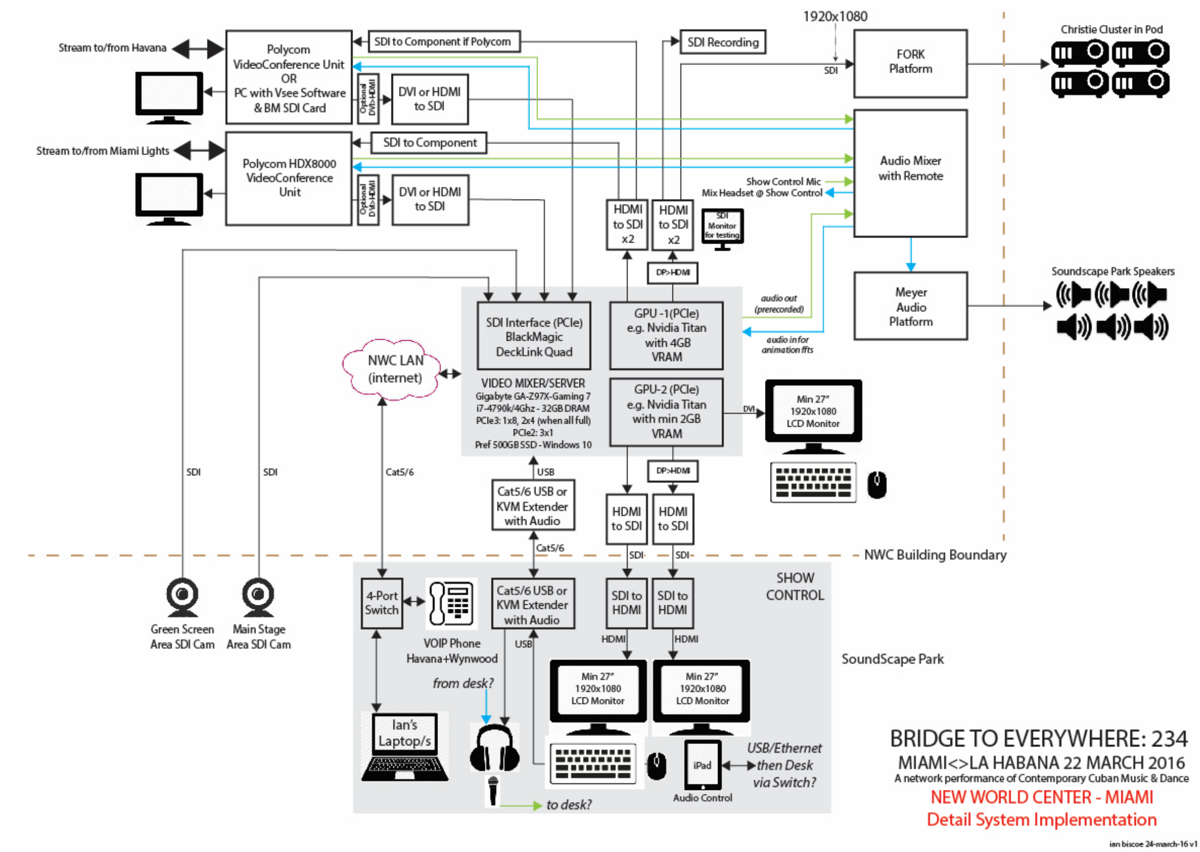

Figure 13: System implementation for *Bridge To Everywhere:234* (2016) at the New World Center in Miami Beach, showing connections to Miami Wynwood and Havana, Cuba.

The visual elements for the performance were an amalgam of new sketches, paintings, computer graphics, and video shot while in Havana. In several scenes—such as in the *apartment scene*—the surfaces of building outlines were rendered with new paintings. Two of these were based on a crude reworking of paintings by the Cuban artist Wilfredo Lam (Fouchet, 1991, see Fig. 27).), including one abstract character now dressed in a superman outfit. Other original images looked to blend the art-deco influenced architectural styles of buildings in Miami Beach with those in Havana from the same period. Other paintings were an abstract blend of the Cuban and US flags. Even though the performance occurred in two different cities, I was attempting to create—again—a common place in which all the performers could come together: a place that was formed by each node but not solely of one.

Animations (video: *Bridge to Everywhere 234 - full performance*, 2016, 00:04:45) were produced in Adobe After Effects (2015). Pre-recorded videos shot in Cuba were edited and processed in both Adobe Premiere Pro (2015) and After Effects (video: *Bridge to Everywhere 234 - full performance*, 2016, 00:03:10) Some pre-composed elements contained a combination of scanned paintings, video and computer animation which were composited in After Effects (video: Bridge to Everywhere 234 - full performance, 2016, 00:09:40).  For the live performance at New World Center in Miami, Resolume Arena was used to perform live composition of the pre-recorded material, animations and live video feeds from Havana, Miami Lights Project and the local camera on the green-screen stage (video: *Bridge to Everywhere 234 - full performance*, 2016, 00:06:34 and 00:15:35 and 00:16:44) in SoundScape Park, in front of the New World Center. Audio —pre-recorded and live from the drummers at Miami Light Project—was fed to the NWC house audio system and played-out on the 160-speaker Meyer sound system installed in SoundScape Park.

Figure 14: In the second scene of *Bridge To Everywhere: 234* (2016) the physically present dancers in Miami Beach perform on the green-screen stage (bottom-left) from where they are captured by video camera, chroma-key processed and composited with a multi-layered set of visuals for projection onto the side of the building by the Wallcast system.

Ethernet (for remote computer control and telephone communications with Havana and Miami Light Project), and SDI video cables, were laid to a small production area in the middle of SoundScape Park, from where I could manage the whole production, live, and with a view to the local performers and the giant projection surface. The final video mix was sent back into the main NWC video control room for relay back to SoundScape Park; the projection booth being situated at the far east-end of the park.

The performance received positive feedback from the NPAPW conference delegates, from the public that we had been able to inform about the event, or who happened to encounter it while passing SoundScape Park that evening. Unfortunately, due to the political situation in Miami, especially with those first-generation Cuban exiles that are against any normalisation in the US relationship with Cuba that excludes the removal of the Castro regime (Torres, 2016), we were not allowed to advertise the event because of a perceived risk by the City of Miami Beach for demonstrations or similar disturbances.

Figure 15: In the third scene of *Bridge To Everywhere: 234* (2016) an animated blockwork wall, projected onto the side of the New World Center, slowly breaks down to reveal a black & white video of street life in Cuba, and then a larger window opens to reveal a live stream of one of the dancers in Havana, peering out onto the audience in Soundscape Park.

The audio/video stream between NWC and Miami Light Project was achieved using a commercial Polycom video conferencing unit. The software used for streaming from Cuba was the same as that used for *Here, Not Here, Where?* the previous year. Despite low-quality and higher-latency than the Polycom solution, it does not use any specific UDP or TCP ports so could get through the Cuban firewall.

*Bridge to Everywhere* achieved most of the artistic goals that had been set for the project, including the integration of different artistic components (network music and dance, pre-recorded video, live video and animation) along with a choreography that connected geographically separated performers through a virtual set. The technical solution had worked well but it was more a set of loosely connected components configured for a specific performance rather than a flexible and reconfigurable system optimised for XR networked performance.

Figure 16: The *Apartment* scene in *Bridge To Everywhere: 234* (2016) projected onto the side of the New World Center in Miami Beach. Green-screened dancers locally in Soundscape park, and remotely in Havana, are placed in the rooms of an animated apartment building

### 2.2.4. Research outcomes in the foundation projects

Whereas, *Here, Not Here, Where?* was the starting point for the evaluation of technologies that would serve my own artistic vision for networked performance, it was *Bridge To*

*Everywhere: 234* that took the outcomes of *Here, Not Here, Where?* and pushed them to test issues of scalability, and as to if they could be reconfigured to support a project that was logistically and technically more complex.

In *Here, Not Here, Where?* the selection of technologies and approach proved to be a workable solution, specifically, with respect to the findings, that:

- As a solution for real-time compositing and switching of pre-recorded video and live streams, the Resolume Arena software was more than adequate. It provided the flexibility required for changes during development, adaptability during installation, and operation of the performance. Though there were occasional crashes of the application during development, it did not exhibit such issues when operating with a tested configuration in the performances. In fact, Resolume has proved impressively reliable throughout its use in the performances discussed in this thesis;

- Vsee was used as the audio/video streaming software solution. Although I knew of more networked performance specific tools—such as LoLa and UltraGrid—they did not then offer the sort of output video mapping of streams required for this project. LoLa and UltraGrid also require public static IPs to work, whereas Vsee works with non-public IPs, employing an internet-based server to resolve dynamic IP addresses when connecting clients. A significant advantage of Vsee for such projects, those dealing with multiple video streams, is its ability to map individual streams to regions of one or more displays, including tools for scaling and changes to display geometry.

- As Vsee does not support any form of video pipelining, a solution was required to feed the received video streams into Resolume, where they could be composited with other streams and with pre-recorded material. A solution using virtual displays was developed. Blackmagic Design's HDMI to SDI adapter, when plugged into the HDMI port of a GPU, appears to the Windows operating system as if an external display is connected. Using this technique, it was possible to map the individual inbound video streams in Vsee to one of two HDMI to SDI adapters that were connected to the PC. The SDI outputs of these adapters where then looped back to

Blackmagic Design SDI PCIe interfaces installed in the same PC, from which they could be ingested into Resolume.

The *Bridge To Everywhere: 234* also used Vsee for streaming and Resolume for video mixing, but tested other functionalities provided by those components. The overall system was also more complex, in that it had to interface with more peripheral equipment, especially at the New World Center in Miami:

- To capture live performers in Miami and place them in the composited virtual world projected onto the side of the New World Center, a solution for real-time green-screen was required. The chroma-key functions in Resolume were used to fulfil this need, although it was difficult to quickly adjust the settings in the case of changing light conditions. A lesson from this experience was to use an automatically adjusting chroma-key solution, or setup external physical controls (such as via OSC or MIDI interface) that could be used to quickly adjust chroma-key parameters in Resolume, rather than fiddling with small on-screen controls using a mouse during the performance;

- Apart from the use of SDI for loopback of received video streams, this project used SDI extensively for connections of sub-systems around the New World Center building and adjoining SoundScape park. SDI fibre connections were used to connect the parts of the system that were located outside in SoundScape park (next to the green-screen stage) with those that were located inside the building. The system solution had to integrate with the New World Symphony's own SDI network, and that which links their permanent production studio inside the building with the Wallcast projection pod, that sits in the middle of SoundScape park. Experience in the use of SDI for this project showed that is a reliable, low latency solution for connection of sub-systems and cameras in systems supporting networked performance.

Although Vsee has not been used in subsequent projects, Resolume, and techniques tested in these two projects—such as the use of HDMI to SDI adapters as physical pipelines for video capture and loopback when application sharing is required—have been. In later performances, I have primarily used UltraGrid as a video streaming solution because it subsequently supported several options for video pipelining, such as through the use of Spout (see: 3.5.9). Despite the need for public static IP addresses, UltraGrid offers lower-latency, and greater flexibility as regards the options for video compression, than that provided by Vsee.

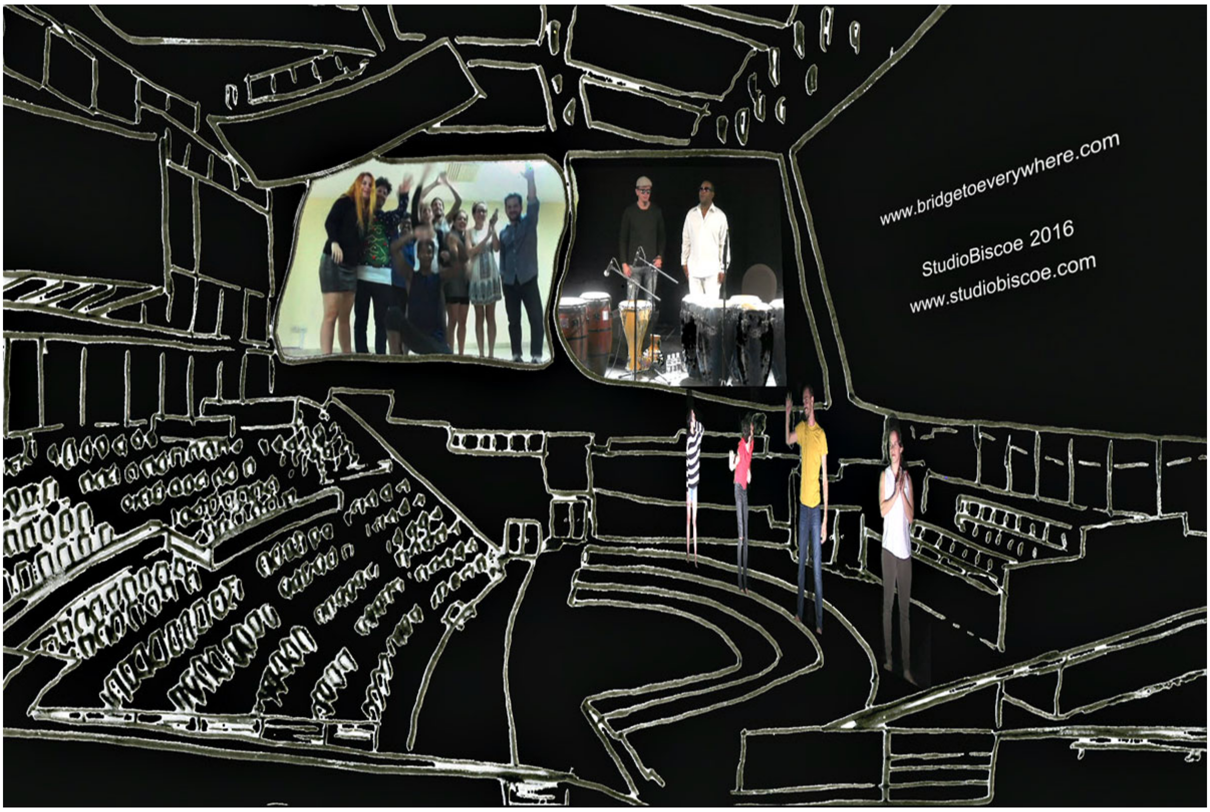


Figure 17: For the credits at the end of *Bridge To Everywhere: 234* (2016) the remote dancers in Havana, the remote drummers in Wynwood, join the physically present dancers in Miami Beach in a hand-sketched model of the New World Center's main concert hall.

## 2.3. Contributory projects

During the years of this research I participated in several other projects, which though not forming part of the primary research methodology of testing the XRNP framework in practice, were useful opportunities in which to test technologies and approaches which would later inform the establishment of the framework. They were also opportunities to collaborate and exchange ideas with others involved in the field of networked performance.

The three projects, which are briefly discussed below, are: *The Online Orchestra* in 2015, *Similarities* in 2017, and *ReTransmission* in 2017.

#### 2.3.1. Online Orchestra

The *Online Orchestra* was an initiative of Michael Rofe at Falmouth University. Knowing of my existing work in the field of networked performance, my work at Falmouth University in research projects such as *Vconect* and my experience with relevant technologies, I was asked to contribute to several areas of the project. The aim of the project was "to design a way of making music online that enables a meaningful and enjoyable musical experience by amateur musicians and children who live in geographically remote communities." (*Online Orchestra – Aim*, n.d.). As such, the project looked to employ many of the same technologies and approaches as used in networked performance environments, but with the focus on an outcome of a networked learning, rehearsal and performance environment for amateur musicians who could then benefit from the activity of "ensemble music-making" (Rofe et al, 2017, p.148) despite their geographic dispersion.

The technical solution for the *Online Orchestra* project was envisioned as one that should use commercial commodity hardware and software components wherever possible, to: minimise integration risks and costs; increase the possibility that such equipment that might already be available within communities could be used; and to keep the specialist technical skills that might be required to operate such systems to a minimum. Most of these objectives were obtained in the project though there were some exceptions given the research nature of the activity and that a system needed to be available to demonstrate the concept as a live performance in July 2015. One such exception was the switch to use separate hardware for audio and video streaming due to intermittent audible clicks present in jacktrip (Cáceres, 2008) audio streams when the Vsee video streaming software was running on the same Mac computer as jacktrip.

With the desire to use the lowest-cost commercial components as possible, while maintaining audio/visual quality sufficient for the task of connecting musical communities, the objective of very low latency was not a core objective of this project. Moreover, considering the use of commercial ADSL and similar internet connections, the latency issue was to be tackled through the initiative of composing-for-latency rather than to attempt to overly manage latency in the network environment and associated systems, or through use of specialist low latency solutions such as LoLa.

The system, as an overview, comprised dedicated components for the audio and video streams.  Audio—of which there were multiple streams in the four-node performance—used jacktrip running on Mac hardware. Patches written in Max/MSP were used for audio routing, mix management, audio/video latency synchronisation, tempo management, metronome and talkback functions.

Figure 18: Truro Cathedral during rehearsal and performance of the *Online Orchestra* (2015). Left: Video management and monitoring, with network monitor in bottom left corner. The red taped rectangles on the three SDI monitors were used to align the outputs of the remote streams from Vsee on virtual displays using HDMI-to-SDI adapters. This awkward method of working was subsequently resolved (in *Opravdoví)* with the combination of Resolume and UltraGrid sharing streams on the GPU using Spout.

Video streams between each node were established using the commercial streaming software Vsee; the same software that I had used previously in *Here, Not Here, Where?.* One of the advantages of Vsee for this project was its native support for multiple output windows, allowing one display or projector to be used for display of the video from each of the other three nodes, in each location.

However, one of the common issues with desktop video streaming solutions that are designed for person-to-person exchanges (also the case with Vsee), is that there is no integrated method or API by which to sink the video stream to other applications at the receiving node. The default condition is to display the video directly from the GPU (Graphics Processing Unit) to one or more physical displays. The limitation with this solution is if we wish to take the video streams and perform further processing, or format them for projection mapping. The workaround for Online Orchestra was like that used for *Here, Not Here, Where?.* Several Blackmagic Design HDMI to SDI converters were configured as virtual displays, to which each of the Vsee video streams were positioned. The SDI outputs were then sent to an installation of Resolume Arena for mapping to the displays in the concert space at Truro Cathedral (video: *Online Orchestra - highlights*, 2015). Software solutions and systems approaches that address this issue in networked performance are detailed in the next Chapter.

The culminating performance of the *Online Orchestra* project was successfully accomplished on 12th July 2015. Audiences and musicians were located at 3 nodes across the county of Cornwall: in Truro Cathedral, a string orchestra, soloist and choir; in the Mullion School, a brass band; and on the Isles of Scilly, in the Five Islands School, a flute choir. A fourth node was established in the campus of Falmouth University, in which the conductor of the performance was located. As with all the other nodes, the conductor could also ee and hear the performers in each of the other three nodes.

The project is comprehensively documented in an issue of the *Journal of Music, Technology & Education*, including the two sections of the project I was partly responsible for: computer hardware and software (Prior et al, 2017a), and peripheral equipment (Prior et al, 2017b).

### 2.3.2. Similarities

My working partnership with Czech choreographer and dancer Jana Bitterová on several networked performance projects led to her own concept for a performance at the NPAPW 2017 conference in Copenhagen. Bitterová's concept was for a "real-time film" which explored the similarities between four different locations in a networked performance (video: *Similarities - full performance*, 2017).

Low latency audio-visual streams from each of four locations were sent to a live mixing station in Copenhagen, where the streams were composed and transitioned in real-time, then fed to an adjacent studio where the audience were seated in front of a large projection screen. The performers in Copenhagen (on the roof garden of the Royal Danish Academy of Music building), Barcelona (in a building adjacent to and overlooking the Museum of Contemporary Art) and Miami (on the roof of the New World Symphony in Miami Beach with views to the ocean) each explored—following an agreed choreography—the similarities of their environments: from small details, through to the reveal at each location. In Prague (at the National Technical Library) the music group The Unlimited Trio provided the live soundtrack, which was streamed to Copenhagen for the audience, and to the other three locations so that each performer could synchronise their movement progression during the performance.

The Czech NREN Cesnet supported the project and provided the equipment in Prague and Copenhagen for the streaming of audio and video channels. Barcelona and Miami were each connected with Prague using point-to-point configurations of UltraGrid. From Prague, the streams from Barcelona and Miami were relayed to Copenhagen, together with the stream of the musicians in Prague and a loopback of the video stream from Copenhagen, thereby synchronising all four locations. The system used to transmit the four HD streams from Prague to Copenhagen was the Modular Video Transfer Platform – 4K (MVTP-TICO-4K) an experimental system developed by Cesnet (Ubik, 2017). The unit used FPGA based programmable hardware to achieve very low latency processing of audio and video streams. The four individual HD video streams were sent as a single 4K stream, where each HD stream occupied one quadrant of each frame. The MVTP-4K unit in Copenhagen was connected to a PC/Windows-based vision mixing platform using four independent 3G SDI cables; one for each quadrant of the 4K carrier stream from Prague. The audio signal was extracted from one of the SDI streams using a Blackmagic Design SDI-to-audio de-embedder.

The technical solution for real-time video composition, comprised an implementation of the commercial software Resolume Arena operating as a video mixer, controlled by use of a patch written in Max/MSP and an external MIDI controller. The buttons and dials of the external controller sent MIDI over USB to the Max/MSP patch which then translated the requests into OSC messages that were used to control the mixing of the video streams in Resolume Arena. The video mixed output from Resolume was sent to a projector in the audience theatre via HDMI.

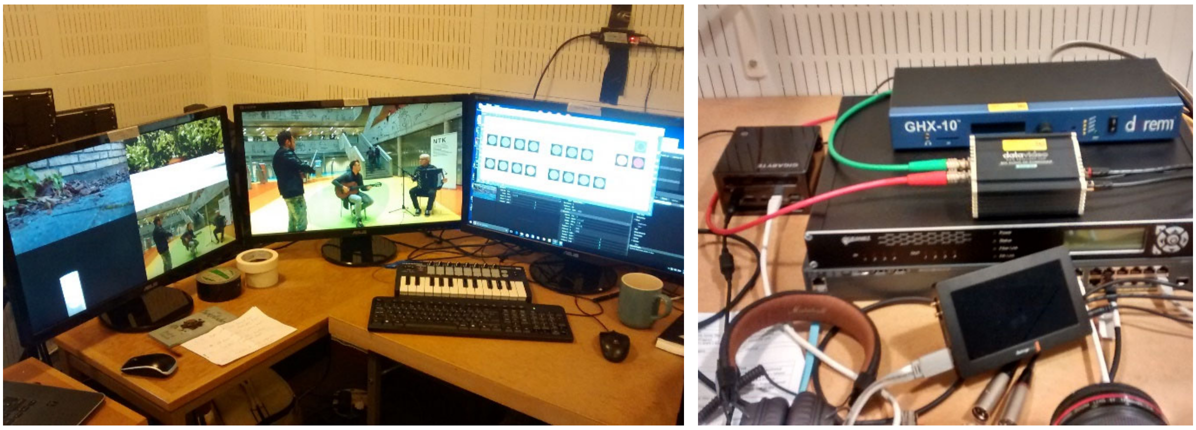


Figure 19: Technical system in Copenhagen for the networked performance *Similarities* (2017). Left: live video editing system configured from patches developed in Max/MSP, Resolume and external MIDI controller. Right: The Modular Video Transfer Platform – 4K (MVTP-TICO-4K) supplied by Cesnet.

### 2.3.3. ReTransmission

With a residency of several weeks in Copenhagen between other projects and performances in 2017 (see also: *Longing for the Impossible*, and *Similarities*) I decided to make best use of the generous access that had been granted to all areas of the Royal Academy's campus to develop a site-specific installation.

The concept was fuelled by the discovery that when Danish Radio (previously, Statsradiofonien), the former owners of the Radiohuset (In English: 'The Radio House'), had still transmitted radio programs from the building that is now home to the Royal Academy, the pause signal (or "call sign") between programs had been played automatically by a miniature mechanical glockenspiel. There was also an interesting glass tower rising from the roof of the five-storey building below; a more recent addition to the 1945 building that had housed experimental masts for radio and television broadcasts.

The idea was to produce a visual installation in the glass tower, accompanied by a simultaneous internet "radio" stream of a new piece of music inspired by the original pause signal tune *Drømde mik en drøm i nat* (in English: *I dreamt a dream last night*). The new soundtrack was composed, performed and recorded by Kalle Hakosalo; a student at that time of RDAM. The final mix and addition of radio-tuning samples was made by Thomas Solak.

The final work comprised four-projectors installed at different levels in the three-storey glass tower. Visuals—abstractions formed from both the musical score and the structure of the glass tower, its windows and spiral staircases —were projected onto the interior surfaces of the windows and to the top and underside of the staircases (video: *ReTransmission - full performance*, 2017). Some of these visuals were created using audio analysis and Adobe After Effects. Because the installation was in one of the higher points of the city and potentially a visible distraction to pilots, permission was sought and granted before operation of the installation from both the city council of Copenhagen and the regional airport authority.

Figure 20: The site and installation for the projection mapped and audio streaming installation *ReTransmission* (2017). Left: the ex. radio and TV broadcast test tower that housed the installation. Top Right: Max/MSP patch providing the GUI, performance scheduler, audio streamer and video controller via OSC to Resolume. Bottom Right: Part of the projection mapping insider the glass top of the tower

Though not in the same format as the other networked performances described in this thesis, *ReTransmission* was a form of networked performance, albeit one with a single location. The systems implementation was a combination of commercial software (Resolume Arena, VLC player and Icecast media server) and two large patches written in Max/MSP. The biggest challenge was to synchronise the commencement of the visual display with the start of the audio, which was streamed to the mobile handsets of the audience from a commercial streaming service hosted in London. To achieve this precise synchronisation of the audio track with the visuals, the audio was first streamed to the Icecast (2017) server in London from a computer installed in the glass tower. The audio was then re-streamed to the project specific website at www.retx.dk (no longer live) where the audience could then listen to the stream on their own mobile internet devices. The show control computer in the glass tower also listened for the start of the stream relayed via the Icecast server in London. An instance of VLC player was configured to receive the stream; the audio output of the VLC player was connected to an audio input on one of the Max/MSP patches. An audio threshold trigger in the Max/MSP patch detected when the audio stream began and then commenced the visual display through control of Resolume. A series of tests was conducted before launch of the project to determine the difference in latency between the stream arriving via a fixed internet connection (that of RDAM) and mobile internet devices using the 3G and 4G mobile operators TDC, Telenor, Telia and 3 (Tre). Through a series of observational tests, I discovered that the difference between the two forms of stream reception were negligible if not unnoticeable. Therefore, this method of synchronisation worked well, and in practice, the audio stream and visual display always appeared to be in perfect synchronisation.

Coordination of the visual display was achieved through a second Max/MSP patch that, through a series of loops and timers, sent OSC control messages to Resolume Arena to trigger the different fixed and animated visuals for display on the four projectors. The installation operated every 15-minutes between sunset and midnight, from 3rd to 5th April, 2017.

### 2.3.4. Research objectives and outcomes in the contributory projects

Unlike *Here, Not Here, Where?* and *Bridge To Everywhere: 234,* discussed at the beginning of this Chapter—and which represented my first forays in the solo production of networked performances—the projects discussed in this section represent different opportunities which supported experimentation in artistic and technical practice. The relationship I had to each of these projects and collaborations was quite different in each case.

In terms of how the projects aligned chronologically with the other work discussed in this thesis, *Similarities* and *ReTransmission* were in the same months of 2017 as *Longing for the Impossible*. While *Online Orchestra* fell between my first solo project *Here, Not Here, Where?* in 2015 and my second, *Bridge To Everywhere: 234*, in 2016.

In all three projects, I had an opportunity to set my own technical research objectives, test and perform artistic concepts. In *Online Orchestra,* I surveyed a wide range of audio and video streaming solutions to ascertain what would work best for the project in terms of its ability to integrate with the overall system; solutions that would also work in situations where open and dedicated network connections were not available. The result of that research was not only useful to the *Online Orchestra*, it made a significant contribution to my own research in terms of understanding what streaming solutions were available, and as to what the strengths and weaknesses of each were. *Online Orchestra* also provided the opportunity to further investigate the work which I began in *Here, Not Here, Where?*, in finding solutions for interfacing video streaming solutions with other software applications: the methods available to source, sink and share video from external applications (such as Resolume) with the chosen video streaming solution.

In *Similarities,* I could evaluate the real-time throughput of Resolume when used as a video switcher and live mixing tool. The project required the reception of a 4K video stream from the Cesnet supplied hardware streaming solution, the separation of video streams, and the ability to quickly mix them for viewing by the audience. Artistically, I functioned as the live video mix operator for the performance, interpreting in real-time an outline choreography that had been agreed with choreographer Jana Bitterova. Working as the systems designer and the operator allowed me to evaluate different methods by which to best control Resolume for video switching and mixing in the performance environment.

*ReTransmission* was a solo project, a networked installation, differing from the other networked performance projects discussed in the body of this research. Being performed between the two sets of performances of *Longing for the Impossible* in March and April 2017, it also provided an opportunity to continue testing of the OSC interface with Resolume that was being used in *Longing for the Impossible,* and the use of Max/MSP patches for scheduling and controlling events between applications with an OSC interface. It also served as a testbed to evaluate the advanced output functions of Resolume for use in projection mapping employing multiple projectors, moving beyond the basic geometric implementation used for *ReTransmission*.

The outcomes of *ReTransmission* supported activities in later performances, such as *The Spaces Within,* where multiple-projector projection mapping was performed in Resolume under OSC control; and in *A Short Journey into Folded Space*, where Resolume—also under OSC control—was used to separate and combine multiple HD video streams into a 4K stream containing HD video quadrants.

# 3. A SYSTEMS FRAMEWORK FOR X REALITY NETWORKED PERFORMANCE

The lack of a systems integration approach and the lack of a systems framework for networked performances of all types, has been discussed in Chapter 1 (see: 1.4). This Chapter firstly addresses that need, by examining the functionality required to support networked performance and the extensions of that needed to support XR networked performance. Although these requirements are based on the needs of my own practice, they are also informed by my knowledge of other practitioner's work and through the experience of my involvement in projects outside of my practice (as discussed in Chapter 2). The discussion proceeds to examine the potential approaches, informed by my background in systems integration in fields other than arts practice, as discussed in Chapter 1 (see: 1.5). As a core component of the systems integration approach, this Chapter also discusses message-based solutions to integrating sub-systems, and a system of systems approach to support XR networked performances.

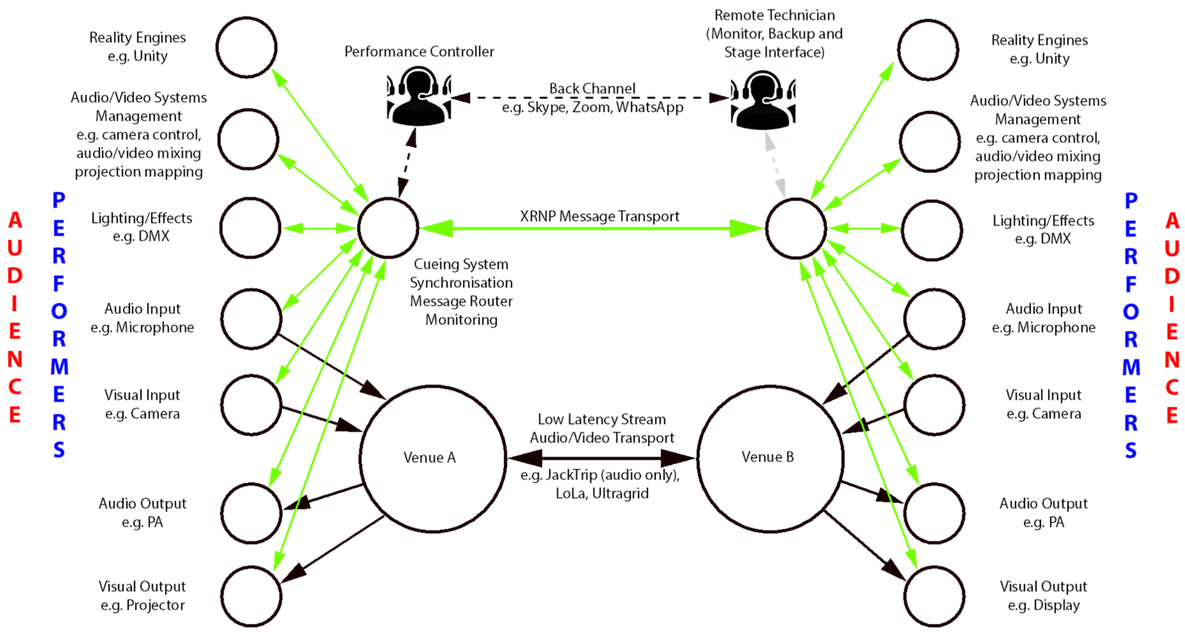


Figure 21: XRNP system implementation for a networked performance of symmetric typology. Contrast this with a typical example of the same typology in contemporary networked performance practice (Figure. 2).

## 3.1. Functional requirements of an XRNP systems framework

To investigate a systems framework for XR networked performance we must first seek to understand the functional requirements of the overall system and its constituent sub-systems. We also need to understand what the affordances of each sub-system are and their contribution to the overall system in the development and delivery of a performance:

- **Audio streaming** - the streaming of digital audio, at different bit rates and levels of data compression, between the nodes of the performance. While the lowest latency possible is desirable, the ability to trade quality and compression against higher latencies is a useful capability in an audio streaming solution for networked performance. Issues with audio quality—such as noise and clicks—are generally more perceivable and disturbing to an audience than might be the case with occasional imperfections in video quality, therefore, reliable audio streaming without interruption is critical to the success of a networked performance that includes audio. The audio streaming solution should provide flexible source and sink options as regards how audio is captured and input to the stream, and how received streams can be sent to other applications or devices for processing and output;

- **Video streaming** - the streaming of digital video between nodes of the performance. The same or similar requirements as for audio streaming, with options for different bitrates, compression rates and encoding formats. The video streaming solution should provide flexible source and sink options as regards how video is captured and input to the stream, and how received streams can be sent to other applications or devices for processing and output;

- **Audio and video acquisition** - the methods and devices by which audio and video are acquired from any node in the network, from physical or virtual sources, for local processing or streaming;

- **Audio and video playback** - the ability to include pre-recorded audio and video, independently or as part of a composition with received streams;

- **Audio and video processing** - real-time processing of audio and video in physical and virtual environments. Examples of video processing include: chroma-keying, cropping, scaling, effects, 2D or3D composition, and projection mapping. Audio examples include: the mixing and distribution of live and pre-recorded audio sources, and the use of effects;

- **Audio and video output** - the methods and devices by which audio and video is output from any node in the network, including audio interfaces, speakers and projectors;

- **Lighting** - the control of lighting in both the physical spaces (e.g. in the theatre) and of virtual environments (e.g. those of computer-generated realities) in the performance;

- **Computer generated realities** - environments for the hosting of virtual worlds, their inhabitation and augmentation by virtual and real-world derived assets (e.g. those of the physical world that are represented in virtual worlds through the likes of video streams or the results of sensors placed in the physical space), their manipulation based on performative constructs, and their placement into and interactions with the physical environment;

- **Performance management, control and synchronisation** - the methods and processes by which the performance is controlled. The use of cues to control all elements, including: audio and video acquisition, streaming, operation of virtual and physical assets, computer-generated realities, processing of audio and video, and audio and video output;

- **Other** - though not considered as core elements in the XRNP framework, a wide range of additional technologies, components and sub-systems might also be required, depending on the concept and scope of the performance. Examples include: motion capture systems, machine learning systems in support of real-time video analysis and background removal, sensors and actuators.

Beyond the core functionality that is required to support the performance, there is a second level of functionality, that which is required for the various components and sub-systems to communicate, to exchange and share information, as part of an elegant integrated systems framework:

- **Application platform** - a computing environment to host software applications and processes, that supports the various physical interfaces required to communicate with external devices and other computing sub-systems;
- **Video sharing** - a method by which to share video between applications and processes on the same computing environment;
- **Audio sharing** - a method by which to share audio between applications and processes on the same computing environment;
- **Data communications** - a method for the exchange of digital information (other than for audio and video streaming), for communication between sub-systems, performance control and synchronisation;
- **Legacy interfaces** - the ability for the framework to work with existing systems and component technologies that do not directly support the selected messaging solution, such as the ability to work with systems that only have DMX and MIDI capabilities;
- **Toolkit** - an application or other programming environment to provide the "glue" logic, the functionality required to support integration of the various sub-systems and component technologies, and for the efficient development of the functionality not available in other sub-systems that might be required to support specific projects. The toolkit should also support experimentation in support of the artistic process;
- **Network** - the networking technologies required to provide the environment for communication of control, audio and video data in the performance. Apart from the existing infrastructure that might be employed in any given performance—the

networks of NREN's, the Internet and the local network infrastructure within a venue—this might include additional routing, switching and monitoring components;

- **Utilities** - additional software and systems required to successfully implement and operate the performance, such as video conferencing for operational communication and remote control of computers and applications.

Though outside of the systems framework, the selection of components and sub-systems to implement the framework should also be considered based on their support from other applications which are required to develop the performance. For example, a video mixing or virtual reality environment should be capable of supporting the output formats of development tools, while there should be a variety of tools which can be used to produce the models, graphics, animations and audio files, that might be used to implement the artistic vision.

In considering the systems framework and its constituent components, I reference the theoretical framework developed in Chapter 1., in which were identified the key criteria in identifying a systems framework that would successfully meet the needs of the practitioner. In summary, one that is: elegant, deterministic, reliable, extendable, scalable, reconfigurable, testable, and cost-effective.

## 3.2. Effect of networked performance typologies on functional system requirements

Four principle typologies of networked performance were presented in Chapter 1 (see: 1.4.1 Typologies of networked performance), these being: centric, off-centric, asymmetric and symmetric. Each typology has different requirements as to the configuration of the supporting systems and the demands it places on them: such factors should be considered when designing and implementing a framework. Whereas centric and off-centric performances focus on one physical audience space, asymmetric and symmetric performances are addressing at least two physical locations with audiences. Performances which have the audience distributed across the nodes of the network, and which are seeking to provide all the audience members with an experience which is approaching equality regardless of location, have greater requirements on the supporting system and networks. Performances that are of the symmetric typology, tend to have the greatest requirements on the design of the system, especially regarding the need to synchronise events across the widely-distributed set of sub-systems.

## 3.3. Latency and determinism

Latency is normally the premier issue encountered in the discussion of systems for networked performance, especially where networked music performance is concerned and the issues surrounding its effects on tempo, rhythm and accuracy in the performance of a score (see: Chafe et al, 2004; Chafe et al, 2010). Whereas there may be a greater tolerance in performances where the visual component is dominant (such as with dance performances, or even in theatre), there is an absolute limit, one which is quite low in networked terms, as to how high the latency across a network can be for musicians at nodes of the performance to successfully collaborate. How much latency can depend on several factors, such as the genre of music, composition, score or improvisation, and even the types of musicians and instruments involved. In a spoken word performance, there is a greater possibility that latency, still depending on distance between nodes, will have marginal effect or can be incorporated into the performance. Holub et al (2007), in examining the effect of delay on conversation in telecommunications networks, conclude that people “show low sensitivity to [a] transmission delay [of] up to 500 milliseconds (one-way) in echo-free connections”, which equates to a round trip delay of up to 1 second. Conversely, acceptable delays for some forms of networked music performance might be as low as 25 milliseconds one-way (Lakiotakis et al, 2018), referred to as the “Ensemble Performance Threshold (EPT)”, whereas Schuett (2002) summarises that suggested maximum round trip delays for a music ensemble vary between 20 to 40 milliseconds for a “true ensemble”, and 50 to 70 milliseconds in the case of a “leader / follower” ensemble, before the effects of latency started to impact the performance.

The major factor for latency is the speed of light, precisely, the speed of light in a fibre optic cable, as this is the medium through which network traffic is sent over long distances. There are delays to be considered in the acquisition of audio and video signals—local cable or digital transport delays, processing and streaming—but these are relatively fixed delays at each node of the performance. The primary variable for overall latency between nodes is therefore distance. However much we strive to reduce latency in areas that we can control, we will always have the speed of light factor to consider. At 299,792 km/S it takes light (in a vacuum) approximately 1 millisecond to travel just under 300km. However, with current technology, light travels in a fibre cable at around 69% (see: Miller, 2012) of the speed of light (depending on the refractive index of the fibre core), so that's around 200,000 km/S or 1 millisecond to travel 200 km. To consider this in a real-world context, the distance between London and New York is 5,585 km[20] so data on a fibre optic network would take approximately 28 milliseconds to travel that distance, not allowing for electrical/photonic conversions, networks switches and router delays, which are likely to add an additional few milliseconds to the transit time. Additional delays may also be incurred due to network congestion. Development in fibre optic technologies (Finley, 2013) may result in the achieved speed of transmission of signals though fibre optic cables getting closer to the speed of light, perhaps as high as 97%., but that will still limit the overall distance between nodes that we connect in a networked performance when we consider the aforementioned upper limits for successful collaboration. It is interesting to consider then how we can build new artistic constructs for networked performance, ones that incorporate latency[21] artistically and support these ways of working within the systems infrastructure.

Another option that can be employed for performances that are using pre-recorded music, which require little if any exchange of live audio between the nodes, is for the pre-recorded audio to be hosted locally at each node of the performance and trigger by distributed cues or by synchronised networked time when required.

[20] This is the shortest path between London and New York (as might be flown) but the length of the network travelled to send data between these two points could be significantly longer, due to factors such as physical cable routing, and that internet traffic may not always travel via the shortest path.

[21] For example, the combined approach taken in the Online Orchestra project (Rofe and Geelhoed, 2017) of locking latency to the desired tempo within the system, and composing for latency-rich environments. Approaches for rhythmic synchronisation in networked performance are also discussed by Oda (2017). Where the networked performance does not involve live musicians but there is a soundtrack for the performance, another solution—as used in *Opravdovi* (see: 4.3.3)—is to playout the audio locally in each venue and use networked cues to synchronise the distributed playback devices.

From the system of systems viewpoint, we can also consider that issues of latency and determinism at the local (sub-system or node of performance) level can be manifestly different to those at the global level. A light or video component at the local level of the performance may require updates in the order of tens of milliseconds, with corresponding levels of determinism to avoid jitter, whereas a global synchronisation event, something that connects all nodes of the performance, might work perfectly well in the range of hundreds of milliseconds or even a few seconds. So, the requirements for latency, determinism, and jitter avoidance across the overall XR networked performance system, in any one performance scenario, is likely to vary depending on issues such as: performance typology; transport of streams vs transport of data for control; and if the control data or stream is a locally or globally initiated and consumed.

From this discourse on latency and determinism, we see that although it is desirable to strive for minimum latency and absolute determinism (without jitter) in our networked performance environment, the reality is that this will likely not be achievable on both counts in all scenarios. The system should support trade-offs in its configuration and operation, between these goals and the ability to architect systems for different performances, depending on the importance of each of these factors.

## 3.4. Standardised interfaces as a framework enabler

As discussed in Chapter 1, the aerospace industry has approached the challenges of large-scale systems integration through the adoption of standard interfaces and communications protocols between sub-systems. Though historically they used interfaces that were especially designed and standardised across the aerospace industry, more recently, the move has been to adopt standards from the wider IT industry. These standards can then be modified to meet specific requirements in aerospace applications, such as higher reliability and deterministic operation that are required in such real-time, safety-critical systems. While the aerospace industry is adopting some aspects of the physical or lower level network protocols from the IT industry, it then builds standardised application-specific protocols on top of these, so that all sub-systems have a common method through which to exchange information, regardless as to the specific function of any connected sub-system.

The equivalent in the performing arts (which does not currently exist) would, for example, be an agreement that all systems—lighting, video, audio, sensors and actuators—were equipped with a common physical interface such as Ethernet, and that an industry-wide application protocol was used to communicate between all these systems.

When using the term ‘interface’ I am considering this to be a combination of the physical and electrical connection between sub-systems, and the protocol that supports the communication process between them. In some instances, this communication is accomplished by an application-specific data format or protocol that utilises an underlying transport mechanism, such as with MIDI over TCP/IP. Communication between software systems may also exist purely in software and require no external physical interface, such as with the use of TCP to communicate between two applications residing on the same host computer.

In the performing arts, we find many communications and control standards which have typically evolved around specific areas of technology within the place of performance, such as DMX for lighting.  More recently, there has been an increasing adoption of standards from the wider spectrum of information technology into arts practice, such as the use of Ethernet and Wi-Fi. Such IT standards have also been used as vehicles to expand the capabilities of arts industry specific standards, such as DMX over IP using Art-NET. However, these moves towards the use of IT industry standards are still at the level of a specific application domain, such as lighting or audio; they are not interoperable across all the technologies and domains of the performing arts.

### 3.4.1. Interface standards currently used in the performing arts

The primary communication and control standards found in the environment of the contemporary performing arts, including those that are in the process of coming to market but may not yet be widely in use, are:

- **DMX512-A** – **Digital Multiplex** (ESTA, 2018) - typically known as “DMX”, developed by the Entertainment Services and Technology Association (ESTA). It is the current version of a standard for lighting control that incorporates specifications for the electrical physical layer—which uses RS-485 (see: Kugelstadt, 2016)—and the protocol by which lighting appliances are controlled. “512” in the name of the specification relates to the number of individual channels that are supported by a single physical network, known as a “universe”, when daisy-chained between multiple devices or in star network configurations. The **RDM** (Remote Device Management) protocol, developed by the Professional Lighting and Sound Association (PLASA, 2011), is an overlay protocol for device management with bi-directional communication (unlike DMX which is unidirectional) and operates using the same physical infrastructure as DMX. Precursors of DMX that can still be found in some equipment and venues, include **D54** (Strand Lighting, n.d.) and **AMX192** (USITT, 1987) but they have mostly been replaced by DMX, making them irrelevant for the purpose herein;

- **Art-NET** - is a protocol for transporting DMX over IP networks using the UDP transport protocol, typically over an Ethernet LAN. It is not produced by a standards organisation but is licensed royalty-free by Artistic Licence Holdings (2017). Art-NET is primarily a solution for distributing multiple DMX universes between lighting systems and other control equipment that support DMX, overcoming the single universe and distance imitations of a standard DMX 512 channel universe and physical RS-485 based network;

- **ACN / E1.17** - the **Architecture for Control Networks** (published as ANSI specification E1.17-2010) is a set of standards developed by ESTA (2015) for control of lighting, theatre effects and audio using standard IP protocols as the underlying transport mechanism but with the addition of their own Session Data Transport protocol (Huntington, 2012, p.260). One component standard of the ACN (ESTA, 2018b) is **sACN** (published as ANSI specification E1.31-2016), typically referred to as “Streaming ACN” or “Streaming DMX”, and is intended as an alternative to Art-NET for transporting multiple universes of DMX data over Ethernet LANs;

- **OCA** / **AES70** - the **Open Control Architecture** is being developed by the Open Control Alliance and the Audio Engineering Society as an “architecture for system control and connection management of media networks” (*Welcome to the OCA Alliance!* n.d.). The AES70 royalty-free standard (AES, 2018) is intended as a protocol for control and monitoring of audio devices (not for streaming audio between devices) and on which the OCA object-orientated architecture can be implemented. AES70 operates over IP based networks, originally, using TCP as the only transport mechanism. The specification was recently extended to support UDP as an optional transport mechanism, and WebSockets using TCP as the transport mechanism (*OCA Alliance to promote AES70*, 2019);

- **MIDI** - the **Musical Instrument Digital Interface** is a specification (MIDI Association, 1996) for unidirectional communication between musical instruments and other computing devices that need to exchange data for the recording, playback and editing of music. The specification defines the electrical interface and the protocol. Many virtual MIDI solutions are available that provide for passing of MIDI data between two software applications on the same host computer without the use of a MIDI electrical interface. MIDI also operates over USB and this is now the most common physical connection. The **RTP-MIDI** specification (*RTP Payload Format for MIDI*, 2011) supports MIDI data transport over Ethernet using the UDP/IP protocol; it is also available as **AppleMIDI** (*MIDI Network Driver Protocol*, n.d.). MIDI Show Control (MIDI Association, 1991) is a superset of the original MIDI specification intended for control and communication with non-musical equipment, such as to send commands to a lighting desk. A MIDI 2.0 specification is due to be released in 2019 (*Details about MIDI 2.0*, n.d.).

- **SDI** - the **Serial Digital Interface** is a set of standards produced by the Society of Motion Picture and Television Engineers (SMPTE, 2008) for the transfer of uncompressed digital video (including embedded audio) between cameras, video processing and switching systems, recorders and playback systems. As such, it provides a dedicated physical infrastructure for the transport of video using a specific set of protocols. However, some manufacturers of SDI equipment also use the SDI interface as a means on which to implement proprietary protocols, for example, Blackmagic Design’s control protocol for their cameras (Blackmagic, 2018), which supports functions such as remote control of aperture, gain and exposure, and d: pan, tilt and zoom (PTZ) functions if an appropriate head and hardware is attached to the camera. The inclusion of SDI in this list of common standards for communication in the performing arts is not because it might form the practical basis for a general communications interface for control and communication with sub-systems but because it is used by some manufacturers for camera control;

- **OSC** - the **Open Sound Control** protocol (Wright, 2002; Freed and Schmeder, 2009) is a transport-agnostic format for messaging between systems, that is, it is not tied to one specific method of transport, such as UDP or TCP. Originally intended as a method to share more complex data sets between musical instruments than is realistically achievable using MIDI 1.0, it has become popular for a wide variety of applications in the arts, and has been integrated into many hardware devices and software applications. OSC is not published through a standards organisation or formal standardisation process, rather, it has been published by its original authors, collectively maintained by subsequent custodians and through user feedback;

- **Proprietary** - there are also a significant number of proprietary[22] protocols that are used in the arts environment. None of them form realistic options for the creation of communications solutions in other areas of system integration; they are either application specific or outdated. Examples include those for projector control, video switchers, video recorders, and streaming devices, where the physical interfaces range between RS-232 and Ethernet. While they may not form options for wider use, some of the interfaces are useful for the purpose they were designed for, and can be utilised as part of an integrated system through the use of software gateways.

[22] The term 'proprietary' is used to identify those protocols that were not developed by an open industry association or user group but by a manufacturer (sometimes a group of manufacturers). The details and operation of these protocols may have subsequently been made public or open-source but were originally concealed to some extent from the end user.

There are also several communications standards for the local[23] transport of audio (or audio with video) data over standard IP-based networks[24] that will coexist with other applications, examples include: **CobraNet** (*Networked Digital Audio*, n.d.), **AVB** (IEEE, 2011), **Dante** (*Dante - The Audio Networking Standard*, n.d.) and **AES67** (AES, 2018b). And, there are also some older standards for audio that use elements of the Ethernet architecture but that will not coexist with other applications, such as **AES50**. All these audio streaming specifications are outside of the core systems framework for X reality networked performance as they are effectively alternatives to the use of discrete analogue cabling (such as XLR), primarily used to connect local audio devices, such as microphones and mixing desks, or to multiplex audio streams between sub-systems.

Likewise, there are several solutions that have been developed for video over LAN. The most popular of these in the past few years is the royalty-free **Network Digital Interface** (NDI) developed by NewTek (*NDI*, n.d.) which supports compressed video and audio. There are several commercial entities that provide solutions for the transfer of NDI traffic over the Internet (between two sites that are running NDI on LANs), typically using **SRT**[25]. Such solutions are primarily intended for broadcast applications, where a delay of one or more seconds in linking a satellite (such as an outside broadcast location) with a production centre might be acceptable but which would typically be too high for the type of networked interactions typical in XR networked performances. However, NDI can be a useful additional tool for local connection of video sub-systems in an XRNP framework, especially when delivery of the performance is not too sensitive to the additional latencies that might be encountered when using NDI as opposed to e.g. USB or SDI connections that are made directly between a camera and the computer that is used for streaming.

[23] The term 'local' is used to delineate those protocols which were originally or primarily developed for use over a LAN, that is, within the confines of a single geographic location, behind a firewall or Internet gateway router or switch. It does not restrict the possibility that adaptions or modifications to the protocol could subsequently allow it to be used across the Internet to link devices on LANs within multiple locations, traversing e.g. firewalls, Internet gateway router or switch.

[24] There are other solutions for the replacement of traditional analogue audio cables with digital multiplexing but which use proprietary interfaces and do not work over standard IP-based networks, such as: the Multichannel Audio Digital (MADI), AES10 standard (AES, 1991) which uses a point-to-point copper or fibre link; and the ADAT Lightpipe (*ADAT project*, n.d.) developed by Alesis which uses a fibre point-to-point link.

[25] Secure Reliable Transport (SRT) is an open source video transport protocol, the development of which is administered by the SRT Alliance (n.d.). It uses UDP as its transport layer.

### 3.4.2. Interface and framework criteria

From the theoretical framework developed in Chapter 1 (see: 1.5) we can use the principles discussed to identify the best available solution for an interface that will support elegant integration of systems for XR networked performance. Development of a completely new type of interface is to be avoided (nor is it considered) as this would negate the potential of easily integrating many existing component solutions that are freely or commercially available; it would also drive up the costs and timescales for integration.

An interface is required that will support the control and exchange of data between sub-systems and component technologies. The interface is not required to support audio/video transport as this will be achieved through use of one or more existing streaming solutions. However, it is preferable that the streaming components can be configured and controlled using the selected interface.

The most appropriate interface solution will be one that best meets the parameters and criteria already established in Chapter 1, those being:

- **Typologies** - (see: 1.4.1) the solution should enable systems that can be configured to support the different typologies of networked performance;

- **Important factors of systems for arts practice** (see: 1.5.1) - in discussing some important—but not necessarily unique—aspects of systems for arts practice, I identified that they need to be flexible (in configuration, and in the ability to support alternative technologies), reliable, reusable, modifiable, support experimentation, and be cost effective;

- **Criteria for XRNP systems framework** (see: 1.5.3) - the framework, and therefore the interface that enables its integration, should also be deterministic, reliable, scalable, suitable for low latency and deterministic applications, and support ease of integration and sub-system test;

- **Industry and open standards** - though not explicitly discussed in the criteria above, the selected interface should be one that is already established as an open or industry standard, and that is compatible and interoperable with as many other relevant standards as possible. It should be suitable for connection of hardware and software sub-systems, and be operable using IP transports as the sub-systems need to connect across: computing platforms, LANs, WANs (Wide Area Networks) and over the Internet. Given that the interface will be employed by systems for the performing arts it is also desirable that the standard is one that is already familiar to practitioners.

### 3.4.3. Interface candidates for sub-system integration

Comparing the selection criteria (see: 3.4.2) against the interface standards already employed (see: 3.4.1) I could immediately eliminate some of the options:

- **DMX, RDM, MIDI** and **SDI** are not IP based protocols;

Of the standards that support IP based transport protocols:

- **Art-Net** and **sACN** exist purely as intermediate transports for distribution of DMX data over IP networks. Even with this ability to transport DMX over IP, the DMX protocol is simply 512-channels per universe, where each channel is a 16-bit value. A single device may be assigned multiple channels but the format is still extremely limited and does not easily support the exchange of data types such as 32-bit integers, floats or strings;

- **RTP-MIDI** and **AppleMIDI** – are the IP transport versions of MIDI but are still limited to the data structures and types supported by MIDI, with no support for data types such as 32-bit integers, floats, strings or arrays;

Of the remaining candidates:

- **ACN / E1.17** - supports transport of a wide range of data types and provides additional protocols for functions such as session management. However, apart from the sACN component of the specification that supports DMX over IP, there has been very little uptake by manufacturers or support of ACN in software applications;

- **OCA / AES70** - is a well-considered and flexible architecture for integration of audio and other systems used in arts, with its object-orientated device model and support for dynamic configuration of devices. The AES70 protocol standard only supports TCP transports at present. The standard was only published in 2016 so to date there are very few implementations of it in hardware or software applications;

- **OSC** - was originally developed to offer greater functionality for musicians when networking music equipment than that offered by MIDI. Though not officially approved by any standards organisation, OSC is the only general message format that has been widely adopted by practitioners, is supported by software applications, and that has been implemented in hardware components. It supports a wide range of data types and offers a flexible addressing mechanism that can be adapted to application specific uses while maintaining a common protocol structure.

Considering this analysis, the ease of which OSC can be implemented and the wide range of applications and devices that support OSC, also the availability of software libraries that implement OSC for 3rd party applications, the decision was made to use OSC as the interface standard for XR networked performance systems. Fraietta (2008) presents some limitations in the current OSC specification, especially regarding bandwidth/processing overheads (compared to MIDI) and the lack of a logical addressing scheme. However, the advantages of an intelligible and flexible namespace scheme in OSC tend to outweigh the cryptic encoding limitations of MIDI, especially when processing and bandwidth are relatively cheap and available, and the overheads for processing are minimal compared to the advantages provided by OSC for the systems integrator.

### 3.4.4. OSC as a message format for XRNP systems integration

OSC was implemented as the primary means of communication between XRNP sub-systems to support the iterative process of technical and artistic exploration. The use of OSC to integrate new sub-systems into the XRNP framework, and to support the different typologies of XR networked performances, is detailed in Chapter 4.

Although OSC does not provide mechanisms for redundancy or session management, these can be implemented at the application layer in a way that can be specific to the system and project requirements (as with the approach taken for Opravdoví, see: 4.3.3) rather than a more heavyweight solution that attempts to address all operational scenarios.

Sub-systems and component technologies that do not offer native support for OSC, such as the Unity games engine platform used within the XRNP framework for its VR and AR functionality, have been integrated using third-party libraries or plug-ins, and through the development of software gateways.

## 3.5. Implementing the different functions within an XRNP framework

The options for implementing the framework functional requirements (see: 3.1) were compared against a review of components and sub-systems available on a commercial or an open-source basis. Consideration was given to options and approaches with which I had positive experience in previous projects. Critically, for the core components that would need to interoperate at the network level, their ability to be easily integrated using the preferred standard OSC interface was an important factor.

### 3.5.1. Application platforms

Due to familiarity with Microsoft Windows and macOS platforms, and in the knowledge that all software in consideration for use in the XRNP framework runs on either one or both platforms, these were the selected solutions, rather than, for example, selecting some implementation of Linux.

### 3.5.2. Toolkit

There are several rapid prototyping and development tools that use a patch-chord approach (one where program objects that provide different functionality are presented visually and the program logic is defined by connecting these objects visually within the GUI) to develop applications. Tools such as Max/MSP, Pure Data, Touch Designer, Isadora and VVVV, are all targeted specifically at the arts practitioner: Pure Data and VVVV are open source while the rest are commercial applications. They all incorporate functionality that is specifically designed to ease the process of building applications that work with audio and video, and that operate with interfaces that are common in the arts, such as MIDI and SDI. Each of these tools includes its own runtime environment: that is, they do not produce compiled code for execution in another environment, rather, they incorporate all the functionality to design, debug and run applications. All these toolkit applications support the reception and transmission of OSC messages, which is essential for their use within the XRNP framework.

In the case of Max/MSP and Pure Data, there exists an extensive library of OSC functionality in the CNMAT (n.d.) package developed by the Center for New Music and Audio Technologies at the Berkeley Department of Music. The functionality provided for these toolkit environments, includes objects specialised to tasks such as OSC message routing, message bundling and unbundling.

The primary alternative to use of such tools is the development of software, in languages such as C#, Java, JavaScript and Python. Though this approach can be useful, and sometimes less abstract than the patch-chord type of application development environments, the need to develop or incorporate libraries for different interfaces and standards can mean that the time to develop is significantly greater, and the opportunity for play and experimentation is not necessarily so spontaneous due to e.g. the need to compile and execute code after each change.

### 3.5.3. Internet audio and video streaming

From the review of contemporary practice in networked performance in Chapter 1, and from my practice in the foundation and contributory projects (see: Chapter 2), I concluded that the most commonly used streaming solutions in networked performance practice are: jacktrip, LoLa and UltraGrid. Specifically, I am considering audio and video streaming solutions that support long-distance connections in low-latency networked performance applications and are therefore ones that work well over the internet, as opposed to those solutions that are intended primarily for use in a LAN environment.

Audio and video streaming solutions, such as NDI (n.d.) and Dante Via (n.d.) provide audio and video streaming over a LAN but are not natively designed to work across the internet. Additional solutions for use with NDI provide LAN-to-LAN connectivity over the internet, such as Sienna's Cloud for NDI (*Global IP Video Network*, n.d.)) and Medialook's Video Transport (*Remote Video Production*, n.d.) but these add delays that would not normally be acceptable in networked performance applications but that are workable in e.g. television production and outside broadcast applications.

### 3.5.4. Video acquisition, processing, playback and output

The video environment for the XRNP framework comprises the complete set of functionality required to acquire live video; playback pre-recorded video; processing, such as chroma-keying, compositing and the application of effects; and the output of video to other devices, locally and at remote nodes of the performance.

Video cameras (physical ones; virtual cameras are discussed in: 3.5.8) are most likely to employ robust professional standards for output of video, especially SDI, but also HDMI, NDI over IP networks, and to a much lesser extent, USB. With appropriate hardware interfaces in each platform, SDI provides a reliable and deterministic method to acquire video from cameras, with formats up to Ultra HD (2160p) @ 60fps at distances of 100m using coaxial cable, or with fibre cable extending over several kilometres depending on use of single or multimode cable. Output of HDMI cameras can be ingested using HDMI capture devices or HDMI-to-SDI converters. USB cameras, when needed for special applications (such as the low latency USB cameras specified for use with LoLa), can be connected via USB extenders that use Ethernet Cat5 or Cat6 cable, allowing the physical connection to extend 100m or more.

There is not one single protocol or method for the remote control of cameras, and there are no cameras that support OSC as a direct method of control. However, intermediate camera control solutions—such as some models of Blackmagic Design's ATEM studio—can work as pseudo-gateways for OSC to control Blackmagic Design's own SDI cameras. Software gateways to control the ATEM models using OSC, include atemOSC (*OSC-bridge for controlling ATEM switchers*, n.d.) and a TCP hardware gateway from Skaarjoj (*TCP control ATEM Switchers*, n.d.). Companies, such as Panasonic (n.d.) also produce SDI and IP streaming video cameras that have remote control options over IP, and which can be controlled using OSC though software gateways.

Real-time video processing is the ability to modify and composite video and related information during the performance, on a frame-by-frame basis, and with no perceivable delay as observed by the audience and performers. Such processing may be achieved through hardware sub-systems (vision mixers and video switchers) or software applications. Devices, such as Blackmagic Design's ATEM and Newtek's Tricaster (*The Most Complete*

*Video Production Systems on the Planet*, n.d.) products, with SDI/HDMI inputs and outputs, are self-contained devices for video switching, mixing, and the application of certain video processing functions. While dedicated sub-systems for video acquisition and switching may not offer the flexibility of some software applications (see below), they do provide useful components in creating a reliable video acquisition, switching and distribution network at the nodes of an XR networked performance; especially as regards the connection of SDI devices, configuration control and management. As aforementioned, some models of Blackmagic Design's ATEM can be also controlled using OSC via software gateways implemented on a host computer.

Numerous software applications are available that can be employed within the context of the XRNP framework to provide the functions of video processing, playback and video output. While originally intended for use in live video performance (such as in VJing), applications, including Resolume, MadMapper (*MadMapper is an advanced tool for video and light mapping*, n.d.), Modul8 (garageCube, n.d.) and VDMX (n.d.) are all capable, real-time video platforms that support video input, playback and processing, and that can be controlled by OSC. Some, like Resolume and MadMapper, also include tools to manage the projection mapping process. Tools like Notch (n.d.) and Smode (n.d.), with a focus on real-time effects generation and compositing of video, also support control by OSC.

Many toolkit type applications (such as VVVV and Touch Designer) can also support video processing and projection mapping. However, in the same way that they are not the most efficient for cue management, they are also not the preferred tools for the simple and efficient management of video related tasks. They do, however, provide video capabilities that are useful for experimentation and the implementation of custom applications involving video, audio, sensors, etc.

One category of video processing and mapping solutions not considered as candidates for the XRNP framework, are software applications that are delivered as part of a dedicated media server environment. Solutions which require the purchase of expensive and dedicated computing platforms and therefore deny some of the flexibility in configuring solutions for each XRNP project based on the open-standards, sub-systems integration approach. Solutions in this category include: Watchout (*Watchout Media Servers*, n.d.), Pandoras Box (*Christie Pandora's Box*, n.d.), Disguise (n.d.), VYV (n.d.) and X-Agora (*Interactive Media Management and Playback*, n.d.).

### 3.5.5. Audio acquisition, processing, playback and output

The audio environment for the XRNP framework focuses on the ingestion (analogue-to-digital conversion and digital transport of audio signals), the storage and playback of pre-recorded audio files, and the output (digital-to-analogue conversion) of streamed and pre-recorded audio.

The XRNP framework does not consider specific solutions for audio capture (microphones) or reproduction (amplifiers, loudspeakers, etc.). Audio mixing desks—of which there are an almost infinite variety—are also not addressed in the framework, though consideration is given as to their inclusion in XRNP systems for the host computer audio interface functionality many of them provide. The capture of audio, and its reproduction, in performance environments—also in networked performance environments—has been covered in detail elsewhere (see: Prior et al, 2017b; Geelhoed et al, 2017).

Solutions for ingesting audio into the host computer environment—so that it can be processed, routed or streamed by software applications—fall, primarily, into two categories:

- External audio interfaces or audio mixing desks that include a host computer interface for streaming audio to/from applications. The physical interfaces are most commonly USB, but alternatives, such as Firewire (legacy) and Thunderbolt, are also common. Examples include those manufactured by Focusrite (n.d.), MOTU (n.d.), RME (n.d.), Presonus (n.d.) and Apogee (n.d.). Audio mixing desks that support streaming of audio to/from a connected host computer include examples of those manufactured by Allen & Heath (n.d.), Soundcraft (n.d.), Mackie (n.d.) and Behringer (n.d.);

- Internal interfaces, typically PCIe based, such as those manufactured by RME, Focusrite and Marian (n.d.). Versions manufactured by RME are among the preferred audio interfaces for use with the LoLa streaming application, due to their low latency in audio acquisition (the delay from analogue interface to PCIe digital interface and readiness for consumption by a host software application) and their audio quality.

Connecting host computer resident applications to audio I/O in the local environment can also be achieved using IP based audio steaming solutions (such as RedNet and Dante), operating over a LAN, connecting with networked-based analogue-to-digital audio concentrators (see: 3.5.9).

Of the many external audio interfaces available, most have some host-computer based application (e.g. for Windows or macOS operating systems) that can be used to control and configure them. However, few have an application interface allowing them to be controlled straightforwardly by MIDI or OSC messages. Of the exceptions, MOTU provide templates for use with the application TouchOSC (*Modular touch control surface for OSC & MIDI*, n.d.) and which therefore allows some models of their audio interfaces (such as the UltraLite AVB) to be controlled using OSC over USB or Ethernet connections.

### 3.5.6. Lighting

Control of lighting in most performance venues is typically by a dedicated lighting desk, or computer with a lighting application. Like other multimedia performances, networked performances will typically require a tight synchronisation between lighting and other elements of the performance. There are two key routes to achieve this in the given context:

- Configure and control lighting scenes using a venue's existing lighting solution (desk or other application), then trigger scenes on that controller, typically using DMX input, or a message such as OSC sent over an Ethernet interface;
- Incorporate a lighting configuration and control function within the XRNP system and use that to talk via a DMX interface directly with lights and dimmers at the venue.

Sometimes, the lighting solution at a venue may be extensive and a house technician is available to support the setup of the lighting and programming of cues on the venue's desk that are required for the performance. However, the time to setup the existing system can also introduce additional get-in time. In touring scenarios, with typically short get-in periods to a venue, the preferred approach is through use of a lighting controller that is tightly integrated with the XRNP system and toured with the equipment taken to each venue, interfacing to the lighting system at the venue using a direct DMX interface.

The toolkit solutions discussed (see: 3.5.2) all support DMX interfaces (such as USB to DMX) and Art-NET for control of lighting but none of them are specifically designed for this task. However, for simple lighting setups, and ones that have a great deal of real-time interaction with other multimedia components of the performance or local set, they can be a good solution and avoid the requirement for an additional application. There are numerous commercial and open-source software applications, running on Windows and macOS, that are specifically designed for lighting control using DMX and Art-NET, examples include: Enttec's D-PRO (n.d.), Lightkey (n.d.), and QLight Controller (n.d.).

QLab, while not initially or specifically designed for DMX lighting control, has had the ability to trigger lighting applications via MIDI and OSC. In version 4, QLab introduced the ability to configure light fixtures and scenes along with other cues, and control fixtures and dimmers directly via DMX and Art-NET. QLab offers some advantages compared to dedicated lighting applications—especially in the case of multimedia performances like XRNP—in that all cues can be managed by a single application. QLab can also be controlled by OSC, allowing individual light scenes or cues to be initiated by OSC across the XRNP framework.

In contrast, dedicated lighting applications or hardware based lighting desks may offer quicker setup of complex scenes, especially those involving the use of complex light fixtures, such as moving heads.

### 3.5.7. Performance management, control and synchronisation

The ability to reliably and accurately control and synchronise all sub-systems within the XRNP framework is one of the critical factors for the system in ensuring the delivery of an XR networked performance.  The capability to quickly test new cues and make modifications to the cueing system is beneficial for experimentation, rehearsals and managing changes that are specific e.g. to each venue's own technical infrastructure, in an efficient manner. As the standard interface for the XRNP framework is OSC over UDP, the selected solution must provide the ability to generate OSC cues using IP transports.

Again, all of the toolkit applications (see: 3.5.2) could be used to manage and generate cues sent to the other sub-systems using OSC, and have the functionality to send and receive OSC cues over Ethernet.  However, none of these applications ae specifically designed for this purpose; they do not provide a GUI that is specifically suited to the programming and management of cues.

There are relatively few applications that are specifically designed for multimedia cue management in the performing arts. QLab is the de facto software used in theatres for cue management, also frequently for audio playback, but it is only available for macOS. Vezér (n.d.), also macOS only, is a more recently introduced application that employs a visual timeline approach to synchronising cues, rather than the grid-list with timer approach employed in QLab. Both products support cues sent via OSC, DMX and MIDI, and can receive commands using OSC.

### 3.5.8. Environments for computer generated realities

The environment required is one that provides for the development and hosting of virtual realities, and from which scenes can be extracted in real-time for use in the physical space of the performance, typically through use of projection. The environment should also support the real-time and high-fidelity ingest of other media, such as video from cameras in the physical performance spaces at any node of the performance.

Games engine platforms are software-development and runtime environments that are primarily used for the development of computer video games, many of which are adding advanced capabilities to support VR and AR. Some of these platforms target Windows and macOS runtime environments in addition to supporting game-playing target platforms, like the Microsoft Xbox.

Two of the most popular games-engines are Unity and Unreal. Both environments include comprehensive development and debugging tools, engines for visual effects and physics, and support for working in VR and AR environments. Unity uses C# as the primary development language, while Unreal uses C++. OSC support is not provided natively in either Unreal or Unity but commercial and open-source plugins or libraries are available to support OSC in both.

### 3.5.9. Audio and video sharing

In addition to streaming of audio and video across greater distances between venues, such as over the Internet, there is also the need in an XR networked performance environment to share audio and video between applications, computing platforms and other devices in the same node of a performance. It is not a necessity that these applications be controllable by OSC as they ae primarily intended as transports or methods of real-time sharing between applications that do have OSC interfaces.

- **Sharing between computing platforms** - primarily using IP transports, can be achieved using the same streaming technologies—jacktrip, LoLa and UltraGrid—that are employed for longer distances (over Internet or WAN). For audio, I also considered IP streaming technologies that are specifically designed for the distribution of audio within a studio or performance venue, such as AVB and Dante (see: 3.4.1). SDI can also be used to transport digital video between computing platforms if SDI hardware interfaces are installed. NDI, introduced as a royalty-free standard by Newtek in 2015, has seen considerable uptake by hardware device and software vendors for the IP distribution of video over LANs.

- **Sharing on the same host computer** - there are two solutions that currently dominate the market for sharing of real-time video between applications executing on the same host computer: Syphon (*Introducing Syphon*, n.d.) for macOS, and for Windows, Spout (*Realtime video sharing framework for Windows*, n.d.). Both applications work by allowing source and destination applications on the same host computer to share video via the GPU using named video contexts. Routing and sharing audio between applications on macOS can be achieved using solutions such as Jack (*Jack Audio Connection Kit*, n.d.) and Loopback (*Loopback Cable-Free Audio Routing for Mac*, n.d.). Jack is also available for Windows, as is the virtual cable solution VB-Cable (*VB-Cable Virtual Audio Device*, n.d.).

## 3.6. Baseline system architecture and sub-system components for XR networked performance practice and research

The outcomes of the review of interfaces and suitable systems that could form the basis of an XR networked performance systems framework were used to develop a baseline architecture that was employed for research practice between 2017 and 2019. These decisions were further informed by experimentation with some component sub-systems in my practice during 2015 and 2016, especially with the projects *Here, Not Here, Where* and *Bridge to Everywhere: 234,* as discussed in Chapter 2.

Use of this framework in the projects *Longing for the Impossible*, *The Spaces Within*, *Opravdoví*, and *A Short Journey into Folded Space*, are detailed in Chapter 4. The text in Chapter 4 also explains how the framework developed during the course of these four projects, how new components were added or specifically developed for each project, and how the use of the standard OSC interface facilitated that process.

The core components selected and used in these projects are:

- **Streaming**: UltraGrid and LoLa (including Lola framework preferred audio and video components, on Windows 7 and Windows 10). NDI has also been used for LAN streaming during development and rehearsal of projects;
- **Software video mixer and mapping**: Resolume Arena (Windows 10 and macOS);
- **GPU video sharing** - Spout (for Windows) and Syphon (macOS);
- **Cue management** - custom applications generated in Max/MSP (Windows 10 and macOS), and QLab (macOS);
- **Lighting** - custom applications generated in Max/MSP (Windows 10 and macOS), and QLab (macOS) with the version 4 lighting options. Entec USB DMX Pro Mk2 interface for direct interface with DMX lighting dimmers or triggering of lighting desk with DMX input;
- **Toolkit software** - Max/MSP (Windows 10 and macOS);

- **Computer generated realities** - Unity (Windows 10) games engine with extensions and project specific code, mostly in C#, to perform live 3D composition and provide virtual sets for the projects *The Spaces Within* and *A Short Journey into Folded Space*;

- **Offline tools** - software applications used to develop code, and audio/visual components in these projects has included: Cinema 4D, Adobe After Effects, Adobe Premiere, Adobe Audition, Adobe Illustrator, Ableton, Processing. Max/MSP, Microsoft Visual Studio, Microsoft Visual Studio Code and Sketchup;

- **Software utilities** - used for network configuration, test and monitoring, and for remote access to remote nodes of a performance: Wireshark, iPerf, Team Viewer, VNC, Skype, and the Ubiquiti Edge Router's management console;

- **Computing platforms** - custom-built PCs running Windows 10, and Apple iMac and Mac mini running several different versions of macOS. Tablet computers have also been used during development and to host custom interfaces for some of the projects, including Microsoft Surface and Apple iPad;

- **Hardware video interfaces, file players, mixer, switch and camera control** - Blackmagic Design Decklink SDI/PCIe interfaces (various models), Blackmagic Design ATEM Production Studio (various models), Blackmagic Design Hyperdeck and Video Assist;

- **Lighting control** - Entec DMX USB interface for control of DMX dimmers directly by Max/MSP patches or using QLab. Control of lighting indirectly by DMX triggers sent to an external lighting console from Max/MSP, QLab or Resolume;

- **Video cameras** - Blackmagic Design SDI cameras (several different models), Polycom, and for LoLa, XIMEA USB cameras. Also, NDI streaming applications running on Android mobile phones;

- **Audio interfaces** - primarily, Focusrite (USB) and RME (PCIe).

# 4. XR NETWORKED PERFORMANCE IN PRACTICE

This Chapter provides details of each networked performance project (chronologically, oldest first) that forms the basis of my artistic and technical practice, and which were used to examine the systems framework for XRNP. For each networked performance, a description of the research and artistic objectives, underpinning technical initiatives, implementation and outcomes are detailed. Within the explanation of each project, the artistic need or opportunity provided by each new technical advance is also discussed.

The projects that were involved in the iterative evaluation and development of the systems framework, are:

- *Longing for the Impossible* - Copenhagen/London/Barcelona, March and April 2017
- *The Spaces Within* - Miami, April 2018
- *Opravdoví / The Real Ones* - Pilsen/Trutnov, Czech Republic, September 2018
- *A Short Journey into Folded Space* - Birmingham/Barcelona, March 2019

All of the projects, except *Opravdoví / The Real Ones*, were supported by opportunities arising within my existing network of sponsors. Although I could not plan these to a fine schedule at the commencement of the research programme, I was confident from the outset that the appropriate opportunities to support testing of the XRNP framework would become available.

Reliance on the support of my network was necessary due to the situation that network performances are technically and organisationally complex, and require a lot of resources: critically, they typically need at least two suitable venues to be available on the same set of dates that rehearsals and performances will occur. Given these circumstances, and my ambition in testing the XRNP framework during the course of the research, it would have been financially and logistically impossible to create four completely independent projects. However, in the case of *Opravdoví*, an important test of a symmetric type of networked performance which also researched the use of OSC to synchronise nodes of the performance, this was self-initiated and mostly self-funded.

The other possibility would have been to try and create just one performance in which all of the technical evaluation of the framework would be conducted. From my prior experience in developing complex systems in new fields of practice, I knew that this approach would not provide sufficient opportunities for experimentation; it would have been the 'big bang' approach. An iterative approach to research was preferable, one in which evaluation of the framework progressed based on lessons learnt in each project.

## 4.1. Longing for the Impossible

*Longing for the Impossible for the moment it is real* (hereinafter "*Longing*") is the starting point regarding a journey into a deeper technical foundation for XR networked performance. It presents the first incarnation of a platform and systems-approach that has since been continually developed to support an evolving practice. And, the first time that OSC was employed to coordinate the multiple components within those systems.

The Royal Danish Academy of Music (RDAM) organises an annual festival of contemporary music: PULSAR. In 2017, they were also to be the host for the annual NPAPW conference and so I had proposed a networked performance for that event. However, the go-ahead was not agreed until a little more then 3-months before NPAPW was scheduled to take place, and only two months before the PULSAR festival would commence.

Some elements of the performance were already defined. The main performance space and audience would be in the 1940's designed radio recording studio of the RDAM building in the centre of Copenhagen. There would be five compositions, each by a Masters' student composer studying at RDAM. The performance would include some musicians performing via network from the Royal College of Music (RCM) in London. This, not just because that it was an interesting element to add to the performance but because they had musicians that were not available in Copenhagen: a countertenor and a harpist. The performance was also to collaborate with dance students from the Danish National School of Performing Arts in Copenhagen, and the Institut del Teatre in Barcelona who had also been tasked with developing some of the remote choreographies. The dancers in Barcelona would perform in an annex of the Barcelona Museum of Contemporary Art (MACBA). We would use the LoLa system for audio/visual streaming from RCM (we needed very low latency for the duets that would involve the countertenor and harpist) and UltraGrid for the connection with Barcelona.

With around 2-months until the first performance we had no linking artistic concept, no set design, and little in the way of a systems design by which to pull the two remote venues (RCM, London and MACBA, Barcelona) into the performance space and render those performers alongside their colleagues physically situated in Copenhagen, in some form that was contextual and meaningful to the audience in Copenhagen.

#### 4.1.1. Longing - research objectives

- Introduce and test OSC as the standard messaging interface for the XRNP system framework;
- Test use of Max/MSP to control lighting (DMX integration) and as a toolkit to create custom GUIs for control of the performance;
- Investigate the use of Resolume Arena as a vehicle to create real-time animations as a composite of pre-recorded and streamed video;
- Test alternative streaming solutions working with the XRNP framework.

#### 4.1.2. Longing – artistic concept

Since *Bridge to Everywhere:234* (see: 2.2.3) the previous year in Miami, I had been considering the issue of spatial representation and the relative positioning of remote and local performers within a physical node of a networked performance. In Miami, I had presented the local and remote performers on a giant screen, layered 2D, situated between other layers of image, animation and video; there had been no real attempt at presenting perspective or the creation of a visual space that was more ‘3D’ in its view from the audience.

I had also been looking to the world of theoretical physics for inspiration in conceptualising time and space within the domain of the networked performance: from orbiting molecular models through to parallel universes and worm holes, many of which would also provide artistic food for future projects. By happy coincidence, I chose to work with the theme of Niels Bohr's model of the atom (Kragh, 2012). Bohr having been born in Copenhagen. Bohr's model was abstracted, for the sake of the performance, to be one where the performance—the 'narrative' itself—was the nucleus., and the performers, regardless of their location—physically present or remotely streamed—were the orbiting electrons.

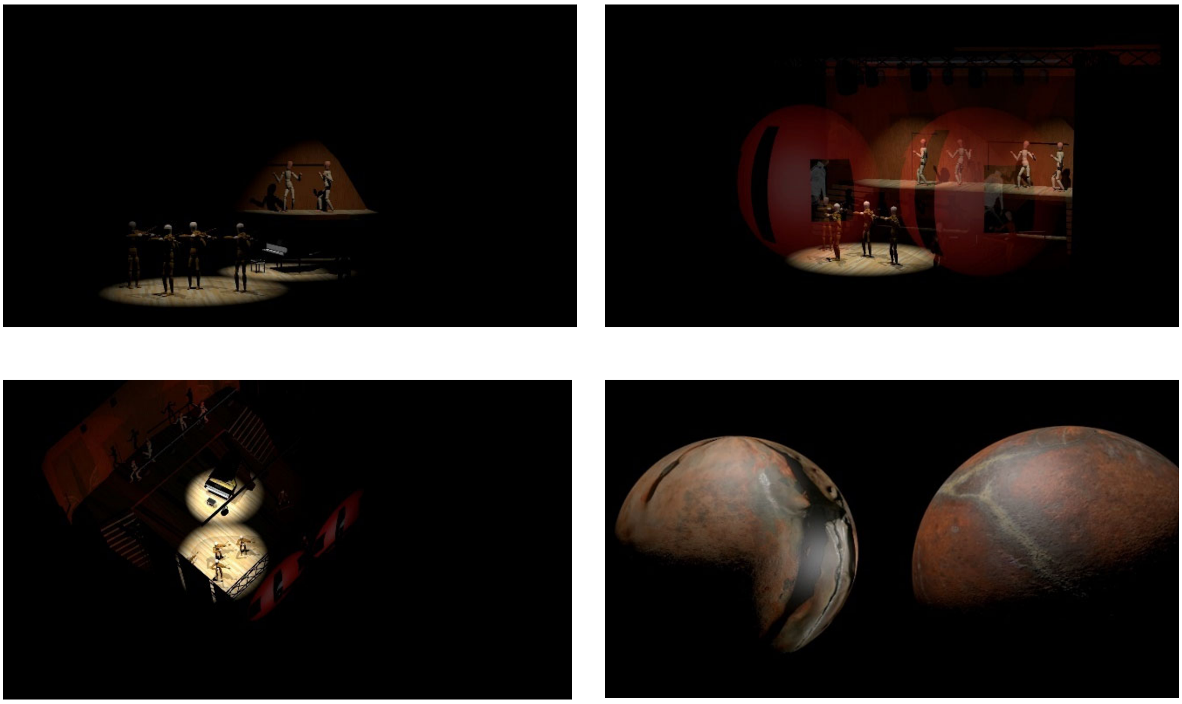

Figure 22: Previsualisations of concepts for *Longing for the Impossible* (2017) produced in the applications Sketchup and Cinema 4D.

At the time of the offer to develop the project, I had been working in Spain experimenting with site-specific landscape projection mapping, mostly in the copper mines around the town of Rio Tinto. I had many photographs of minerals, waste heaps, etc. that were deep in texture and rich in colour: it was images from this collection that would form the rendered surfaces of the spheres that would in turn contain the remote performers, projected within the physical space in Copenhagen. The visual theme allowed the diverse music compositions to link to one consistent performance identity. The use of different types of spheres for each composition was sympathetic to the individual scores and facilitated dance artists to compose choreographies that reflected both the overall visual framework and the individual pieces.

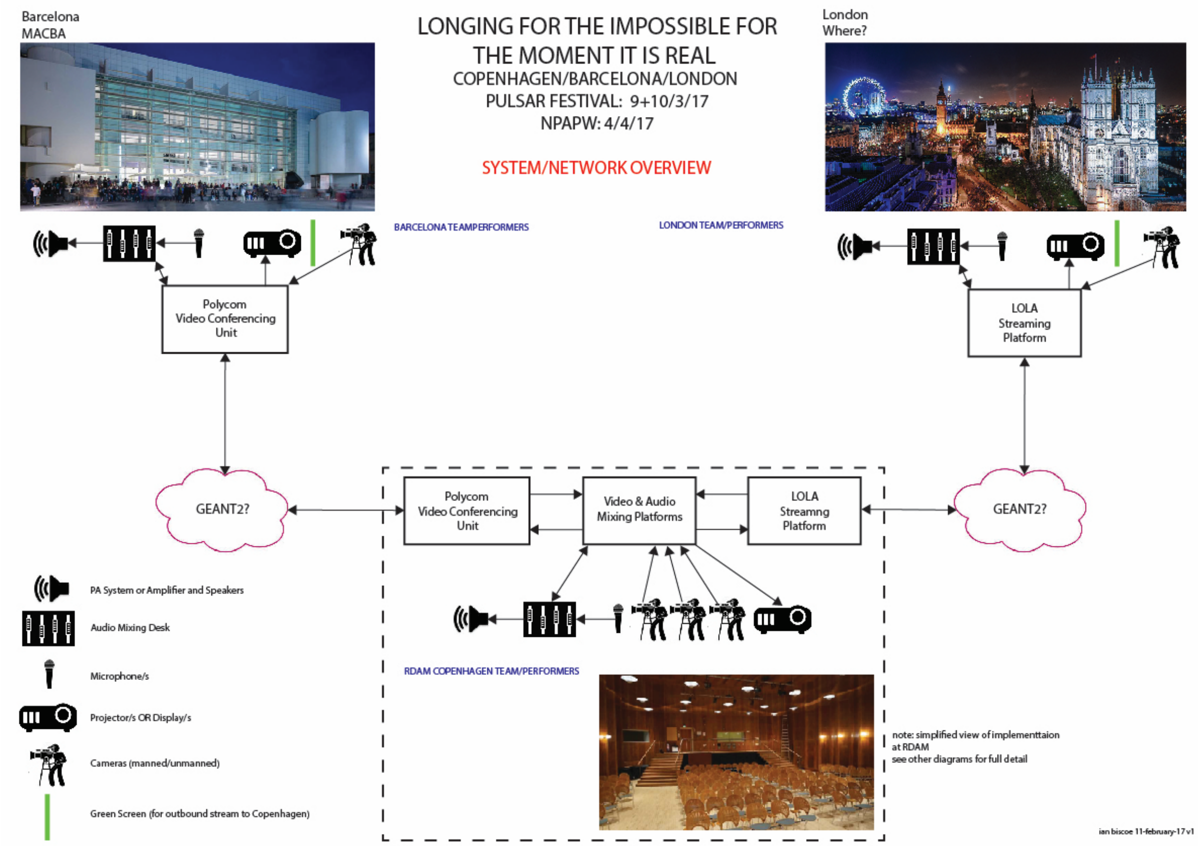


Figure 23: System overview for *Longing for the Impossible* (2017) showing the three nodes of the performance in Copenhagen, Barcelona and London.

### 4.1.3. Longing – realisation

For the performance space in Copenhagen, a physically free-standing, black-box performance space was constructed within the historic recording hall: nothing could be attached to the existing structure due to its listed status. It was formed of trusses, drapes and a sharkstooth scrim at the front of the space, situated between the performers and the audience. The use of a sharkstooth scrim to the front of all the physically present performers provided several opportunities:

- The physically present performers were effectively hidden from the audience unless they were lit behind the scrim: this is a common trick when using theatrical scrims;
- Images of the remote performers—including animations and other visual components they were composited with—could be projected onto the scrim. The scrim being semi-permeable means that some light also leaks through to the

surfaces beyond the scrim, and in a very dark room this heightens the feeling of depth or ethereality of the images from the perspective of the audience who are situated in front of the scrim;

- The space behind the scrim was quite deep, more than 10m, with an elevated balcony to the rear, which left the audience perception open as to exactly where the physical performers beyond the scrim were situated. This helped the artistic concept, in that all performers—physically present or remote—were all situated within a common 3D space that had an elusive depth.

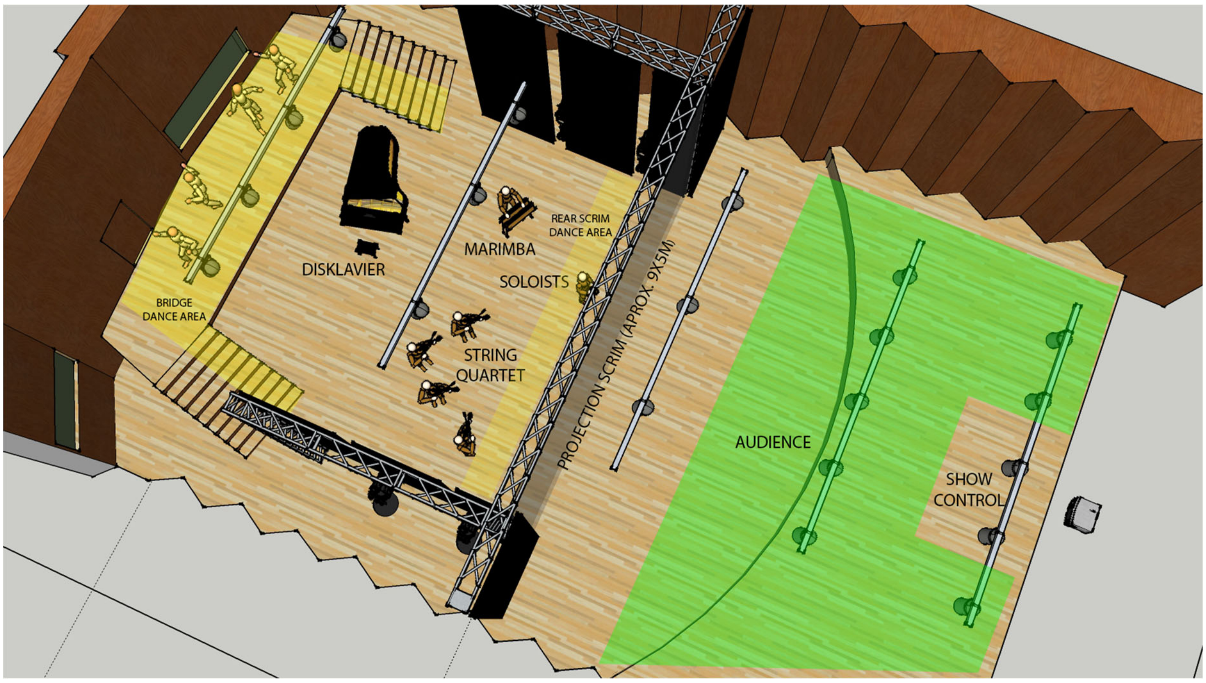


Figure 24: Set design for the Copenhagen node of *Longing for the Impossible* (2017) showing the deep stage in which the physical and virtual performers were positioned, separated by a sharkstooth projection scrim to the audience.

The spaces for the remote performers, in London and Barcelona, were both equipped with green-screen backdrops. The video stream sent from each location to Copenhagen therefore comprised the performers silhouetted on green-screen. The dance space in Barcelona was also fitted with a green floor.

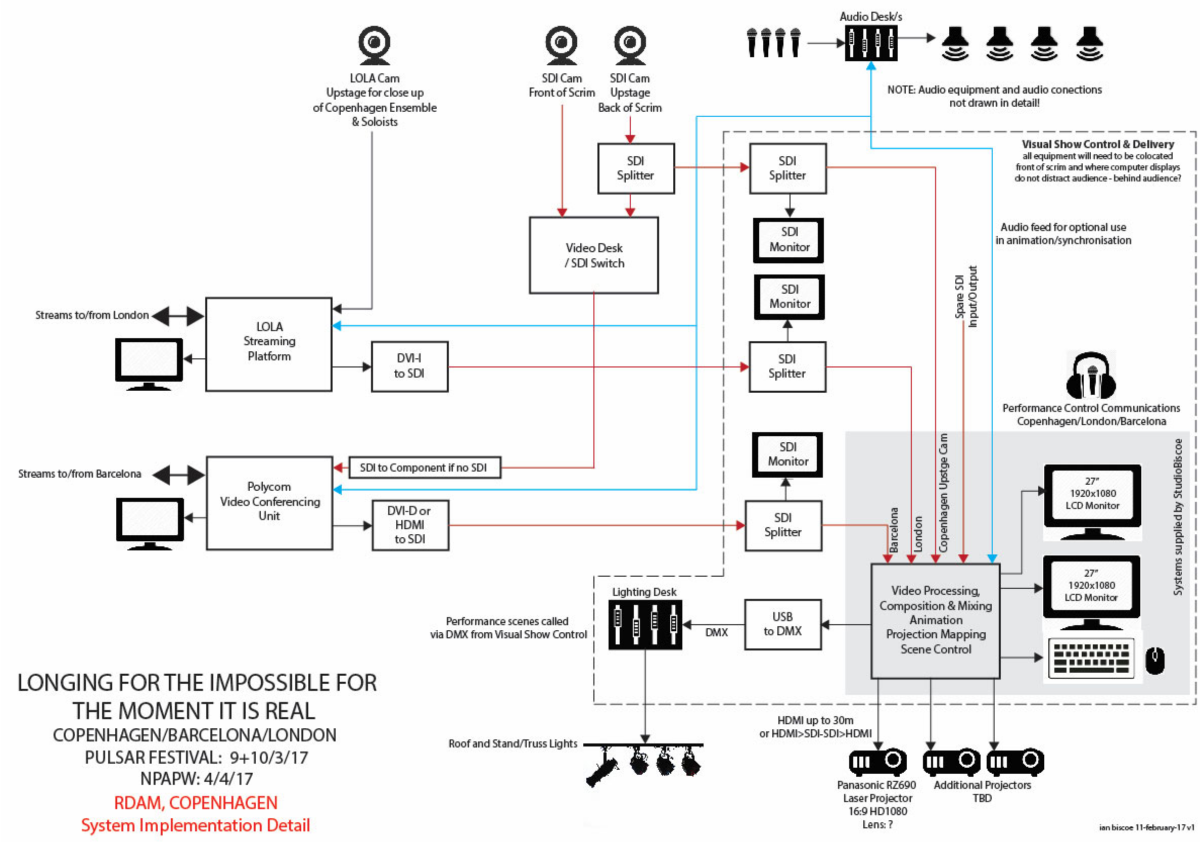


Figure 25: System diagram for the Copenhagen node of *Longing for the Impossible* (2017) showing the detail of audio, video and lighting sub-systems.

### 4.1.4. Longing – technical evolution

As I was yet to commence the integration of Unity into the systems framework, the lack of a real-time 3D engine led to an approach of manipulating the X, Y and Z position parameters of projected 2D video in real-time, to achieve the feeling of movement within the physical space of the concert hall in Copenhagen. This was achieved by developing a series of Max/MSP patches that communicated with Resolume via OSC. The 3D effect was heightened in the performance space though the use of the sharkstooth scrim projection surface.

During the development phase, a series of animated rotating 3D spheres were produced in the software application Cinema 4D. These spheres were rendered in various textures, and included areas on each sphere—that during the period of the animation—would change in texture to an RGB chroma key green (R=0 G=255 B=0). The completed animations were rendered to video clips in the Resolume preferred encoding format of DXV3.

In Resolume, layers were allocated to the video streams from Barcelona and London, to the animated sphere video clips, and to various related effect layers, such as effect masks that ensured the smoothness and boundaries of the video feeds during live composition.

During the performances, live video streams from Barcelona (Polycom) or London (LoLa) were fed to the layer clips in Resolume, where the chroma-key effect was used to remove the green screen background of the performers in either location. The chroma-keyed video streams were then composited with the animation clips and mask effects—using the layer-router function in Resolume—into a separate layer. The composite of the live video stream, animated video clip and effects, were then positioned horizontally (x), vertically (y) and scaled (depth; z) in Resolume per the OSC data sent from the Max/MSP patch.

Figure 26: Technical setup for *Longing for the Impossible* (2017) in Copenhagen. Left: show control, with interfaces for Resolume and show control GUI in Max/MSP, and monitors displaying live video streams from Barcelona and London prior to processing and composting for projection. Right: performance space, showing audience view though the sharkstooth scrim towards the location of the physically-present performers.

The formulas in the Max/MSP patch were designed to orbit the sphere on a series of elliptical paths, moving closer in perspective to the audience in each full path (video: *Longing for the Impossible* - full performance, 2017, 00:01:05). The X/Y/Z coordinates were sent in an OSC message every 15 milliseconds, equating to a frame rate of just over 60 fps.

The pre-recorded animation clips were stacked in front of the live streams so they also acted as masks. As each animation proceeded, and parts of the texture changed to chroma-key green, another chroma-key effect was used to make this area of the animated sphere transparent, revealing another area of the live video stream in the layer below. The combination of the live composition and the effect of 3D spatial positioning within the physical set resulted in orbiting spheres, which gradually revealed or concealed the performers in the remote locations (video: *Longing for the Impossible - full performance*, 2017, 00:02:15). The spheres appearing to the audience as if they were moving between the spaces occupied by the physically present performers in Copenhagen.

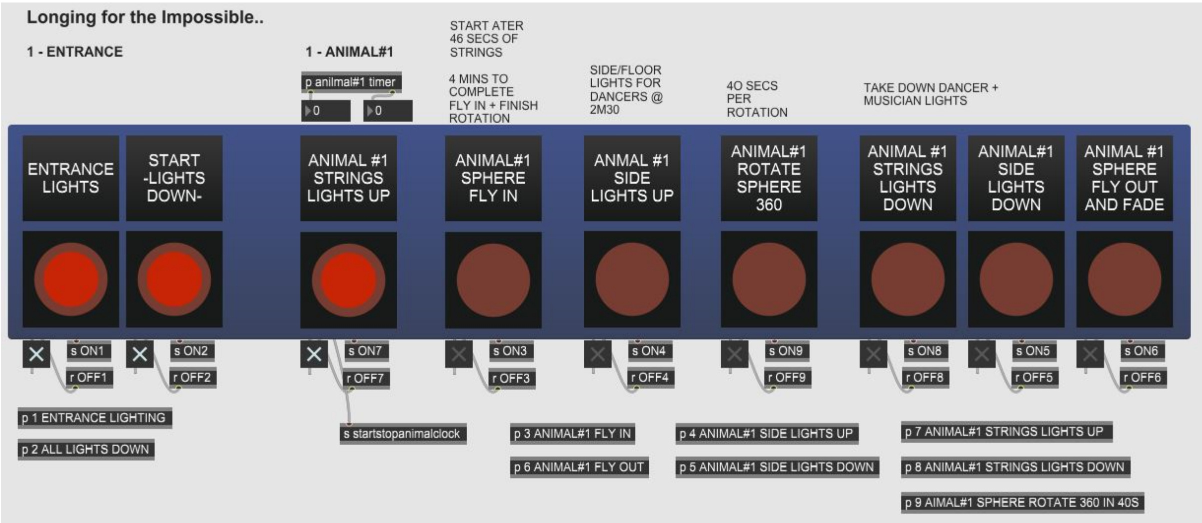


Figure 27: Part of the GUI for control of the performance *Longing for the Impossible* (2017) which was developed in Max/MSP. Each major element of a scene had a dedicated cue button which—through the logic in the associated patch—would control lights via DMX, or send sequences of OSC message to Resolume to control video effects and stream composition. The Max/MSP *bpatcher* objects encapsulate reusable code for individual tasks, such as sphere animation, and light fades.

The performance comprised five major scenes (one for each piece of music) but each scene had hundreds or thousands of individual cues, especially the scenes in which OSC commands were used to perform the 3D spatial animation effect in Resolume. A user interface was developed in Max/MSP which presented all the major cues of the performance to the operator. The individual cues were then responsible for triggering lower-level Max/MSP patches which would in turn control functions in Resolume or lighting. The DMX light dimmers in the Copenhagen venue were connected to the same set of Max/MSP patches using a USB to DMX interface (the Entex DMX Pro MK2). The cue interface patch also displayed the status of the cue, if it had been executed successfully and the time left before execution was completed.

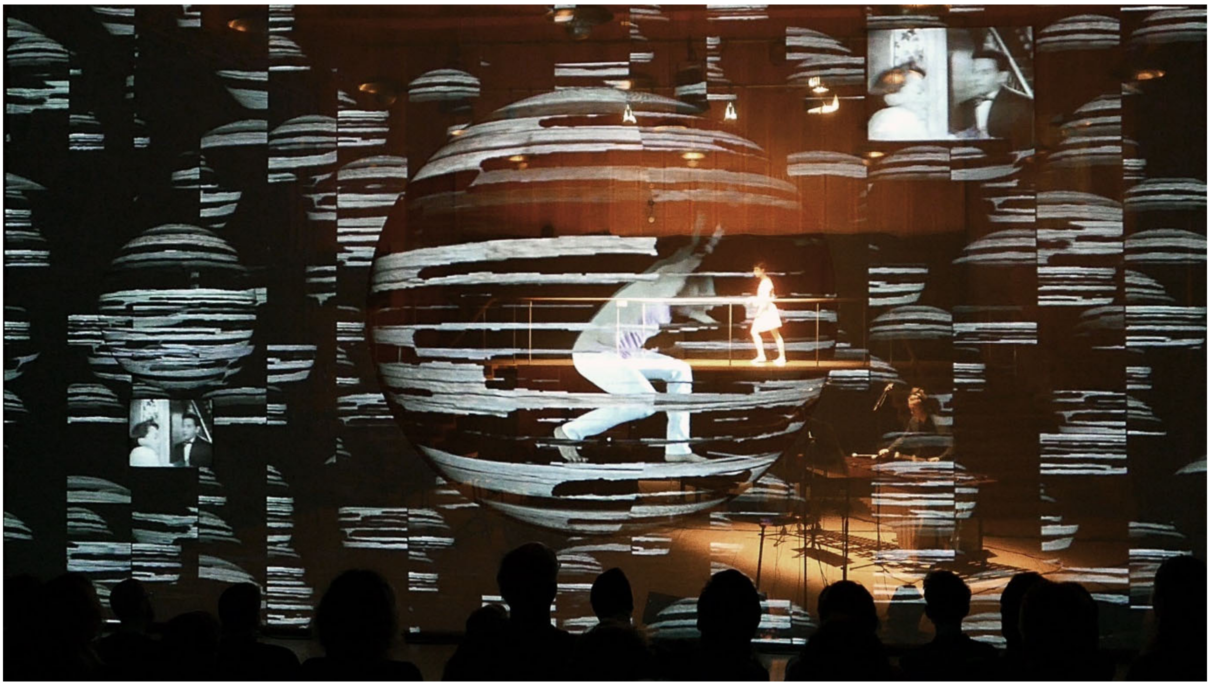

Figure 28: A view from the final section of *Longing for the Impossible* (2017), the performance of the last of five music compositions. The dancer in the sphere to the front is extracted from a live stream from Barcelona (MACBA) while the percussionist to the right and the dancer on the balcony to the rear are physically present in Copenhagen.

### 4.1.5. Longing – outcomes

Though this project only used some of the components that had been identified for the XRNP systems framework—primarily Resolume working with Max/MSP via OSC—the solution provided for rapid prototyping and exploration of the artistic concept and a reliable delivery of the final project, performed on three dates over a period of one month.

Measured against the research objectives for this project (see: 4.1.1):

- OSC proved a capable interface for the control of Resolume, not only as a mechanism for selecting clips and video mixes within Resolume, but also able to support rapid bursts (up to 200 messages per second) to control X, Y and Z absolute clip positions within Resolume, to achieve the orbiting sphere effect;
- Patches developed in Max/MSP (the toolkit application selected for the XRNP framework) formed the control GUI for the performance, including the generation of cues; controlled sequences and animations in Resolume; provided the maths engine

for the orbital paths of the animated spheres; and controlled the lighting in the venue via an Entec USB-to-DMX interface. This project proved Max/MSP to be a good solution for the rapid development of the 'glue' middleware in XRNP projects, and also as a capable engine for the integration and routing of OSC message flows;

- The test of the developing XRNP platform as regards alternative streaming solutions, was primarily to see how well the parts of the system I had brought to Copenhagen would interface with the components that RDAM already had in-house. Only one LoLa system was available, so this was used to connect with the RCM in London due to that being the node from which a vocalist would duet with another vocalist in Copenhagen. The London connection was more latency-sensitive than the connection with Barcelona, which was only a video stream of the dancers performing in MACBA. The XRNP platform connection with the existing streaming solutions in-house at RDAM was achieved using similar GPU-to-SDI interfaces that had been employed to implement video-loopbacks in *Here, Not Here, Where?*. Although the approach worked well with the Polycom video conferencing unit, it was sometimes problematic trying to get the LoLa application to see a virtual-monitor (the Blackmagic Design HDMI-to-SDI adapter, itself connected to a DVI-to-HDMI adapter) as a display to which it should output the received stream. Though not necessarily a problem with the LoLa software, this finding was important as it demonstrated the need to find a method of obtaining a tighter systems integration between the video streaming solutions used and the software applications of the XRNP framework, such as Resolume and Unity.

There was one small error in the maths routines of the Max/MSP patch so that on a few of the elliptical orbits the sphere appeared to jump a few steps. An error in my code and not an issue of the supporting system.

Figure 29: A scene from the middle of *Longing for the Impossible* (2017), a green-screened dancer performs in a sphere—a pre-animation, rendered with a photograph in Cinema 4D—accompanying a physically present dancer and pianist behind.

## 4.2. The Spaces Within

Knowing of the excellent resources available at the New World Center in Miami Beach (from *Bridge To Everywhere: 234* in 2016) I made a proposal to work with the New World Symphony as a part of NPAPW 2018: an opportunity to test the next evolution of the XRNP system. Rather than develop a networked performance project which stretched over great distances, I wanted to focus more on the differences between the nodes of a performance, and to consider the differences in the involvement of performers, engagement of audience and staging between the nodes. Another aim was to work on the evaluation and integration of a platform for computer generated realities into the XRNP system framework. A proposal was made and agreed with the New World Symphony: a plan that would also engage some of the music fellows in the artistic development process so that they could experience different ways of working.

### 4.2.1. The Spaces Within - research objectives

- Integrate and evaluate the Unity games platform as a sub-system for the development and hosting of computer generated realities;
- As elements of the process to evaluate Unity within the project, also test:
    - OSC configuration and control of virtual worlds and objects,
    - Use of live video streams in virtual world models through the ingest of SDI and GPU shared video, and the rendering of these streams to objects within Unity,
    - Use of virtual lighting in the Unity model, controlled by OSC,
    - Use of OSC controlled virtual cameras inside Unity, to capture different scenes and export them using either SDI or GPU video sharing.
- Test Integration of Resolume and Unity using SDI and Spout GPU video sharing.

### 4.2.2. The Spaces Within – artistic concept

As an aspect of this research was to investigate networked performance practice over the full range of physical and mediated realities, it was this project where I focused on the integration of a virtual environment capability into the systems framework that had developed over the previous two projects.

The concept presented to the NWS fellows was one of exploring my imagined hidden dimensions of the New World Center. The NWC building (as presented in the discussion of *Bridge to Everywhere: 234*) was designed by Frank Gehry. It is effectively a large rectilinear box that is filled with “Gehryesque shapes” (Ampey, 2011, p.7) that are more familiar to Gehry’s other buildings, such as the Guggenheim in Bilbao and the Walt Disney Concert Hall in Los Angeles. This kind of ‘inside-out’ approach by Gehry for the NWC was due to the planning limitations of the City of Miami Beach, who basically wanted an architecture that was more in keeping with the art deco style that is historically predominate of the area. So, taking the abstract interior landscape of the NWC as a starting point, I proposed that a visitor to the building could not easily differentiate where one mass began or ended, on which floor any selected void commenced and was completed. And, for the fellows, the concept that they had discovered a continuity of those Gehryesque shapes that extended beyond what was visually manifest, both physically and sonically.

Figure 30: Sketch concepts for *The Spaces Within* (2018), showing (left) the idea that the New World Center conceals hidden spaces, and (right) a possible staging of physically present performers and virtual world projections in the main concert hall of the building.

### 4.2.3. The Spaces Within – realisation

The first challenge for the fellows was to propose some selected scores that would evoke in the audience the feeling of exploration of these spaces: real and imagined. There were a series of skype discussions with the fellows who had put themselves forward to help run the project. We all agreed that several pieces by Iannis Xenakis would work as regards the concepts of imagined spaces but that the limited number of musicians we had, and the instruments they played, precluded anything quite so ambitious for this choice of score. The final decision, was to construct the score from two pieces: Charles Ives' *The Unanswered Question*, and excerpts from Aaron Copland's *Appalachian Spring*. An important aspect in the decision to include *The Unanswered Question* was that Ives' notes for the staging of this work requested that the musicians were placed in three different groups and that the "string quartet or string orchestra, if possible, should be 'off-stage', or away from the trumpet and the flutes" (Ives, n.d.). From the perspective of timing in a networked performance, Ives also aided the possible approaches in his notes, when he proposed that the flutes in their response to the trumpet part "need not be played in the exact time position indicated. It is played in somewhat of an impromptu way".

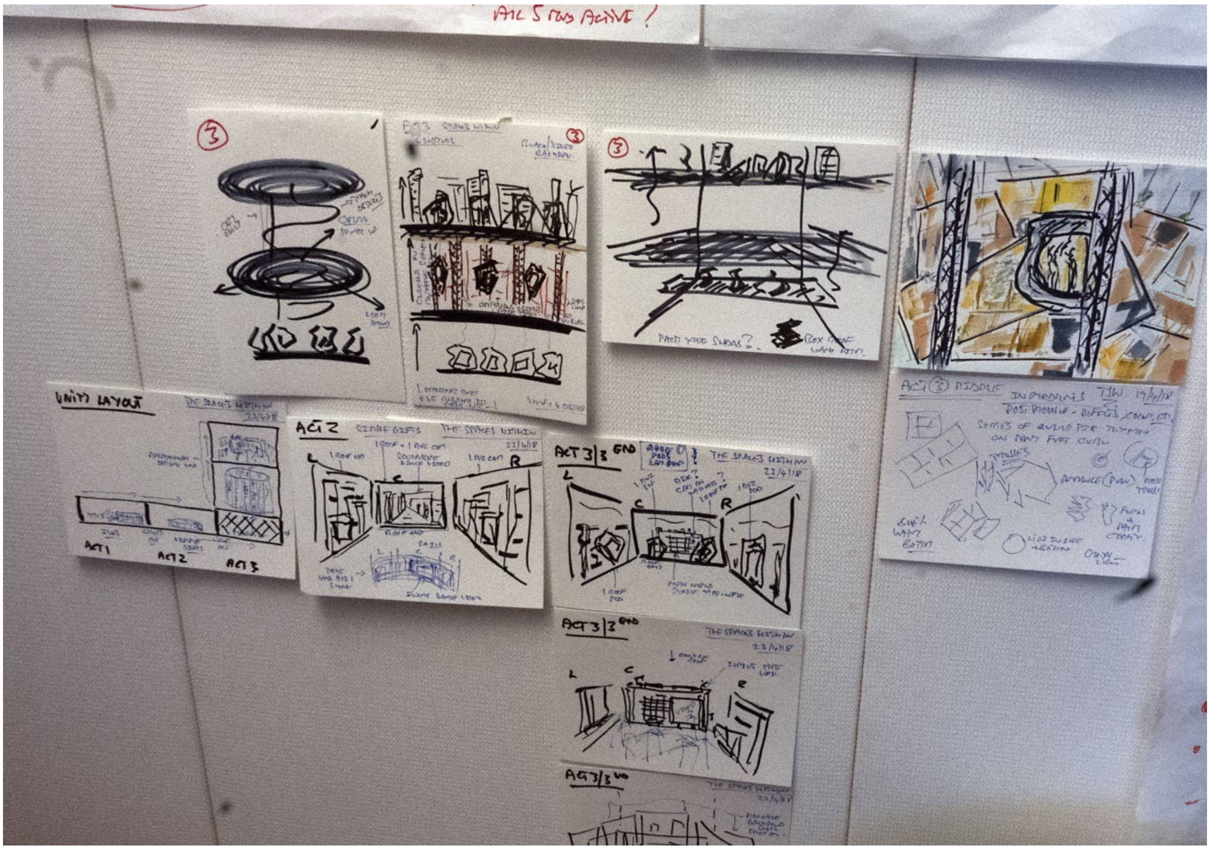


Figure 31: Storyboarding wall at the New World Center in Miami Beach
during final stages of development of *The Spaces Within* (2018).

The networked performance was staged across three nodes around the New World Center building:

- On a mezzanine at the 2nd floor of the atrium was the string quartet – “off-stage” as proposed by Ives in the performance notes for *The Unanswered Question*. The quartet also played parts for *Appalachian Spring;*

- Looking out over Miami Beach with views to the Atlantic Ocean is the rooftop garden. The second group of musicians, a string ensemble who played in both pieces, were located here on an outside terrace. Above them, on the elevated part of the building, was the projection of the composite performance;

- In the main concert hall, the trumpetist for the solo in *The Unanswered Question,* and the piano and bassoon for *Appalachian Spring,* were situated on small balconies to the left and right of the main performance space. As a contrast to the minimal number of physically present performers in this huge space, the visuals of the composite performance were projected on the immense projection sails surrounding the hall.

The visuals projected in the main performance hall and on the roof terrace were of scenes from a VR world model, composed from the abstracted shapes of Gehry's architecture. These scenes included live streams of the musicians from the other locations, which had been placed within the VR model (video: *The Spaces Within – highlights*, 2018, 00:00:00). By the projected visuals, the audience were taken on a journey through the imagined spaces of the NWC (which were synchronised with the score) meeting the musicians from the different physical spaces of the NWC as the virtual cameras moved through the model. There were in fact two synchronised VR models: one for the projections on the roof terrace and another for the projections in the main hall (video: *The Spaces Within – highlights*, 2018, 00:02:10).

Figure 32: A musician, who is physically located in the main concert hall, simultaneously travels in a pod through the virtual world model of imagined spaces underneath the New World Center, during the performance of *The Spaces Within* (2018).

The performance consisted of three movements and five visual scenes. In two of the scenes, pre-recorded video was also used as elements within the VR world models. Immediately after Ives' *The Unanswered Question*, there was the first extract from *Appalachian Spring*, the piece commonly known as *Simple Gifts*. To accompany this second movement, a choreography was produced for two dancers: a light-hearted slapstick inspired intervention. It was pre-recorded in Soundscape park, in the front of the NWC building, and augmented in the VR model so that the dancers appeared to perform behind a window of part of the imaginary building (video: *The Spaces Within – highlights*, 2018, 00:03:08). For the final scene of the performance, accompanied by the final section of *Appalachian Spring*, the live video streams of some of the musicians were placed in pods on vertical rails within the VR model, travelling from the underworld of the imaginary building and emerging onto the lawn in Soundscape park. To provide a backdrop for this section inside the virtual model, a thirty-minute time-lapse sequence was recorded at sunset—facing the NWC building across Soundscape park—and composited into the scene.

Figure 33: View from the audio-visual production suite of the New World Symphony's main concert hall, overlooking the auditorium, during the performance of *The Spaces Within* (2018). Multiple projectors are used to present the views from the Unity virtual world model onto the 'sails' that surround the performance space. The scene is in the middle of the performance: it shows a composite of three live video streams and one pre-recorded stream (the dancers) captured from inside Unity using a set of three virtual cameras which are under OSC control.

The complete performance was played twice, with the two halves of the audience moving between the performance hall and rooftop garden during the interval. The reason for this was to get audience feedback on the experience of viewing the performance from two different perspectives. The two audience groups were guided though the building during the interval and did not meet again until the end of both performances. The string quartet who performed on the atrium mezzanine were only ever seen performing remotely in the performance, although the audience members would see them resting on the 2$^{nd}$ floor as they passed on their transit through the building during the interval.

Figure 34: In the final movement of *The Spaces Within* (2018) musicians travelling in virtual pods arrive in SoundScape Park in front of the New World Center, inside the Unity virtual world model. The background is a render inside Unity of a time-lapse video of the period around sunset.

#### 4.2.4. The Spaces Within – technical evolution

With the artistic concept wanting to explore the hidden and imaginary spaces of the New World Center, an environment that could support virtual environments was required. From the framework development and component selection process, the games engine Unity had been selected as the best solution for this task. Unity does not natively support an OSC interface but there is an active market for free and commercial software assets (including: plug-ins, code libraries, tools and visual components) that can be added to the Unity development and runtime environment to provide additional functionality.

Several OSC assets for Unity were evaluated. Initially, I selected UnityOSC (*Open Sound Control (OSC) for Unity 3D*, n.d.) and started to develop with this asset but after an update of the Unity engine this no longer worked and the developer did not quickly release an updated asset. It was not possible to stay with an earlier release of Unity as the functionality of the new version was required for the project. The extOSC (*extOSC - Open Sound Control Protocol for Unity*, 2018) plugin was selected as a replacement OSC plugin and this has continued to be the one used in the framework for future projects where Unity has been used.

A method by which to stream live video into Unity was also required. The artistic vision was to take the live video of the performers at different nodes of the performance within the New World Center, place and composite them within the virtual model, and then use Unity virtual cameras to generate the live video outputs that would be mapped to the physical spaces within the New World Center: the projection sails in the main performance hall and the exterior wall of the elevator shaft that rises above the rooftop garden. Two options were considered: the first was to use a Unity asset (*Spout plugin for Unity*, 2017) that supported the rendering of textures inside Unity that were captured on the GPU from a named Spout input; the second, was to use a Unity asset (*AVPro DeckLink*, 2018) that provides for the input/output of SDI video using the Blackmagic series of Decklink SDI PCIe interfaces. The Spout asset was tried first but proved to be unreliable in the current version. The SDI video asset worked well and this was the solution used for the project.

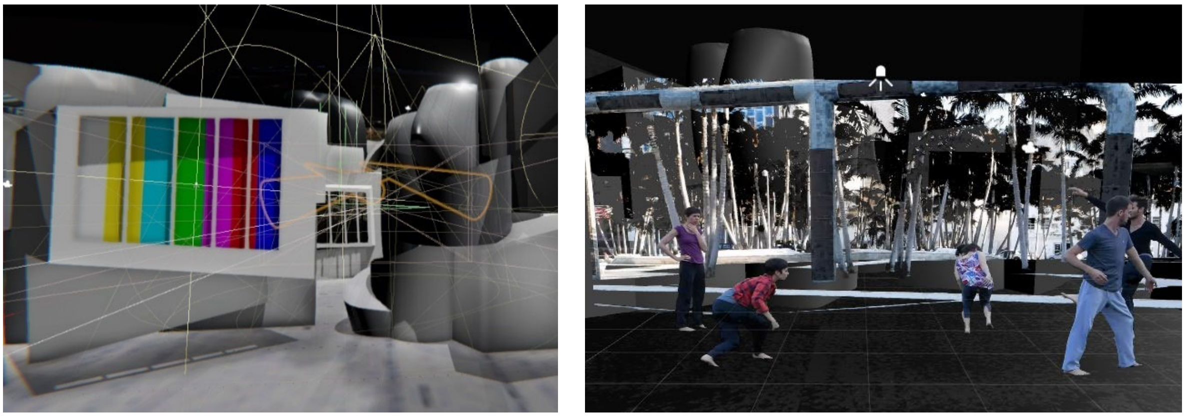

Figure 35: Testing placement of live video streams as render textures in a Unity model during development of *The Spaces Within* (2018) using a video pattern generator (left) and chroma-key of performers in video (right).

Scenes for the virtual model of the imagined spaces within the NWC were created in Cinema 4D as abstractions of the physical reality within Gehry's architecture. The objects were exported from Cinema 4D and imported into Unity as assets. The final model was developed directly in Unity using the Unity editor. Textures for the model included some taken from photographs of the physical New Wold Center building that I took in 2016 and 2018.

Pre-recorded video for the second scene (the dance in Soundscape Park) and the final scene (sunset time-lapse for pods arriving in Soundscape Park), were imported to Unity as video assets and rendered onto objects in the model using the Unity video render texture function. The videos were filmed in 4k/29.97 fps. After editing and cropping they were rendered as HD/29.97 fps files for import to Unity.

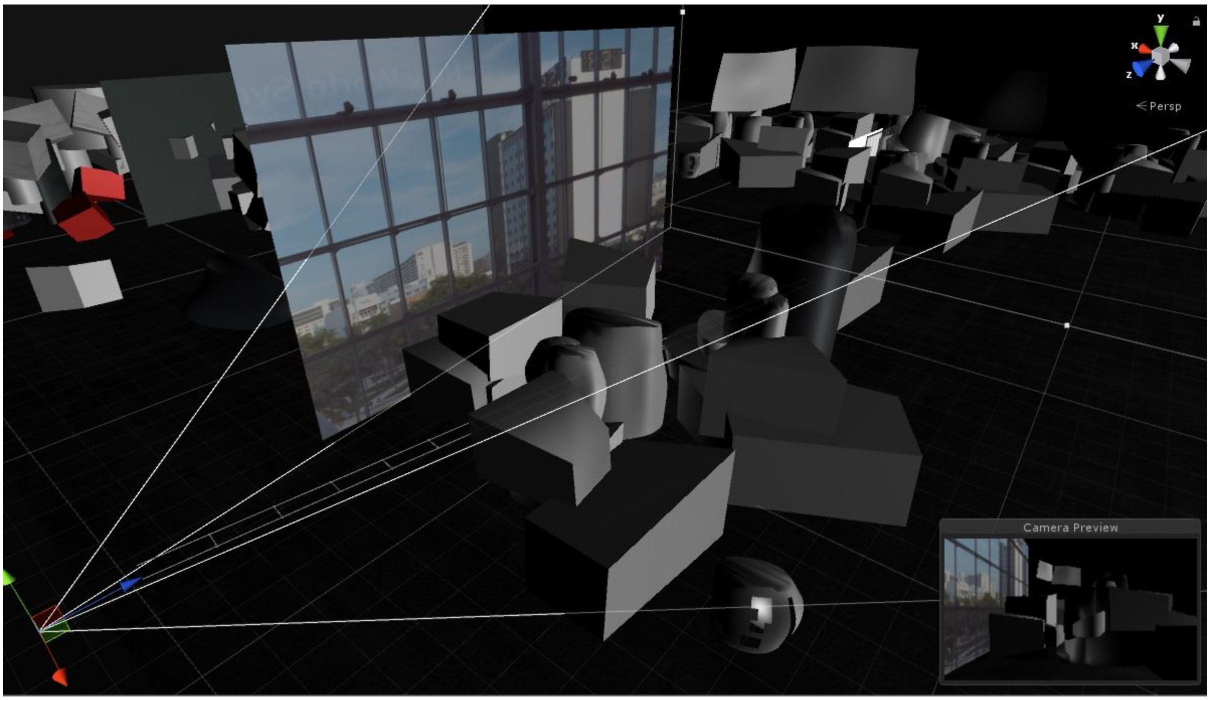


Figure 36: Prototyping the imaginary spaces of the New World Center inside the Unity virtual model that forms part of *The Spaces Within* (2018).

The final setup and workflow for the performance comprised two PCs with Intel i7 CPUs running Windows 10, each with multiple SDI video interfaces. SDI video from the main performance hall was sent directly from the camera switcher in the control booth; video from the roof was sent over fibre links; and video from the mezzanine—which was on the same floor as the control booth—was sent via copper coax. Each PC ran an identical virtual model: one of the PCs was used to generate the visuals for the roof terrace projection; the second PC was used to generate the visuals for the three projection sails (the middle 3 of 5 "sails") in the main performance hall. The model that was used to generate scenes for projection on the roof terrace was populated with live video streams of the musicians in the performance hall and on the mezzanine. The model that generated scenes for projection in the main performance hall was populated with live video streams of the musicians on the roof terrace and the mezzanine. The two models received the same OSC messages from the cueing system so remained synchronised throughout the performance. The video streams from the virtual cameras in each model were sent from Unity via an SDI loopback (SDI output wired to SDI input) to Resolume for final formatting and adjustment before being sent for projection. Video output streams from Resolume were sent to a series of HDMI to SDI converters (Blackmagic Design 4k SDI-HDMI); the HDMI adapters acting as virtual displays for Resolume. From the HDMI to SDI converters, video for the roof terrace projector was sent via SDI fibre link. Video outputs for the main performance hall displays (3 sets of projectors) were sent via SDI copper coax to the in-house projection control system; the Pandora's Box video product of Christie.

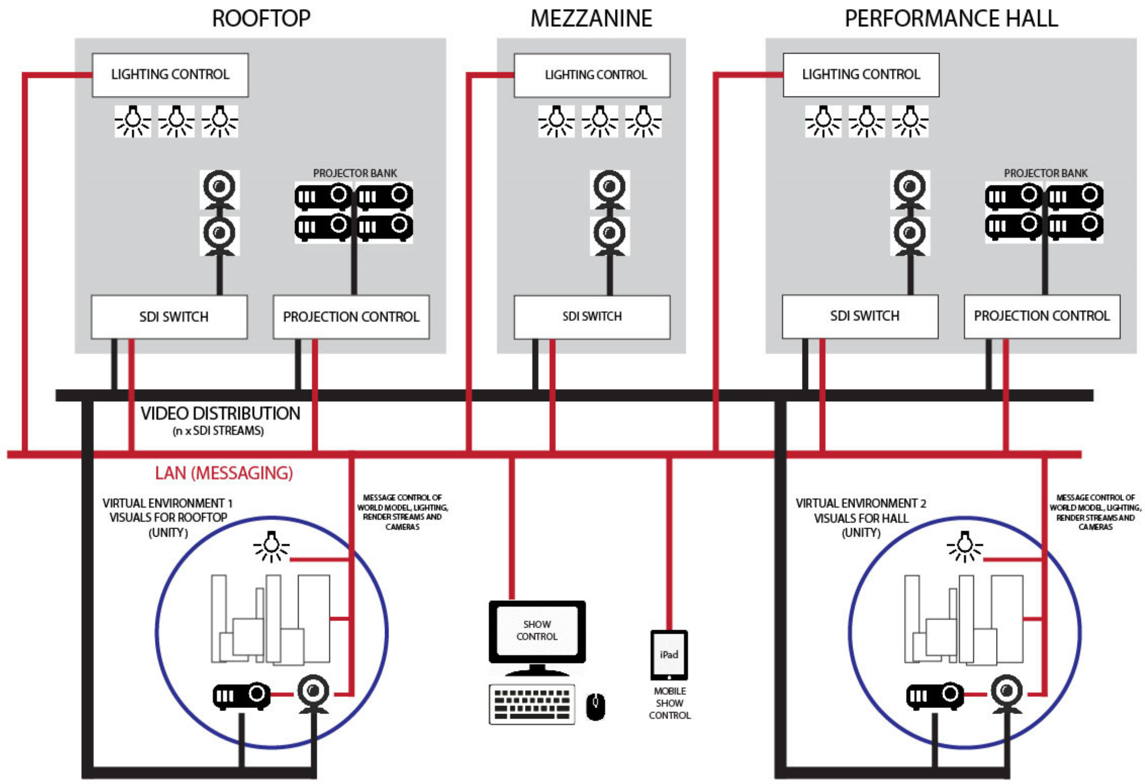


Figure 37: Overview of the system architecture for *The Spaces Within* (2018).

For the performance, the visual concept was that the camera views into the virtual world (the composite of the model and video streams of the live performers) should be from the perspective of another person moving through that world model. A solution as to the method by which to move the virtual cameras within the model was investigated. In a game scenario, the camera views are most likely from the perspective of the game-player, such as in a first-person shooter (Nacke and Lindley, 2008, p. 81) or as experienced in driving simulations. However, in these examples, the camera is effectively being moved by the player as part of their gameplay interactions. During the development phase for *The Spaces Within*, Unity released the Cinemachine (*Powering cameras for films and games*, n.d.) functionality which supports cinematic camera techniques within Unity, such as the use of dolly tracks, camera pan/tilt/zoom, and tracking shots. The Cinemachine functionality includes a timeline module so that every camera action can be assigned to its own timeline. Virtual dolly tracks were created for each scene of the performance, threading through the virtual world models in Unity. For the version of the model used to feed the single projection screen on the roof terrace, a single virtual camera was moved along its track. For the second instance of Unity, that would be used to generate projection output for the three-display sails in the main performance space, three virtual cameras were mounted on the dolly, each with a viewing angle of 60-degrees, to create a three-screen output with an effective 180-degrees of view into the model.

Show control and cueing was from a user interface in Max/MSP, reusing objects that had been developed for *Longing for the Impossible* the previous year. OSC messages sent to the two Unity hosted virtual models controlled: lighting, scene selection, and the Cinemachine dolly tracked cameras and associated timelines. A set of Unity scripts were written in C# to implement the corresponding functions within Unity. One script was used to process and route inbound OSC messages from the Max/MSP control patch. Function specific OSC scripts attached to Unity objects (primarily lights and cameras) then acted to implement specific functions, such as: light values, camera view, and control of Cinemachine timelines.

As the New World Center has an extensive distributed audio system, it was this in-house solution that was used to manage the audio in the performance. Audio from microphones in each of the three spaces where musicians were performing was sent to a central mixing desk, then distributed to the PA systems on the roof terrace, the mezzanine, and in the main performance hall.

#### 4.2.5. The Spaces Within – outcomes

The project supported the iterative process of artistic and systems development in XRNP, especially regarding the integration of Unity as a platform for computer generated realities within the framework. The integration was achieved through the addition of OSC to the Unity platform. The development of a set of code libraries in Unity enabled management and processing of OSC messages for the control and configuration of virtual lighting, scenes, and virtual camera operation using Unity's Cinemachine and timeline functions. The ability to integrate and composite live video streams with the virtual model (augmented virtuality) was investigated and delivered as an important visual component of the performance. The use of the matched virtual cameras, traveling on the OSC controlled Cinemachine dolly track within the Unity model, successfully produced the real-time coordinated images of a near-180 degrees wide field-of-view scene onto the sails of the main performance hall.

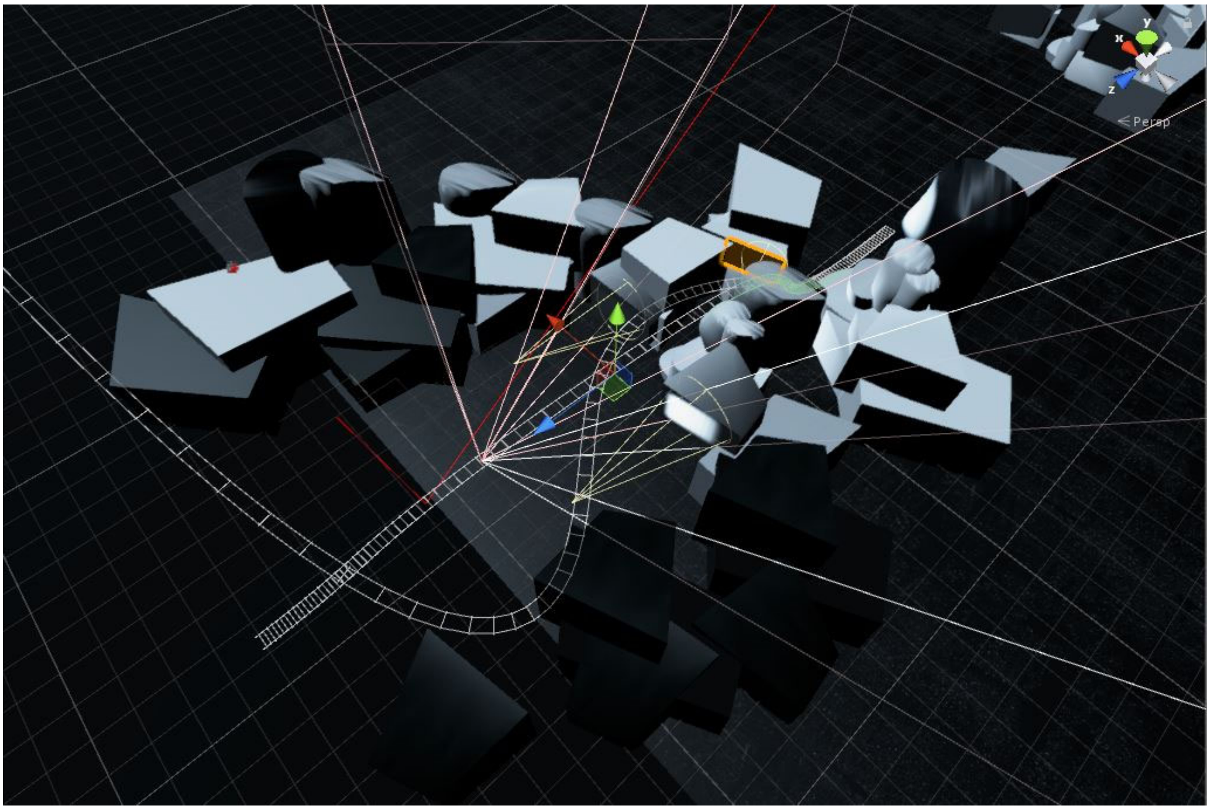


Figure 38: Virtual camera dolly tracks inside part of the Unity virtual world model for *The Spaces Within* (2018). The set of three virtual cameras—configured to give a 180-degrees field of view in individual 60-degree segments—are associated with a timeline on which there are location markers for different scenes in the performance, which in turn can be triggered by OSC messages sent to Unity.

While it had been planned to control the PTZ remotely operated physical cameras in the main performance hall through the cueing system and OSC gateway, this proved impossible due to the limited time available for access to these systems during the residency at NWS. I had wanted to further investigate the relationship between control of real cameras—that were streaming video into the virtual model—and the virtual cameras that were producing the composite tracking shots for projection back into the physical spaces.

Compositing live streams in the virtual world model was relatively easy from the perspective of positioning and rendering, but much more complex with respect to the real-time control of brightness, contrast and saturation. The key difficulty was with respect to managing the lighting of performers in the physical spaces of the performance, in locations within the NWC that were not equipped with lighting suitable for video work and the lack of portable equipment to overcome that problem. This resulted in relatively dark and low-contrast video streams from physical cameras, compared to the more reliably controlled lighting within the  virtual world where the physical camera streams would be composited.

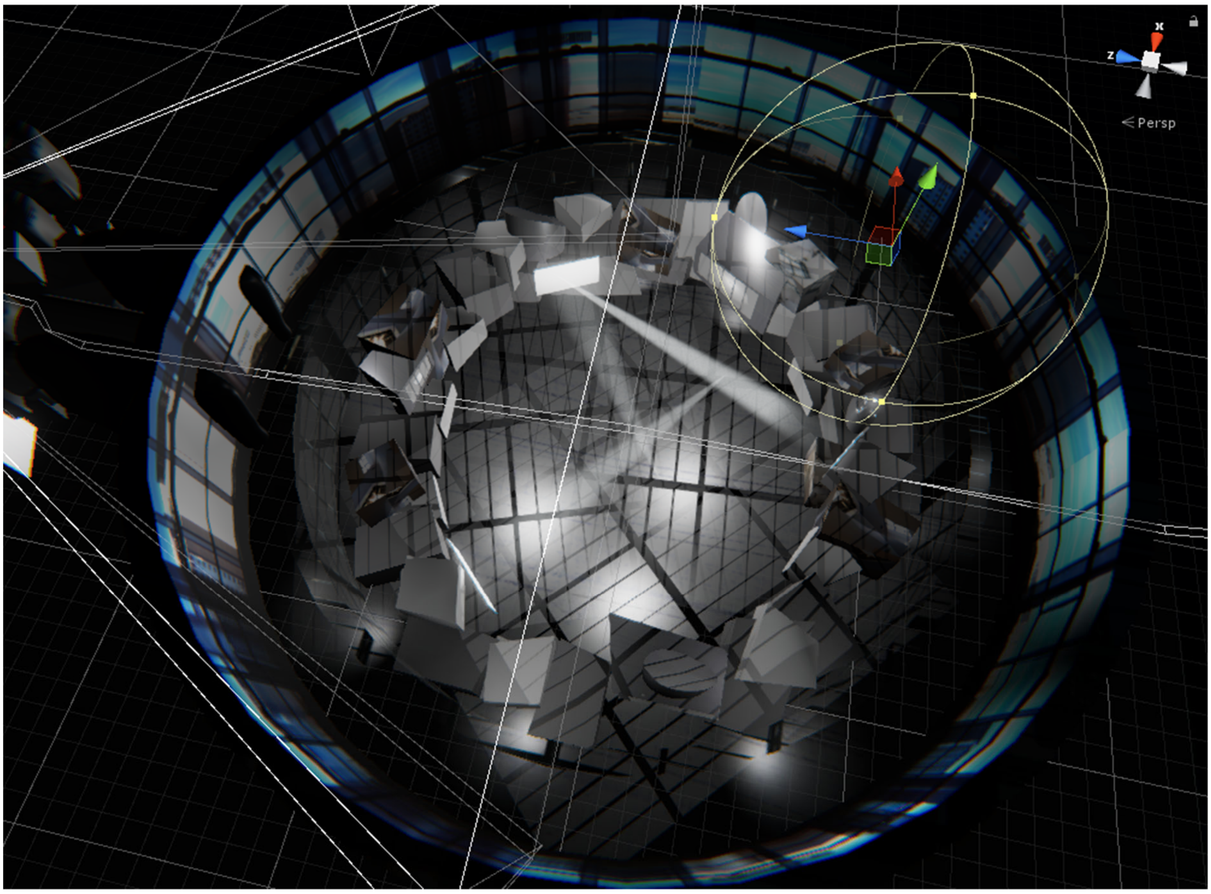


Figure 39; Configuring lighting inside the Unity virtual world model for *The Spaces Within* (2018).

In summary, the outcomes of the targeted research objectives for this project were:

- Unity was proven as a suitable environment for the development and hosting of computer generated realities within the XRNP systems framework. The ability to share live video and performance data with the Unity virtual model meant that it functioned—notwithstanding issues with blending physical and virtual lighting—as a performative corollary of the real-space elements of the XR networked performance world;

- Two methods of streaming live video into and out of the Unity environment were investigated. The option to use a physical SDI interface in conjunction with a Unity plugin that supported the Blackmagic Design Decklink series of SDI interfaces worked best for this project, due its reliability and ease of integration. However, the GPU sharing software-only solution offered by a Spout plugin, would have been a useful option (subsequent improvements to the plugin meant that it could be used in later projects, see: 4.4.4);

- The use of OSC was expanded to include the control of virtual world components inside Unity, in addition to its previous role in control of Resolume and actions within Max/MSP toolkit patches. The use of a standard messaging construct, in conjunction with the speed at which new object interactions can be created inside Unity (by writing new C# scripts that convert OSC commands into object actions), meant that it was possible to produce new functionality within the XRNP framework in a timely manner, and one which also supported experimentation during the development of the project.

## 4.3. Opravdoví / The Real Ones

In many ways, the initiative and development of *Opravdoví / The Real Ones* (the project was developed in the Czech Republic, 'opravdoví' being the closest translation for 'the real ones') was the most critical project in the research practice.  It was used to test the extension of the system framework and messaging solution to support a performance of symmetric typology. One, where both nodes of the performance would be identical in terms of set (except for minor differences due to the design of each venue), mediating technologies, script and artistic objectives for audience engagement.

### 4.3.1. Opravdoví - research objectives

- Evaluate the XRNP framework in a performance of the symmetric typology, one where the two nodes of the performance are equally balanced regarding performative actions and audience engagement;
- Implement and test a reliable and deterministic solution for the use of OSC to control and synchronise sub-systems at each the node of the performance;
- Integrate and evaluate QLab as a cueing system, one in which QLab contains the master list of cues and communicates with the various sub-systems across all nodes via OSC;
- Evaluate the audio player and lighting control (DMX) features of QLab;
- Investigate a solution for the remote configuration and control of SDI cameras within an XR networked performance, especially as regards the ability to reconfigure cameras at remote nodes of the performance during setup and rehearsal;
- Integrate UltraGrid as an audio/visual streaming solution.

### 4.3.2. Opravdoví – artistic concept

The idea to strip back the visual complexity of recent projects was a cornerstone of the artistic thought process for *Opravdoví*. It resulted in a minimalist symmetrical set, one where a single physical dance performer was in each node of the performance.

As the name of the piece suggests, the performance—through the concurrent movement of solo performers in two identical locations and their encounters of each other—explored what it means to be the 'real one'. It was the artistic investigation of the questions of identity arising from the concept of parallel realities in a multiverse. There are several theories debating the idea of the multiverse (Carr and Ellis, 2008; Kaku, 1995, p. 217), but that which I took for this project defines it as “a hypothetical space or realm consisting of a number of universes, of which our own universe is only one” (OED, 2018). Although the narrative of the piece was quite loose and open to interpretation by the audience, it also aimed to artistically questioned the right of the individual to occupy a specific space, and the uniqueness in identity of each person.

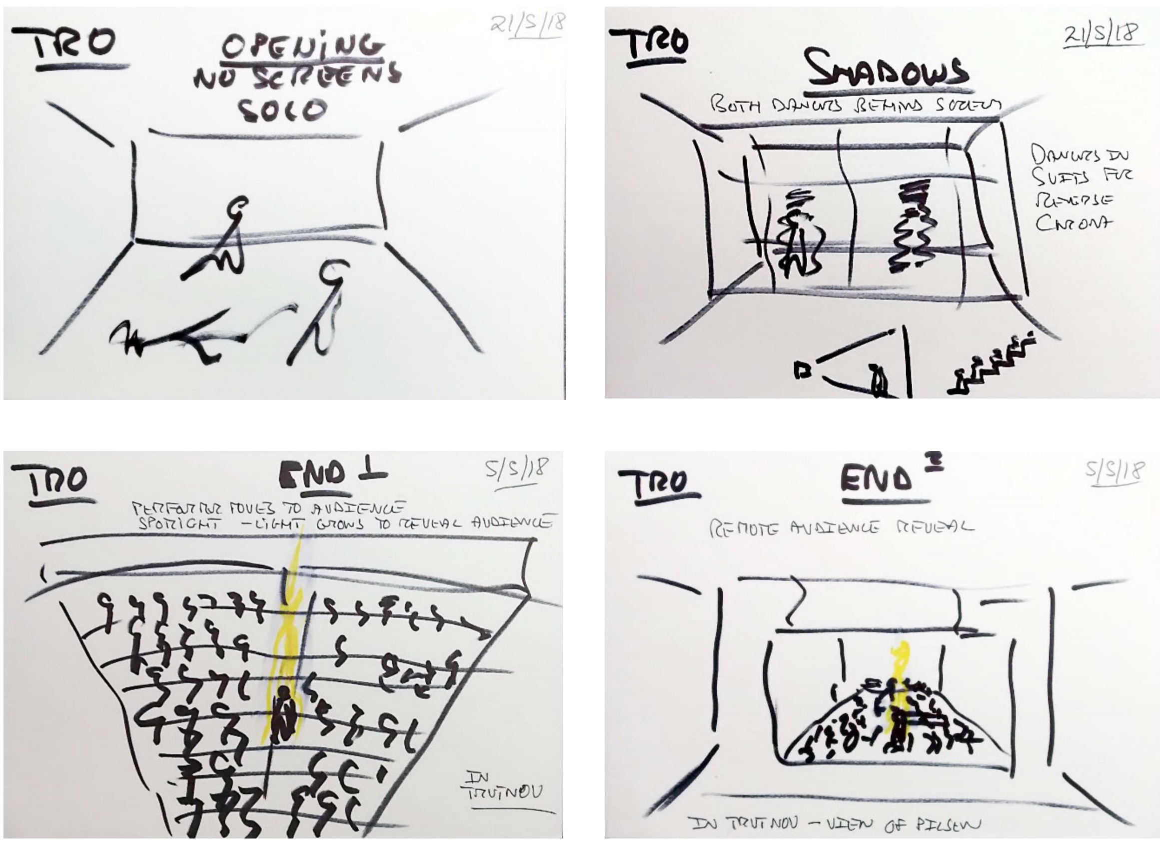


Figure 40: Early concepts from the storyboard for *Opravdoví / The Real Ones* (2018).

At the beginning, the piece commenced as if it was a non-networked performance, with each performer engaged only with their local audience. As the performance developed, the remote dancer was introduced to the other location so that a dialogue between the two of them was commenced. In the final scene, the two dancers entered a space that was conceptually somewhere else, which was in fact behind the projection screens. This dramaturgy was intended to promote the idea that they were somewhere in between the two universes (the two locations) of the performance.

### 4.3.3. Opravdoví – realisation

Development of *Opravdoví* commenced in early 2018, artistically, and investigating approaches to extending the systems framework to operate across multiple nodes of a symmetric performance (see: 4.4.3).

Figure 41: Developing two nodes of a networked performance in a single location. The co-location of two stages and all parts of the XRNP supporting system during development of *Opravdoví / The Real Ones* (2018) at the UFFO theatre, Trutnov, Czech Republic.

Thanks to the support of Czech theatres, we had nearly 3 weeks for development in the UFFO theatre in Trutnov and just over one week in the Moving Station theatre in Pilsen. We also arranged one more week for development in the Kinonekino theatre in Planá, 60km northwest of Pilsen. In the large and contemporary setting of UFFO, it was possible to create an area large enough to erect two full sets. The complete floor plan of the theatre is covered by a technical grid, so we could hang two rear-projection screens and the additional lighting required for the project. With this arrangement, we could develop both nodes of the performance in a single location, with both performers present. The technical equipment that would be distributed between the two nodes in the performance was arranged in the centre of the floor area between the two sets.

The performance space consisted of a rear-projection screen, with the performing space in front and behind it. Video cameras were positioned: stage-left looking towards stage-right; over the top of the stage with a view onto the floor of the performing space in front of the projection screen; and upstage—behind the projection screen—pointing to the rear of the screen. A fourth mobile video camera was handheld by the performer.

The scenery of the set in each location included four industrial-style ex-factory lamps: three hanging above the stage and one above the audience. These lights were used as core dramaturgical items during the performance: in one case, the lamp was used by the physically-present dancer to hide from the overhead camera, and in a later scene, the light above the audience was used as a mechanism through which to introduce the remote audience members to each location.

The performance was set over eight scenes. The opening consisted of a pre-recorded video of one of the industrial lamps swinging randomly across the set. This had been filmed on a green-screen background and then processed to appear as a light in a dark room, alluding to the space behind or between the locations, and introducing the concept of light illuminating the different elements and spaces of the performance to come.

After the introduction of the physically-present dancer to their local audience in the first scene, the second scene introduced the remote dancer into each of the venues. The initial sighting of the remote performer was designed to bewilder the audience, so that it was not clear which dancer (the physically present or remote) was the one they now saw on the rear-projection screen. This effect was possible because in each venue the dancer was hiding from the top camera under one of the factory lights that hung over the stage. The performer started to expose their limbs from under the cover of the lamp (video: *Opravdovi Trutnov node - full performance*, 2018, 00:04:45) but it was this slow reveal from the other location that was sent to the rear-projection screen, rather than that of the local dancer. As the scene progressed, the image on the screen switched between the local and remote dancers, sometimes blending the two of them (video: *Opravdovi Trutnov node - full performance*, 2018, 00:06:14; and *Opravdovi Pilsen node - full performance*, 2018, 00:06:00).

Figure 42: The two performers in *Opravdoví / The Real Ones* (2018) during a dialogue about identity, supported by a composition of first-person (mobile camera), side camera and top camera across the two locations of the performance.

In the fifth scene, each performer went off-stage to collect an android phone with video streaming capability. The next images the audience saw on the rear-projection screen were some seemingly random video of back-stage areas of the theatre as the dancer returned towards the auditorium (video: *Opravdovi Trutnov node - full performance*, 2018, 00:23:24; and *Opravdovi Pilsen node - full performance*, 2018, 00:23:10). In each location, the performer moved into the audience, streaming live video of them on to their local screen. Eventually, the performer arrived at the audience member that had seated themselves under the hanging factory lamp and focused the mobile camera onto them. The phone was then pointed up into the light as it started to get brighter, until the image on the rear-projection screen was just the bright, white, light from the lamp (video: *Opravdovi Trutnov* *node - full performance*, 2018, 00:27:00; and *Opravdovi Pilsen node - full performance*, 2018, 00:26:46). As the phone was then angled back towards the person under the lamp, the video on the projection screen was no longer that of the local audience, but that of the remote one; this was the first time when the audience at each location had been made aware of the remote audience members. This scene required a particularly tight cueing of technical elements: the synchronisation of audio tracks in each location against which the performer was working; the switching and mixing of video streams between the two locations; and the correlation of these components with the timing of DMX control of the lights in each location.

Figure 43: Performers 250 km apart share traces of their encounter in *Opravdoví / The Real Ones* (2018).

For the final scene, the concept was that each performer—having discovered each other through the medium of the performance, having questioned their identities and rights of presence in each location—would now adjourn to a common space, an 'in-between place' which was not specifically identifiable. It was also important artistically that this scene was not considered a happy-ending or a loving outcome, just that it was another reality in another dimension of the performance world. To achieve this, the performers changed into chroma-green suits out of site of the audience. In each node of the performance, the dancers entered the space behind the rear-projection screen, so that they were seen by their local audience as a silhouette, illuminated only by the light of the projector. The camera, focused on the back of the projection screen, captured the image of the performer in their chroma-green suit. Real-time reverse chroma-keying was used to remove the image of the dancer from the background. Video of the performer at each location was then streamed to the other location where it was projected as a silhouette, alongside the silhouette of the physically present local performer. Using this technique, the audience at each location saw two performers as silhouettes moving together behind the screen: it was as if they occupied a common space and had a common appearance (video: *Opravdovi Trutnov node - full performance*, 2018, 00:38:50; and *Opravdovi Pilsen node - full performance*, 2018, 00:38:36).

Figure 44: The dancers in two locations share a shadow world in the final scene of *Opravdoví / The Real Ones* (2018)

The performance ended with a moderated networked discussion between the two audiences. This was followed by an invitation for the audience to occupy the stage at each location, where they experienced the space shared between them through a composition of camera views across the two locations, projected on the rear-projection screen (video: *Opravdovi Trutnov node - full performance*, 2018, 00:44:46; and *Opravdovi Pilsen node - full performance*, 2018, 00:43:48).

Figure 45: The audiences in two theatres (UFFO, Trutnov, and Moving Station, Pilsen, in the Czech Republic) share the stage after the premiere of *Opravdoví / The Real Ones* (2018).

The music composition for the performance was developed by Belgian composer, George de Decker. The music was selected from sections of his existing works, then mixed by de Decker to create the final soundtrack.

The premiere of *Opravdoví* took place between Trutnov and Pilsen (250 km apart) on the 26th September 2018. Two performances were played on the same day: one in the morning for schools, and the second in the evening. The project will tour several city-pairs in the Czech Republic in October 2019, after submission of this thesis. This is likely to be the first time that a networked performance will be toured.

#### 4.3.4. Opravdoví – technical evolution

The key technical challenges in delivering *Opravdoví* were:

- Network Infrastructure – as the two theatres were not connected to the Czech NREN Cesnet, the performance needed to use the existing network connections at each theatre;
- As the performance was of the symmetric typology, all aspects of the performance across the two nodes had to be tightly synchronised;
- Due to the need for synchronisation between the venues, and the desire to minimise the requirement for extra technicians to support the performance, a reliable distributed cue management system would be required;
- As lighting changes and video switching (camera selection) also formed an important part of the dramaturgy of the performance, it was necessary to develop a method whereby these technologies could also be controlled remotely.

Unlike the previous two projects, in which we had little time for rehearsal in the performance venues, *Opravdoví* would be developed in a series of lengthy residencies, working with choreographer Jana Bitterová and the two dancers. Thanks to these conditions there was a lot more time for experimentation and fine-tuning of the performance: how the cameras were used, the combination in different scenes of local and remote live video, and lighting. The cue management system built in Max/MSP— as used in *Longing for the Impossible* and *The Spaces Within*—had worked very well but it was not a solution for quickly changing many cue structures during the development process.

The decision to integrate **QLab** into the framework was made to enable a quicker and iterative method of experimenting with the cues that controlled the various sub-systems for *Opravdoví*. QLab also served as the audio player for the soundtrack, and the DMX controller for all lighting. Max/MSP was retained for its continued use as a toolkit application.

In order that all elements of the performance could be synchronised across the two venues (XRNP members), a solution to reliably and deterministically control events in both locations was essential. A **conductor/associate**[26] **approach** was adopted, one where theatre A would be the conductor member location and theatre B would be the associate member. The cues for each location (video, lighting and audio) were held locally on a local installation of QLab. The cue lists were identical in each theatre with the exception that the conductor location also held cues to trigger and synchronise QLab in the associate location.

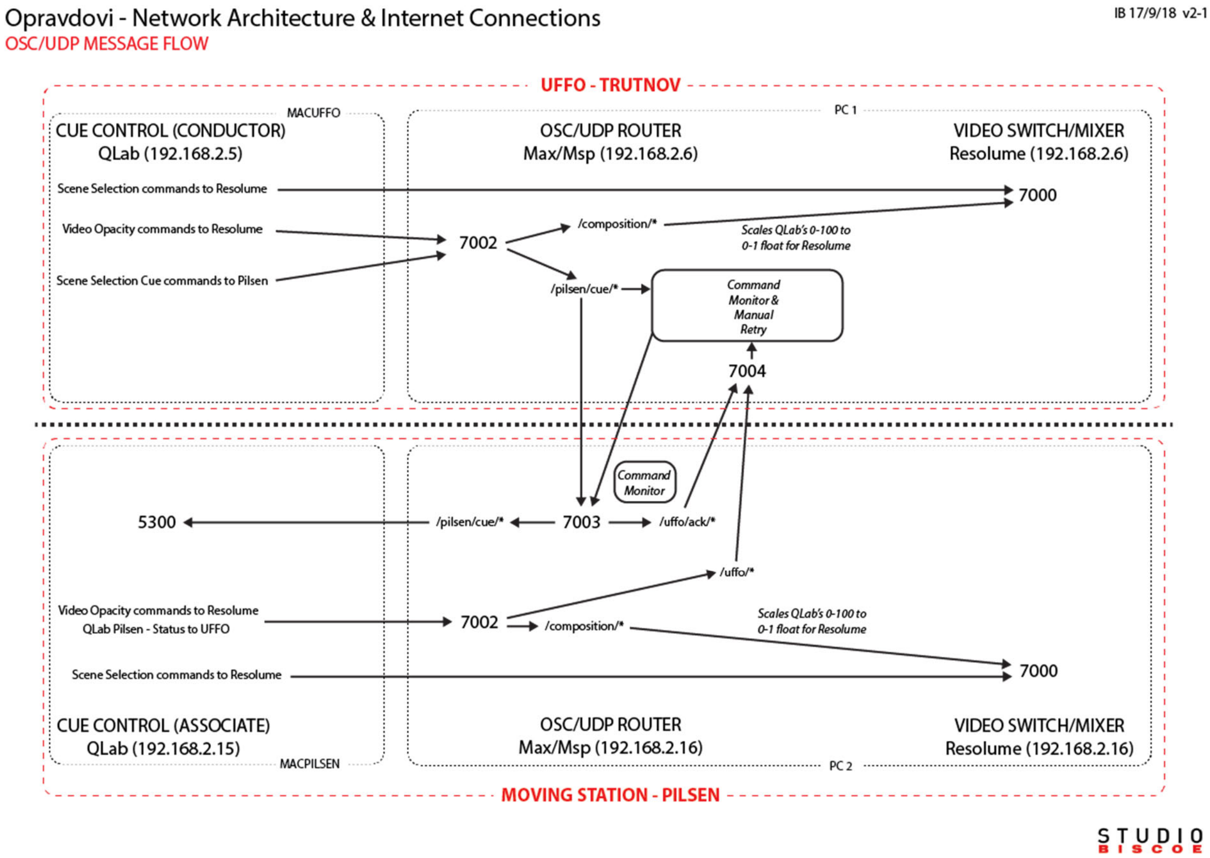


Figure 46: Conductor/Associate OSC/UDP message flow as implemented between two nodes of a symmetric networked performance in *Opravdoví / The Real Ones* (2018).

UDP is the transport most often employed for OSC messaging over LANs and managed WANs; it is normally as reliable as using TCP. The advantages of using UDP is minimal latency (there is less overhead due to UDP not using handshaking) and no risk that a failed

[26] All nodes of an XR networked performance are considered to be members of the total performance environment. One node is implemented as the Conductor member and is responsible for coordinating the actions of the associate member nodes. This technical architecture was originally termed "Master/Slave" – a long established terminology in systems, network and data bus definitions, especially in the avionics systems world - but this terminology is now considered a) inappropriate (Knodel, 2018), and b) the use of the term "member" better indicates that all nodes of the performance (their performers and audience) are equally important within the artistic construct of an XR networked performance.

message delivery can initiate a retransmission process, which could continue for an indeterminate period. The disadvantage of using UDP is that there is no guaranteed delivery. Using the TCP transport for OSC provides guaranteed delivery of the message but with the risks of higher-latency and the possibility of entering a TCP retry mechanism which could further delay or obfuscate the clarity as to when the message is delivered, or even if it has yet been delivered. A mechanism was required that would provide the benefits of UDP's low latency and determinism while – in the context of an XR networked performance – provide a level of assurance of delivery that was closer to that provided by the TCP transport.

The solution developed was an intermediate **OSC/UDP router** node at each location, one that would observe the OSC message flow between QLab conductor (theatre A) and QLab associate (theatre B) and that would provide the technical operator of the performance with a visual indication of communications integrity, raising an alert in the case of a failed message delivery. The conductor and associate routers were written as Max/MSP patches, hosted on the Windows 10 PC in each location. All messages were sent using UDP transport. The performance was divided into nineteen major scenes, so it was only necessary to send major scene change commands to the associate QLab instance in theatre B.

The **conductor/associate messaging system** was implemented as follows (see: Figure 46: Conductor/Associate OSC/UDP message flow as implemented between two nodes of a symmetric networked performance in *Opravdoví / The Real Ones* (2018).):

- The conductor instance of QLab (in theatre A, the UFFO theatre in Trutnov) contained an OSC cue at the beginning of each major scene e.g. *pilsen/cue/one* which was sent to the conductor router Max/MSP patch in the same location;

- The OSC/UDP router identified from the address that the message was to be sent to the associate location (theatre B, the Moving Station theatre in Pilsen), forwarded the message to the public static IP of the associate location using the UDP Port number allocated for the associate OSC/UDP router, and concurrently started a one-millisecond accuracy round-trip timer and a 1 second response-timeout timer;

- In the associate location, the network router at the public static IP, routed the message to the IP address of the associate OSC/UDP router, based on the UDP port and IP table in the network router;

- On receiving the message, the associate OSC/UDP router forwarded it to the associate instance of QLab;

- When the associate instance of QLab received the message, it initiated the next major scene and concurrently sent an acknowledgment message to the associate OSC/UDP router e.g. *uffo/ack/one*;

- The associate OSC/UDP router forwarded the acknowledgement to the conductor OSC/UDP router in theatre A;

- On receipt of the acknowledgement message from the associate gateway, the conductor gateway stopped the round-trip timer and the response-timeout timer.

Both the conductor and associate OSC/UDP router patches had **graphical user interfaces providing controls, status, alerts and manual retransmission functions**. The conductor OSC/UDP GUI (see: Figure 47: Conductor/Associate message router GUI - developed in Max/MSP. Conductor node at UFFO theatre, Trutnov during the premiere of *Opravdoví / The Real Ones* (2018)., provides:

- Status of messages received from the QLab conductor, sent to the QLab associate, and acknowledgements from the QLab associate;

- Display in milliseconds for each OSC cue sent to the associate node, incrementing until acknowledgement message received from the QLab associate;

- Alert warnings in case of acknowledgements not received within the response timeout default period of one second;

- Controls to manually resend any OSC cue message to the QLab associate.

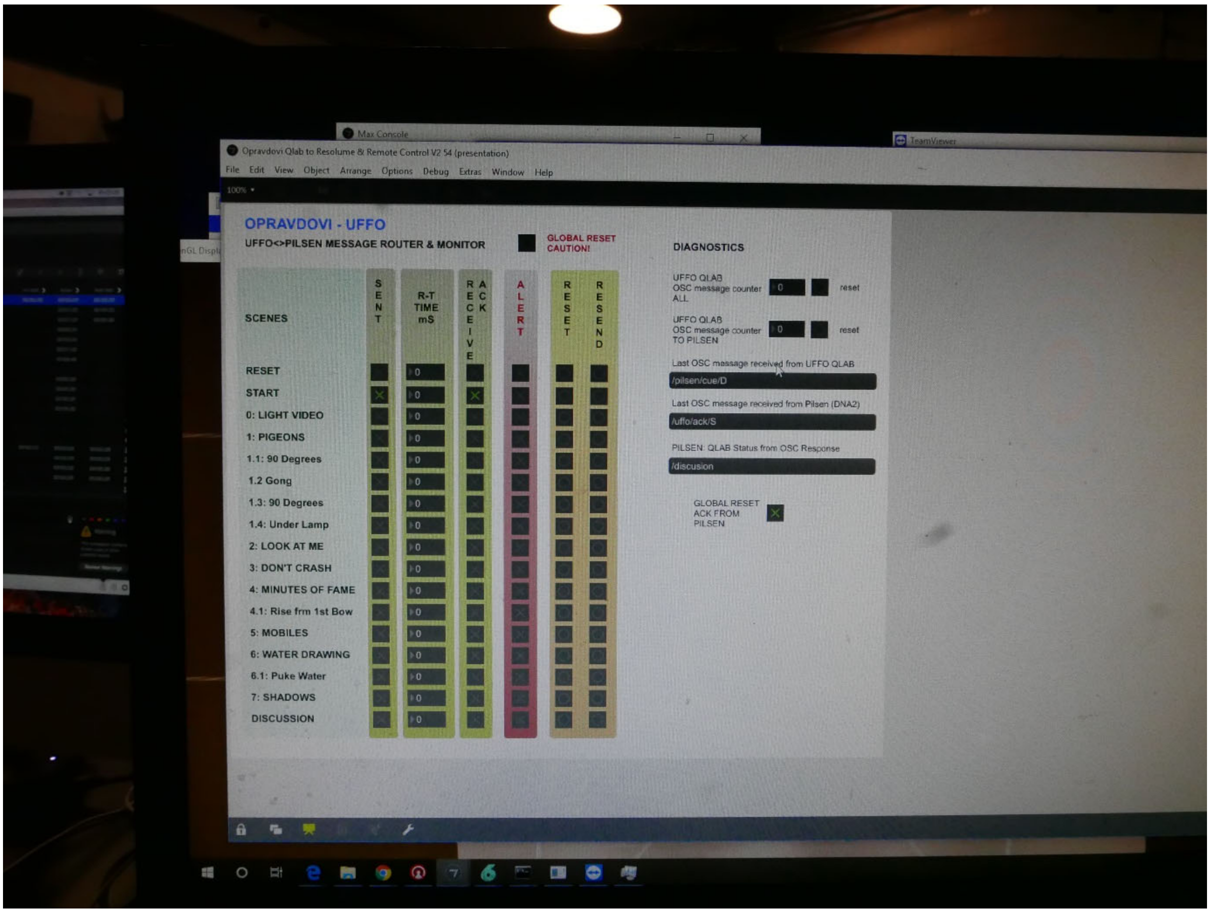


Figure 47: Conductor/Associate message router GUI - developed in Max/MSP. Conductor node at UFFO theatre, Trutnov during the premiere of *Opravdoví / The Real Ones* (2018).

In the case of using UDP acknowledgements to verify delivery of UDP requests and no acknowledgement being received, there is a question as to if it was the request message that failed or the acknowledgement message that failed. The monitoring of the integrity of the communication link between the two theatres required a successful request/acknowledge cycle, so in the case of no acknowledgment there is a 50% possibility that it was the acknowledgement that was not received within the round-trip timeout period rather than the request message not being received at the associate location. As an additional tool to verify the possible breakdown in the request/acknowledgement cycle, the operator at the conductor node can also look at the overview live video stream from the associate node (normally via skype on a s separate internet connection to the one used for audio/video streaming of the performance) to see if the latest major scene change has been implemented, as requested by the QLab conductor to associate cue request.

Figure 48: Show control setup at the UFFO Theatre conductor node in *Opravdoví / The Real Ones* (2018), comprising: remote view of Moving Station theatre in Pilsen (Skype), remote view of QLab in Pilsen (TeamViewer), OSC conductor/associate messaging GUI, QLab local node, Resolume, ATEM monitor (stage left and stage top cameras), Ubiquiti Edge Router network monitor, and independent monitors for SDI stage front camera and projection mix SDI feed.

During the 10-days we had a live network connection between the two theatres for test, rehearsal and showing of *Opravdoví*, with more than 40 hours of OSC message requests and acknowledgements being sent between conductor and associate nodes, there was only one occasion when an acknowledgment was not received from the associate (which could have also been the result of the request not being received by the associate) and a manual retry was immediately successful.

The same OSC/UDP router Max/MSP patch was used to resolve some small lack of functionality in QLab, for example, when linear fades were required in OSC values. A set of scaling functions were created in a patch, so that when a fade in a Resolume layer was required, the cue from QLab would send an OSC message to the Max/MSP patch, which then scaled the required parameters and sent them to the appropriate control in Resolume as an updated OSC message.

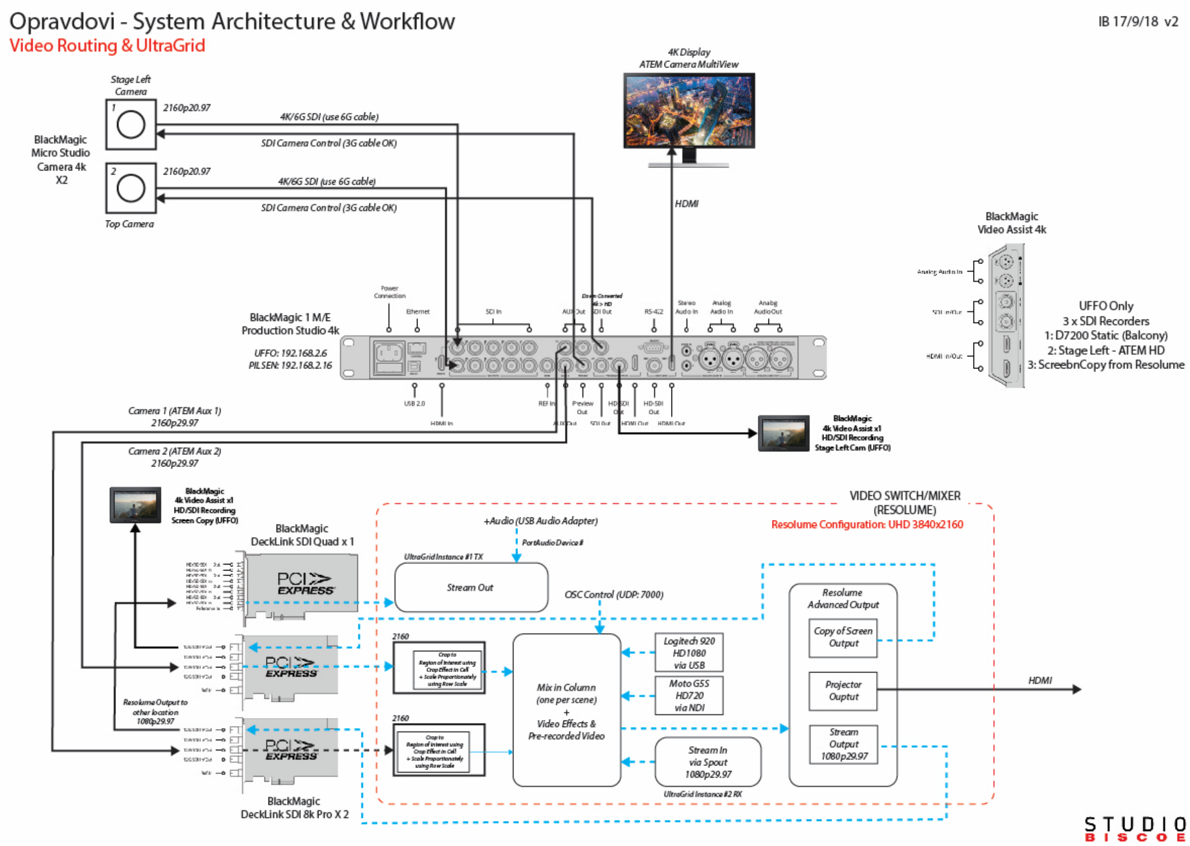


Figure 49: Video acquisition, routing and processing architecture for each node in the symmetric networked performance *Opravdoví / The Real Ones* (2018).

The iteration of the systems framework, and the configuration of the audio/video sub-systems, for *Opravdoví* therefore comprised:

- A Windows 10 custom-built PC with Intel i9 CPU, Nvidia GTX 1070 GPU and Decklink SDI interfaces. The PC in each venue hosted Resolume Arena, UltraGrid, the Conductor/Associate communications and the QLab gateway Max/MSP patches, and the user interface for the Ubiquiti router so that live network traffic and diagnostics were always available. Three 27" HDMI displays were also connected to the PC. The PC was also connected to a Focusrite (Scarlett 2i2) or an Edirol (UA25) USB audio interface, which in turn was connected to the mixing desk for input/output of streamed audio during the post-performance discussion;

- An iMac (macOS) equipped with an Entec DMX USB interface (Mk.2 Pro), running QLab 4.0 and the user interface for the ATEM Studio video switch and remote camera controls.  The iMac was connected to the audio desk via a DI box for playout of the soundtrack;
- An SDI video switch and camera controller (Blackmagic Design ATEM Studio 4K 1ME);
- Two SDI 4K cameras (Blackmagic Design Micro Studio Camera) - one positioned stage-left on a tripod, the second mounted directly above the stage at a height of around 6 metres and looking down directly to the stage floor. The two cameras were connected by dual-SDI coax cables to the ATEM video switch;
- A Logitech C920 USB HD web camera mounted on a tripod positioned 5 metres behind the rear-projection screen. The camera was connected to the PC using a Cat6 USB-to-USB Ethernet extender;
- A fourth camera, an Android Motorola G2 mobile phone was used by the performers in the handheld camera scene. The phone used the NDI streaming protocol to send video over Wi-Fi using the dedicated WLAN installed for the performance;
- A 7,000 to 10,000 lumen HD laser projector (depending on venue) was connected to the PC using am HDMI-to-HDMI Cat6 Ethernet extender, or an SDI output to coax cable terminated in an SDI-to-HDMI converter at the projector end;
- In each venue, a separate laptop PC was available for Skypes between the technicians in Pilsen and Trutnov, and TeamViewer for setup and diagnostics of applications at the remote venue. UFFO, Trutnov was the conductor location for this performance, so the Skype camera in Pilsen also sent back a live view of the complete stage area there.

The system installed in each venue was identical, except for the configuration of the conductor/associate communication systems, and the control and monitoring GUI.

Although both theatres had internet access, it was also shared with other users of the buildings, which made it unreliable for the performance, especially when considering the relatively low bandwidths that were available. In both cases, we worked with the theatre and their Internet providers to install new, temporary, point-to-point wireless links which then provided 20 Mbps symmetric connections without firewalls, dedicated to the project. We installed our own LAN infrastructure in each theatre, using the Ubiquiti EdgeRouter Lite as the router and Netgear 1 Gbps switches for connection of PC, Mac and video switches. For the scene where the performers use a hand-held camera, a dedicated Wireless LAN was installed; this used an Ubiquiti wireless access point connected to the Netgear switch.

The audio was played locally from QLab in each venue, synchronised by a global OSC start cue, so that it was unnecessary to stream the pre-recorded audio from one location to the other. This approach resulted in a tight synchronisation for the dance performers in each venue and reduced the bandwidth requirements for the performance as we would only stream video. Measurements of the delayed start of audio playout at the remote venue showed that the difference between the two locations was in the range 10-15 milliseconds, which was therefore unnoticeable to the audience or the performers.

#### 4.3.5. Opravdoví – outcomes

Opravdoví addressed the concept of multiple realities in an XR networked performance using contemporary scenographic theatre techniques combined with the real-time synchronised manipulation of local and remote video streams. It was planned and delivered as a truly symmetric networked performance: one where there was complete balance between the two locations, and where the audiences were connected through the occasion.

The project demonstrated the successful integration of additional sub-systems into the XRNP framework, using the OSC interface to provide a flexible and reliable method for the configuration and control of distributed cues. Whereas Resolume had been controlled using cues set from Max/MSP in previous projects, the ability to connect sub-systems via OSC meant that it was ‘only’ a matter of routing and message content changes to integrate QLab to perform these functions. QLab offered a greater flexibility and speed when developing XRNP projects compared to using the Max/MSP patch approach of previous projects. However, with its support for OSC (enhanced by use of the CNMAT OSC libraries for message filtering and routing), Max/MSP provided the missing elements in QLab that were required to expose to the cueing system all the functionality available within Resolume.

To summarise the measured outcomes of the research objectives for this project (as outlined in 4.3.1):

- With the addition of the newly developed approach to transporting OSC traffic between nodes of the performance, it was possible to implement a networked performance of symmetric typology. The solution worked as designed and was reliable in delivering the performance;
- The OSC message router provided deterministic synchronisation and control between the nodes of the performance. The GUI provided for real-time monitoring of link integrity and message delivery. Although only used once in many hours of testing and performance, the manual resend feature provided a fall-back in the unlikely event of a message delivery failure;
- QLab was evaluated as an improved solution for managing cues in XR networked performances and was found to be an efficient means by which to quickly configure and test OSC cues for control of Resolume and Max/MSP patches. As QLab includes a flexible audio player and software audio patcher, it was also used to provide the audio playout—with OSC synchronisation—for the two nodes of the performance. The minimal limitations of QLab—such as its inability to send a ramping sequence of float parameters in OISC messages—were overcome by development of simple patches in the Max/MSP toolkit application;
- Though Resolume can provide many of the video switching and compositing functions required in an XR networked performance, it does not have any functionality that specifically supports the control and configuration of SDI connected cameras. In the case of cameras from Blackmagic Design, a solution was available in the form of Blackmagic's ATEM production studio: a unit that incorporates multiple SDI inputs and outputs, and which provides for control of many SDI camera parameters via a second SDI coax cable connected to the remote camera. The performance used ATEM units integrated into the system at both nodes of the performance, and as the ATEM is equipped with an Ethernet interface, it was possible to control the unit remotely from a GUI on either macOS or Windows

computers. There is no native support for OSC but third-party solutions offer this functionality. However, they did not at the time of the project support the camera control functions of the ATEM. In place of an OSC interface, the Blackmagic supplied GUI in the conductor node was IP routed to either node so that manual control could be achieved. This outcome was workable but did not provide for automation of camera control, such as changing of shutter speed or sensor gain at cued points within a performance;

- UltraGrid was integrated into the XRNP system architecture and was proven to be a reliable and deterministic solution for delivery of the performance. As UltraGrid is a command-line application—one that has many operating parameters that can be passed from the command line during initiation—a method was required whereby this task could be automated. The ability to programmatically control UltraGrid was important for some scenarios: when a system might need re-initialising with the minimum of delay following a program interruption or computer crash during a performance; or in cases where the compression or encoding parameters need to be changed—almost 'on the fly'—due to issues such as a congested internet connection. AutoIT (*AutoIT Script Editor*, n.d.) was used as a script based solution to automate the command-line sequences required to initiate and configure UltraGrid. The UDP functionality within the AutoIT environment allowed external OSC messages to request the execution and termination of predefined AutoIT scripts that in-turn controlled UltraGrid sessions.

The additions to the systems environment for *Opravdoví*, following the planned XRNP framework approach, resulted in a system that was now capable of delivering symmetric XR networked performances. The final project, *A Short Journey into Folded Space (*described in the next Chapter), though not a symmetric performance project, built on the system developments of *Opravdoví*, and through further integration of a platform for computer generated realities (Unity), resulted in a system that can deliver symmetric XR networked performances encompassing multiple realities.

## 4.4. A Short Journey into Folded Space

Jisc, the operator of the UK's NREN, organise Digifest, an annual conference on educational technologies for senior and higher-level managers. In 2018, Jisc created an opening performance (*Digifest 2018 LoLa stream*, 2018) for the conference, in which students of the Royal College of Music performed on the stage in Birmingham, joined over a single LoLa connection by a small group of students who were playing at Edinburgh Napier University. Due to the success of the performance in 2018, Jisc decided to have a similar performance for the opening in 2019. As I was seeking an opportunity to further evaluate the XRNP framework, and I had previously worked with Jisc (*Here, Not Here, Where?* performed at NPAPW 2015), we agreed that I would produce that performance. The support of Jisc in the project meant that there was an opportunity to test elements of the systems developed for *Opravdoví* and *The Spaces Within* on a greater scale, and to develop a final piece that would further the research through practice methodology of this study. I commenced development of *A Short Journey into Folded Space* (hereinafter "*A Short Journey*") in 2018.

### 4.4.1. A Short Journey - research objectives

The requirements on the system framework to support this project were a hybrid of that employed to deliver *The Spaces Within* and *Opravdovi*. The primary research objective was therefore to test a greater integration and use of Unity as a sub-system for the 3D composition of streamed video assets and virtual environments in an XR networked performance, specifically:

- Test the capability of Unity to manage multiple concurrent inbound and outbound video streams, using SDI and GPU video sharing;
- Develop and test OSC control of objects within Unity virtual world models, including movement and physics attributes;
- Improve and evaluate the control of light and camera objects, so that single OSC requests would initiate sequences of events that were then performed by Unity using newly developed C# scripts.

### 4.4.2. A Short Journey – artistic concept

Jisc set nearly no artistic restrictions for the performance, although they had expressed a preference for a piece that involved dance movement. So, I was free regarding the concept and realisation of a piece to open the Digifest conference in the International Convention Centre (ICC) in Birmingham. Returning to the influence of theoretical physics and the rich world of possibilities therein available for exploration in performances crossing time and connected space, I decided to investigate the concept of folded space: the concept of bridges through space-time, such as the wormholes theorised in the Einstein-Rosen Bridge (Einstein and Rosen, 1935) which connect different points in space-time through a pair of back-to-back black holes.

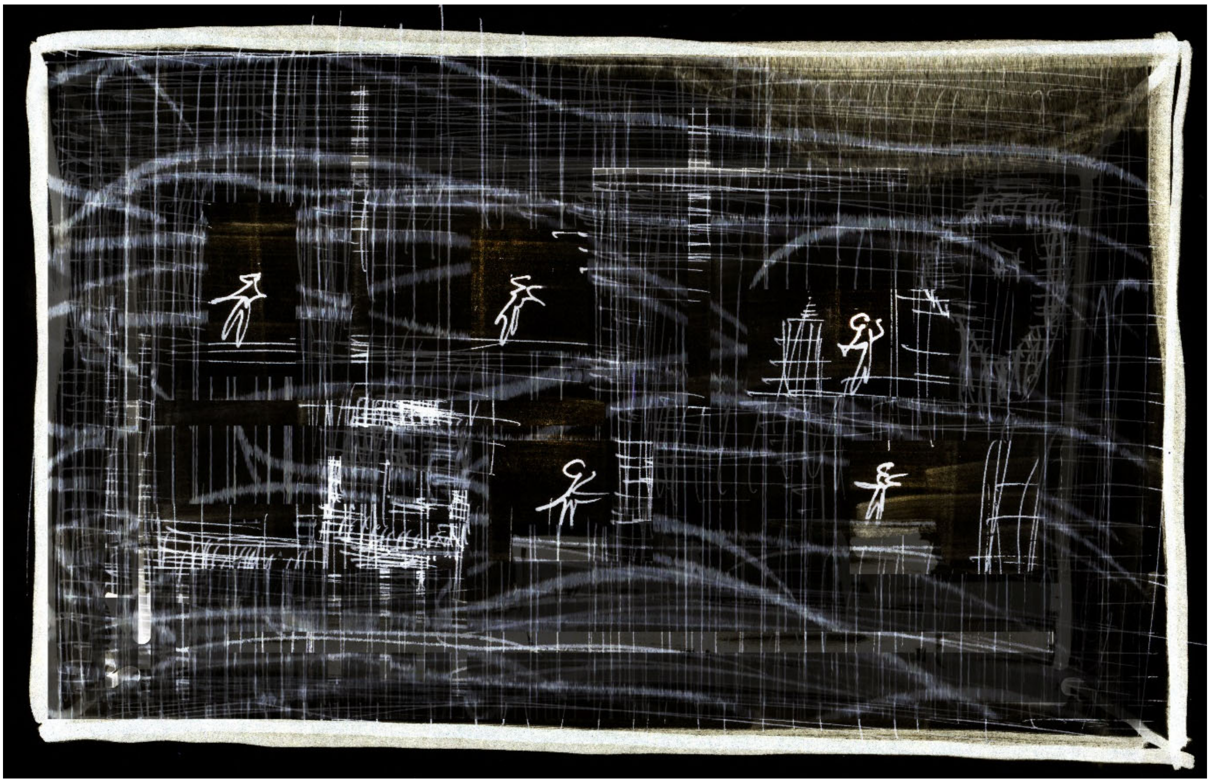

Figure 50: Concept sketch for a scene in *A Short Journey into Folded Space* (2019)

With the concept of folding two locations into each other during the performance, and the decision that a virtual model within Unity would be used to achieve this, the exploration of visual design possibilities was commenced. The idea to use small particles (or cubes) as the visual building blocks arose during a visit to MACBA (Museu d'Art Contemporani de Barcelona), which was to be the remote node of the performance (see: 4.4.3). MACBA's architecture is visually composed on a grid structure with cubes apparent throughout, there were also several square white cube seats in the atrium which choreographer Jana Bitterová played with during our exploratory visit. The combination of these factors led to the decision to use cubes as a main element, both in the visual design and as a developmental tool in the choreographic process.

Regarding the concept of folding space: the desire, was that during the performance some movement inside the virtual model would create the effect of collapsing the spaces of the ICC and MACBA into a unified virtual space, one that would then be manifested into the physical space at the ICC in Birmingham, and which all of the performers would inhabit.

#### 4.4.3. A Short Journey – realisation

As the performance was to be for a large audience (up to 1,500) in Birmingham, and to be presented at an important conference with a tight schedule, a reliable partner was required for the remote node of the performance. Having worked with the Catalan NREN CSUC on previous projects I knew of their professional approach and interest in networked performances, so was pleased when they accepted my invitation to support the project.

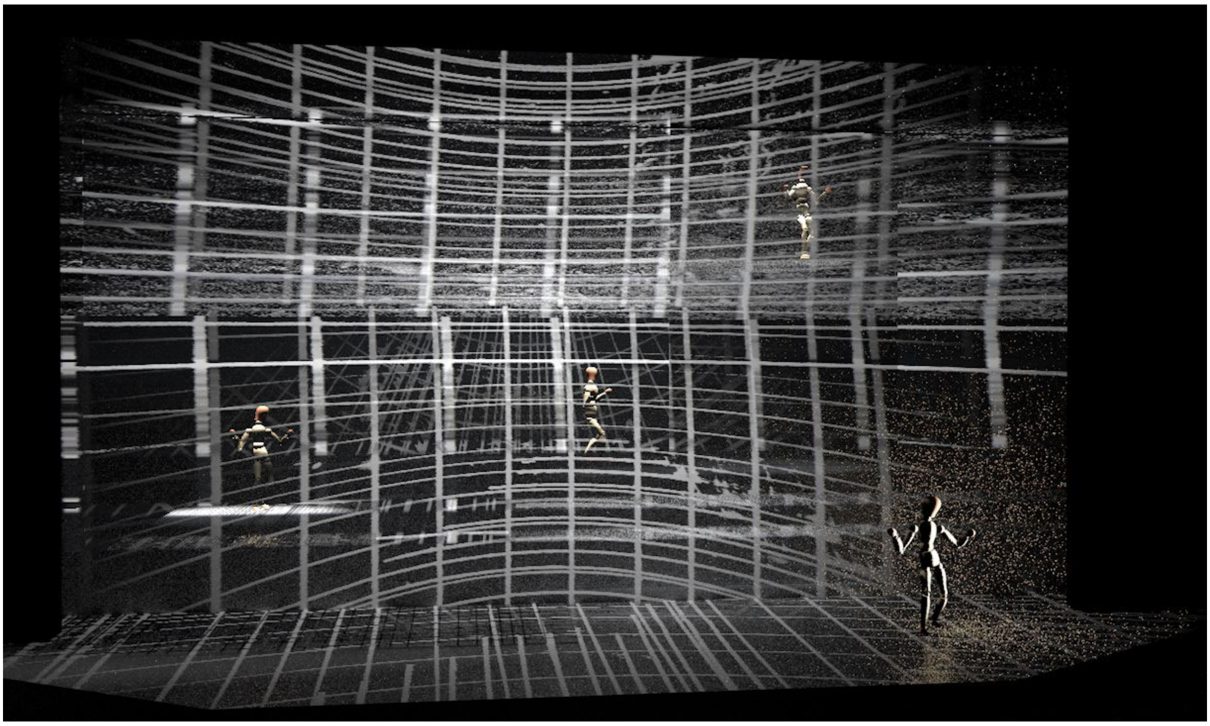

Figure 51: Pre-visualisation concept of scene in *A Short Journey into Folded Space* (2019) during development in December 2018.

Given that Barcelona would be the remote node of the performance we sought a location that had a similar spatial scale to that of Hall 1 of the ICC in Birmingham and that also had an excellent internet connection with peering through CSUC's network in Catalonia. I was soon down to a short-list of not so beautiful spaces within Barcelona-based universities or the annex at the Museum of Contemporary Art (MACBA) that I had encountered in previous networked performance projects linked with Barcelona. I much preferred to use the central atrium of the Richard Meier (Meier, 1995) designed MACBA building. It's a massive glistening white atrium, full of light, four-stories high, with long ramps ascending between floors; fronted by a glass façade that connects the building with the public space of Plaça dels Àngels which is much beloved by skateboarders. I was fortunate in the request as Tuesday was the weekday of the Digifest conference and the one day of the week when MACBA were closed to the public. MACBA generously agreed to let us use the complete atrium space for the performance and for evening rehearsals the week prior.

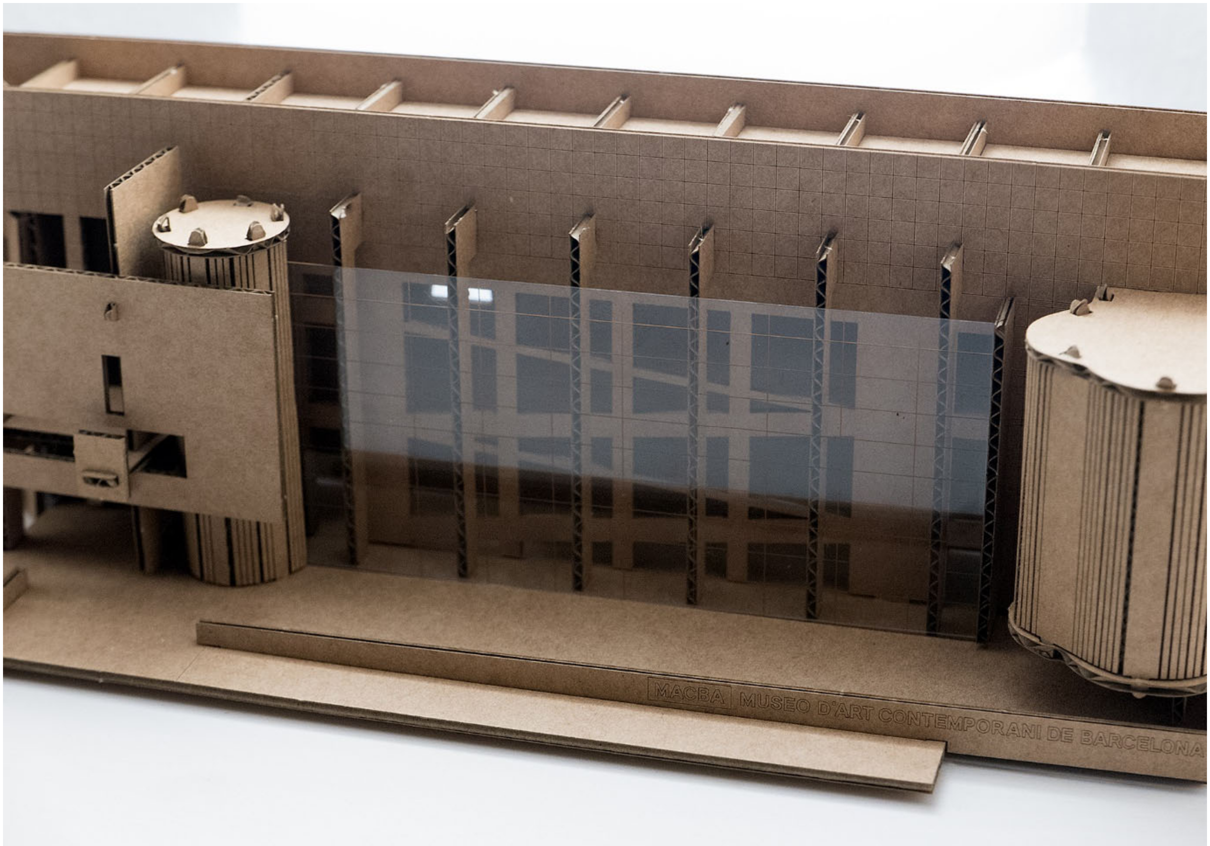


Figure 52: Considering performative possibilities for the Barcelona node of the *A Short Journey into Folded Space* (2019) using a laser-cut cardboard model of MACBA. The regular grid layout and the internal ramps exposed to Plaça dels Àngels can be observed through the glass facade.

The stage in Birmingham at the ICC is large and it was going to be used for many presentations during the conference, so I could not monopolise it with a complex set design. Therefore, the concept was to make much greater use of a virtual set and bring that to bare in the physical space, using only a large sharkstooth scrim and the floor as projection surfaces. Two 30 k lumen projectors—one for the floor and one for the scrim—would augment the physical space of the ICC with scenes from the virtual model running in Unity. Video feeds of the performers in Barcelona and Birmingham would be positioned inside the virtual model so that composite scenes for projection back into the physical space could be created in real-time. These scenes could be combinations of any physical performer and attributes of the virtual set.


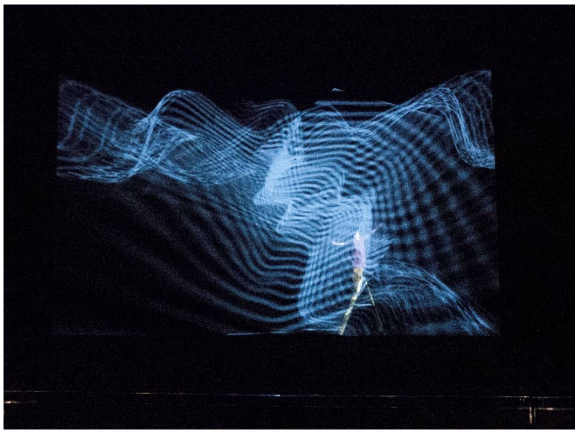

Figure 53: Testing visual and projection possibilities for *A Short Journey into Folded Space* (2019) during a visit to the ICC, Birmingham in November, 2018.

Out of a discussion with the organisers about the general mood of the performance, I decided to commission Dutch composer Anthony Fiumara to develop a new music composition for the project. Over the winter months, I discussed various sketches in a dialogue with Fiumara and choreographer Bitterová. The resulting score for *A Short Journey into Folded Space* was rooted in Fiumara's interest and practice, influenced by American minimalist composers such as Steve Reich, combined with digital effects and glitching. The instrumental part of the composition was recorded by the saxophone ensemble of the Fontys Hogeschool voor de Kunsten in the Concertzaal Tilburg, the Netherlands, and then mixed with the other electronic music components by Fiumara to produce the final soundtrack.


Figure 54: Rehearsal (left) and performance (right) in MACBA, Barcelona for
*A Short Journey into Folded Space* (2019).

Initial work on choreography was with two of the dancers who would perform in Birmingham. This commenced in February 2019 in Portugal. We then moved the team to a warehouse scale space in Badalona, a city adjacent to Barcelona, courtesy of the Catalan collective La Fura dels Baus and their Èpica Foundation. In their space, I constructed one environment to represent the stage in Birmingham, complete with projection scrim, and a second space to represent the atrium of MACBA. The complete system rig for both locations in the network performance was installed, together with the video cameras, video switches and networking equipment that would be used in each venue, everything except the venue lighting and the physical network connections that would be provided by CSUC, Jisc and GEANT peers in the final performance. This was a method of working I first adopted in the development of *Opravdoví* in 2018: the bringing together of the performers and specialist systems from all nodes of the networked performance into a single location for development and rehearsals, and the pseudo creation of the two spaces of performance within a single physical place. A benefit of this approach is that all the performers—who will be geographically scattered in the actual performance—get to work together, physically in-contact, increasing their artistic and emotional bonds for when they perform in networked mode, connected only by electrons and photons.

For the performance, the network connection between Barcelona and Birmingham was a 1 Gbps circuit, implemented by CSUC in Barcelona and Jisc/Janet in Birmingham, peered across Europe by GEANT and the Spanish NREN RedIIRIS. UltraGrid was used as the streaming solution. From Barcelona, three HD video camera streams from different locations in MACBA and one HD test pattern were streamed as a compressed 4k video grid. From Birmingham, a 4K stream to Barcelona comprised the three HD camera streams from the stage and one HD test pattern.

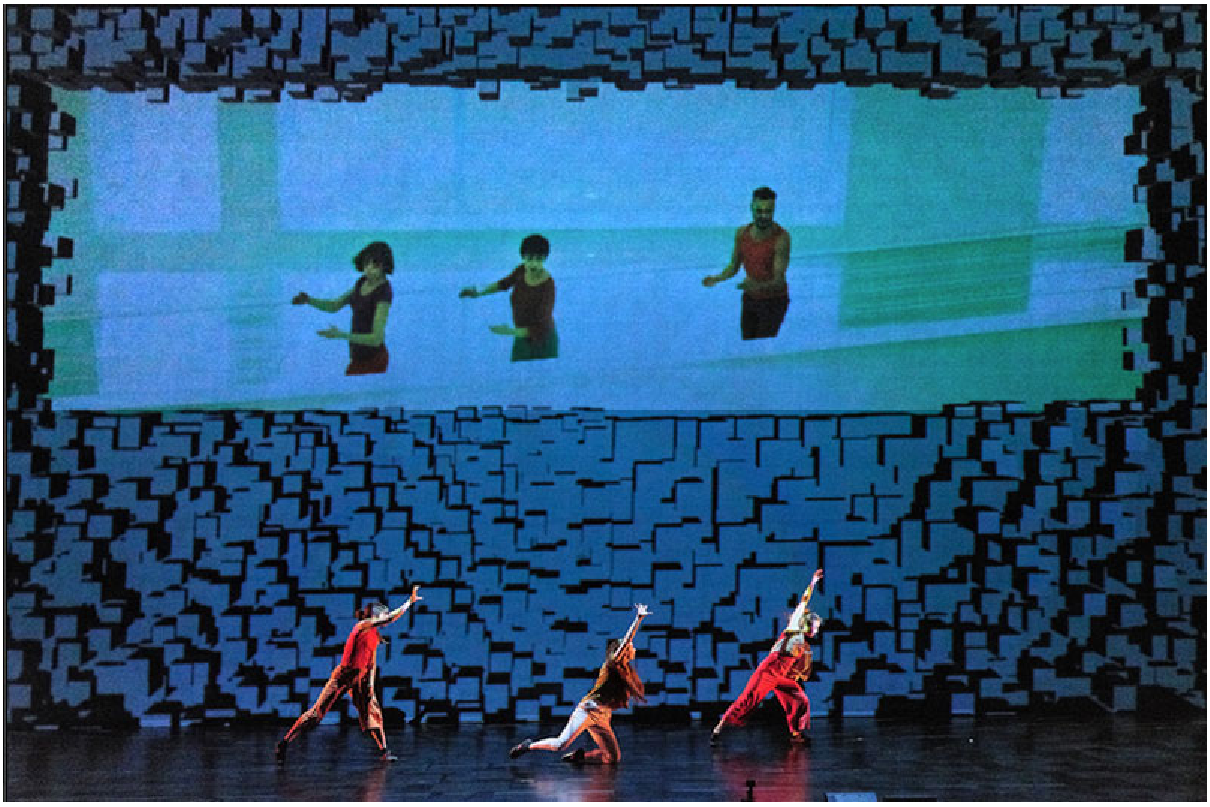

Figure 55: Dancers in Birmingham and Barcelona meet in *A Short Journey into Folded Space* (2019). Credit: Jisc.

In Birmingham, three dancers performed on the stage, interacting with the animated visuals which contained streams of the remote dancers, and in the final scenes, also local streams of themselves (video: *A Short Journey into Folded Space* - full performance, 2019, 00:11:57). The  three dancers in MACBA moved through the different floors of the atrium, captured by three cameras from different angles, revealing the scale of the architecture. Due to the challenge of capturing the site specifics of MACBA, and the dancers' interactions with the building, I decided not to attempt a full audience experience in Barcelona. However, a small invited audience was present to witness the event, observing both the dancers in the building and work of the local technicians.

### 4.4.4. A Short Journey – technical evolution

The project built on the integration of Unity into the framework that was first used for *The Spaces Within*. For *A Short Journey*, the virtual world in Unity served as the set for the performance, which was then captured in two planes by virtual cameras in Unity and projected onto the floor and scrim of the physical set in the ICC, Birmingham. The virtual set provided an environment for the real-time spatial composition of the video streams from MACBA and the local cameras in the ICC. The virtual set in Unity was dimensioned to match the arrangement of the physical set in the ICC, resulting in minimal task or overhead in mapping of the virtual to the physical in the projection process.

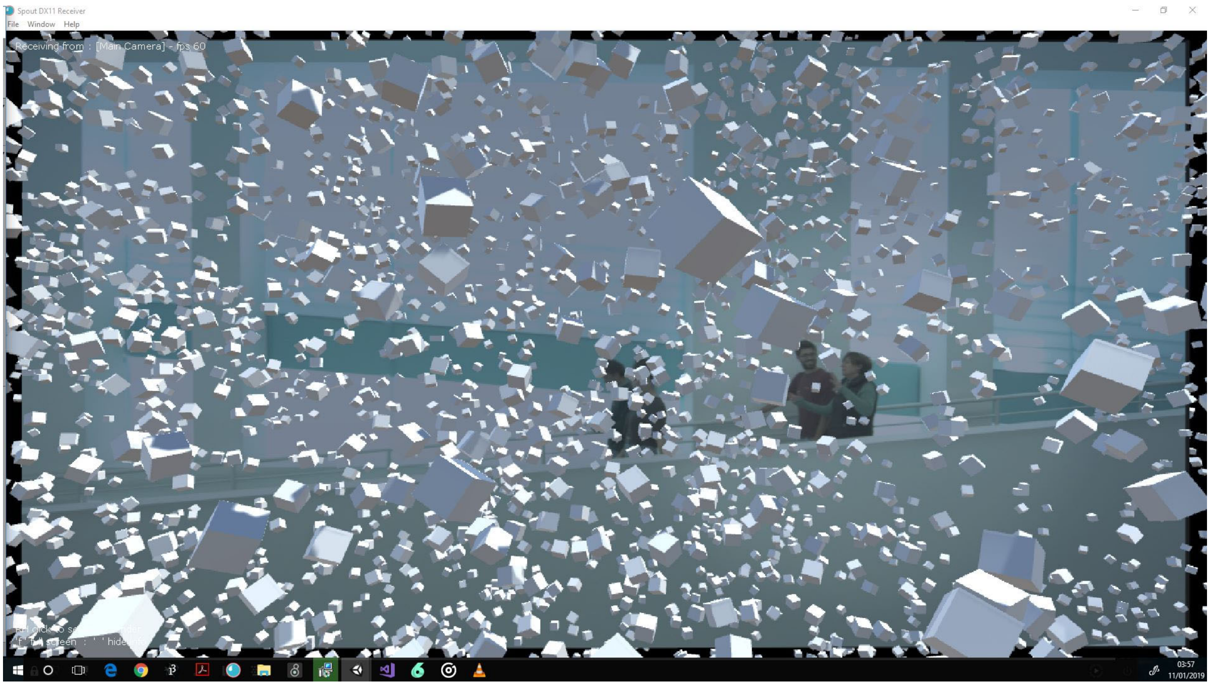


Figure 56: Testing OSC controlled objects with physics in Unity during development of *A Short Journey into Folded Space* (2019).

To support the performance, new OSC interfaces and associated C# scripts were implemented in Unity:

- **Physics** - the virtual environment for the performance was comprised of thousands of small rendered cubes which were then projected into the physical space of the performance. Simulated interactions between the virtual cubes and the physically present dancers were achieved using OSC control messages sent to Unity. A set of OSC message types were defined, and associated scripts developed that could be attached to the cube objects within Unity. Through this method, the physics properties of the cube objects could be configured in real-time using OSC commands. The physics functions could also be enabled and disabled by OSC. As motion capture was not being used for the performance, OSC controlled virtual collision objects were created within the Unity model: these were then controlled by OSC cues sent from QLab during the performance to create effects between the dancers and the model. An example of this was the disappearance and reappearance of cubes—projected on the scrim surface as a scrolling pattern—as the dancer ran across the width of the physical stage (video: *A Short Journey into Folded Space* - full performance, 2019, 00:04:29);

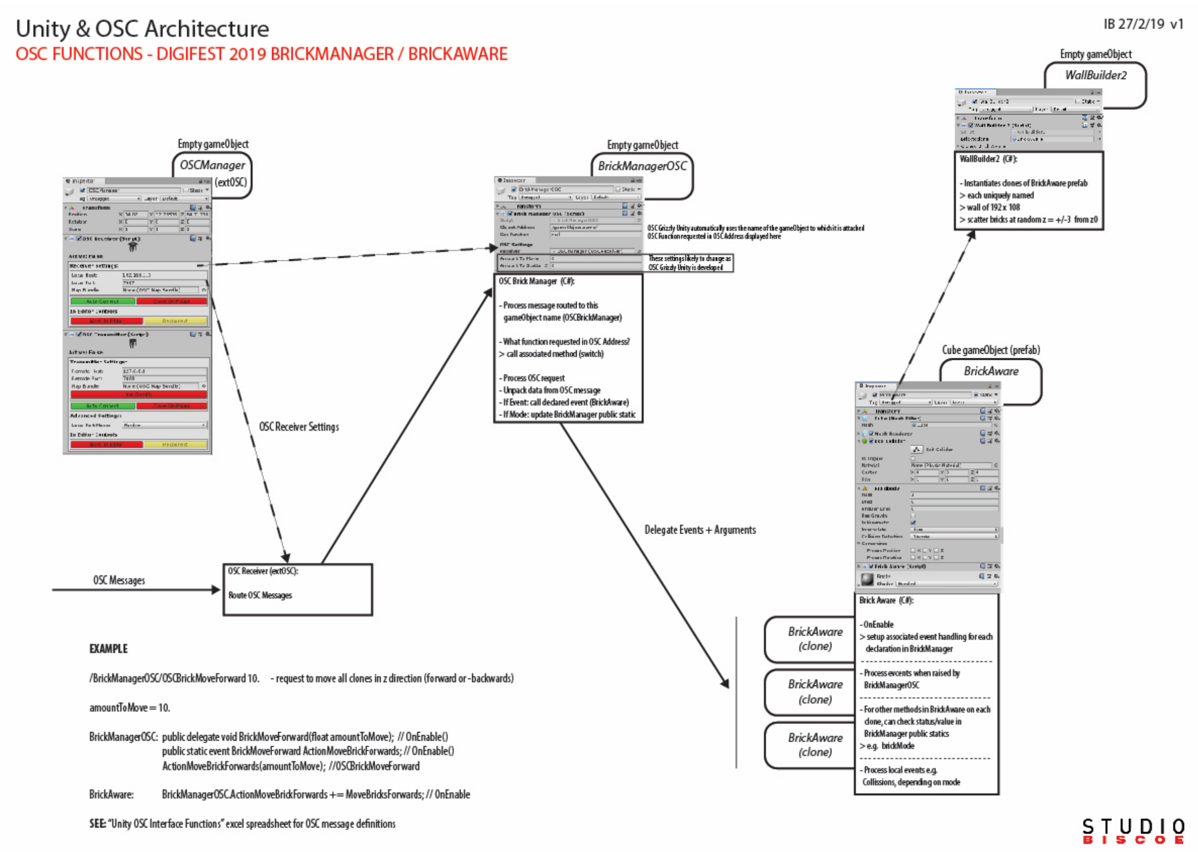


Figure 57; Model, interactions and functions of an OSC controlled 'brick' object in Unity that is used in the construction and deconstruction of a block wall inside a virtual model for *A Short Journey into Folded Space* (2019). Each brick is an instantiated clone of a prefab, where each brick has independent physics and movement properties that can be configured and controlled by OSC message.

- **Virtual fly tower** - the ability to manipulate horizontal and vertical planes in the model using OSC messages and scripts. These layers would serve as virtual layers when projected out onto the physical scrim or floor of the set. Each layer being rendered with any combination of virtual, pre-recorded or live video streams. The general operating principle being akin to that of physical scenery being lowered or raised from a fly-tower in a theatre;

- **Virtual moving-head spotlights** - control of light objects within Unity by OSC so that they act as if they were moving head lights in the physical world, with the ability to rotate to a specific set of coordinates, rotate over time, and move to a set of coordinates within the model, immediately or over time (video: *A Short Journey into Folded Space - full performance*, 2019, 00:10:47);

- **OSC control of lights** - the previously developed functions were extended (depending on light object type) to support control of beam width, range and intensity by OSC message and associated C# script in Unity.

The virtual moving head spotlights in Unity were also required to work choreographically with the dancers in the physical space of the stage in Birmingham. However, there was very little time available for setup and rehearsal in Birmingham, so a solution was required to quickly experiment, program and calibrate the relationship between lights in the virtual set in Unity, the physical stage and the movements of the dancers once in Birmingham at the ICC. To support this, a set of additional patches were developed in Max/MSP that would run on a Microsoft Surface Pro with a touch screen interface:

- **Virtual object trackpad** - a touch screen interface that represents any associated plane within Unity. The relationship between the resolution of the touch screen interface and the dimensions of the plane within the Unity model can be mapped as required. Actions on the touch-screen trackpad interface can be used to manipulate the lights within the Unity model in real-time;

- **OSC recorder/player** - records received OSC messages with timestamp for on-demand replay. Multiple banks of OSC records can be recorded and recalled using the touch screen interface. Replay files can also be recalled and played using OSC requests sent to the patch.

The functionality encapsulated in these two Max/MSP patches was not limited to the control, recording and playback of virtual spotlights. The patches were designed so that they can effectively control—via OSC—any associated parameter of an object, or object attached script, within a Unity model. This resulted in a flexible toolset for live interaction and programming of Unity objects and how their visual image is projected into the physical space of performance.

Whereas the Spout video libraries supporting Unity had proved troublesome in 2018 (the SDI I/O library being used for *The Spaces Within* to receive, transmit and share video streams) the 2019 updates to Spout/Unity worked well. As six video streams (three from MACBA via UltraGrid and three locally from the ICC stage cameras) needed to be placed inside the Unity virtual model for the performance, it was therefore easier to use Spout for this rather than additional SDI interfaces in the host PC. As the video streams also had to be cropped and positioned prior to ingest to the model in Unity, this approach meant Resolume could be used for the task. The video flow for the performance as realised was therefore:

- The 4K stream from Barcelona was sent to Resolume using Spout sharing between UltraGrid (Spout server) and Resolume (Spout client). In Resolume, the constituent HD camera views of Barcelona—contained in the 4K grid format—were each placed on a separate video layer. Any cropping or other video processing functions were then performed individually on each video stream in Resolume. The output of each layer was then shared with render textures inside Unity, using Spout sharing between Resolume (Spout server) and Unity (Spout client);
- The three HD camera signals from the stage in Birmingham were ingested into Resolume using Blackmagic Design Decklink SDI interfaces. As with the feeds from Barcelona, each was then shared from Resolume using Spout, with associated render textures in Unity. The three local camera feeds were also assembled by Resolume into a 4K grid—with a test pattern on one of the quadrants—and sent to UltraGrid

for transmission to Barcelona, using a physical SDI loopback connection between Resolume and UltraGrid running on the same PC. The 4K stream transmitted to Barcelona included the ICC front-of-stage camera so that the complete crew in Barcelona could observe;

- The output of the virtual cameras in the Unity model, used to capture the visuals that were projected on the scrim and floor in the physical space, were shared via Spout back into Resolume. The advanced output mapping functions in Resolume were then used to position the video feeds that were sent to the two projectors via SDI outputs.

The complete system for the performance was controlled by an instance of QLab in Birmingham, with an associated instance of QLab in Barcelona. A similar setup to that used for *Opravdoví* but with less functionality required in Barcelona due to there being no lighting or other set elements to control, and as the primary audience was in Birmingham. OSC was used to control and synchronise all elements of the performance in Birmingham (Resolume, Unity, Max/MSP patches and video), audio playout and video in Barcelona.

Figure 58: An impact of physics objects—under OSC control—in the Unity virtual world model creates a new dynamic during *A Short Journey into Folded Space* (2019). The portal to folded space on the left reveals a different view of the dancers in Birmingham from a camera to stage-left which is fed into Unity via Resolume and Spout. The portal to the right will shortly reveal the dancers in Barcelona, a view taken from the 4K steam from MACBA, via Resolume, Spout and Unity. Credit: Jisc.

### 4.4.5. A Short Journey – outcomes

In terms of the wish to find a method to visualise the merging of spaces between the two venues into something that might be considered a folded space, I feel that this was not quite achieved in *A Short Journey into Folded Space*. The concept was well considered and the framework fulfilled its requirements for supporting an XR networked performance of this configuration and functionality. However, the challenges of compositing scenes that comprise natural and artificial lighting in the physical world with scenes in Unity that are purely virtual, then projecting the composite scenes back into the physical space of performance (locally or remotely), is one that continues to be challenging. One of the factors in this performance was the natural daylight that can fill the atrium in MACBA. During all of the tests and rehearsals we had seen bright consistent lighting but on the morning of the performance it was a sunny, yet windy and partly cloudy day in Barcelona:

this resulted in the light dramatically changing almost every minute during the 20-minute performance.

These lighting issues are likely not specific to the realm of XRNP; similar situations are likely to arise in other scenarios involving the mixing of physical and computer generated realities in real-time. The situation in XRNP is however complicated by there being more than one physical location to consider. Also, that in the case of this performance, the video of the performers from the real-world was also being composited as components (augmented-virtuality) within the virtual model. There is a third issue to consider in XRNP, and that is the need to also provide sufficient light for the video cameras in each physical space of performance, while balancing the contrast of the projected surfaces and the light required for the local audience to feel adequately immersed within the performance. These requirements further complicate the task of rendering scenes that have the same visual richness, colour balance and lighting dramaturgy as when dealing purely with a physical or a virtual environment. A great challenge survives in the creation of a multiple reality networked performance mise-en-scène that is as subtle in realisation as it is in the mind of its creator.

In Unity, the pixel granularity of the cubes (objects with physics enabled being called 'rigid-bodies') was larger than I would have liked. The original plan was to have about 20,000 cubes but this was reduced to 5,000 as the physics engine within Unity could not manage this amount of processing—when physics was independently activated for each cube–without the update frame rate falling below 15 fps. Whereas some elements of the Unity platform are multi-threaded, user generated code that uses the Unity API is only single-threaded and therefore cannot benefit from a CPU with multiple cores that can run many threads. The Intel i9 CPU used has 16-cores and supports 32-threads. As the Unity physics engine uses the CPU for its computations, a higher-performance GPU also does not assist the physics engine performance.

Despite these misgivings as to the realisation of the visual elements of the artistic outcome, the organisers and audience responded enthusiastically to the performance. The networked aspects worked reliably, and the choreography was well rehearsed, performed and met its ambitions.

From the perspective of the performance's value to the methodology and focus of this research, the project facilitated extensions to the framework and further demonstrated the flexibility of the use of OSC as a standard interface. Especially, with respect to the ease with which new controls were implemented in Unity; the provision of a touch-screen tracker to control Unity objects; and an OSC recorder/player for use in development and rehearsals.

In considering the objectives for this project (see: 4.4.1), in which the primary goal was to investigate the closer integration of Unity (as the environment for computer generated realities) within the XRNP system framework, we can summarise the outcomes as:

- The requirement for the previous project (*The Spaces Within*) was for a virtual world model in which there were multiple video feeds augmenting the model, and from which multiple cameras would capture composite moving images for projection into the physical spaces of the performance. The question was therefore, how many simultaneous video streams could be placed in, and captured from, a Unity model in near real-time. Rather than using the SDI loopback approach (as employed for *The Spaces Within*), one which would require several physical SDI interfaces in the host PC, the preferred approach for *A Short Journey* was to use the updated version of a Spout plugin for Unity. The Spout plugin supported exchange of video streams with other applications that had client or server implementations of Spout, via the GPU in the host PC. The approach worked reliably for four HD video streams simultaneously in each direction (augmenting the virtual and physical worlds of the performance) with a measured GPU load of 38% (Nvidia GTX 1080 Ti) and CPU load of 18% (Intel i7 8700K @ 3.7 GHz) above baselines; the streams were with Resolume Arena acting as both the Spout client and server;

- The development of new Unity object-specific C# scripts provided the OSC interface with greater control of elements of the virtual world created for the performance. The decision to use OSC as a standard messaging format showed great benefits as regards the relative ease with which new control mechanisms could be established in Unity. Once Unity objects were OSC-enabled they could easily be manipulated by cues in QLab, custom control and utility patches in Max/MSP running on Microsoft

Surface touch screen devices, and coordinated with video switching and compositing actions in Resolume.

# 5. CONCLUSION AND CONTRIBUTIONS

In this chapter, I present a summary of the technical and artistic research which forms the body of this thesis, and the original contributions to knowledge that have been formed in that process. The chapter concludes with some notes on future directions and opportunities for research.

## 5.1. Research summary

As discussed in Chapter 2, my initial work in and around the field of networked performance involved a series of collaborations and the first two networked performance projects I conceived and produced (*Here, Not Here, Where?* and *Bridge To Everywhere: 234*) in which I tested different technical and artistic approaches. From this experience—gained over a period of three years—I formulated the basis for my future artistic work: that which I was to term X reality networked performance (XRNP or XR networked performance). From an extensive review of technical solutions that could support my artistic practice—considered from my background in systems design and engineering—I concluded that there was no suitable solution or defined system architecture that I could employ to support XRNP projects. Though there are some solutions which have been specifically developed for the low latency streaming aspects of networked performance (e.g. LoLa and UltraGrid) these do not encompass the many other platform requirements I had identified, and that would be necessary to support my practice.

From this realisation, the **research aim** was synthesised as: **the creation of a systems framework whereby existing hardware and software components can be continuously integrated with bespoke components to provide an elegant platform for the delivery of X reality networked performances**.

The systems framework components and functionality required to support my arts practice were then categorised (see: 1.4.3), and can be summarised as:

- **Streaming** - the components or sub-system required to provide reliable, flexible, deterministic and low latency transport of audio and video streams between the sub-systems and nodes of the performance;

- **Data communication** - the reliable and deterministic means by which data is passed between sub-systems;

- **Toolbox applications** - a development and execution environment for the creation of applications and other software needed to provide the "glue" in XRNP systems, and for the rapid creation of utilities and components for specific projects;

- **Augmented and virtual reality** - a development and execution environment for the creation of computer generated realities;

- **Video processing and presentation** - applications and sub-systems for tasks such as video switching, video compositing and projection mapping;

- **Distributed cue management** - tools, applications and sub-systems that allow for the rapid creation of the configuration and control mechanisms required to deliver a performance, including the management of the various sub-systems;

- **Network infrastructure** - the additional network equipment and tools required to deliver a performance, beyond that which might already be available at the venue of performance.

Drawing on prior experience in other fields of system design and integration, I looked to the field of avionics (see: 1.5.2) as an exemplar for best practice in the design and integration of complex distributed systems. Good avionics system design practice considers issues such as modularity, deterministic operation and reliability, all of which I weighted to be important criteria in implementing a systems solution to support my arts practice.

The **research question** therefore considered the approaches taken for the implementation of complex distributed 'real-time' systems in the aerospace sector, to define a systems framework for my practice in XR networked performance. Specifically, to test if a **systems integration approach to providing a technical platform for X reality networked**

**performances, one that employs strongly-defined interfaces and communication protocols, and that is based on open and industry standards** would best serve said practice.

From this same legacy of systems engineering, and in consideration of the requirements of my arts practice, I appreciated that such a systems solution should also possess characteristics (see: 1.5.3) that made it: elegant, deterministic, reliable, extendable, scalable, reconfigurable and testable, and that should be cost-effective.

To implement the XRNP systems platform in a way that was guided by comparative approaches in avionics systems engineering, it was necessary to identify appropriate interfaces and communications protocols. These needed to be ones based on open and industry standards, and that were likely also familiar in the world of equipment and systems already used in the arts. A review of potential solutions was undertaken (see: 3.4) with the conclusion that OSC as a message format, combined with TCP and UDP protocols running over IP networks, would best meet the requirements. The review showed that although there were some other potential candidates (such as ACN / E1.17 and OCA / AES70) they were emerging standards that were not yet widely adapted or implemented in potential COTS and MOTS components that might be employed in the system. Whereas, OSC—though not enshrined by an official industry standardisation body—has been widely adopted in the arts, especially as a replacement for MIDI in more complex music systems, and as a generic format for exchange of information between sub-systems. It has good support in the applications that were being considered for the XRNP platform, such as those for cue management and video processing. For applications that did not natively support OSC, there was a growing community of independent developers that were creating libraries of plug-ins to enable data exchange using the OSC format.

The review also considered the other requirements of the XRNP framework, such as the sharing of video and audio in closely coupled sub-systems: those located in the same node of an XR networked performance, or applications residing on the same host computer. The outcomes of which were discussed (see: 3.5) and employed in the XRNP system solution developed to support the performances discussed in Chapter 4.

To achieve the aim of the research, **three objectives** were proposed (see: 1) and have been realised though the course of the research, as outlined below:

- **Definition** - the requirements of a platform to deliver XR networked performances were identified (see: 1.4.3 ), definitions of core components produced (see: 3.1) and selection of candidate sub-systems, components and applications made (see: 3.5). Considerations were also made for the effects of XR networked performance typologies on the system (see: 3.2 ), and issues of latency and determinism (see: 3.3);

- **Exploration** - the use of a message-based approach to communication between—and integration of—disparate sub-systems in a distributed systems architecture was explored though the lens of my background in avionics systems design (see: 1.5.2). Candidates for an appropriate messaging solution in XRNP were considered (see: 3.4) and a suitable candidate selected (see: 3.4.4), the use of which was explored in the third objective;

- **Creation** - the XRNP platform, its architecture and capabilities, and the use of OSC as the selected messaging communications interface, were developed and investigated in the creation of four new XR networked performance projects, as detailed in Chapter 4.

**The four XR networked performance projects** which provided the vehicle for testing the XRNP framework and architectural principles were presented in Chapter 4. For each project, a set of research objectives and outcomes were provided, in addition to a presentation of the artistic proposition, realisation and technical evolution of the project.

*Longing for the Impossible* in 2017 (see: 4.1) was the first project to test elements of the XRNP framework, and the commencement of an iterative process of systems integration in the XRNP platform that would continue over the following three projects. The project proved the usefulness of OSC in connecting a range of functionalities (cue control, animation and light control) required for the performance, which were developed as patches in Max/MSP. OSC also provided a deterministic and reliable integration between Max/MSP patches and Resolume (as a core video processing component) that allowed real-time compositions of streamed and pre-recorded video content to be animated during the performance. As with earlier project, the performance also demonstrated the need for a closer integration with a suitable streaming sub-system.

The core objective for *The Spaces Within* in 2018 (see: 4.2) was the integration and evaluation of Unity as an environment for the creation and delivery of computer generated realities. The key challenges were: the control and synchronisation of elements of the virtual world in Unity during the performance; and the efficient and reliable exchange of real-time video streams with Unity in the process of augmenting the virtual environment with elements of the physical world, and using composited scenes from the virtual environment to augment the physical environment. OSC was used for all aspects of virtual world control in Unity; the ability to control virtual cameras was proven as a result of the performance at the New World Center in Miami Beach. It was not possible to fully evaluate GPU sharing for exchange of video streams with Unity but an alternative solution (using a plug-in to connect with a physical SDI interface) was successfully employed as the video exchange mechanism between Unity and Resolume.

*Opravdoví / The Real Ones* in 2018 (see: 4.3) was the first project to attempt to deliver an XR networked performance of the symmetric typology (see: 1.4.1). As such, it required a method by which to reliably control and deterministically synchronise all aspects of the performance across the two nodes. A conductor/associate communications solution was developed using Max/MSP patches, including the implementation of a control and monitoring GUI, and an OSC message router. With this system configuration, OSC was proven as a reliable method to implement a symmetric performance, achieving synchronisation of performance events across the two nodes at differences as low as 10 milliseconds, at the performance distance of 250 km. As identified in the previous two projects, a tighter integration of an audio/video streaming solution was required to fulfil the XRNP platform objectives. UltraGrid was selected, especially for its range of input/output options (hardware interfaces and software pipelines). Automation of UltraGrid was achieved by the use of command line scripts and OSC requests. Both SDI and Spout GPU sharing were successfully tested as methods to exchange video streams between XRNP client/server applications and the UltraGrid service. Though patches created in Max/MSP had been used to implement show control in the previous two project, it had limitations as regards the speed and efficiency with which cues could be created, modified and reorganised during development and rehearsals. QLab was integrated as a dedicated cue control solution, also as an audio server and DMX light controller. The ease with which QLab was integrated into the platform as a replacement for the use of Max/MSP in these functions, demonstrated again the reconfigurability and extendibility of the framework due to the use of OSC as standard interface.

Lastly, *A Short Journey into Folded Space* in 2019 (see: 0) was used to further test the integration of Unity as the sub-system supporting computer generated realities with the XRNP platform. A key objective for this project was to evaluate the greater use of some of the attributes of the Unity platform—such as the physics engine—and to see how efficiently complex actions involving many objects in Unity could be controlled via OSC. The functionality of the exiting OSC interface was considerably extended, along with new object scripts, and utilities for controlling and recording OSC interactions with Unity using touch-screen interfaces.

## 5.2. Contributions to knowledge

The contributions to knowledge arising from this research are anchored in technological and artistic domains. The result of an applied methodology that is supported by an ongoing investigation of technologies, ones that enable the delivery and are the seed of new possibilities in the field of networked performance arts practice. The key contributions are: a) the use of a message-based communications approach to provide elegant solutions for the realisation of X reality networked performances, and b) a body of artistic work that explores new dimensions within the field of networked performance, especially those that consider and incorporate X realities in their conceptual design and realisation.

### 5.2.1. Message based communication for elegant XR networked performance systems

A message-based communications approach—based on open and industry standards—supports the process of continuous integration to provide an elegant systems solution for the delivery of X reality networked performances. The research also proved that system design and integration approaches employed in the field of avionics systems (where such message based approaches to systems integration and communication are common practice) can be successfully applied to the creation of similar distributed, real-time systems for arts practice.

The solutions investigated during this research were informed by the limitations of those supporting early projects (see: Chapter 2), where standalone solutions were employed, ones which required greater time to configure and did not support the operational and experimental characteristics identified as beneficial to technical art practice (see: 1.5.1).

Results of the four research performance projects (as presented in Chapter 4) has quantitatively and qualitatively proven the applicability of the systems integration approach to the provision of a platform enabling XR networked performances. The solution has measurably delivered against the core XRNP framework objectives, in that it has been shown to be:

- **Deterministic** – in all use cases the platform has supported the delivery of control and synchronisation events, and the exchange of audio and video streams, within the time-frames required for performative actions to be seamlessly delivered across the nodes of the performance, without any observable variances by the audience or the performers;
- **Reliable** – the platform, in its various configurations during this research, has proven its reliability by consistently delivering on the requirements for failure-free performances. Features considered in the design of sub-systems—such as the use of monitoring and manual overrides in the OSC message router—provided added levels of operational reliability;
- **Extendable** – the use of a standard messaging format and interface construct has supported constant expansion of the platforms functionality throughout the period of the research;

- **Scalable** – the solution has scaled to support different types of performance, from operating at only one node of a centric performance typology, though to a multiple subs-system implementation across two nodes of a performance of symmetric typology;

- **Reconfigurable** – as the primary sub-systems communicated with other sub-systems using a standard messaging construct, functionality provided by one sub-system could be replaced by that in another, to support project specific requirements, or system upgrades to support operational flexibility. For example, the switch from cue management in Max/MSP to QLab;

- **Testable** – the use or implementation of an OSC messaging interface in as many of the XRNP subs-systems as possible has resulted in a solution where each sub-system has a defined interface to the other sub-systems. As in the field of avionics integration, this approach has resulted in sub-systems that can be tested and developed in isolation of the other sub-systems. In most cases, a simulation of the other systems (e.g. executing on a networked PC) could be used to develop and test new functionality in any one sub-system. The approach supported continuous integration of new functionality without the risks of a big-bang style of integration;

- **Cost Effective** – cost is relative, but in terms of a complex system for what is currently a niche and experimental arts practice, the approach to system integration that allows the use of both commercial and non-commercial components (physical sub-systems, and software applications) is one that can be deemed as cost effective. This is especially the case due to the ability to easily integrate a wide variety of software applications with the minimum of time and cost overhead; many of which are free, free for non-commercial, or free for limited commercial use.

Due to its ability to meet the framework objectives—through an iterative development and integration process, and delivery of four complex networked performances, across five countries in a period of 24-months—the solution can be deemed as one that is **elegant**. It has provided a message based distributed system, capable of controlling and presenting multiple realities, in the delivery of X reality networked performances.

### 5.2.2. New expressions and dynamics in networked performance practice

The networked performance projects that have been created and implemented during this research have been used to test the XRNP system platform by which they were developed and delivered. Indubitably, the reason for the technological activity in this research was not purely the pursuance of advancing systems engineering but the development of a technical framework and platform which would benefit the performing arts. Specifically, how an elegant systems approach might enable the incorporation of XR concepts and practice within networked performances, that new forms of artistic expression and performance dynamics might be realised.

In the example of *Opravdoví*, the subtle interactions of two geographically distanced performers were possible thanks to the ability to reliably synchronise and perform the switching and mixing of video streams, alongside simultaneous changes in lighting and audio, across the environments of the performance. This brought about a new intimacy in the realm of the physically dislocated performers' networked coexistence, structured within an XR environment. The developed technical platform, supporting immediate interactions during development, rehearsals and performance of the work, enabled a networked choreography where performers were drifting between the physical and the virtual, appearing in the local but then also instantaneously and fleetingly in the remote. The playfulness of extended space within the performance emerged.

In the cases of the projects *A Short Journey into Folded Space* and *The Spaces Within*, the site specificity of the physical locations was revealed: in the local, in the remote and in the virtual. The physical locations also inspired the aesthetics of the imaginative virtual environments with which they were merged, creating X reality worlds that provided spaces for the performers to meet in new and unconventional situations. It allowed choreography to be "virtually" site specific: the ability to exploit the affordances of remote specific locations, conventional stages and virtual worlds simultaneously.

In *Longing for the Impossible,* the fictional world of spheres encapsulated both local and remote performers. It provided a unique visual identity for the musical compositions—not only formally, but also existentially—as this imaginative world was the vehicle for the coexistence of all musicians and dancers.

These artistic qualities in realised projects would not have been possible without the flexible, reliable and low latency synchronisation functionality provided by the message based XRNP systems platform. The elegancy with which this platform functions supports artistic exploration of XR networked worlds in a similarly elegant fashion.

### 5.2.3. Additional outcomes

In addition to the core contributions to knowledge, the process of research and thesis production resulted in several additional outcomes:

- It presented the opportunity to classify important aspects of my practice in networked performance and XR networked performance. Critically, these include my definitions of networked performance as **an artistic performance that occurs simultaneously across physically distributed spaces, which by means of a communications network allows the participants to collaborate in a single event**.

- In consideration of a review and discussion around the historical context and contemporary practice in networked performance, and an investigation as to the current thinking and terminology in the field of computer generated realities (not least, a discussion of the reality-virtuality continuum), I further developed and clarified my definition of X reality networked performance as being **a network of simultaneous realities across the nodes of a networked performance, where X represents the variable superset of the combinations of realities on the reality-virtuality continuum, fictional realities, the interactions with and between them, and between the objects existing therein (including physical and virtual performers, and the audience).**

- Also, a **new typology of networked performance** - experience in many networked performance projects, coupled with the findings of the research process, provided the grounding through which to define a set of typologies (see: 1.4.1) for networked performance. The four typologies being: Centric, Off-Centric, Asymmetric and Symmetric.

## 5.3. Future directions and research opportunities

Though this research has proven the adopted systems integration approach to be essential for the delivery of complex XR networked performance scenarios, it is by no means the conclusion of development and use of the platform. As a unique medium, XRNP offers almost limitless artistic possibilities for exploring the relationship of distributed audiences and performers, the context of their locations, and the means by which these relationships might be questioned through the use of fictional and computer generated realities as modifiable components of the performance world. The process of iterative development of the XRNP platform continues, to support planned performances, and in the provision of a platform for experimentation. It also seeks to address current limitations, especially that related to the balance and control of light across physical and computer generated realities within the same performance.

Some planned and future directions for the research, include:

- Multiple venue touring of *Opravdoví / The Real Ones* in October, 2019 will also serve to test the "tourability", continued reliability and scalability of the platform. It will provide valuable input as regards any future improvements in design, configuration and operation that are necessary to support larger scale tours;

- In 2020, the establishment of a networked performance research, development and practice environment within an arts university. A 10 Gbps high-performance fibre NREN network connection will be dedicated to the research;

- Refinement in use of virtual environment platforms—such as Unity and Unreal—for the composition of live video and 3D visual components. Especially, as regards the composition issues encountered when blending multiple physical realities and live-rendered virtual environments, where the lighting conditions (physical and virtual) of each reality have to be balanced in the blending process before composited images are projected back into physical or augmented environments;

- Investigating the methods for physical interactions between real and virtual objects across the realities of an XR networked performance;

- Exploration of the opportunity to incorporate machine learning visual systems as a means to improve the artistic possibilities for non-chroma key background removal in live performance: supporting real-time placement of physical objects into other realities of the XR networked performance world.

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# Appendices

## A. Practice Documentation

Videos of the performances that form part of the practice-based research presented in this thesis are provided on the USB memory stick attached to review copies. All video material was taken and produced by the author unless otherwise credited in Appendix B. **Please note that some videos are embargoed and therefore not for general release: they are only provided for viewing by examiners and supervisors.**

### Foundation Projects (in Chapter 2)

- **Here, Not Here, Where** (Here, Not Here, Where? - full performance - 2015 - Ian Biscoe), 640.9MB, 00:18:15.
- **The Bridge to Everywhere: 234** (Bridge to Everywhere 234 - full performance - 2016 - Ian Biscoe.wmv), 655.4MB, 00:19:24.

### Contributory Projects (in Chapter 2)

- **Online Orchestra** (Online Orchestra - highlights - 2015 - Ian Biscoe.mp4), 24.7MB, 00:01:17.
- **Similarities** (Similarities - full performance - 2017 - Ian Biscoe.mp4), 474.2MB, 00:16.14.
- **ReTransmission** (ReTransmission - full performance - 2017 - Ian Biscoe.mp4), 128.8MB, 00:02:15.

### Core Framework Projects (in Chapter 4)

- **Longing for the Impossible** (Longing for the Impossible - full performance - 2017 - Ian Biscoe.mp4), 8.5GB, 00:50:48.
- **The Spaces Within** (The Spaces Within - highlights - 2018 - Ian Biscoe.wmv), 211.8MB, 00:03:54.
- **Opravdoví / The Real Ones (4 videos)**
    - **Pilsen node** (Opravodvi Pilsen node - full performance - 2018 - **EMBARGOED**- Ian Biscoe - **NOT FOR DISTRIBUTION**.mp4), 3.4GB, 00:45:25.
    - **Trutnov node** (Opravdovi Trutnov node - full performance - 2018 - **EMBARGOED** - Ian Biscoe - **NOT FOR DISTRIBUTION**.mp4), 2.8GB, 00:45:57.
    - **Highlights** (Opravdovi - highlights - 2018 - Ian Biscoe.mp4), 837.6MB, 00:05:50.

    - **Promotional Teaser** (Opravodvi - promotional teaser -2018 - Ian Biscoe.mp4), 233.1MB, 00:01:34.
- **A Short Journey into Folded Space** (A Short Journey into Folded Space - 2019 - full performance - Ian Biscoe.mp4), 303.7MB, 00:18:20.

## B. Performance Credits

### Here, Not Here, Where? (2015)

(London - Manchester - Falmouth)

**Producer, Visual Artist & Systems Engineer**: Ian Biscoe
**Choreographer/Dancer**: Margherita Bergamo
**Dancers**: Ina and Tiia Veneranta
**Falmouth Technical Operations**: Dan Thompson and Josh Butcher, Joint Effort Studios
**Manchester Technical Operations**: Jason Crouch
**Floating Surface Fabrication**: Dom Allen (DAW Electronics)
**Sound Recordings**: David Prior

**Funded by:** This project was partly supported with funding from Janet/Jisc.

**Premiere**: 4th May 2015, Royal College of Music and remote venues: Falmouth University and Contact Theatre, Manchester.

### Online Orchestra(2015)

(Truro – Mullion – Isles of Scilly – Falmouth)

**Principal Investigator**: Dr Michael Rofe -
**Co-Investigator, Performance**: Dr Jon Hargreaves -
**Co-Investigator, Composition**: Professor John Pickard -
**Co-Investigator, Technology**: Dr David Prior -
**Researcher, Composition**: Jim Aitchison -
**Researcher, Technology**: Ian Biscoe
**Researcher, Experience Design**: Erik Geelhoed
**Researcher, Composition and Technology**: Dr Federico Reuben
**Researcher, Performance**: Andrea Rushton
**Researcher, Technology**: Dr Philip Reeder

**Funded by:** The Arts and Humanities Research Council (AHRC).

**Premiere:** 12th July 2015, Truro Cathedral (Strings, Choir, Percussion), Mullion School (Brass), Five Islands School on the Isles of Scilly (Flutes) and the conductor John Hargreaves at Falmouth University.

## Bridge to Everywhere: 234 (2016)

(Miami Beach – Miami - Havana)

**Producer, Visual Artist & Systems Engineer**: Ian Biscoe
**Choreographer & Artistic Adviser**: Jana Bitterova
**Performers**: Miami dancers – Liony Garcia, Alejandro Ransoli, Samantha Pazos, Ivonne Batanero; Havana dancers – Rosario Cardenas Company (Claudia Lorena Rodríguez, Yanet Garau Rodríguez, Daniel Belcourt Valdés, Luis Angel Delgado Gómez)
**Music**: drummers – Dennys Papacho Savon, Eduardo Rodriguez, additional music by Nacional Electrónica and Andrew Yeomanson / Spam Allstars
**Technical team of the New World Symphony**: Isis Blanco (Lighting), Eventz Paul (Sound/Video), Kristina Villaverde (Technical Director)
**Technical & production support in Havana**: Marcel Márquez Martínez, Laura Araño Arencibia

**Supported by**: New World Symphony, Miami Light Project, Compañía Rosario Cárdenas, Florida International University, Manana Cuba, CopperBridge Foundation, Falmouth University, Jisc/JaNet, Network Performing Arts Production Workshop, Polycom, Verity Partners, Latin Percussion, Inc., Gon Bops.

**Premiere**: 22nd March 2016, New World Center in Miami Beach, Florida and remote locations Miami Lights Project and Havana, Cuba.

## Longing for the Impossible for the Moment it is Real (2017)

(Copenhagen – London – Barcelona)

**Director, Scenographer, Visual Artist and Lighting Designer**: Ian Biscoe
**Producer**: Thomas Solak
**Networked Choreographer/Artistic Adviser**: Jana Bitterova
**Composers**: Esben Nordborg Møller, Xavier Bonfil, Anna Nikolova, James Black, Rob Durnin
**Composer Coordination**: Niels Rosing-Schow
**Musicians**: Kalle Hakosalo, Cecilie Emtoft, Martyna Kulpińska, Marcus Mukherjee, Daniel Sledzinski, Caitriona Finnegan, Anne-Kristine Skov Vognsen, Feargal MostynWilliams, Henriette Poos, Anna Nikolova, James Black, Xavier Bonfil
**Dancers/Choreographers**: Marie Lykkemark Simonsen, Georgia Kapodistria, Indrek Kornel, Bruno Ramri, Irene García, Elia Genis
**Vocal Coordinators**: Ann Somerville, Eva Hess Thaysen
**Networked Technical Partners**: Maria Isabel Gandia Carriedo, Tania Lisboa
**Audio, Video & Network Technicians**: Jesper Andersen, Peter Barnow, Juan Bayona, Jonas Krossli, Javier Iglesias, Pedro Lorente, Toni Lucea, Weronika Wierzba, Casper Augustenborg

**Supported by**: Royal Danish Academy of Music, Copenhagen; The Danish National School of Performing Arts, Copenhagen; MACBA, Barcelona; Institut del Teatre, Barcelona; Institut de Cultura de l'Ajuntament de Barcelona; CSUC, Barcelona; Royal College of Music, London; Studio Biscoe, UK; DeiC, Denmark.

**Premiere**: 9th March 2017, Royal Danish Academy of Music, Copenhagen and remote location: MACBA, Barcelona and Royal College of Music, London.

## Similarities (2017)

(Copenhagen – Miami – Barcelona – Prague)

**Artistic Director & Choreographer**: Jana Bitterová
**Editor & System Engineer**: Ian Biscoe
**Network Solutions**: CESNET
**Musicians**: Unlimited Trio

**Copenhagen – The Royal Danish Academy of Music**
**Performer/Choreographer**: Jana Bitterová
**Camera**: Sybilla Tuxen
**Technical Team**: Sven Ubik, Ian Biscoe, Thomas Solak

**Miami – The New World Symphony**
**Performer/Choreographer**: Jocelyn Perez
**Camera**: David Marin
**Technical Team**: John Henry Dale, Justin Trieger

**Barcelona – MACBA**
Performance/Choreographer: Rosa Sanchez – Konic Thtr
**Visuals**: Alain Baumann
**Camera**: Adolf Alcañiz
**Network coordination**: M. Isabel Gandia (CSUC)

**Prague – National Technical Library**
**Musicians**: Unlimited Trio (Nikita Krein, Aliaksandr Yasinski, Ilya Blackwedge)
**Camera**: Vojtěch Votýpka
**Prague video production**: Pavel Pečiva
**Technical Team**: Sven Ubik, Jiří Navrátil, Martin Kolbe, Jakub Halák, Jiří Melnikov, Jiří Kubišta

**Premiere**: 3rd April 2017 in The Royal Danish Academy of Music – Copenhagen and remote locations: The New World Symphony - Miami, MACBA – Barcelona, National Technical Library – Prague.

## ReTransmission (2017)

(Copenhagen)

**Producer, Visual Artist & Systems Engineer**: Ian Biscoe
**Music**: Kalle Hakosalo
**Audio Engineering**: Thomas Solak

**Premiere**: 3rd April 2017, DKDM Copenhagen.

## The Spaces Within (2018)

(Miami)

**Producer, Visual Artist & Systems Engineer**: Ian Biscoe
**Musical Direction:** Roman Yearin, Christopher Robinson
**Music**: Charles Ives: The Unanswered Question, Aaron Copland: Appalachian Spring (excerpts)
**Networked Conductors**: Roman Yearin, Christoper Robinson, Gregory Cardi
**Musicians**: Peiming Lin (Violin 1), Hye Jin Koh (Violin 1), Alex Lee (Violin 1), Margeaux Maloney (Violin 2), Ju Hyung Shin (Violin 2), Kip Reicken (Viola), Jesse Yukimura (Viola), Esther Chae (Cello), Jack Gallahan (Cello), Doug Aliano (Bass), Stephany Kim (Flute), Chloe Turdi (Flute), Johanna Gruskin (Flute), Jesse McCandless (Clarinet), Ansel Norris (Trumpet), Darren Hicks (Bassoon), Michael Linville (Piano).
**Choreographer**: Jana Bitterova
**Dancers:** Ivonne Batanero, Samantha Pazos
**Audio:** Alan Miller, John Henry Dale
**Robot Cameras & Video Tech:** Dan Slentz, Mike Van Roy, Shaun Wright, Bryan Rider,
**Lighting**: Luke Kritzeck
**IT**: Luis Quintero, Andrew Salman
**Technician**: Michael McEvoy
**Special Thanks To**: Justin Trieger, John Kieser
**Photography & Videography**: Studio Biscoe, Justin Trieger, New World Symphony

**Supported by**: New World Symphony

**Premiere**: April 2018, New World Centre, Miami.

## Opravdoví / The Real Ones (2018)

(Pilsen – Trutnov)

**Concept, Direction & Production:** MovementTouch (Bitterová & Biscoe)
**Visual Art, Scenographer, Systems Engineer and Lighting Designer:** Ian Biscoe
**Choreography**: Jana Bitterová in collaboration with performers
**Performers:** Helena Šťávová Ratajová, Roman Zotov-Mikshin
**Music**: George De Decker
**Lighting**: Ian Biscoe
**Costumes:** Jana Bitterová
**Production Assistant:** Zuzana Hájková
**Software Assistant:** Aleš Zemene
**Technicians, Moving Station, Pilsen**: Petr Beránek, Jonáš Špaček, Jan Strnad
**Production, Moving Station, Pilsen:** Eva Kraftová, Roman Černík
Technicians, UFFO, Trutnov: Ondřej Beier, Jiří Kesler, Radek Ježek
Production, UFFO, Trutnov: Zdeněk Fibír

**Supported by**: Nadace Život umělce; Město Trutnov; Královéhradecký kraj; Plzeňský kraj; Kinonekino – Město Planá; UFFO – společenské centrum Trutnova; Moving Station, Plzeň.

**Premiere: 26th September 2018,** Uffo – Trutnov & Moving Station – Pilsen (Czech Republic).

## A Short Journey into Folded Space (2019)

(Birmingham – Barcelona)

**Producer, Visual Artist & Systems Engineer**: Ian Biscoe
**Choreographer and co-producer:** Jana Bitterova
**Co-producer:** Benjamin Goodway – Jisc
**Original music composition:** Anthony Fiumara
**Dancers:** Erica Mulkern, Maitane Sarralde Ussia, Bruno Ramri, Laia Mora, Paula Carmona Jimenez, Margherita Bergamo
**Visual art, scenography and technology:** Studio Biscoe
**Lighting:** Matthew Tyler
**Barcelona network support:** Maria Isabel Gandia Carriedo
**Barcelona audio visual support:** Pedro Lorente Adamuz, Fco Javier Iglesias, Gracia Alicia de Manuel Lozano
**Birmingham network support:** Anthony Ryan
**Birmingham audio visual support:** ICC
**Recording musicians:** AMPA Saxophone Ensemble
**Conductor:** Andreas van Zoelen

**Supported by:** Jisc; Consorci de Serveis Universitaris de Catalunya (CSUC);
Barcelona Museum of Contemporary Art (MACBA); Fundación Épica, Badalona; Academy of Music & Performing Arts (AMPA), Tilburg; Associação Desportiva e Cultural da Raposeira.

**Premiere**: 12th March 2019, ICC, Birmingham and remote location MACBA, Barcelona.