New Approaches in Glass Investment Casting - Creative Practitioners Researching and Innovating in the Field of Digital Fabrication

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Abstract

This paper describes a research project aimed at delivering innovation in a combined 'sphere' of digital fabrication and glass investment casting.

The project has established an entirely new method for creating glass casting moulds directly from three-dimensional computer drawings without the need for a physical mould pattern. The method developed is based on Additive Layer Manufacturing (ALM) technology using a three-dimensional printer, a process commonly known as 'Rapid Tooling' (RT). The method developed has a number of significant advantages compared with conventional investment casting techniques.

The project was instigated as a joint initiative by a glass artist and a designer aiming to explore this research space by combining our tacit knowledge of materials, making processes and digital design technologies

While the paper includes a narrative concerning the development of the moulding process, (including a number of technical details) the central argument is rooted in research/innovation methodology. The project, which is on-going, is being developed an approach based "emergent methodologies" (Bolt 2007), and employs central elements of "reflective practice" (Schon 1983). However, other methodologies, such as empirical testing were also employed during the project. In order to facilitate a way to effectively log the various data from these investigations, we have developed a database template for a 'rich media' research journal. This research tool will be presented in the paper.

Another main argument of the paper is based on our position as creative practitioners undertaking research and innovation in an area that could previously have been seen as the

preserve of specialist engineers or material scientists. Our contention is that this is a position which enables us to contribute with different perspectives, knowledge bases and approaches in the innovation process, and we argue that this is a key part of the foundation for the success of the project.

Key words: Rapid Tooling (RT), Additive Layer Manufacturing (ALM), user innovation, reflective practice, research journal, emergent methodologies.

Introduction / Context

The Researchers' Profile

Central to the argument of this paper is our profile as creative practitioners and the impact this has on the role we have as the main 'actors' in the research/innovation scenario of this project. Consequently it is highly relevant to briefly outline our background as a part of the context for this research.

Matthias' has a long career as a glass artist and university tutor in contemporary craft practice. Jorgensen initially trained as a craft potter before becoming a designer in the ceramic industry. Latterly Jorgensen has focused his practice on academic research into the use of new digital design and fabrication tools but integrates this work within an active creative practice.

The scope of the project (the research aim) emerged out of fairly open-ended technical and creative exploration, gradually becoming more focused in response to test results and discoveries. Although Matthias had experience with the ceramic shell moulding technique, which in large parts was the inspiration for the project, both materials and processes used in trying to solve technical challenges were left 'open to change' in response to the test results. Such an approach could be termed as an 'emergent methodology' - a phrase which has been used to describe the characteristic qualities of practice-based research undertaken by artists and designers (Bolt 2007).

Context – Digital Fabrication And Additive Layer Manufacturing

The field of Additive Layer Manufacturing (ALM), and digital fabrication in general, is currently undergoing rapid development and growth. While these are technologies that artists, designers and other independent practitioners have long explored the *use* of, the technical innovation in this sector has largely been the preserve of the *manufacturer* of the machinery and technology rather than the *users* of it.

However, this situation appears to be changing. A number of pioneering projects have emerged in the last few years which are helping to enable and inspire independent innovators from a wide

range of backgrounds to make an increasingly significant impact on this field.
Of particular significance is the RepRap project from University of Bath lead by Dr Adrian Bowyer (Jones et al. 2011). This project, aimed at exploring kinematic self-reproduction has resulted in the development of a simple and very affordable Rapid Prototyping (RP) machine. The technical principle for the RepRap is very similar to commercial Fused Deposition Modelling (FDM) RP machines produced by Stratasys (Stratasys Inc 2012). These machines all use a heated nozzle to extrude plastic filament (usually ABS plastic) to build parts via the ALM principle. Crucially, RepRap project have made all plans and software code available for everyone to access and use freely as an open-source project (Raymond 1999). As a consequence the RepRap project has been extraordinary successful in enabling individual innovators to operate in the field of digital fabrication. Drawing on this feely available open-source knowledge a fast growing cottage industry has emerged with many individuals developing their own derivative RepRap designs, known as 'Repstraps' (Jones et al. 2011, p.188)

While the RepRap project has been one of the most visible projects in terms of widening the opportunities for independent innovation in digital fabrication, other projects such as the MACH3 (Newfangled Solutions LLC n.d.), Arduino (Arduino n.d.) and Processing (Fry & Reas n.d.) are also contributing with powerful and low cost tools which enable individual innovators to operate in this sector with increased ease.

While taking inspiration from projects such as RepRap, our project concerns a different ALM technology using a powder based 3D printing technology from developed by ZCorporation (ZCorp) (3D Systems n.d.). Our project differs further as it not concerning the manufacture of finished parts, (as is the case with RP) but instead that of 'Rapid Tooling' (RT) concept. Broadly speaking RT is the approach where moulds are made via ALM technologies for use in subsequent manufacturing processes. The RT approach is far less explored than RP, but as a concept holds significant potential as it enables the use of process and material knowledge established in 'conventional' manufacturing processes to be utilised in new contexts.
Apart from this project, glass casting via the RT approach has seen very little exploration and no established procedure or commercial system has so far been established.

Context – Glass Investment Casting

The general process used in glass investment casting has changed little over many decades with most practitioners relying on traditional casting processes based on the use of bulky moulds made of a mixture of plaster and quartz. Heating such moulds requires high levels of energy and the quartz powder used in this method is hazardous if inhaled. Despite these drawbacks, little innovation has taken place in this aspect of glass artefact production.

The few projects which have explored alternative moulding techniques include Thwaites & Seybert (2002) and McCartney (2001), the latter investigated the use of the 'ceramic shell' technique for glass casting – a technique which was originally developed for metal foundry applications. The ceramic shell technique is based on creating moulds by applying a series of refractory layers on a wax mould patterns, using a so called ‘lost wax’ approach, where the mould pattern is removed by a ‘melting’ or ‘burning’ out procedure. The ceramic shell layers are created using a ceramic slurry based on colloidal silica (Silica Sol) dusted with fired, crushed ceramic granulate (Molochite). This creates thin but strong moulds that have significant advantages compared to the conventional glass moulds, particularly lower energy use in the firing process. However, despite these advantages, this technique has to date seen little use. Matthias worked with McCartney on his research and has explored the technique independently in her own creative practice.

Project Narrative

The initial phase of the research was focused on exploring what we had in terms of in-house ALM equipment at our college, which at the time constituted a single Stratasys FDM RP machine. Jorgensen had previously undertaken experiments with the use of FDM RP parts for bronze investment casting with ceramic shell moulds. The process of using ceramic shell with FDM patterns is also based on a ‘lost wax’ approach and is well documented having been developed by other researchers (Winker 2008). However, to our knowledge this process had never been explored with glass as the investment medium and was therefore an obvious starting point for our project.

Figure 1. Initial test with FDM patterns, photos: Jorgensen 2010

We started our investigation with a series of tests with FDM patterns created in ABS plastic. These tests quickly exposed a problem with this particular combination of processes and materials. The issue appeared to stem from the special composition of the ceramic shell coating that is needed for glass casting - a composition which had been developed by McCartney (2001). McCartney established that in order to accommodate glass’ ‘coefficient of thermal expansion’ a modified ceramic shell layer (different from that used in metal casting) had to be used in order to create a ‘softer’ shell that allowed the glass to contract in the cooling phase without developing cracks. We found that this 'softer' shell composition would inevitably develop cracks during burn-out stage of the RP patterns, as this weaker mould shell was simply not strong enough to contain the thermal expansion of the ABS plastic during the heat ramp before the final 'burn out' stage occurred.

While still undertaking the experiments with the FDM parts, we were approached by a sales agent for ZCorp 3D printers. ZCorp's ALM technology is based on building parts by spraying binder on layers of powder, a process which has been developed from two-dimensional inkjet printing technology. While we had little experience with this particular ALM technology, we were aware that the ZCorp 3D printers could work with a number of different powders, both in-organic plaster-based compounds and organic, starch-based materials. The starch-based powder was the initial focus of our interest, as we expected that this material could replace the FDM RP patterns in a lost wax approach, potentially without the problems of the material expanding and cracking the ceramic shell moulds during the heating ramp. Sensing the potential for a sale the agent supplied us with free test parts built from our three-dimensional files so we could test the concept.

Using the starch patterns did resolve the cracking problems which we had experienced with FDM patterns; however the surface of the starch models were of much lower quality than the FDM models. Furthermore, the starch models were also very fragile, making them difficult to handle in the moulding process. These issues were helped to some degree by impregnating the patterns with hot wax, but these initial tests still indicated to us that this approach had limited 'real-life' potential due to the low surface resolution and a lengthy and difficult moulding process.

However, as well as supplying the starch patterns, the ZCorp agent also supplied a small test piece (in the shape of a little vase) which had been created in a new build medium. This Medium, the zp150 powder, had just been launched by the company and featured a very high surface resolution. We processed this small sample packed with glass shards through a standard glass casting cycle. The test piece emerged visually unchanged after the firing, and the glass had melted to a small billet in the base of the vase.

Figure 2. First test with the zp150 powder, photos: Jorgensen 2010

This result indicated that the zp150 build medium had reasonable good heat resistance capabilities. And while not intended for the creation refractory moulds, (but as a general build medium to produce wide range of prototypes of CAD designs) it appeared, indeed, to be perfectly suited to this application.

Encouraged by this result we were keen to proceed with another round of tests with this material, however the moulding concept with these tests had to be altered from the 'lost-wax' approach we had taken with both the FDM and the ZCorp starch mould patterns. With this approach we were effectively printing the mould directly with the 3D printer, thereby eliminating the need for creating a physical mould pattern. The forms for the mould patterns would only be virtual representations in computer modelling software. As previously mentioned, this process is commonly known as 'Rapid Tooling' (RT).

The RT concept is, however, nothing new in terms of ZCorp technology. The company had for a number of years been selling a refractory build medium called ZCast, (3D Systems n.d.), for the creation of moulds for metal investment casting, but the use of this build medium had always remained very limited, perhaps due to a very low surface resolution.

Relaying the result of the glass casting test back to ZCorp agent generated a significant level of interest and the agent agreed to sponsor a further collection of tests created in the zp150 powder. We designed this range of test pieces as 'RT moulds' with wall thicknesses ranging from 2 to 6mm. The forms for these pieces were created as clusters of geometric primitives (cubes, spheres and cones) using the 'Grasshopper' (Davidson 2012) generative scripting facility in Rhino 3D modelling software (Robert McNeel & Associates 2012).

Figure 3. RT moulds printed in the zp150 material, photo: Jorgensen 2010

Casting glass in these test RT moulds, exposed serious limitations with the concept. We discovered that while the zp150 material had refractory capabilities, the material lost much of its strength during the firing and the moulds would fracture and collapse under the weight and pressure of the molten glass. We rationalized that the reason for the success of the initial test with the vase was likely to be the very small size of the piece and geometric integrity of the round vase form. From this series of tests we also discovered that the zp150 would shrink about 5 persent when exposed to the temperatures needed for glass casting (750 – 800ºc).

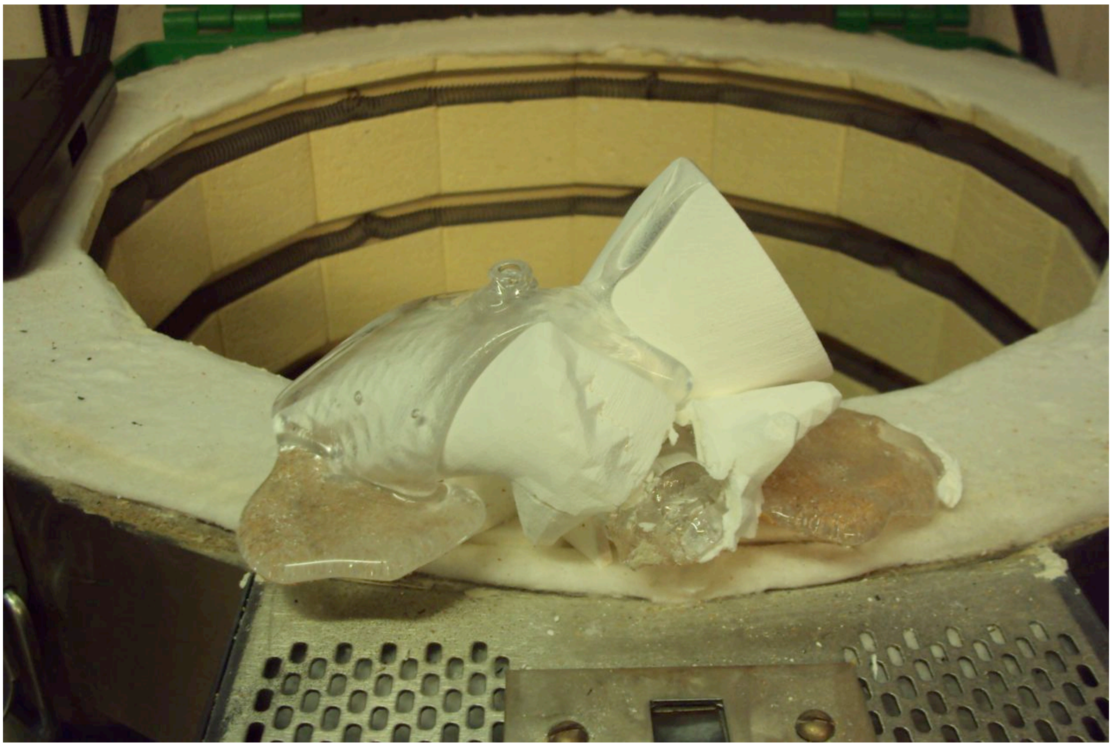

Figure 4. A failed test cast exposing the weakness of the zp150 material and the challenges ahead for our investigation, photo: Jorgensen 2010

While this cycle of tests exposed some distinctive limitation with the concept, there were also a number of 'indicators' which encouraged us to continue with this particular line of exploration. Firstly, while the zp150 material only appeared to have had limited structural integrity during the firing process, we expected that the material's refractory capabilities could be enhanced with coatings, infiltrates or other methods. Secondly, glass cast against the zp150 material seemed to have a better surface quality compared to that achieved with a conventional plaster/quartz mould. Furthermore, we discovered that RT moulds made in the zp150 material would dissolve completely when immersed in water, making de-moulding much easier than with conventional moulds. Equally, if we could make the standard zp150 powder work for this RT process, the versatility of a ZCorp 3D printer unit would be greatly enhanced, as a single printer could be used for both prototyping (RP) and fabrication (RT) without a change of the printing powder being required (using build mediums such as starch or ZCast, requires a complete clean out of the machine, which in practice means that users are unlikely to change build medium very often).

In many ways this stage of project could be characterised as the point where our work changed from a more open-ended inquiry to a much more focused investigation. Our initial explorative inquiry had served as the provider of the core concept for an innovation in glass casting, but also exposed the technical challenges we had to overcome to establish this innovation.

We continued with further tests, trying various ways of strengthening the moulds with outer coatings, drawing mainly on Matthias' knowledge of the ceramic shell technique. While still not establishing ideal methods, some of these experiments did result in some fairly successful glass casts.

We presented these casts along with a description our research at the Time Compression Technology (TCT) 2010 show in Coventry (the TCT show is one of the main annual RP and ALM industry events in Europe).

During the show we met with ZCorp's chief executive, John Kawola, who saw good business potential in our approach and offered to sponsor a ZCorp 310 printer to our project to facilitate further development of concept.

We took delivery of the machine in early 2011, which enable us to ramp up our investigation significantly as we were now able to print our own test moulds and experiment freely with the technology.

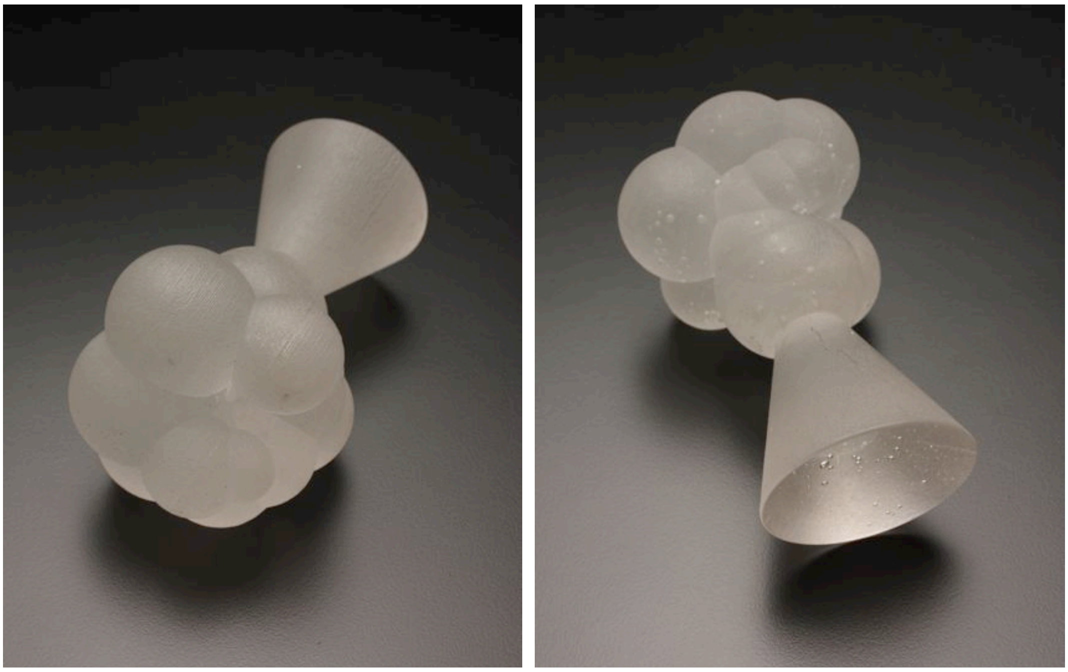

Figure 5. Successful glass cast, presented at the 2010 TCT show, photo: Jorgensen 2010

While it had been a relatively easy process to establish the core concept and create some reasonably successful test casts with simple small forms, developing a robust method which could be used with a wide range of geometries and sizes proved far more challenging. Strengthening the zp150 with a ceramic shell coating was an initial obvious way to resolve the zp150 material's loss of strength during the firing process. But in this approach the shrinkage rate of the zp150 material posed a challenge, as a standard ceramic shell coating have virtually no shrinkage when exposed to glass firing temperatures. This incompatibility resulted in a gap between the inner zp150 layer and the outer ceramic shell coating. While overall the moulds would still remain structurally sound during the firing, this gap would cause small cracks in the surface of the zp150 inner layer, as it was not fully supported by the outer ceramic shell coating. This shrinkage incompatibility issue remained the greatest challenge in the research and to the success of our concept. Consequently, solving this issue became the main focus for the next stage of our research.

While we were fairly certain that the zp150 powder largely consisted of a variant of 'Plaster of Paris' (plaster), the exact material composition was unknown to us. Tests we undertook confirmed that the characteristics of the powder were broadly similar to that of plaster, but when we fired the material we observed that it had an unusual high shrinkage rate. An obvious step was to ask ZCorp to supply us with the composition details of the zp150 powder, so we could identify which compound(s) caused this shrinkage. However, the company made it clear that while they were happy to support our research, the powder composition remained a closely guarded industrial secret, as the company's business model is based on the sale of consumables rather than the 3D printer hardware.

Without the complete knowledge of the zp150 powder's composition we had to find a way to reduce or eliminate the shrinkage of this compound, potentially by the use of infiltrates or coatings.

In an attempt to achieve this objective we undertook a series of material tests and experiments. We were partly successful in this task, discovering ways of reducing the shrinkage rate to 2 - 3%. But in order to make this 'inner' mould layer compatible with subsequent strengthening layers, we still had to find or develop a refractory coating with a compatible shrinkage rate.

In this search we undertook tests of a wide range of refractory materials and compounds. In several cases we found materials that would have the required shrinkage rate, but only during the drying stage rather than the firing stage. For each set of tests we had to develop new approaches and 'theories' about how we could succeed in the task. We considered that the solution could be achieved in a number of ways, either based on mineral compounds, or alternatively achieved by an organic / mineral mixture - where shrinkage would be caused by the organic matter 'burning out' during the firing. A solution could also potentially be provided (or partly provided) by a particular way or sequence of applying certain materials.

Throughout the process of experimenting and testing we frequently questioned ourselves; if we, as creative practitioners, had a suitable background and training to undertake such research? Or would professionals, such as engineers or material scientists, who have far greater theoretical scientific knowledge to draw on likely to be more successful in this innovation scenario?

During parts of the investigation we did seek assistance from a science-based team at a neighbouring university, who carried out analysis of some of the compounds. While very approachable and helpful we found that the scientists' theoretical knowledge to be so specialized that it was difficult to draw solutions from their expertise to our particular challenge as the task appeared to span several knowledge spheres including: mineralogy, silicate and polymer chemistry, all crucially, applied to practice. Essentially the solution we were aiming for had to be a process that would extend or improve on the existing moulding techniques for glass casting, and theoretical knowledge was only relevant if it could lead to a practical process for this application.

To compensate for our limited theoretical (or scientific) knowledge, we drew heavily on our practical knowledge of materials and processes - a comprehensive 'library' of tacit knowledge which we had built up over years of creative practice. Just like Schon's (1983) descriptions of how practitioners would construct their *own* theories in order to respond to unfamiliar situations and challenges (and specifically within the context of these situations) we too, continued to develop our own hypotheses and theories in response to the 'feedback' we had from our practical tests, or as Schon's describes it: *"a reflective conversation with the situation"* (1983).
In this exploration, our limited knowledge of scientific theories may also have given us other advantages as innovators, as through our 'ignorance' we were perhaps more likely to explore a wider range of solutions and materials to solve the challenges that we encountered. Our investigation included experiments with a diverse range of materials including: PVA glue, corn flour, fishing tackle, plastic bags, soil additives, paints, as well as a wide range of minerals and compounds.
Many of the tests were complete failures or lead to 'dead-ends' but others did provide unexpected and promising outcomes, and now (after 2 years of project development) we finally have achieved a combination of materials and processes which is very close to a highly promising RT method.

The method we have established enables glass practitioners to create a thin 'inner skin' moulds via a ZPrinter using the standard zp150 powder, with virtual forms created with 3D digital drawings. Shapes can also be recorded via 3D scanning existing objects and using these files as the virtual mould patterns. The RT moulds are then post-processed using a number of coatings and processes to create strong, but also thin refractory glass moulds.
For practitioners who may not have their own ZPrinter (which is highly likely to be a vast majority) ALM bureaus exists which will print on demand.

The list of the potential advantages of the RT glass moulding technique compared with existing methods includes:

» New creative opportunities though the use of 3D software to create forms
» Very easy transition from virtual files to glass artefacts
» Significantly reduced moulding material use
» Reduced energy use through lower temperature and shorter firings
» Easier and safer de-moulding
» Safer materials
» Better glass surface quality (in some cases)

The potential advantages of the process in the context of ALM/ZCorp technology includes:

» Easy transition from RP to RT
» Works with all current ZCorp 3D printers - no need for retro fit
» Utilizes the zp150 standard building medium - no need for specialist binder or build medium
» Applications beyond glass, such as metal alloy investment casting
» Very low cost materials

We are still in the process of undertaking usability tests of the process, and have not yet released the method for general use. Equally, we are currently considering whether to exploit the process commercially via protected IP or disseminate the knowledge to other practitioners via an open-source or Creative Commons[1] licence, thereby enabling other practitioners to build on our research and improve the method that we have developed.

Recording the Research Data

Recording this research project presented a particular issue in terms of logging a variety of data, not only the results from empirical material tests (generally as numerical data) but also the recording of our ongoing reflections on the research. The process of reflection is to us a particularly important aspect to 'capture', as we consider it to be a key aspect of the methodology of our practice-based research.

Initially the research was recorded through paper forms only, with 'boxes' for recording numerical details of shrinkage rates, mixture compositions etc. While we did include spaces to record comments and reflections, it was challenging to facilitate a way which combined these records effectively. Comments and notes became increasingly 'scribbled' all over the forms and we had to conclude that this approach was a largely unsuccessful way of recording (and retrieving) our reflections on our practice.
Equally, throughout the project we carried out extensive photographic recoding of test results (and the research process in general) and looked for ways of 'linking' these digital images with the tests notes and reflections. We recognise the potential of a well functioning research journal as highlighted by Gray & Malins (2004), and in an attempt to find a format to compile all the information we gathered into complete journal entries we experimented with the use of a private blog. However, we also recognise the importance of recording both the empirical data and reflections as 'close to the source' as possible, but the 'messy' environment of the plaster workshop where we undertake most of our research is badly suited for computer laptop use, and therefore limits the use of the blog to record the data. The environment forced us to use an office away from the practical research to logg the recordings, but we found this arrangement to be time consuming and 'too separated' from the research 'coalface', and as a consequence our use of the blog soon petered out.

[1] http://creativecommons.org/

The Development of a Rich Media Research Journal

As described above we struggled throughout large parts of the project to find a good format for a research journal which could facilitate a comprehensive capture of all the various data sources in an easy to use format and, crucially, within the actual research environment.
However, recently we have been exploring a method that is showing great promise in fulfilling this need. The method is based on using the 'Filemaker Pro 12' (FileMaker, Inc 2013) database building software.
Filemaker Pro is by no means a new application, and using such database software to record and organise research is also nothing new, but what presents new opportunities with this latest release of the software is the linked IOS app: 'Filemaker GO' (Apple Inc 2012). This free app enables the use of databases developed with the 'Pro' version of the software on iPhones and iPads (but not via Android devises).
For us a critical aspect of the software is that it enables the creation of media "container-fields" within a database entry template. Such fields can be used to record a wide range of rich media such as images, movies, audio or even 'finger drawn' sketches. This mean that we can now record our reflections as audio (or video), alongside the numerical data we collect from the tests results, 'data' which can be further backed up by images, sketches and movies.
An equally important feature is that fields for textual input (recorded either via the on screen keyboard or the voice-to-text software SIRI) will expand to take unlimited number of words. Consequently reflections recorded this way can have an unlimited word count without 'spoiling' the template structure of the database entry - unlike the paper-based forms we first employed.

In developing this approach we took inspiration from the notion of the "thick description" – a concept first defined by Geertz (1973) in the field of anthropology. It is a way of recording multilayered data to explain not only central observations but also the wider context of these observations. In the same way our aim is to establish easy-to-use templates that enable a multilayer recording of the research using rich media input.

The use of an iPad (or iPhone) as the input devise is also a critical aspect of the usability of this research journal system. These devises are very easy to 'have to hand' at all times during the research, and with a protective case can be used in 'messy' environments - such as our plaster workshop.

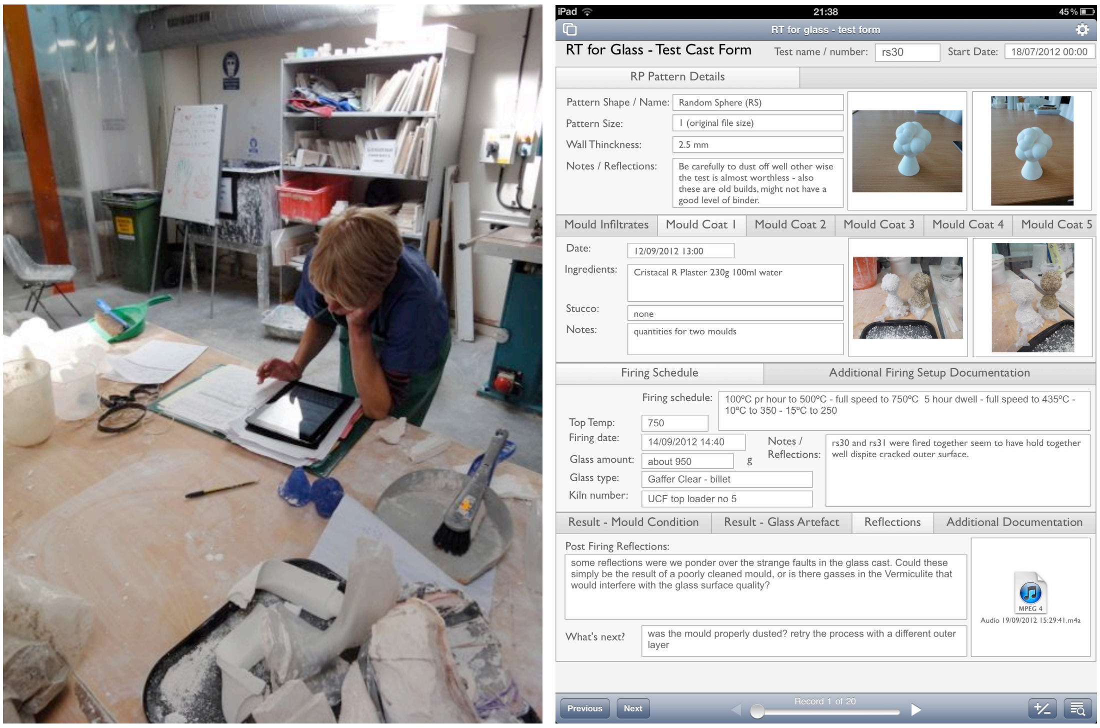

Figure 6. Using our rich media research journal via an iPad (with a screen shot of an journal entry on the left), photo: Jorgensen 2010

Conclusion

It is important to highlight that this project is still only in the initial 'invention' phase of a complete innovation sequence (the commercialisation or dissemination phase is still to come). However, even at this early stage of the innovation sequence we believe that some conclusions can be drawn.

To our knowledge this project is the only university research project which ZCorp has ever sponsored, and we consider it to be significant that the company should choose to support a project from an art college rather than one from a science based university for such sponsorship. We believe that this provides indicative evidence of the value of creative practitioners undertaking research and innovation using emergent methodologies.

Many authors on innovation highlight the importance of external or independent 'actors' in the innovation scenario, or as Pursell states: "almost per definition new products, processes and attitudes must come from outside the status quo" (1994, p.38).
As creative practitioners (and not engineers of digital fabrication equipment) we consider that our 'outsider' knowledge played a key part in the research and innovation process. Such a notion is also highlighted by authors on innovation theory such as Smith (2005). Equally, this research has throughout the project been guided by our needs and knowledge as *users* of technology. Such work is described by Von Hippel (2005) as "user innovation" – a concept which appears to be

increasingly evident particular in the field of digital fabrication and we believe that projects like ours will increasingly be the source of innovation in this field.

Finally, it is worth considering that in some ways this project concerns two innovations. While the primary innovation is focussed on the glass moulding method, the development of the Filemaker Pro database template and the method of using rich media to combine quantitative research data with reflective practice, might also constitute an innovation in its own right. This method, which was created as a response to the specific needs for recording the data of the main project, we believe could be significant tool to assist the work of other practitioner-researchers, and thereby contribute to increased use of the emergent methodologies. Methodologies which we consider to have played such a significant part in the success of our project.

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