Re-engineering Watt: a case study and best practice recommendations for 3D colour laser scans and 3D printing in museum artefact documentation

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ABSTRACT Mirroring the adoption of photography as the new media of the 1800s is the growing availability and early adoption of 3D imaging as a service for museum documentation. This short paper considers the opportunities for 3D imaging and printing systems within a museum or conservation workflow and comments on the best practice that needs to be developed in order to match the available technology to the needs of users of 3D digital and printed artefacts. It is supported with a case study illustrating the full production cycle from an original negative plaster cast to the final product in the form of a physical exhibition replica.

Why is 3D imaging relevant for the museums of today?

The 1800s saw the adoption of photography as a new medium in museums, where its use demanded specialist skills and scientific rigour in composition, exposure and chemical processing and printing in order to achieve results that could augment the established recording techniques of drawing and description. The advantages of photographic recording were recognized through the resourcing of expert photographic laboratories and service centres within all major museums. More recently these groups have adopted digital imaging, digital image processing and presentation to develop new media outputs that can exploit the internet to greatly extend museum outreach into the home. A recent example is the Public Catalogue Foundation,[1] which has a remit to provide on-line access to the national collection of oil paintings in public ownership in the United Kingdom.

Mirroring the potential for the photographic breakthroughs of the 1800s is the growing availability of 3D recording as a mainstream service. 3D capture is certainly not new, but it has moved on from its technological home in specialist photogrammetric groups of the 1960s to 1990s,[2, 3] to parallel digital imaging advances and adopt automated algorithms for 3D reconstruction from the computer vision community.[4] There is enormous potential for non-contact imaging and the resulting high-resolution digital 3D models to complement traditional methods for conservation analysis and museum object documentation. Output capabilities are also growing with the latest web browsers including accessible 3D graphics, the growth of 3D television in the home and classroom and the production of replicas for visitor engagement drawing upon 3D printing colour technologies. Within the museum low-cost interactive exhibition displays and smartphone applications,[5] educational use or web resources (to make objects accessible to the public and to researchers from a broad range of disciplines)[6] are increasingly possible.

Over the past 10 years there has been a step change in the variety of 3D image capture systems in the market place. Systems have been developed by a wide range of academic and commercial groups to meet equally diverse applications and price points. Examples range from the internet-accessible David system,[7] through mid-range devices such as Mephisto and PicoScan,[8] to systems founded in industrial measurement such as GOM ATOS,[9] SmartScan,[10] and Arius3D Foundation System.[11] Competition between manufacturers has delivered improved capability, but most importantly it has enhanced the availability of 3D recording technologies for museum object documentation. The resulting increase in access to both equipment and outputs has given rise to a plethora of object recording for a wide variety of purposes and exposed users to data that are highly variable in quality and fitness for purpose.

Increasingly the data from 3D imaging are used to create physical replicas for cultural heritage by e-manufacturing by means of additive (3D printing/rapid prototyping) or subtractive (computer numerically controlled milling/laser cutting) manufacturing methods. 3D prints can be built in different materials: Z Corporation produces machines for colour gypsum printing,[12] while EOS GmbH has specialized in laser sintering systems to produce prototypes in metal, plastic and sand.[13] Subtractive methods provide replicas made from a block of material, e.g. foam, granite or marble. A drill mounted on a robotic arm is controlled by the 3D model or computer-aided design (CAD) geometry on a five-axis computer numerical control (CNC) milling machine.[14] These procedures allow replicas to be reproduced in their original material.

Figure 1. Wrapped objects and plaster-cast moulds on the shelves in the garret workshop. Image: www.flickr.com/photos/_mia/.

As the technologies and their supporting software become more mature there is a clear requirement for common standards and best practice guidelines suited to scientific evaluation and understanding of 3D colour digital data in the museum domain.

Working group at University College London

The authors are part of a research group based in Engineering Sciences at University College London (UCL), which is perhaps comparable in 3D capture capability and skills to the museum photographic laboratory of the future. The Photogrammetry, 3D Imaging and Metrology Research Group carries out a wide variety of scientific and applied research directed towards the acquisition and understanding of accurate, precise and reliable measurements of a diverse range of natural and manmade objects, structures and the accurate spatial and colour recording of fine art and cultural heritage artefacts. Expertise encompasses photogrammetry with image networks and sequences, vision metrology, laser scanning, range imaging and a wide range of digital recording and 3D modelling techniques.[15]

The group has built up extensive expertise working with the cultural heritage and museum sector, most notably with University College London Museums and Public Engagement, but also with London and international museums. It currently operates a range of active and passive measurement technologies, including digital camera equipment and two 3D colour laser scanners developed specifically for imaging cultural heritage artefacts. This core resource is augmented by more conventional terrestrial, triangulation and handheld

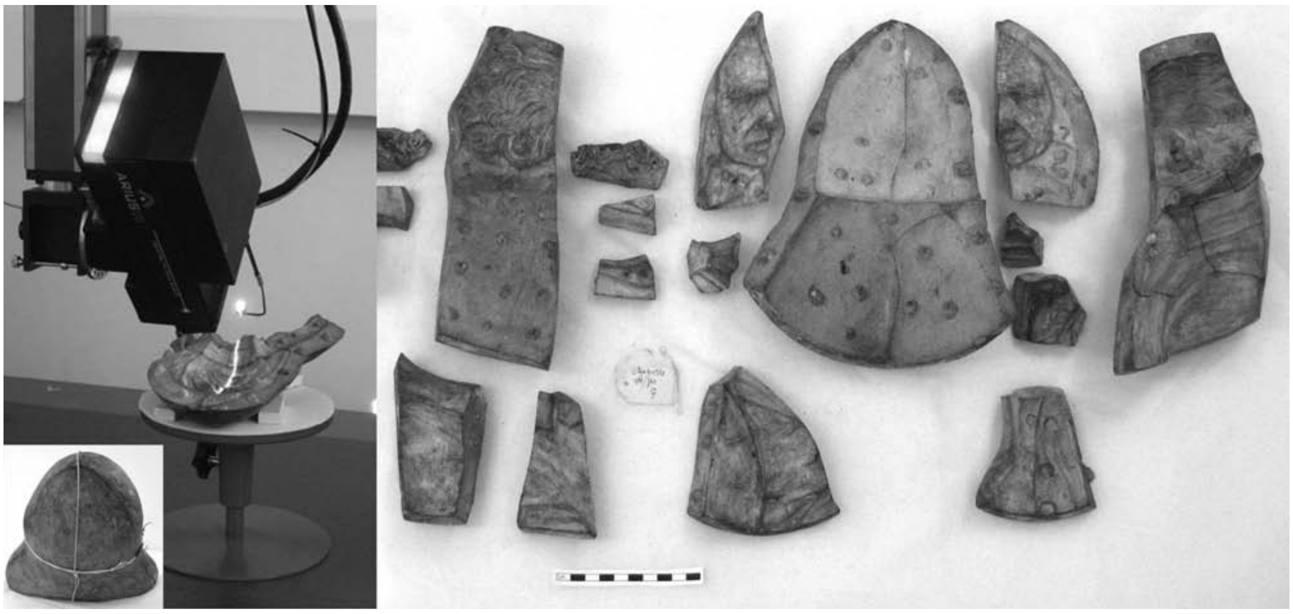

Figure 2. The closed plaster-cast mould of Watt's bust (bottom left); the mould after dismantling (right) and the 3D colour laser scan in progress (left). Images: Morgan Nau and Ben Russell © Science Museum, London.

laser scanning, fringe projection, photogrammetry and reflection transformation imaging (RTI).[6] Outputs flow from these systems through a variety of software systems to produce 3D library material, web-based content and physical models via the Digital Manufacturing Centre at the Bartlett School of Architecture. This skill and resource set represents much of what might be required for the next incarnation of the museum 'photography' department.

Our approach to 3D imaging for museums seeks to develop a bridge between conservation analysis methods and engineering metrology by closely analysing the possibilities and limitations of imaging technologies, with the goal of gaining a comprehensive knowledge about cultural heritage artefacts. Current activities include the development of best practice for 3D imaging, analysis and printing as part of the daily conservation and curation work in a museum and matching output digital artefacts to the needs of both professional and public audiences. Examples of recent work include the Arts and Humanities Research Council (AHRC) E-Curator project,[16] and the commercially funded 3D Encounters project.[17] The following case study demonstrates the full production cycle from the first inception of a project to the final product in the form of an exhibition piece. Three-dimensional monochrome recording and rapid prototype replica production by selective laser sintering (SLS) are explained.

'Face to face' with James Watt

A plaster-cast mould of an unknown man

This project follows a request in late summer 2010 from Ben Russell, curator of mechanical engineering at the Science Museum, to produce a physical 'positive' replica of an original 'negative' plaster-cast form. Non-contact and non-destructive imaging methods and 3D printing were to be used for this unique artefact. The final purpose was to integrate the replica into the exhibition *James Watt and our World: The Workshop, the Man and the New Industrial Age* that opened in spring 2011.

Watt's workshop is the legendary 'magical retreat' of the engineer James Watt after his retirement, preserved as it was when he died in 1819. The workshop represents a historical time-capsule containing the original furniture, windows, doors and fireplace, and more than 8,000 fascinating objects left as they were in Watt's lifetime. In 1924, his complete workshop was carefully removed and transported from Birmingham to the Science Museum in London[18] where it was exhibited in a somewhat hidden corner with sparse interpretation, limiting visitors' appreciation of its unique significance. The new installation is now placed in a prominent position in the main Turbine Hall and for the first time visitors can enter the workshop and enjoy a multimedia interpretation. A great diversity of artefacts is visible around the shelves and tables, including flutes, sculptures and unknown inventions. All these objects are shedding more light on the multifaceted personality and interests of James Watt.

Amongst the objects in the workshop are 23 plaster-cast moulds, most of which had never been opened and were still bound with their original string, Figure 1. During the reinstallation of the workshop the moulds were carefully dismantled, inspected and documented by a conservator. The moulds varied in size and complexity and were generally in a good structural condition. The inventory revealed that there were mostly moulds of classical topics, but included two especially complex portrait moulds.[19]

It was common practice in Victorian times to take home plaster copies of classical figures from European travels, but less usual to collect the moulds. Watt was interested in reproducing statuary, which also explains his design for a new sculpture reproduction machine in the centre of the workshop. His collection of plaster-cast moulds is unique, since in most cases only the final cast positives survive and the fragile moulds have been destroyed.

One of the portrait moulds was a bust of an eighteenth-century male figure (approx. 30 cm high) dating from 1807 (M.23/ Science Museum inventory), which generated

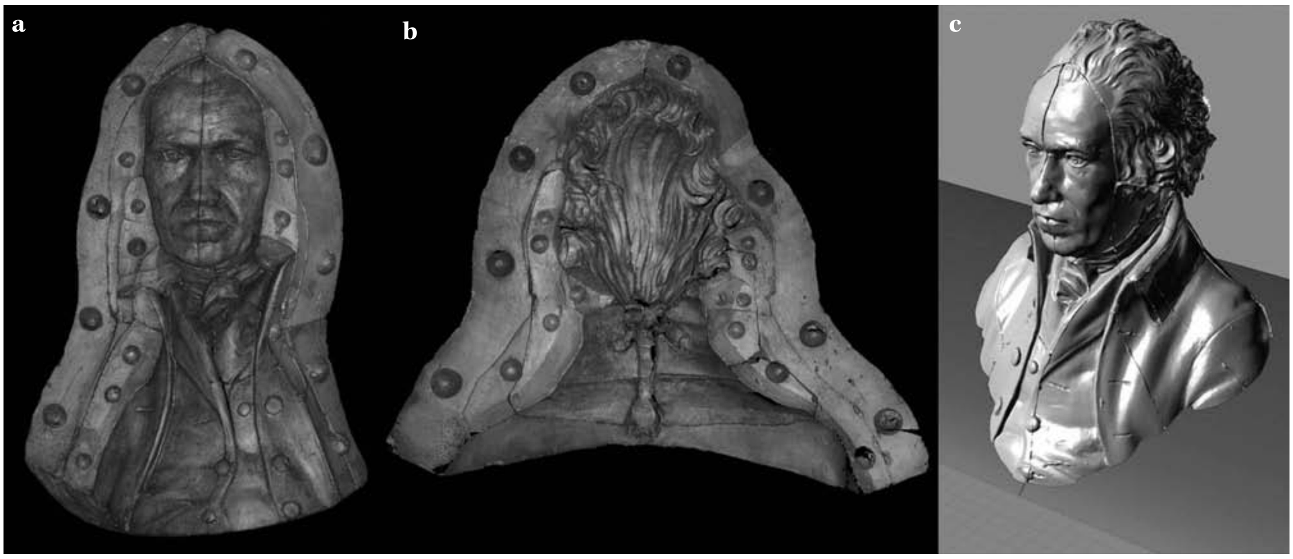

Figure 3. Data models from the scan: the 3D point cloud showing the negative from the Arius3D scan (left) and the processed 3D polygon mesh showing the positive model, ready for 3D printing (right).

significant interest among the curators. Was it a portrait of James Watt himself? The bust was found inside the workshop around 1807 and a hint in a letter implies that it was recreated from a mould that may have been cast by Lucius Gahagan for Watt. Unfortunately, the written records were inconclusive and this theory needed to be confirmed by seeing the positive cast itself. Therefore methods of casting the historical form were explored. The traditional method would be to pour plaster into the sealed form and then extract the positive from the mould once the plaster had set. However, given the importance of the mould collection and the conservation principles followed in the museum today – a complete preservation of the original object with evidence of use and residues – it was paramount to find a non-contact method that did not disturb the inside of the mould. The form was very complex, composed of four main pieces that contained 29 separate pieces, Figure 2.

Cutting edge technology for non-contact reproduction of a plaster cast: 3D laser scanning

3D imaging was recognized by the museum conservator as an excellent non-destructive alternative to gypsum casting and the state-of-the-art Arius3D Foundation Model 150 scanner at UCL was selected to make the recording.[20]

This autosynchronized scanning technology was developed and patented by the National Research Council Canada (NRC),[21] and has been employed in partnership with Canadian museums for detailed 3D colour object recording and visitor displays. On a commercial basis NRC has licensed the technology to Arius3D who has continued to develop the technology.

The scanning process requires complex 3D objects to be manipulated so that the imaging head can be directed at each area of interest. At UCL object manipulation is carried out either by a curator or an approved and trained object handling specialist. This approach is usually adopted in order to meet insurance stipulations for the safety and security of the artefact. In this case the conservator accompanied two moulds to the 3D scanning laboratory for two days. The space is temperature and humidity conditioned to accommodate different object conservation needs.

The Arius3D Foundation Model 150 is a 3D colour laser scanner for small- to medium-sized museum objects and comprises a three-colour laser scan head fixed to a coordinate measuring machine (CMM). It is used to create detailed object 'fingerprints' of a range of artefact types and deliver 3D coloured point data at a sampling interval of 0.1 mm (~250 dots per inch) at an accuracy of the order of 0.025 mm over the surface of an object. The scanner collects 3D geometry information through the use of a laser triangulation system, while colour is simultaneously collected by analysis of the reflected light from three RGB lasers.

Objects to be scanned with the system are supported either on a turntable or the rigid table structure beneath the bridge of the CMM. 3D scanning with the CMM permits the object to be recorded without touching it while building up the surface geometry by scanning multiple paths at different angles. The portrait bust M.23 is very complex and was split into its four main components for scanning: front, back and sides. To avoid undercuts and shadowing the components of M.23 needed to be moved to multiple positions and angles during recording to capture all surface details. Careful handling of the fragile pieces was executed by the gloved hands of the conservator, Figure 2.

3D colour scan data were collected in swathes 50 mm wide with a 50 mm depth of field using Arius A3DScan software. The software allows the operator to visualize data in 'real time', to assess overlap between component scans and to monitor live profile and colour data. Scan data collected during the primary recording process are archived to provide a raw data record before any further data processing is carried out, Figures 3a and 3b. The raw record comprises a point cloud including position (XYZ), colour (RGB), surface normals (Nx, Ny, Nz) and machine information including mirror angles and raw sensor data for each point. These data files represent a metric and colorimetric documentation of the object surface and constitute the key scientific record from the scanning process.

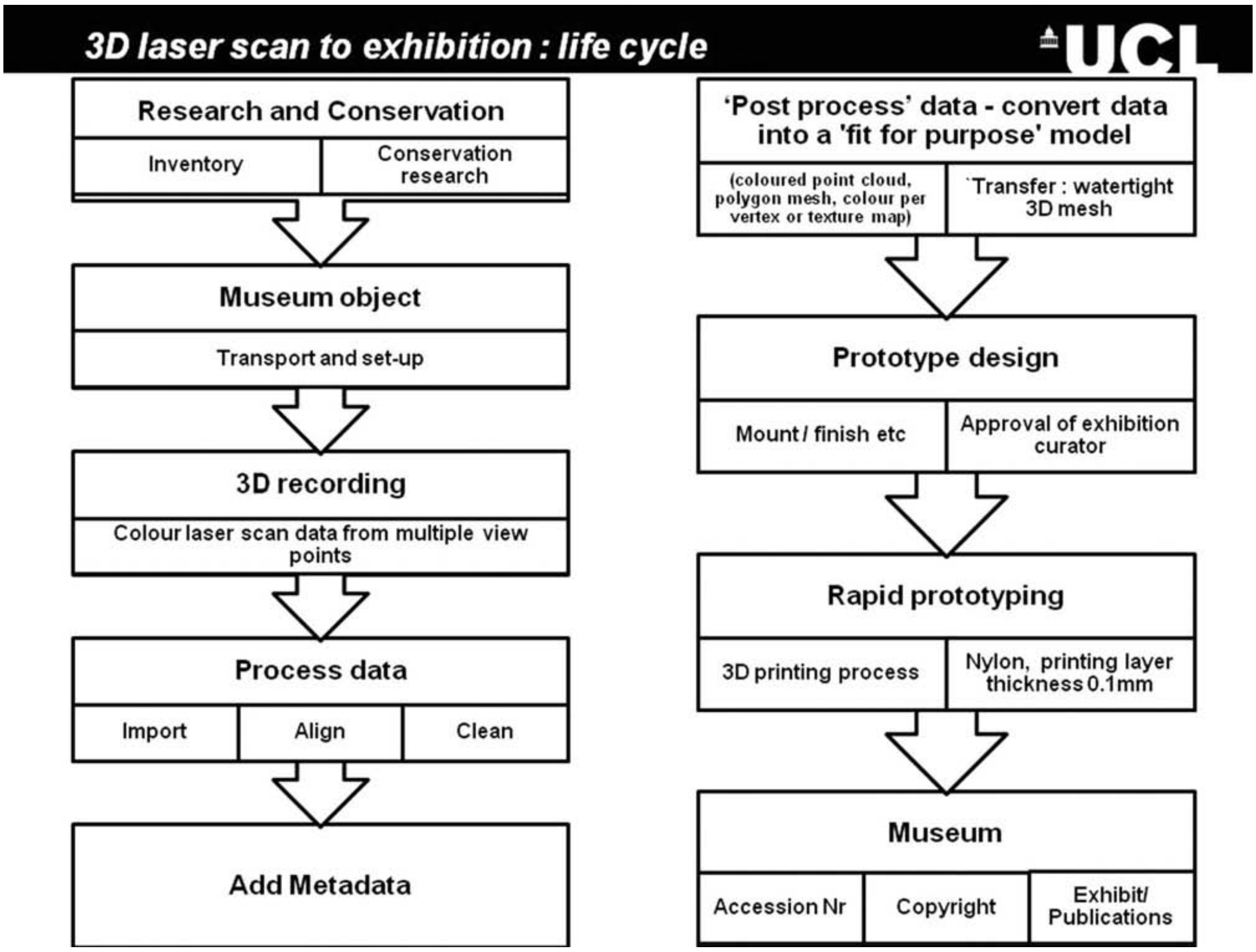

Figure 4. Diagram of the life cycle from museum object to 3D physical model.

3D processing and data reduction process, involving aesthetic decisions

Further processing of the data was achieved by importing and automatically filtering the raw data into Pointstream software, where separate 3D scan records can be registered into a common coordinate system with best overlap. The task of the processing was to represent a complete positive picture of the negative form. Therefore the surface normal direction was inverted and the four forms of M.23 were aligned. Extraneous data, which did not constitute part of the surface, were cut away; these included the connecting components of the cast forms around the sculpted form. The result was a first image of the cast and this was immediately recognized by the curator as a previously unseen portrait of James Watt, Figure 3c.

The negative form, with its reversed surface normals, included the joint parts of the different forms. The curator decided that the model should show the manufacturing process of the casting and that the joint lines of the single cast form should remain visible and elevated.

In a subsequent step the full resolution 10.5 millions points were transferred into a high-resolution polygon mesh. The 3D model was prepared in collaboration with the 3D printing technician. The surface was modelled to be a completely closed surface geometry without holes (i.e. watertight), especially around the shirt sleeves; an artificial cutting curve was introduced to form an even base and a bore hole on the back for mounting the bust was integrated. The mesh was then altered to 1.5 polygons with intelligent reduction. This produces small triangles in regions with high geometric complexity, e.g. around the eyes, and a reduced number of triangles by creating larger sides in regions that are more flat, for example the forehead.

The 3D print

The 3D model was transmitted to the Digital Manufacturing Centre (DMC) at the Bartlett School of Architecture.[22] At the DMC two options for 3D printing were discussed with the curator: first, rapid prototyping on the base of gypsum powder solidified by a liquid binder, with the option to print a coloured model; second, SLS by fusing nylon powder using a high-powered infrared laser, which selectively draws on and melts the nylon powder and fuses the layers together. Both technologies additively build up the geometry of a 3D model by vertically stacking slices of cross-sections on top of each other with a layer thickness of 0.1 mm.

The decision was made in favour of the SLS, using a Formiga SLS System P385 to produce the final sculpture. This allowed a smooth surface finish without treatment and offers higher durability and strength than a gypsum print. SLS systems build highly accurate, feature-rich models with excellent strength and longevity.

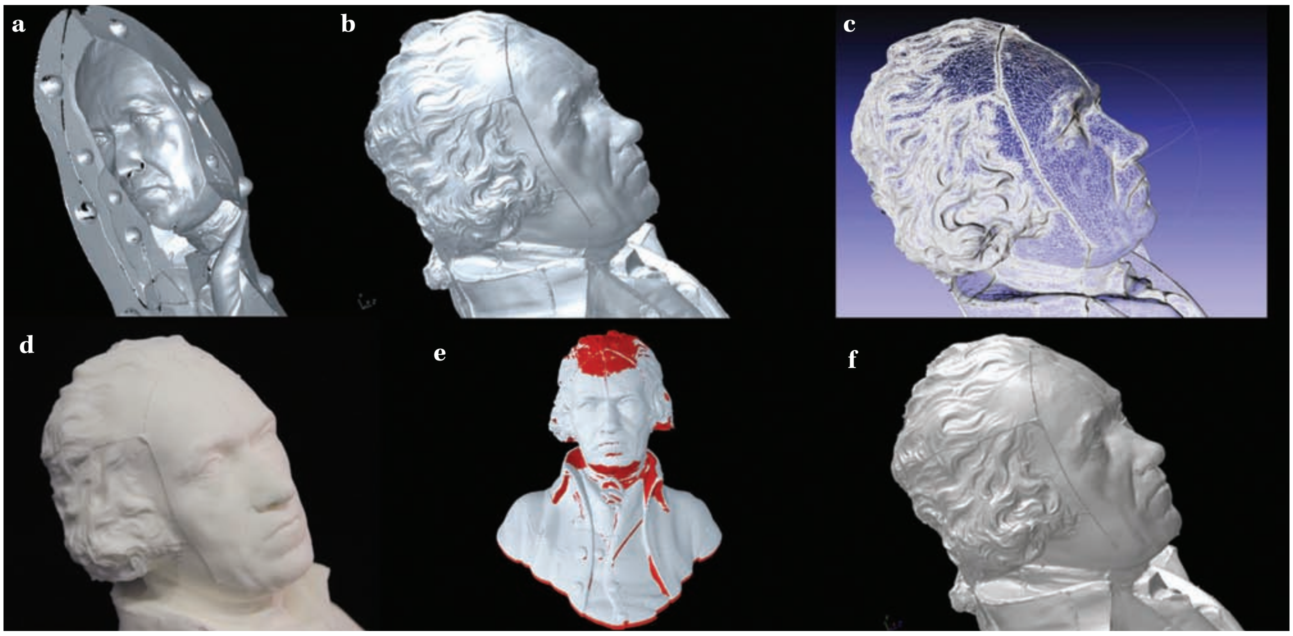

Figure 5. Life cycle of the production of the 3D SLS print: 3D laser scan of negative form (top left); 3D image with inverted surface normals and hole filling (top centre); preparation of the dataset for 3D printing, showing the transfer into a polygon mesh – triangular irregular network (top right); reduced mesh showing significant resolution reduction (bottom right); quality control, showing a comparison of the prepared mesh to the final print – the 3D data model is shown in red and is 2% higher than the 3D print in the z-axis (bottom centre); and the 3D replica in nylon printed with a 0.1 mm layer thickness (bottom left).

In order to verify that the print would be fit for purpose, a test piece of just the face was produced for viewing and approval by the curator. Important aspects of the test piece were general surface finish and the possibility of seeing the manufacturing process of the cast and the 3D print (the build of layers on top of each other). Following curatorial approval the bust was printed overnight. For metric quality control, the 3D print was recorded under the Arius3D laser scanner before hand-delivery to the Science Museum.

Case study outcomes: 3D imaging and 3D printing

The 3D imaging and 3D printing technology employed in this case study has produced a physical, tangible model of a previously unseen portrait bust of James Watt, one of the Industrial Revolution's greatest engineers. The complete life cycle of the production is shown in Figures 4 and 5.

Several conclusions about the process can be drawn. The collaboration and clear communication between all stakeholders (curator, conservator, 3D scanning technicians, 3D printing technicians) was essential; this is a prerequisite for a good project. Decisions and specifications of the final product were clearly communicated and defined. There was a great deal of enthusiasm and curiosity about the feasibility of the production via 3D technology on the part of the Science Museum. Copyright questions were met by handing over all rights to model and products to the Science Museum.

The initially highly resolved 3D surface data enabled the viewer to discern the smallest detail (e.g. eyes and forehead lines, Figure 5b). The subsequent data reduction of the model – necessary to produce a closed geometry (watertight) model suitable to the current 3D printing workflow – produces a loss in surface detail, Figure 5d. Therefore, if the 3D print was the only specified outcome, other faster 3D imaging sensors could have been employed to produce the same resolution and triangle count in the prototyping dataset. However the 3D point cloud dataset enables the virtual 3D model to be viewed on screen, explored and maybe deconstructed (e.g. into single elements of the cast form); as such, it represents a wealth of knowledge about the object.

To learn about the quality of the printed model, the post-processed model prepared for 3D printing and the final outcome of the print were compared. Quantitative comparison showed that the 3D printed model experienced significant shrinking in the vertical (Z-) axis that can average 2% (or up to 5 mm: Figure 5e). This is a known phenomenon in rapid prototyping and is usually addressed by introducing a shrinkage correction factor to guarantee metric accuracy.[23] For this case study, the exhibition replica itself met the visual requirements and specifications; the slight height distortion is not discernible to the visitor, but needs to be assessed accurately for future work.

In conclusion, the 3D data acquisition of the negative cast form produced a high-resolution 3D virtual model as a point cloud that can be regarded as the digital equivalent of the mould. From a conservation point of view the longevity of this nylon print on exposure to light needs to be considered, since at some point such 3D replicas will become artefacts in their own right just as Watt's moulds have become. The 3D print has been officially accessioned (Science Museum number 2011.14). Like the sculptures of Naum Gabo from the 1940s, which are suffering from extreme conservation problems caused by the inherent instability of early plastics,[24] the 3D nylon print might suffer from damage. Long-term studies on the lifetime of 3D rapid prototyping products should be undertaken. A strategy is needed to preserve the digital record so that future copies can be produced. From the preventive conservation perspective questions arise about the possible emission of pollutants by the replica when in a museum case and the influence of these on other objects. This is certainly a subject to further research for all 3D rapid prototyping products.

Figure 6. View of the gallery during the *Watt and our World* exhibition at the Science Museum, London. Watt's bust is at the left of the case. The insets show the 3D print (left) and cast parts (right). Images: © Science Museum, London.

The exhibition Watt and our World

The new exhibit of Watt's workshop was mounted in the Energy Hall of the Science Museum, accompanied by a case showing the existing portraits of James Watt alongside the newly discovered bust as a 3D print. The display was placed in a prominent position opposite the steam engine and as such had considerable public exposure, Figure 6.

The newly discovered portrait of James Watt was taken up as the publicity launch story for the exhibition,[25] and the previously unseen sculpture was also discussed in comparison with known portraits by a scholarly article.[26]

Watt's garret workshop contains a three-dimensional copying machine of his own design, on which he tested sculpture reproduction, also using busts of his own portrait. As a Georgian superstar and a creator of a cult around his person, and with his attention to detail, Watt would surely have been delighted to find an accurate metric reproduction of himself made with the latest advances in technology.

Development of best practice recommendations for 3D imaging in the museum

The accession of the 3D print as a museum object at the Science Museum, including all 2D and 3D image data on a DVD, shows that museum object management has started to branch out in new ways. The Science Museum will integrate all these data into its object information database for further reference. This highlights the possibility of employing 3D digital artefacts in the daily museum workflow: in documentation for accession, collection management and provenance, condition monitoring and documentation before and after a conservation treatment, and finally object monitoring and use in education and display, Figure 4.

However, not only does the generation of 3D imaging data pose the need to obey requirements of quality control and adopt a best practice framework, it also emphasizes the importance of maintenance and digital preservation. The first guideline to summarize the significance of 3D digital records as valuable assets, with a recent extension to 'digital provenance', was the London Charter.[27]

Availability of standards in different domains relating to 3D documentation in museums

A great number of standard regulations are available from different domains that can inform the development of a best practice recommendation. These include guidelines for 3D imaging quality control in the engineering metrology domain (e.g. developments in ASTM E57 and VDI/VDE 2617 and 2643); other available standards come from graphic technology and photography and these ensure image quality via psychophysical experiments (ISO20462). In the cultural heritage domain there are clear guidelines in museum conservation and codes of ethics (ICOM and ECCO), while museum documentation standards (such as SPECTRUM) include recommendations related to database fields and records.

Requirements of museum professionals and user acceptance

Preliminary user testing within the E-Curator project with curators and conservators demonstrated how they would like to consult 3D digital images to understand artefact materials and to learn about manufacturing techniques.[28] Key practical features of a 3D record are encompassed by the following factors: high resolution up to the level of a hand lens, realistic rendition of colour/colour fidelity, reflectivity and texture to the extent that materials can be recognized.

Future work

To enhance the scientific foundation for 3D imaging, a portable test object for heritage and museum applications with known surface and geometric properties is under development. This object will be used for numeric evaluation and comparative imaging on different systems.

Assessment of the data produced will be made using quantitative tools from engineering metrology in combination with more qualitative approaches founded on interactive user testing to pinpoint specific user requirements and evaluation criteria. Further user testing will be carried out in association with museum professionals and tailored towards applications in conservation and curation.

The outcomes from both quantitative and qualitative testing will inform the development of best practice recommendations for 3D recording, data processing and viewing with available imaging technology, keeping in mind the UK museum framework and conservation ethics.

Conclusions

The critical factor for future 3D colour museum object recording is to facilitate the right communication and technology transfer between imaging technologists and cultural heritage professionals, as well as the development of convincing and feasible best practice recommendations to ensure high-quality models, optimal presentations and viewing conditions.

The approach will, therefore, develop a bridge between conservation analysis methods and engineering metrology by closely analysing the possibilities and limitations of imaging technologies, with the aim of acquiring holistic knowledge about cultural heritage artefacts.

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