Digitally-Assisted Stone Carving on Canada's Parliament Hill

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In this paper, we discuss the results of a collaboration between the Carleton Immersive Media Studio (CIMS), the Dominion Sculptor of Canada, and the Heritage Conservation Directorate (HCD) of Public Works and Government Services Canada (PWGSC), on the development of a digitally-assisted stone carving process. The collaboration couples the distinguished skill of the Dominion Sculptor with digital acquisition and digital fabrication technologies in the reconstruction of a stone relief sculpture on the façade of the East Block building of the Canadian Parliament in Ottawa, Canada. A variety of digital technologies were used including, hand-held laser scanning, digital photogrammetry, 3d-printing, CNC milling, and robotic stone milling, in initial research for the fabrication of maquettes and the collaboration with the Dominion Sculptor.

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While there is much interest in the use of digital fabrication technologies in the design and construction of new buildings, there is little research being undertaken for the application of these same technologies in the conservation and rehabilitation of heritage buildings. At the same time, the digital datasets generated by laser scanners and photogrammetry, which can be utilized by digital fabrication equipment, have become integral to heritage documentation (Gilboa et al. 2013; Guarnieri et al 2010; Fatuzzo et al. 2011; Staley et al. 2009). Our research at the Carleton Immersive Media Studio (CIMS) develops new workflows and methodologies for computer assisted acquisition and fabrication in the rehabilitation of significant heritage assets. Ultimately, it is intended that these new methods of working will not only contribute to heritage conservation, but more generally undermine the hegemony of standardization that currently dominates the architecture, engineering and construction (AEC) industry. To that end, we are developing protocols for meaningful collaboration between architects and the craftspeople and fabricators that actually construct the elements of a building.

In this paper, we discuss the results of a collaboration between CIMS, the Dominion Sculptor of Canada, and the Heritage Conservation Directorate (HCD) of Public Works and Government Services Canada (PWGSC), on the development of a digitally-assisted stone carving process. This collab-
oration couples the distinguished skill of the Dominion Sculptor with digital acquisition and digital fabrication technologies in the reconstruction of a deteriorated stone relief sculpture on the façade of the East Block of the Parliament Hill National Historic Site in Ottawa, Canada. The Dominion Sculptor is responsible for creating significant architectural stone, wood, and bronze sculptures on Parliament Hill.

CONTEXT
Canada’s Parliament buildings were conceived in 1859 after Ottawa was chosen as the capital of the then Province of Canada. The three gothic revival buildings sit atop a rugged escarpment along the Ottawa River in the centre of the city. The Centre Block, which contains the House of Commons and the Senate, is flanked on either side by the West Block and East Block - each containing offices for senators and members of parliament. Over the next decade, a long-term work plan will see all three buildings rehabilitated.

The West Block was vacated in 2011, and interior finishes were removed to facilitate asbestos abatement and masonry consolidation. The HCD has been tasked with documenting the exposed masonry structure of the West Block during the rehabilitation using laser-scanning, photogrammetry and record photos. CIMS has been working with HCD to explore novel applications for the extensive point-cloud datasets being generated during the documentation process. One of these applications - the focus of this paper - explores the use of digital fabrication for the rehabilitation of traditionally cut sculptural elements.

TRADITIONAL WORKFLOW
There are a number of possible workflows for replacing a sculptural stone element on a heritage building. These are determined by the specific location, condition and context of the sculptural element and the building more generally - as well as the heritage conservation standards of that specific jurisdiction. While some of these workflows include removal of the sculptural element for the replacement or repair process - in the case of this project - the existing sculpture will remain in the East Block façade until the replacement has been carved. Further, the new sculpture is to be as exact a copy of the original as is reasonably possible. The traditional workflow described below, therefore follows these parameters.

The traditional process of re-carving a damaged or weathered stone sculpture begins with creating a copy of the existing stone sculpture. A mould is created of the sculpture that is to be replaced by applying a layer of silicone rubber to the stone, followed by a layer of plaster. The silicone rubber captures the fine details of the stone surface and the plaster provides rigidity for the mould. The two layers of the mould are removed from the stone, and filled with plaster to create the copy of the sculpture. The damaged or eroded areas are rebuilt on the plaster copy using modelling clay. The sculptor’s work in clay may be based on existing similar sculptures, historic photographs of the sculpture prior to the damage, or in the absence of any definitive evidence, the repairs are guided by the sculptor’s artistic judgement. When the sculptor’s work is completed, the moulding process is repeated and a second plaster cast is made to create a homogenous model that incorporates the sculptor’s work.

To transfer the geometry of the plaster model to stone, the sculptor uses a device called a pointing machine (Figure 1). Formalised in the 18th century, a pointing machine uses a large needle at the end of an adjustable armature to locate a single point in space on the surface of the plaster copy. The pointing machine is transferred to the uncut block of stone and the sculptor chisels away the stone until the needle reaches the same point, or more typically a few millimeters proud of the point. The sculptor roughs-out the stone by repeating this process of transferring a single point from the plaster copy to the stone over and over. The pointing machine is set aside after enough points have been transferred and the sculptor uses a variety of tools to add the final details to the stone sculpture.
Another common process in the rehabilitation of sculptural stone elements is to repair the element rather than replace the entire sculpture (Gimmer 1984). This is typically performed where a piece of the sculptural element has broken off and is missing. A model of the replacement piece is sculpted using modeling clay and fit into place on the sculptural element. A stone copy of the clay model is carved and affixed to the sculptural element using non-corrosive pins and epoxy.

DIGITALLY-ASSISTED WORKFLOW

Through the Carleton University School of Architecture, two main digital fabrication technologies are available to CIMS: a Dimension SST 1200es 3D printer and a large AXYZ three-axis CNC router. The 3D printer uses fused deposition modeling technology to build up thin layers of ABS plastic to create physical objects. In opposition to the 3D printer which builds up material, the CNC router removes material with a rotary cutting tool to shape an object from a block of material. The two different technologies have specific advantages and limitations. The CNC router can cut large objects up to 2440mm x 1220mm, but is limited to three axes of movement and therefore is not capable of creating "under cuts". The 3D printer has essentially no limits to the complexity of geometry that it can produce, but it is limited to objects smaller than 254mm x 254mm x 305mm. Relatively small objects of complex geometry are therefore more suited to the 3D printer. As a quick proof of concept to demonstrate to the various parties involved in the rehabilitation process what digital fabrication is, a gargoyle from the courtyard of the West Block was digitized using photogrammetry. The gargoyle was scheduled for repair because the wings were missing and required replacement. A maquette of the existing conditions was fabricated at 1:10 scale using a 3D printer. The ABS plastic gargoyle was well received, but it was learned that the masons working on the West Block work with 1:1 maquettes of damaged sculptural elements.

The next experiment was to fabricate, at a scale of 1:1, two sculptural elements - both in states of disrepair - with the intention that the masons could make use of these digitally fabricated maquettes. The first was a 1200mm wide sandstone tympanum that had eroded significantly since its creation in the 1860s and required a complete replacement. The tympanum was digitized using Photocall, photogrammetric software and due to its substantial size and regular geometry was milled using the AXYZ CNC router from medium-density fibre board. One side of the tympanum maquette was fabricated to show the current weathered condition and the other side was speculatively reconstructed using Rhinoceros modeling software to show what it might have looked like when originally constructed (Figure 2). The second sculptural element was a pilaster capital from the courtyard of the West Block, with a broken volute that required only repairing of the missing portion of the volute. The capital was digitized using a Creaform VIUScan handled laser scanner, and due to its freeform geometry and smaller scale was fabricated using the 3D Printer. The size
of the build area of the printer meant the capital was divided and printed in four pieces (Figure 3). While these modelling technologies and workflow were discussed with project managers and contractors working on the West Block rehabilitation project, the masons, while impressed with the technological feat of digitizing and fabricating the tympanum and capital, argued that their traditional methodologies were better suited for the task at hand.

OWL AND THISTLE RELIEF SCULPTURE
The West Block project is a wholesale rehabilitation with significant construction infrastructure in place including extensive scaffolding. Removing stones from the façade and even dismantling portions of the building is part of the rehabilitation process. The East Block on the other hand, is operating under normal day-to-day conditions without any construction infrastructure in place. As part of the ongoing preservation work undertaken by PWGSC, a single sandstone relief sculpture was identified on the façade of the East Block to be replaced due to its deteriorating condition. The sculpture features an owl among thistles carved into a 1725mm x 1120mm piece of Berea sandstone (Figure 4). It is found above the entrance to the courtyard on the 1910 wing. CIMS was ap-
Figure 4
The owl and thistle relief sculpture in its current weathered state.

proached to collaborate with the Dominion Sculptor and HCD on the task of creating a replacement carving, building on the initial investigations of the gargoyle, tympanum and capital, with the aim of extending the workflow beyond the fabrication of maquettes to include digital fabrication of the stone itself.

The owl and thistle sculpture is in poor condition, and actively deteriorating. The vertical face-bedding of the stone, combined with decades of erosion and freeze-thaw cycles have resulted in much of the carved detail in the stone de-laminating and spalling off. This is most evident on the face of the owl, and the lower right corner of the sculpture, which has completely disappeared.

Building on the workflow developed for the West Block projects, the digitally-assisted stone carving process developed for the East Block begins with creating a copy of the extant stone carving. Rather than using a plaster casting process to create a copy, however, the relief sculpture was digitized using photogrammetry. A series of photographs were taken with a D-SLR from a man-lift elevated to access the sculpture on the second story of the East Block. Using PhotoScan photogrammetric software, a polygon mesh model of the relief sculpture was generated. The mesh was optimized in Geomagic Studio in preparation for digital fabrication. From that digital model, a copy of the sculpture was milled from high-density polyurethane foam using the AXYZ 3-axis CNC router at the Carleton University School of Architecture. The foam maquette, taking the place of the plaster copy, served as the basis for the Dominion Sculptor to rebuild the damaged areas with modelling clay (Figure 5). With the modelling clay-overlay applied, the maquette was digitized again using a Creaform VIUscan close-range laser scanner.
Figure 5
The foam maquette of the relief sculpture with modelling clay applied.

Figure 6
The digital mesh model inclusive of the sculptor's work and digitally constructed moulding.
Knowing in advance that the clay work would be digitized the sculptor repaired two narrow sections of the surrounding moulding at the top and bottom of the moulding, rather than the entire moulding. Profiles of the narrow sections were extracted from the scan data and were used to digitally reconstruct the entire moulding.

From this second digital model (Figure 6), which incorporates the clay work of the sculptor and the digitally reconstructed moulding, the relief sculpture is being milled from sandstone using a 6-axis industrial robot. The robot will mill the sandstone to within 1.5mm of the surface of the digital model (Figure 7). This provides material for the Dominion Sculptor to remove using traditional stone carving tools in the process of adding details and textures to the entire surface of the relief sculpture. To ensure the end result of the robotic milling has the appropriate level of detail - enough for the sculptor to work without a pointing machine, but not unnecessarily excessive and time consuming - a series of test pieces were milled from foam to determine suitable milling parameters. After the sculptor's hand finishing is complete, the relief sculpture will be installed in the façade of the East Block building on Parliament Hill.

**RESULTS**

The integration of digital technologies into the workflow brings many benefits in the context of the East Block relief sculpture. One of the benefits of the process is in creating the initial copy of the existing stone sculpture. The traditional mould-making process is difficult to execute in-situ, on a vertical surface and requires the erection of scaffolding for several days. The digitization process requires only a man-lift for a few hours to take photographs or use a handheld laser-scanner. Additionally there is no physical contact with the stone if using photogrammetry and minor contact of small adhesive targets if using the Creaform VLIUscan. These non-contact technologies eliminate residues left on the surface of the stone from the silicone rubber moulding material. For a sculptural element that is too brittle and may be damaged during the moulding process, digital acquisition technologies provide an alternative.

The work of the Dominion Sculptor was reduced in the reparation of the surrounding moulding, as described previously. The digital construction of the moulding also allowed for a quick revision to the profile of the bottom section of the moulding after concerns about water drainage were raised. The moulding was revised digitally to ensure water sheds off the bottom of the moulding instead of collecting and contributing to the deterioration of the stone.

Most importantly, the digital technologies extend the capabilities of the Dominion Sculptor without supplanting them. All of the processes in the workflow that require a high level of skill or handcraft remain in the domain of the sculptor. The clay sculpting work and the appearance of the missing or damaged elements such as the feathers and the face of the owl, both require the same level of skill and knowledge of stone carving required whether digital technologies are used or the traditional workflow is followed. The interpretation of the original tool marks and the final finish applied to the stone using traditional stone carving tools are not replaced by the robot. The rebuilding work in clay by the sculptor provides the geometry of the sculpture for the
robotic milling process, but the texture and patterning of the clay is not intended to be the finish of the stone. The final tool marks can only be practically added by hand.

DIGITAL ANALOGIES

The production of stone sculpture has a long history of sculptor’s employing others, whether apprentices within their own studio or artisans outside their studio, to perform a variety of tasks including plaster casting and stone carving (Putnam 1939; Rich 1956). A typical workflow for a sculptor might be to create a clay maquette of a sculpture, have a stone carver perform the roughing out process with a pointing machine, and then the sculptor finish the stone carving process themselves. The Dominion Sculptor works essentially on his own, without the benefit of apprentices within his studio. Without apprentices to perform the roughing out process, the robotic milling process is seen as a digital surrogate. Similarly, laser scanning can be seen as a digital surrogate for the use of the pointing machine. A laser scanner is essentially a digital pointing machine measuring the position of millions of discrete points on the surface of the stone or maquette, whereas the pointing machine requires manual input to measure the position of a single point.

Another process that is analogous to a traditional stone carving technique is the digital construction of the moulding surrounding the owl and thistles. Traditionally, the replacement of a stone moulding begins with the creation of a profile traced from the existing stone moulding. The profile is used to make a template which guides the stone carving process of the new moulding. In the case of the digitally-modelled moulding, the first step was to extract a profile from the scan data from the two narrow sections of the moulding repaired by the Dominion Sculptor. The extracted profile was then used to generate the new moulding via the "sweep" command in Rhinoceros.

CONCLUSION

The work on the East Block relief sculpture used a hybrid digital/analogue workflow that takes advantage of the benefits of digital technologies, without inhibiting the skill of the Dominion Sculptor. The process of applying the hand finish has not begun, but the workflow has thus far proven to be a viable one. Additionally, the workflow need not be carried out in its entirety to be of benefit. Based on the available technologies and the level of skill and knowledge of sculptors and/or stone carvers available for a given project more emphasis may be placed on the digital techniques or on the traditional ones. For example, based on available craft-labour, creating a copy of the existing stone using the traditional silicone-mould and plaster casting process might be more feasible than the digital process, but at the same time there are no stone carvers available for the roughing out process. In this case, a plaster copy is created traditionally, repaired using clay by the sculptor, but the stone is milled robotically and hand finished by the sculptor. Alternatively there may be a scenario that the stone is extremely brittle and cannot be physically contacted, but robotic milling of the replacement stone is not feasible. The workflow can be modified so that the existing stone sculpture is digitised using photogrammetry, and a maquette is created using 3D printing or CNC routing, but the complete stone carving process is done traditionally by hand.

The workflow developed for the East Block project is intended for the replacement of sculptural stone elements in their entirety. Further research is planned in the area of sculptural stone repairs, where portions of the sculpture are repaired by attaching newly carved pieces of stone to the existing sculpture using metal rods and epoxy. This was the case of the gargoyle and capital described previously. Other areas of further research include exploring the limits of digital reconstruction prior to fabrication similar to the example of the tympanum, and the surrounding moulding on the East Block project.
REFERENCES
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