THE USE OF 3D LASER SCANNING AND 3D MODELLING IN THE REALISATION OF AN ARTISTIC VISION; PRODUCTION OF LARGE SCALE PUBLIC ART IN TUDOR SQUARE, SHEFFIELD

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ABSTRACT:
The documentation of cultural heritage in 3D using non-contact laser scanning, and the wide variety of applications that the resulting data can be used for, are well documented. Increasingly, the 3D data is being used by artists, both in their work, and as a tool to realise their ideas. During recent regeneration, Sheffield City Council awarded the remit to design sculptural planters for Tudor Square, Sheffield to the artist Stephen Broadbent. Using the industrial environment of Sheffield and the natural landscape around the city as inspiration, the artist created sculptures based on natural pebbles and boulders. These hand-made maquettes were one tenth of the size of the final sculptures. From these maquettes, ten sculptural planters have been milled into natural stone. Computer aided design (CAD) modelling based on standard geometries was not appropriate to produce a data set which could be used in the milling process. Instead, a combination of 3D laser scanning, surfacing and digital modelling was used, not only to scale up the maquettes and create a set of files for each planter in blocks of size which could be machined, but also to facilitate later changes in the design to sections of each planter. In this paper we describe the 3D modelling process we undertook on the datasets obtained by laser scanning the artist’s maquettes, and the preparation of the data for 6-axis computer numerically controlled machining.

1. INTRODUCTION

1.1 3D Laser Scanning in Cultural Heritage

The documentation of cultural heritage in 3D using non-contact laser scanning, and other comparable techniques,[1] and the wide variety of applications that the resulting data sets can be used for, are well documented.[2] Indeed, in some areas, the use of laser scanning of cultural artefacts to solve certain conservation or access problems is becoming common place.[3] Despite this ongoing evolution of the process of 3D laser scanning from curiosity to everyday tool, there is still a large untapped set of applications for which 3D datasets of cultural artefacts and works of art could be exploited. In some ways, the myriad of possible uses for a given 3D dataset could be considered a blank canvas. Like a blank canvas, to make the most of these possibilities requires creative, artistic input. It is not surprising therefore, that 3D data created by laser scanning is being increasingly used by artists, not only in their work as the art itself, but also as a tool to realise their ideas.

1.2 The Use of 3D Laser Scanning and Associated Technologies by Artists

Digital artists were some of the first artists to use 3D data produced by laser scanning and related techniques in their work, both in its raw and manipulated state. Such work has taken many forms including 2D print outs of representations of manipulated 3D data sets, or objects created in part by causing disturbances in, and deviations from, the rapid and computer numerically controlled (CNC) manufacturing processes.[4] Using rapid prototyping technologies artists have exploited the ability to produce multiple near identical replicas in their work.[5] Moreover, as art often seeks to re-examine its own legacy and play with a society’s perception of a valuable object, replica objects of cultural artefacts have been re-worked, and even destroyed to create artistic works.[6] Throughout history, artists have made and used maquettes (small scale versions of a work or sculpture). Techniques such as pantography, have been used in conjunction with craftsmanship and skill, to aide the artistic process and the ultimate realisation of, often large and complex, works. However, once a 3D data set of an object exists, such as can be produced by non-contact laser scanning, extensive re-modelling and digital manipulation is possible in the virtual world. Operations such as scaling an object up or down in size, mirroring an object, and reworking geometric sections of a work are trivial operations using a variety of software packages.[7] More complex remodelling operations can be performed using curve networks and by combining geometric shapes into the data set. Totally organic modelling is also possible using haptic devices and associated software.[8] Such technologies mean that works can be refined more easily than by re-sculpting a maquette, and extensively visualised before production commences. In some cases these technologies have also enabled artists to create works that would not have been feasible using traditional methods.[9] Although for gallery based works artists have utilised the wide variety of modern materials (including plastics and fused metals) available to them by employing rapid

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prototyping technologies, the materials of choice for outdoor works remain natural materials such as wood, metal and stone. That is not to say that artists creating works for display outdoors have not embraced emerging technologies. From the pioneering use of aluminium in the creation of the Shaftesbury Memorial in Piccadilly Square in 1893 to the use of CNC machining in the production of the Diana Memorial[10] in Kensington Gardens in 2004, the realisation of large scale outdoor public art in recent times has a legacy of employing new materials and technologies.

To create a replica object in wood or stone from a 3D data set necessitates the use of CNC machining. In recent years the size and complexity of objects that can be machined in stone using CNC machining has increased considerably. In the late 1990s the field advanced from employing mainly 3-axis machines to using machines with 5-axis movement of the drill head. This, accompanied by an increase in machine bed size, enabled fully 3D life-size marble sculptures to be produced.[11] In 2000-2002 the use of combined 6-axis robotic movement and milling became more common. The use of these larger 5 and 6-axis machines is enabling larger works to be machined faster.[12]

1.3 Tudor Square Sheffield

The City of Sheffield, UK, is known for its visionary regeneration of its city centre areas and a commitment to integrating inspirational artwork within its public realm.[13] Tudor Square is at the cultural and visitor heart of Sheffield, hosting nationally renowned theatres, 2 galleries, the central library and winter gardens. The square is a popular space but did not function well as the focus for the city's key cultural venues.[14] In 2008, Sheffield City Council decided to redesign these facilities to create a high quality public facility. Central to the re-design was the provision of seating and the addition of green areas within a multifunctional space. Seating was envisaged to be integrated into raised planter beds, which were to be produced in natural materials such as bronze and stone.

1.4 The Artist Stephen Broadbent's Design for Tudor Square's Sculptural Planters

The design of these sculptural planters was awarded by Sheffield City Council to the artist Stephen Broadbent in 2008. Using the industrial environment of Sheffield and the natural landscape that surrounds the city as inspiration, the artist created sculptures based on the shape of natural pebbles and boulders in varying sizes. These organic shapes would incorporate the space for the planned planting inside an outer rim of stone containing the seating areas and designs inspired by Sheffield and its surroundings. Three hand-made plaster maquettes were produced by the artist at one tenth of the size of the final sculptures. From the outset of the project it was envisaged that, from these three maquettes, ten sculptural planters (some over 10 metres in width) would be milled into natural stone quarried from the areas surrounding Sheffield.

1.5 Realisation of the Design

The production of the sculptural planters in natural stone by CNC machining necessitated the production of 3D data sets of the maquettes created by the artist Stephen Broadbent. The designs are highly complex in shape, and both the artist and design team at Sheffield City Council (SCC) decreed that the organic nature of the planters was integral to the overall feel of the work. As a result it was felt that the production of 3D data sets by computer aided design (CAD) modelling based on standard geometries would not be appropriate. It was considered that the free-flowing non-geometric shapes of all the sculptural planters would render the task of modelling the sculptures from basic geometries too time consuming and potentially unsatisfactory. Instead, a combination of 3D laser scanning, surfacing and digital modelling was used, not only to scale up the maquettes and create a set of files for each planter in blocks of size which could be machined, but also to facilitate later changes in the design to sections of each planter.

In this paper we describe the 3D modelling process we undertook on the datasets we obtained by laser scanning the artist's maquettes, and the preparation of the data for 6-axis CNC machining. We also briefly discuss the communication and workflow structures that were established by all parties involved (the artist, 3D modelling team, Sheffield City Council regeneration project design team, the machinists at Myers Group, and the onsite installation team) to enable the 3D laser scanning and modelling processes to fit into the project management structure of one of Sheffield City Council's major regeneration schemes.

2. METHOD

2.1 Creating 3D Data Sets of the Maquettes

The 3 plaster maquettes of the sculptural planters created by the artist, all measuring less than 1 metre in width, were recorded using a ModelmakerX laser scanner emitting a stripe 70mm wide mounted on a 7-axis Faro Gold Arm. The scanner and arm combined have a typical accuracy of +/- 0.1mm. Modelmaker 7 software was used to collect the 3D data during scanning and to sample the data prior to alignment and meshing. The IMAlign module in Polyworks V10[15] was used to register and align the data sets from different scanning stations and to fine align all stripes within the single point clouds. All the mesh editing, 3D modelling and NURBS surface creation was carried out using Polyworks v10 in conjunction with Rapidform2006,[16] Rapidform XOS,[15] and 3D SudioMax.[17]

All the raw point cloud data was sampled at 0.2mm prior to registration and alignment. The standard deviation for the alignment of the point data for each maquette was 0.02 or less. Filtering of overlapping points (reduction overlap) was carried out during the meshing process. Smoothing and reduction tolerances were kept below 0.008mm during meshing, although a reduction tolerance of 0.01mm was applied to each unedited mesh. Basic mesh editing, (hole filling, localised mesh optimisation, localised smoothing) resulted in watertight meshes (see Figure 1).

Figure 1. 3D laser scanning the maquettes (left), and screenshots of the processed meshes of two maquettes (right).

The bases of the 3D models were capped with planes created by taking an average of the rough highly textured base of the model and offsetting by approximately 1mm. This was to ensure a flat base for each maquette. The area designated as soil (the centre section of each planter) was removed by trimming along a hand-drawn freeform curve. By reducing and optimizing this hand-drawn curve and re-inserting it into the model, this edge was smoothed and refined to leave the planters with a flowing rim.

2.2 Scale-up, Design Reworking and Internal Geometry

2.2.1 Scale-up: The maquettes were created at one tenth of the size the sculptural planters were to be produced at. Although, as previously mentioned, the actual scaling up of a 3D mesh is a trivial operation in most 3D software packages, scaling up a hand-made maquette by a factor of 10 has implications for the design and look of the work; each mark and scratch created intentionally or unintentionally during the production of the plaster maquettes becomes a major surface feature on scale-up.

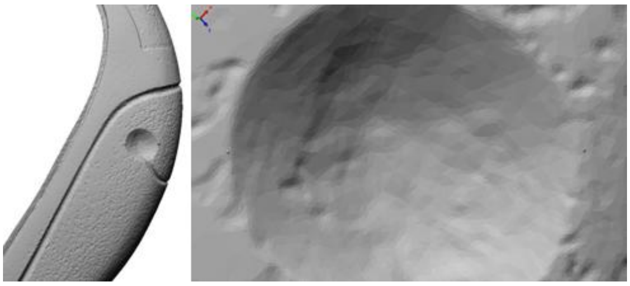

Figure 2. Screenshot of a feature from the medium planter at maquette size (left) and final sculpture size (1:10) (right).

Moreover, as the 3D digital meshes of the sculptural planters were worked and viewed on standard PC monitors, the implications of this effect were hard to visualise. Following the provision of imagery of the type in *Figure 2* to the design team and the artist, the decision was made to apply extensive smoothing to the digital models of the planters. The final planters were to retain the organic free-flowing geometries of the maquettes, but all surface texture was to be removed.

2.2.2 Smoothing and re-working of the gutters: The removal of the surface texture in areas of the planters which did not contain design features was completed using area constrained, brush smoothing and mesh reconstruction mesh editing tools. The smoothing tools had to be set at the more extreme end of the scales available, and in some areas it was necessary to delete sections of heavily textured surface mesh and smooth fill the resulting holes. One particular type of design feature found on large sections of each maquette, the gutters, follow the natural shape of the pebbles from which the planters take their inspiration. In addition, the gutters vary in width and height gradually and randomly along their length. The 3D surface texture resulting from the hand carving of the maquettes meant that the gutters, once scaled up, were subject to a serious ‘wobble’ that needed to be corrected (see *Figure 3* top left). Examples of full gutter remodelling (i.e. creating a tube of constant radius, slicing it in half to create a gutter and inserting it into the 3D model) were provided to the design team and the artist. This method was deemed to produce an undesirable harsh and “over-manufactured” final look. Therefore the existing gutters were re-worked with the aim of producing smooth gutters that retained a hand-carved feel (see *Figure 3* bottom left). Hand-drawn curves were traced along each gutter’s highest edges and lowest troughs and then converted to sharp edge curves (see *Figure 3* top right).

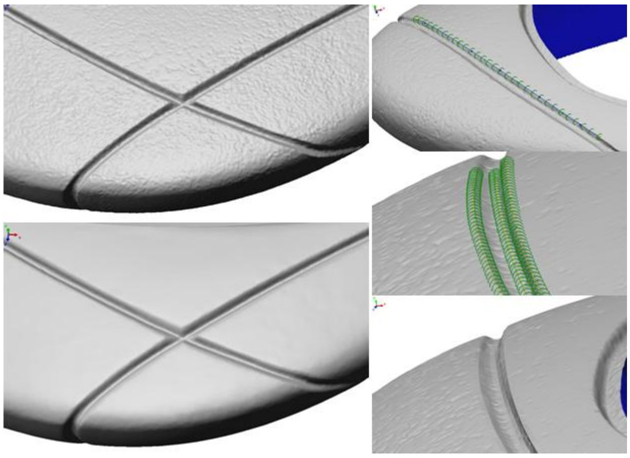

Figure 3. Screenshots of the re-working process for the gutters. On the left before (top) and after (bottom).

Low tolerances and low numbers of control point were used to relax these curves to become smooth and flowing, thereby removing the “wobble” (see *Figure 3* middle right). The resulting curves, which floated above and below the 3D model, were inserted into the digital models to produce fluctuating “V” shaped gutters that followed the artist’s original lines (see *Figure 3* bottom right). Finally, smoothing was applied to the reconstructed sharp edges using radii taken from the original gutters.

2.2.3 Smoothing and re-working of non-gutter features: In addition to the gutters, all the sculptural planters have designs based on gouges, dishes, spheres and steps. The smoothing required to remove the surface texture (described above in section 2.2.2), resulted in substantial and unacceptable loss of definition from these features.

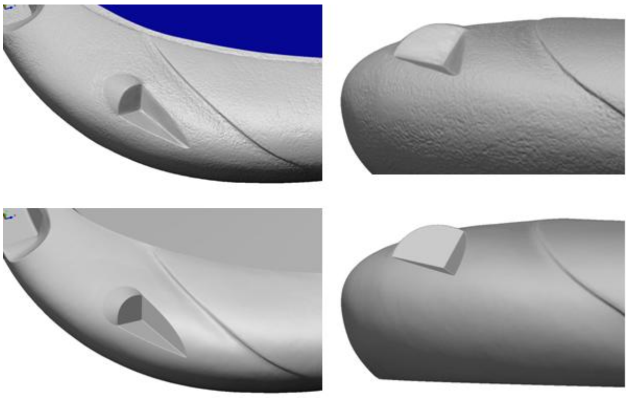

Figure 4. Screenshots of two of the design features before (top) and after (bottom) re-working.

The design team and artist decided that these features should be sharpened, but also re-modelled based on standard geometries to complement and contrast the re-worked gutters. Geometric shapes such as spheres, pyramids and cuboids were created by anchoring standard reference geometries to the original features in the digital models. Gouge shaped features were created by extracting sets of intersecting planes from the original surfaces in the digital models. These newly created geometric features were converted to mesh data (in STL format) and re-integrated into the digital models.

2.2.4 Re-design of the seating area on the large planter: The largest of the three planter designs has a semi-circular seating area incorporated into it. Wooden slats and armrests would be added to complete the seating area once the stone planter had been machined and installed on-site (see Figure 10). However, the seating area on the hand-made maquettes was of incorrect height and length with respect to the design drawings.

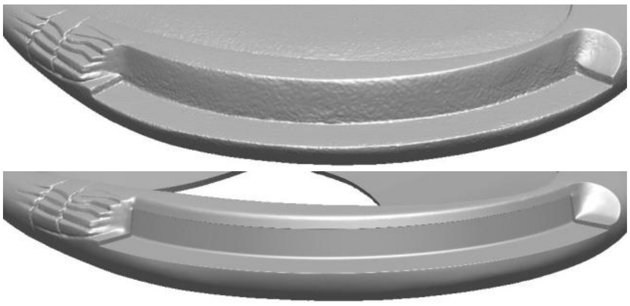

Figure 5. Screenshots of the seating area of the large planters before (top) and after (bottom) re-working.

To correct this, a circle that encompassed the outer most limit of the seating area on the plans was used as a template for the reworking of the digital model. Further circles were created at various heights and with various radii to establish the edges of the front and back of the seat and the top of the seat back. To enable the wooden slats to sit flush with the stone at the top of the seating area a 'bull-nose' was also created using a further two circles. Surfaces were created by lofting between these sets of curves. These NURBS surfaces were then converted back into polygonal meshes in STL format and incorporated into the 3D models of the large planter. Smoothing using fillets of various radii were applied to the sharp edges to remove any areas that could be vulnerable to damage on the real-world stone planters.

2.2.5 Internal geometry: At this stage of the 3D re-modelling process the digital models were "hollow bands." Initial specifications for internal faces of the planters were drawn up by the design team at Sheffield City Council and the machinists at Myers Group. This internal structure needed to be as small as possible to accommodate large volumes of soil and root balls. However, the internal faces also needed to be of sufficient size, so that enough stone would remain on the inside of each section of planter to counter weight it and stop it toppling over during machining and installation on-site. These internal faces were initially designed from cross-sections taken from the digital models. Initial attempts to create sets of curves to construct these internal faces were unsuccessful due to the organic shape of the planters. As a result the internal faces were designed separately for each planter. A series of steps of varying heights and depths and with varying slopes that could be altered in response to the changing shape of each planter was used. These steps were created by offsetting the original soil edge curve to the correct locations inside each planter. The final internal faces were created by lofting between these sets of offset curves, creating a set of NURBS surfaces. These NURBS surfaces were converted into polygonal meshes (in STL format) and incorporated in the 3D models. (see Figure 7).

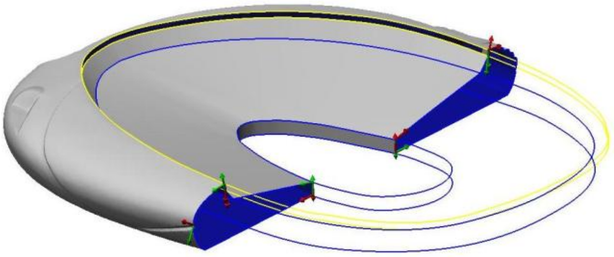

Figure 6. Screenshot of the construction on the internal faces on the large planter.

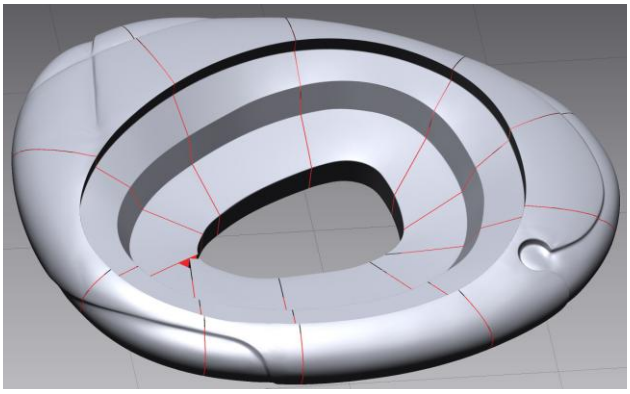

Figure 7. Screenshot of the small planter once the internal faces have been created and the model divided into 10 blocks.

2.2.6 Further re-design: The design brief for Tudor Square incorporated 10 stone sculptural planters. From the 3 maquettes created by the artist originally, 3 small, 3 medium and 4 large planters were to be produced. To create variety in the planters the artist sculpted variations of the design features for selected areas of the planters. These newly sculpted areas are known as "nodes." The 4 large planters have 3 nodes each; the 3 medium planters have 2 nodes; and the 3 small planters have 2 nodes each. To allow the nodes to fit seamlessly into the digital models of the maquettes, the artist Stephen Broadbent took moulds of the sections of the original maquettes which were to be changed. He then re-carved these cast areas to create each node. These sections were then laser scanned, scaled up by a factor of 10 and aligned into the digital models for each maquette. These areas were then remodelled and refined as described in sections **2.1 – 2.2**.

2.3 Cutting the Sculptural Planters into Blocks

The final digital models used to machine the sculptural planters ranged in dimension from 0.65m (H) x 3.80m (W) x 3.15m (D) for the small planters to 0.96m (H) x 10.50m (W) x 7.50m (D) for the large planters. However the maximum block size that could be machined was 2m in width. The artist designated areas where he felt divisions in the design would work best, and stipulated that the block sizes should be irregular wherever possible. The digital models of each planter were split in roughly correct locations using planes created by eye. The resulting blocks were measured to ensure they were all less than 2m wide, and examined from all angles. This was to ensure that the cutting had not compromised any design features or created edges vulnerable to breakage during installation, freeze-thaw cycles, or general wear and tear. Following the required adjustments, the planes were offset to the left and right by 2.5mm. These offset planes were the final cutting planes. The 5mm of data between each block was deleted to create space to allow the real world stone blocks to be installed on site. As a result we divided each of the 3 small boulders into 10 blocks (as can be seen in Figure 7); each of the 3 medium planters into 17 blocks and each of the 4 large planters into 23 blocks.

2.4 Creating NURBS Surfaces of Each Block

The two most commonly used file formats used in CNC machining of cultural artefacts and artworks are the binary STL and surface IGES formats. Tests were undertaken on small sections of data to see how the two file formats affected the machining process and to assess the results. The smaller file size of the IGES format data set was found to be a serious advantage to the machinists on a project of this scale, allowing faster data manipulation and tool path generation. Moreover, the IGES format data produced a better, smoother finish, faster. It was clear that the project would require NURBS surface IGES files to achieve the results required by the artist and the design team, within the timescale of the project. Initially it was considered possible to produce NURBS surfaced models of each sculptural planter before it was divided into blocks. We envisaged that this would avoid any problems with design features that ran over several blocks. However, due to a combination of the very large file sizes, the scale of the objects to be surfaced and the complexity of some of the features, it was not possible to produce a NURBS surface of good enough quality and validity for use in machining. It was therefore necessary to split the polygon mesh STL model of each planter into its constituent blocks (as described above) prior to NURBS surfacing. High quality B-Class NURBS surfaces were then created from hand-drawn curve networks for each of the 79 distinct blocks that make up the 10 planters.

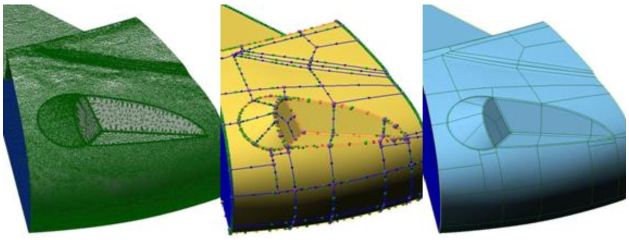

Figure 8. Screenshots of a section of data in polygon mesh format (left) and as a set of NURBS surfaces (right).

2.5 6-Axis CNC Machining

The NURBS surface IGES files of each block were used to generate machine tool paths in Mastercam CAD/CAM software.[18] 3 6-axis Staubli robots were used to machine the blocks into sandstone at the Myers Group Johnsons Wellfield Quarry site in Huddersfield. A total of 9 people spent 7 months machining the 173 blocks that make up the 10 planters; 5 creating robot billets (preparing the blocks for machining); 3 full-time programming and operating the robots; and 1 project manager. There is approximately 200m^3 (500 tonnes) of sandstone in the planters, and it is estimated that 1000 tonnes of stone has been extracted from the ground in total during this project. However, wastage of stone on the Tudor Square planters was less than 10% as the material removed to create the robot billet was cut into slabs of a useable thickness and used in the quarry's general ashlar products.

From the outset of the project, the artist had envisaged that texture would be applied to the surface of the planters. At the start of the project it was unknown whether this texture would be applied to the 3D digital models, or added using traditional tools once the blocks had been machined into stone. The artist examined the textures created by the tool during the CNC machining process during different stages of production and felt these patterns worked well in the design. The artist reflected that recreating the traditional stonemason's marks that develop naturally in the realisation of an artwork could be seen as a little dishonest. He felt that it would also be disrespectful of the surprisingly beautiful textures created by the machining, by these "new tools". Working closely with the machinists, the final tool paths for each block were set to produce patterns and textures according to the artist's design.

Figure 9. 6-Axis robotic machining (left) and an example of the textures applied to the planters during machining (right).

2.6 Installation and Planning

Planning of the installation of the 173 stone blocks in Tudor square was not trivial. To aide this process, a set of 2D line drawings (DXF format) displaying the footprint and maximum extents of the blocks within each planter was provided (see figure 10). These drawings were created by projecting a curve describing the outline of each block within a given planter, the footprint curve of the planter and its maximum boundary curve (all viewed from above) onto the base plane of the model.

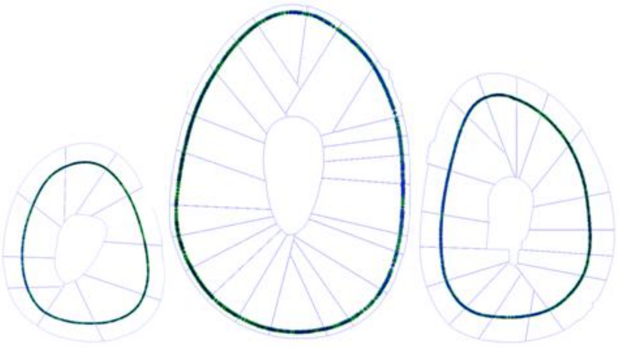

Figure 10. The footprint curves for a small (left), medium (right) and large (middle) planter.

2.7 Timescales, Communication and Workflow

The timescale of the 3D laser scanning and modelling work was 7 months. Crucial to the project was approval of any changes made to the 3D models by the artist, the design team and in the latter stages of the work, the machinists. Several changes to the original design were requested. Communication about virtual 3D objects relies on 2D sketches and imagination. Translation of ideas into the 3D models is hampered by the practicalities and limitations of the software package and the comprehension by the operator of what is required. Throughout the 3D scanning, modelling and surfacing stages of the project, there was excellent communication between all parties. The best approach was often for all parties to sit in front of the same computer screen and rotate the models during discussions. 2D screenshots were very useful at the end of the project to check that the design features were correct once the NURBS surfacing had been undertaken. However, during re-modelling we found that deciding a course of action to resolve an issue in 2D often didn't translate 3D as anticipated. This was particularly pertinent in the design and implementation of the internal faces of each planter. However, sitting together, is not always practical, and such forums are hard to document. As discussed in section 2.4, it was initially considered possible to produce NURBS surfaced models of each sculptural planter before it was divided into blocks. This would have been useful not only because it would have been easier to ensure that design features that ran over several blocks retained their integrity, but also, it would have allowed the machinists to start working on tool paths earlier in the project. We were able to supply the blocks for each planter in STL format before the re-design work was complete and before we had created the NURBS surfaces for each block. This aided the machinists in the processes of selecting and assigning blocks of stone, and in starting the process of removing excess stone from the blocks. However, the NURBS surface IGES files were required for the preparation of the tool paths and, therefore, for machining to start.

3. CONCLUSIONS

Using 3D laser scanning and digital modelling data sets have been produced from which large scale public art has been machined. The organic nature of the artwork meant it would not have been possible to achieve the desired results using traditional CAD modelling and standard geometries.

Figure 11. On-site installation of the planters in Tudor Square.

By completion of the project, 10 sculptural planters in 173 sections will have been machined into stone from data sets created by laser scanning 3 small scale maquettes and 17 design feature sections. At the time of writing, 167 blocks have been machined and the 33 blocks which make up the first large and small planters weighing up to 3.5 tonnes each have been installed on site in Sheffield. Tudor Square, with all 173 blocks in place, is due to be opened in May 2010.

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[1] Examples include; Photogrammetry, systems that employ structured light, holography, and CT scanning.

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[7] Any 3D software manipulation package. Examples include: SolidWorks, Geomagic, CATIA, Autodesk Maya, Studio VIS.

[8] SensAble Technologies (http://www.sensable.com/)

[9] For example references: 5 and 6.

[10] For example: Princess Diana Memorial Fountain, http://www.stonebusiness.us/index.php?option=com_content&view=article&id=660&Itemid=67

[11] Replication of a 17th-century life-sized marble statue of Pomona, http://www.liverpoolmuseums.org.uk/conservation/technologies/casestudies/3d/pomona/ (accessed March 2010).

[12] For example: See reference 10; The story of Dream, http://www.dreamsthelens.com/site.do?id=1018 (accessed March 2010);

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[14] Sheffield City Council Website, http://www.sheffield.gov.uk/roads-and-transport/maintenance/highway-design/tudor-square (accessed March 2010)

[15] Innovmetric Software Inc. (http://www.innovmetric.com)

[16] Rapidform (http://www.rapidform.com/)

[17] 3D Studio Max, Autodesk (http://usa.autodesk.com/)

[18] Mastercam (http://www.mastercam.co.uk/)