UNDRAWABLE ARCHITECTURE

Digital workflows for the conservation of heritage buildings and the discovery of digital tectonic

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Abstract. This paper presents a data centric perspective to historical building conservation using digital media. In particular we explore a workflow based on large volumes digital data acquired via 3D scanning technology, virtual restoration using 3D modelling and physical artefact reconstruction using 3D printing technology. We offer an alternative perspective in contrast to the prevalent approach of reverse engineering or geometric rationalization via parametric design technology; highlight the research and design opportunities as well as the challenges of the approach.

Keywords. Digital conservation; 3D scanning; rapid prototyping.

1. Introduction

Approximately every one or two decades, historical buildings require conservation work. Unlike practices in the West (Chung, 2005) where material preservation is paramount, it is common in Asia for large parts of buildings to be periodically disassembled and reproduced. The Ise Shrine in Japan, perhaps one of the most famous examples of this tradition, is rebuilt every twenty years (Adams, 1998) while the Temple of Heaven in Beijing, a world heritage monument (UNESCO, 1998), underwent disassembly, restoration and reassembly in 1971, 1991 and 2005. The long tradition of conservation by reconstruction has both technical, as well as cultural significance: prevalent use of organic material, for example timber in contrast to masonry, paired with the regional climatic conditions means that historical structures require regular maintenance and replacement of damaged building components. By coincidence or necessity the process is also aligned with a very different philosophical understanding of historical value (Wells, 2007) which does not primarily interface with material and form but rather time and place.
Reconstruction does not merely preserve the physical embodiment of historical artefacts but also the artisan processes and technics of their creation (Figure 1).

Introducing digital methods in a domain we characterize as the realm of undrawable architecture is fascinating in as much as challenging. Undrawable architecture underpins a process of tacit tectonic knowledge passed along generations which was never formalized, and a product of artisan craftwork of phenomenal complexity that was manually re-produced but never rationalized. While it is possible to geometrically model historical artefacts using conventional computer aided design methods it is foreseeable how impractical an enterprise as such may be. Conventional digital methods and tools adhere to a reductionist paradigm: we use computer models as accurate yet coarse but nevertheless effective abstractions of reality. We work analytically using Cartesian constructs but we are aware that we can only physically construct approximations thereof. This is not a property of digital media but rather relevant to the notion of rationality or modernity in design (Alexander, 1964). However when confronted with artefacts governed by radically different regimes of thought and modes of production we may naturally raise questions on the efficacy of rational methods: it is perhaps no longer only a question of feasibility, whether or not we can effectively reverse engineer craftwork, but also one of whether it fundamentally makes sense to do so. The end results of analytical modelling would also have been most likely problematic as for instance specifying building works via linearized representations of physical artefacts that contain not even a single straight line, hints not only of the difficulties with the process but also those of the products.

Figure 1. Top: The Yueh Hai Ching temple in Singapore prior to 2011 restoration, Bottom: Damaged gold gilded timber ornamental bracket being replicated on site by craftsman.
Instead, we approached digital conservation from a data oriented perspective, operating on large sets of raw information produced and processed by scanning, computing and prototyping technologies. The decision for taking a hyper-realistic approach, that is a paradigm where the more data the merrier, offers us an opportunity to examine an alternative mode of digital praxis where focus is shifted away from expressing and retaining well-defined explicit relational design states of geometry to an arena of big data and flows.

The proliferation of scanning and visualization technologies during the past two decades has expanded the scope of cultural heritage to realm of Virtual Heritage which broadened the discourse of the experience and interpretation of culture places and artefacts (Affleck and Kvan, 2005; Rahaman and Tan, 2009). The recent introduction of digital fabrication technologies in architecture (Schodek et al., 2004; Kolarevic and Klinger, 2008) has the potential of enriching the discourse through the study of the physical dimension of cultural heritage which we attribute as the digital heritage tectonics. The notion of digital tectonics, a methodology of integrating design software with traditional construction methods, (Beesley and Seebohm, 2000) is extended here by establishing conduits between prior and posterior physical conditions via digital sensing, processing and making. We are interested in the implications of digital prototyping and fabrication of historical artefacts as they offer the ground for technological research as well as philosophical debate: Can we foresee future replacement of historical artefacts by digital prototypes? What if we record and digitally reproduce crafting processes, not merely forms, by CNC machines? We note that when reconstruction is integral to conservation, due to practical urgent reasons for doing so, it is critical to accept and embrace the importance of reinterpretation. Reinterpretation in almost certainly unavoidable as building components are recreated by different craftsmen using affine techniques and based on partial remains or photographic evidence. Questions of authenticity have been and are still extensively debated by international heritage conservation organizations such as ICOMOS and UNESCO (Lemaire and Stovel, 1994; Engelhardt and Rogers, 2005). In this respect our effort cannot aim at efficient reproduction of frozen-in-time artefacts but extends to contributing to the debate of reinterpretation and fostering knowledge acquisition through observing and making experiences of architectural heritage.

In this paper we focus on the development of a workflow from scanning-to-fabrication. We present the opportunities and challenges of digital conservation through the case study of an on-going historical building restoration program; namely, the Yueh Hai Ching temple situated at the centre of Singapore’s business district. The extant building, built between 1895 and 1896, is being restored since 2011 having last undergone a program of conservation in 1996. Our paper offers a starting point for practitioners and educators in design technology and historical
building conservation sharing a critical assessment of means and ends analysis of relevant CAD methods.

2. Relevant Work

Architectural conservation of built heritage overlaps with engineering, topography, archaeology, and computer science. Reverse engineering and redesign is relevant in the reproduction of objects by analysis of physical artefacts as well as in process-knowledge acquisition, which may lead to future design improvements (Otto and Wood, 2000).

Reverse engineering methods, such as shape rationalization, using geometric fitting, are employed for the reproduction of industrial design objects which are the result of already rational geometry and manufacturing methods. In this respect, archaeology is certainly closer to heritage conservation in the nature of the evidence under study as its artefacts are results of traditional arts and crafts. Topography and land survey offer precursors of contemporary data acquisition methods such as terrestrial scanning instruments descend from topographic survey techniques (Bohler, 2006; Georgopoulos et al., 2009). Computer graphics made impact in heritage conservation by the introduction of technologies for the study of heritage with focus on the visual aspects of the objects under investigation. Geometric surface reconstruction (Hoppe et al., 1992), point set registration (Desl and McKey, 1992) and visualization of large data sets (Gobbetti and Marton, 2004) have been extensively investigated during the past decades. Notably the Digital Michelangelo Project (Levoy, 1992) offers a pioneering study of 3D sensing technologies for the geometric reconstruction of historical artwork. Architecture has a long tradition of historical study and building conservation and has followed closely the advancements of digital design technologies. Notable as well as one of the early examples of digital conservation is the study of the Segrada Familia Cathedral by Mark Burry investigating the tectonic dimensions of Antoni Gaudi’s architecture using parametric technologies (Burry, 1992).

Our study is situated at the intersection of architectural history and architectural computation in the light of by-now widely available mass sensing, parallel computing and rapid prototyping technologies. Digital tectonic also denotes an interest in the discovery of the interplay between material, form and the formation process in historical architectural artefacts.

3. Workflow

The conventional workflow of building conservation involves efforts in archival research, documentation and planning. Construction entails a process of careful
disassembly, analysis and evaluation of damages, reproduction of components and final reassembly. As traditional crafts are fading due to modernity certain building parts are often shipped to China where they are recreated from fragments and/or alternatively craftsmen travel on site for extended periods of time. Our workflow will inevitably replace, while not substitute, this process. For the time being we aim at augmenting conservation practices by easing documentation and planning at the front-end, while potentially assisting in end-production, for instance shipping replicas in their original condition instead of damaged components. Our workflow is comprised of three segments: (a) Acquisition of data, (c) Computer modelling and (c) Digital fabrication and rapid prototyping (Figure 2).

Architectural artefacts span a wide range of scales, from hundreds of meters to fractions of a millimetre. Unfortunately, there exists no technology capable of addressing the entire range without shortcomings (Boehler and Marbs, 2002). We thus defined multiple levels of resolution (Guidi et al., 2009) for data acquisition: Building Scale: using long-range terrestrial light detection and ranging technology (LIDAR), generating registered point-clouds, and Component Scale: using near-range structured light equipment generating photo texture mapped meshes.

Our attempts to operate on massive data sets using architectural computer aided design software was utterly unsuccessful because they were not designed for

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**Workflow Augmentation Opportunities**

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<tr>
<th>Archival Research</th>
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<td>Drawing Generation</td>
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<td>Disassembly</td>
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<tr>
<td>Storage, Shipment</td>
<td>On / Off Site Works</td>
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<td>Database Indexing</td>
<td>Digital Fabrication</td>
<td>and Documentation</td>
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**Scanning»Modelling»Prototyping**

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<tr>
<td>Mesh Point Clouds and Merge Mesh Fragments</td>
<td>Close Holes, Remove Bad Faces, Correct Edges</td>
<td>Create Various Resolutions</td>
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<tr>
<td></td>
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<td>Add Thickness, Store Data</td>
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</tbody>
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Figure 2. Diagram of macro-scale workflow augmentation opportunities and micro-scale workflow actions from scanning, to digital processing and physical or visual prototyping.
such purposes in terms of both memory management and available editing tools. Instead we used a range of specialty commercial, open source and in-house developed tools. At the point of publication we are the alpha stages in the development of “Digital Heritage”, an extension of a commercial CAD application (Figure 3) to mitigate the aforementioned obstacles and enable architectural historians and domain experts to access the data under a familiar computing environment. We are able to load very large sets by employing view optimizations, we offer selection filters to clean up point clouds, prototyping tools for producing 3D printing ready files and exporting methods for storing data in optimized format for offline and online applications. Digital Heritage also includes a web application viewer, using experimental graphics acceleration technology and dynamically loads point cloud and meshes via progressive streaming of compressed geometry.

Given the convoluted workflow requiring investment in know-how, labor-time and expenditures in computing and scanning power, a reasonable question arises as per the cost-benefit of digital conservation. These concerns are valid but we should expect that, if technology advances at the current rate, software and hardware will become affordable in terms of cost and learning effort. However the inquiry as per what can we really do to demonstrate the unique capabilities in big-data in contrast to conventional reverse engineering rationalization is a research

*Figure 3. Left: Digital Heritage (alpha) extension for Rhinoceros 3D CAD. Right: online point cloud and mesh web-application viewer available at: http://ds1.jeneratiff.com.*
question. Our notion of undrawable architecture raises a question about production: within our industrial manufacturing regimes of production undrawable also means un-reproducible as no conventional fabrication method can effectively substitute craftwork without rationalization and/or the offsetting premise of mass-production. However, digital methods of production can exactly fit in those constraints. Our proposition is simple: we can bridge directly between computer sensing to digital manufacture letting digital input talk to digital output. Scanners, desktop computers, 3D printers or CNC machines are oblivious to the volume of information but more sensitive to format. We thus have an uncanny circumstance where historical craft meets contemporary mass-customization.

4. The Dragon Wall

We investigated the feasibility of 3D printing for real scale artifact reproduction. The granite dragon carving mounted on the wall of the Yueh Hai Ching temple during its last restoration program in 1996 was removed in order to restore the wall to its original ceramic shards ornamentation. This provided the research team the opportunity to carry out trial experiments without the need to take precautionary measures necessary with historic artefacts. Geometrically the wall is highly complex featuring deeply concave and undercut surfaces with impressive fine details given its extremely hard material (Figure 4). Scanning required only a half-day session producing circa 10GB of data. Processing amounted to a week’s effort generating geometry at various resolutions: 3 million polygons per square metre for archival, 700 thousand for fabrication / prototyping, and 64 thousand for visualization (Figure 4).

We targeted plaster powder 3D printing for post-processing workability even though our polymer printer produced more accurate and durable parts. As the wall

Figure 4. Left: Granite dragon wall carving removed from the Yueh Hai Ching temple. Right: high-resolution mesh geometry generated by structured light 3D scanning technology.
dimensions exceed the printer’s build volume we segmented the model into 3D tiles and embedded fixing sockets in order to prop the dragon off a planar substrate. 71 tiles were produced in a 30-day period of 20-hour printing cycles; each print contained two to three parts. Cyanoacrylate adhesives were used to reinforce the weak plaster material and allow the supporting props to thread directly into the printed sockets. Post-processing and assembly required three weeks of work (Figure 5).

We produced a fairly impressive one-to-one replica (1.7x1.2x0.2m) of the original solid granite wall in an almost egg-shell thin structure (3mm) with minimum material use and weight (50Kg). We feel that the emergence of a hybrid material grain merging hints of the original stone carving tool, traces of mesh triangulation and the layered 3D printing process presents an interesting perspective towards re-interpretative reproduction. Interestingly, our assumptions about prototyping material weakness were unfounded. The final plaster-CA composite was surprisingly resilient to the degree that we could have produced a self-supporting thin-skin wall without additional supports. The printing technology used produced dimensional errors both after printing and in excess after infiltration due to chemical thermal expansions. Additional finishing was required to mitigate visible errors. Printing time was the bottleneck in the process and with currently available technology the only way forward is performing segmentation optimization for minimizing effective print volumes. The approximate cost for the wall was circa 6,000 SGD which while it is not dismissible it is also not unreasonable given the size and complexity of the prototype.

5. Conclusions

In conclusion we presented an outline for a digital workflow with big-data for architectural historical conservation with focus on digital fabrication. Our study
offers an overview and highlights potential and challenges involved. As we are building methods and techniques from the ground up, we are still at early stages in the discovery of the digital tectonic: the core principles of the arts and craft in heritage buildings. Our future goal is to understand the interplay of individual parts and the whole, the structural and material domain of historical buildings and the reproduction of carpentry and masonry components using CNC technology. Moreover as part of our curriculum we plan to offer joint courses between architectural history and technology where students will have the opportunity to engage with architectural heritage through both literature review but also hands-on experiences with digital recording and fabrication.

Insofar, lessons learned from historical building conservation and digital design methodology we observe there is a different kind of architectural complexity contrasting historical and contemporary form. While our digital techniques are flexible, expressive and forgiving, their results are relatively straightforward, predictable and thoroughly rational. After-all, the genotype of digital form is an excruciatingly descriptive process which invariably surfaces into the object itself. This is unlike historical form, which while it is governed by principle, its formal expression is artisanal, improvisational and less divisible due perhaps to the stronger bonds between geometry, material and craft. It is arguable to what degree those processes and products are relevant in contemporary design praxis, however the progressively shorter spans between design and production via digital fabrication brings interesting potential for the near future. In one or two decades when 3D scanning will be performed using mobile phones and prototypes may be 3D print at home it is also arguable that we will think and make the same way we are today.

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References


