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Conserving Mesoamerican Stucco Facades Using Three-dimensional Imaging and Computer-assisted Fabrication for the On-site Installation of Replicas

The Late Preclassic masks on the terraces at structure 5C-2nd of Cerros are an instructive example important of stucco in Maya architecture. Erected about 50 BC, these masks represent the sudden introduction or innovation of pyramid decoration, a development coinciding with the public center building program that buried the village surrounding the site. These ornate monuments also show a fully articulated symbol system that predates the Maya system of writing (Freidel 1986:6). In other words, the many symbols that express the world view of the Classic Maya are presented at Cerros and many other sites *before* the development of formal writing. So it is, then, that structures which embody the emergence of Maya civilization and reveal a vital iconography that spans the momentous transition from prehistory to history are presented in that most fragile of building materials, stucco. The Roman poet Ovid observed in *Ars Amatoria* "What is harder than rock, and what is softer than water? And yet, the hard rock is made hollow by the soft water." Ovid's comments came shortly after the completion of the Cerros masks in a world away from Mesoamerica. The challenges of conserving monumental art today, however, confer upon his observations a premonitory tone. In one dramatic example of the accelerated weathering of monumental art, studies centered on the sandy limestones of St. Rombout's Cathedral in Belgium, documents the yearly loss of several tons of stone material washed from the cathedral by rain water (Roekens and van Grieken 1989:272). Monumental art worldwide is suffering such severe effects from pollution induced weathering that models for the synergistic complex of atmospheric pollutants must now be considered globally (Camuffo 1992:247). Sadly, the effects of acid rain have long been associated with Maya sites (Coe 1992:196; Kinoshita 1990:94; Dayton 1989:32).

The need to preserve stucco facades

Mesoamerican stucco facades are also lost to influences other than those produced by acid rain. Monumental art suffers the wet-dry cycle of a torrential rainy season followed by a desiccating dry season, producing a similar stress to the freeze-thaw cycle of other climates (Jones 1992:243). Hurricane Andrew in 1992 showed yet another threat as its produces cracks and fissures, thus creating opportunities for the destructive moisture path crossed the Yucatán peninsula and severely damaged several exposed stucco masks. Earthquakes, common in some areas of Mesoamerica, exact a further toll. Seismic activity penetration of the wet-dry cycle. Volcanic eruption can also rain abrasive ash and sulfuric acid droplets, scouring paint and stucco as at Palenque in 1982 with the eruption of El Chichón (Kinoshita 1990:94). Of all the urgent challenges to the conservation of stucco facades in Mesoamerica, however, there is a certain irony that issues attending tourism present the most significant problem. Beginning with early expeditions, impatient explorers used fires to clear the tangled forests surrounding Palenque thus damaging delicate reliefs (Stierlin 1964:141). In more recent times, the pressures of tourism result in similar compromises in conservation. The corrugated metal shelters at Bonampak, for example, raise the temperature during hot days and lower it during cool nights (Kinoshita 1990:95). Elsewhere, the soot belched by rows of idling tourist buses is blackening the murals of Tulum (p. 97).

Once unearthed and exposed, stucco monuments deteriorate in a matter of years. The fragile, powdery remnants of two-thousand-year-old stucco quickly crumble and fall from facades leaving only the rough-hewn blocks of limestone armature. It is within this context, then, that the economic development so vital to the nations of Mesoamerica has created a dreadful incentive to unearth and display stucco monumental art as it is discovered. Tourist revenues are the single largest source of hard currency for these areas. The result is that priceless monuments, rich in value both to science and to our cultural heritage, are exposed and lost forever to collect the tourist revenues of a few seasons.

The challenge of maintaining stucco

"Once you've found them, you may as well write them off," observes National Geographic Society archaeologist George Stuart. "That is why we want to record them — for all time." Although commenting on Maya murals painted on stucco (p. 97), Stuart's admonition is appropriate for the more exposed stucco of masks and bas-relief. The reasons for this concern lie in the unique properties of stucco. Employed widely in the massive program of monumental art begun in the Late Preclassic, stucco is a fine plaster obtained by firing limestone. When mixed with water, the resulting powder forms a workable paste-like medium. Maya artisans thus spread and sculpted delicate stucco facading over rough armatures of limestone architecture. Although stucco was commonly used as a surface for mural painting, a truly magnificent application was the creation of many large, anthropomorphic masks as a part of their program of public art. The largest yet known of

these sculptures is a giant mask over 16 ft high and 36 ft wide. Despite the splendor of these structures, stucco is nonetheless a material that required of the Maya a vigilant program of regular painting and repair.

Painting is a particularly effective maintenance technique because it fills and seals hairline cracks that otherwise enlarge and let in moisture (Grimmer 1990:119). Since painted murals are frequently recessed as at Chichén Itzá or Tulum and are also found in the interiors of buildings as at Bonampak, there are often detailed traces of the original pigments sealing and protecting the stucco. In marked contrast, masks and other bas-relief, originally painted in brilliant colors are often in a more exposed position. This frequently results in the complete erosion of protective paints and pigments. The original inhabitants of Palenque, for example, would be startled to see their monuments mottled by the stark white of exposed stucco and the black scale of pollution-induced weathering. As the weathering of paint and pigment progresses, the intricate detail of exposed stucco facades is structurally compromised. Most stucco monuments have portions that are seriously eroded or are crumbled beyond recognition. It is not uncommon, for example, for a facade once rich in iconographic information to be reduced to small pieces of rubble. Researchers then have no alternative but to painstakingly sift and sort stucco fragments no more than a few centimeters across (Coggins 1983:22). The reconstruction of a monument after it has fallen would be difficult enough if all the pieces were intact, but fallen stucco faces further problems. The impact often riddles the piece with minute cracks and the subsequent effects of acid groundwater and other destructive forces can result in the dissolution of the piece entirely (Sease 1988:113).

The lack of alternatives for conservation

Clearly, stucco facades are too fragile to display without some form of conservation effort. Conventional options, however, do not hold promise for solutions within the near future. There are, for example, ongoing experiments using silicone solutions to harden limestone against erosion, but it is not yet considered appropriate to apply this technology to carved stone (Jones 1992:244) much less to a material with properties as different as stucco. Similarly, other solutions such as acrylic copolymer resins have been used to consolidate crumbling stucco (Fernandez de Castro 1990), but the long term implications of these treatments are unknown. Indeed, the history of conservation technologies is full of well-intentioned and unexpected results. In the 1960s, for example, the Bonampak murals were injected with silicone to stabilize the walls. The silicone has since slumped and the murals are worse off now than they would have been if left untouched (Kinoshita 1990:95).

More expensive alternatives such as moving the facades involve enormous technical complexity and the process of moving is only the first step before a series of activities in the conservation laboratory (Sease 1988:116). Enclosing facades in a protective building is another possible action, although this introduces problems that range from compromising the general look of the site to temperature and humidity maintenance in remote areas. Both potential solutions, however, ignore economic fundamentals that make it highly unlikely the involved governments would commit precious resources for this type of project.

A final alternative for the conservation of many types of Maya art, one that will very likely dominate conservation efforts of the future, is to produce replicas and install them on location. Again, moving a stucco facade presents significant difficulties, but in many instances these facades can be stabilized to prevent further deterioration. Replicas that have been engineered to match the vapor permeability of the materials they duplicate can then be installed over the reburied originals to preserve both the original facade and the aesthetic integrity of the site. The critical issue in securing stucco facades, and other types of monumental art, is how to effect a high-quality reproduction. One obvious option is to have artisans or craftsmen sculpt the replicas. Efforts to craft reproductions of these subtle and intricate sculptures, however, have yielded unsatisfactory results and instead have confirmed the mastery of the original artists. Perhaps it should come as no surprise that a highly specialized artistic tradition that spanned hundreds of years can produce graceful lines and symmetries that surpass the artistry of modern masonry and its emphasis on the installation of prefabricated elements.

A different reproduction technique is to cast in materials such as plaster, latex and silicone. These have been used extensively on a variety of hard surfaces with good results. In fields such as paleontology and physical anthropology, casts of sufficiently high quality are obtained that the reproductions are of considerable value to researchers. The friable nature of stucco, however, precludes the use of any present or foreseeable casting agent. After attempting to cast in silicone the comparatively hard rock surfaces of petroglyphs, for example, Canadian conservators recently offered their experiences as a warning to anyone attempting to cast petroglyphs. Infrared spectroscopic analysis confirmed that a discoloration of the petroglyphs resulted from the presence of vulcanized rubber silicone (Wainwright 1990:69). Each potential casting technology, then, involves direct contact with the original and many require the surface of the original to be coated with an application of sealers or releases. Even minimal adhesion to the surface of a stucco facade would compromise the structural integrity of its surface. Thus, conservators of Mesoamerican stucco facades face a complex and momentous dilemma. Exhibited facades are subjected to accelerated destruction and yet the very real benefits of tourism and economic development result in the exposure and display of more of these fragile treasures. Unfortunately, the traditional options for conservation are inappropriate for this type of monumental art.

Non-destructive three-dimensional imaging

The idea of applying three-dimensional imaging to archaeological applications is not new. Technical developments in the 1970s and 1980s allowed some scholars to anticipate and experiment with various imaging and reproduction technologies (Dorrell 1989:251; Wainwright 1990:75; Taylor et al. 1987). There are today, then, several technologies that allow the capture of three-dimensional coordinate data and the delivery of that data to a computer. In essence, these devices capture sets of x , y and z coordinates, points in three-dimensional space relative to a reference. A single coordinate may be used to specify or measure the placement of a surface on a part. Two or more coordinates can describe the

orientation of a surface or the distance between two objects. Three or more points can describe planes. Ultimately, a dense enough set of coordinates can describe the surface contours and intricate features of a stucco mask.

The low end of commercially available three-dimensional digitizers captures or produces datasets used in applications such as manufacturing and quality control. Another, more prominent, role is the generation of three-dimensional datasets used in special effects animation sequences for television and film. Some systems use a probe that, when placed on an object and triggered by an operator, measures a coordinate by generating an acoustical, light-based or magnetic signal that is captured by three or more stationary receivers. By computing from the known position of the receivers, these systems triangulate on the signal produced by the probe and calculate its position in three-dimensional space. Other low-end systems illuminate the object to be digitized with points or planes of laser light and use a charge-coupled device (CCD) array offset from the laser source to perform essentially the same triangulations to measure the depth of the object. These systems vary considerably in price, portability, resolution and object size to be digitized. A few of these systems boast accuracies within hundredths of an inch, but the basic configuration of each technology is inappropriate for imaging monumental art. Some systems require target objects to rest on a tabletop rotating platform while others such as operator-triggered systems take too long to capture the thousands of coordinates necessary to render the complex surface of a sculpture.

The high-end of commercially available digitizers includes many truly impressive machines. Generally found in engineering-intensive applications such as the aerospace and automotive industries, these devices are frequently similar to low-end machines with the big difference represented by accuracies to millionths of an inch. Some systems consist of massive stone gantries weighing tons for the isolation of error-inducing vibration. These can profile precision parts for aircraft manufacturing, for example. Other systems are portable enough to check as luggage on an airline and yet accurate enough to use inside NASA rockets for inspecting vital dimensions. Some machines collect a limited number of highly-accurate points of data at a time for such uses as determining correct wing placement on planes. Other devices capture megabytes of scene-wide coordinate data within a several-second laser burst for close-range parts inspection. However, with one or two possible exceptions, this class of digitizer is constrained by tradeoffs in portability, data capture rate or related concerns.

Other technologies that could be adapted for three-dimensional imaging include such diverse fields as photogrammetry and ultrasonic imaging. Although photogrammetry is normally applied to terrain mapping, the contours of hills and valleys are quite comparable to the features encountered in a bas-relief sculpture. Moreover, the accuracy of close-range photogrammetry was used quite early in taking the overall dimensions of monumental art as a reference for future conservation efforts (Badekas 1976). More recently, photogrammetry and conventional surveying techniques were even used to construct a computer model of the Giza Sphinx (Lehner 1992). As with probe-based digitizers, however, the limitations of operator-directed point-by-point capture of data raise questions about how economically photogrammetry can be applied to this project. It should be noted that recent advances in the field hold some promise for increasing the data capture rate. Progress toward the automated

processing of photogrammetric images, for example, argues for a further review of this technology. Another concern involving photogrammetry, however, is the issue of estimates and subjective judgements required of an operator in digitizing certain contours (Wainwright 1990:76).

A second related option, ultrasonic imaging, passes a non-contact transducer or receiver over the surface of a sculpture while image processing software extracts coordinate data from the reflected ultrasonic images. An interesting potential of ultrasonic imaging is the capture of subsurface features such as the configuration of the stone armature beneath stucco. Although an acceptable resolution is possible, however, again the rate of data capture is unacceptably limited. The narrow physical width of the input signal on a high resolution transducer, in some cases but a fraction of an inch, would require too much time to capture a data set on monumental art meters in diameter.

A final potential option, which addresses most of the difficulties outlined above, involves a process known as *moire metrology*. In essence, this is the projection of structured light onto an object, its capture using a CCD array and the use of image processing software to extract three-dimensional data. More specifically, the projection of light through the superposition of two grids of similar period creates a pattern of wavy appearance often popularly called an optical illusion. Known as a moire fringe, this wavy pattern can be quite attractive and is often used in the graphic arts. Its value for archaeological conservation, however, stems from the fact that it is a field-worthy technology that can capture a high-resolution three-dimensional image. Laser holographic interferometry offers a comparable, if more complex, imaging technique. Ironically, it is one measurement method used to document the erosion rates of limestone in one study consulted while preparing this paper (Baedecker et al. 1992:147). Moire metrology, however, offers completely analogous options to laser holographic interferometry at a significant reduction in complexity and, accordingly, cost (Kafri and Glatt 1989:72).

The reproduction process

Following the acquisition of three-dimensional coordinate data, the use of image manipulation software is the first of several important tasks. In very large facades or very deep reliefs, multiple images taken from different angles may be required. Small reference targets placed in each image allow a computer to *mosaic* or *composite* the multiple images into an entire relief. Similarly, superimposing redundant images in a smoothing function is one of several other image processing techniques available to enhance the accuracy of the raw data. The next step involves the use of computer assisted drafting (CAD) systems and rendering software to perform the necessary design work. One important function, for example, is to decide what if any portions of an original sculpture are to be restored in the reproduction. The reconstruction of lost or damaged features is a powerful tool that has important implications for both conservators and researchers. Interestingly, efforts to reconstruct images of Maya sculpture date back around one hundred years as Teobert Mahler trimmed separate negatives to "restore" fragmented monuments (Graham 1990:43).

Similarly, three-dimensional images of sculptural fragments, even those in different collections, can be combined to produce an integrated replica. Draft versions of various restoration alternatives then can be distributed to conservators via disk or modem so that an iterative design process optimizes results. Computer simulation of different lighting schemes can model changing hours or seasons. Different color selections can help with a final design. Scale models can even be produced to preview the design before production begins.

A second aspect of this CAD work, however, is to engineer the structural integrity of the reproduction and its anchoring and fastening systems. Care should be taken in the structural engineering of the replicas and their placement over the monument to protect the original with a minimum of maintenance. Depending on the unique shapes involved and other site specific considerations, fabrication techniques may be modified from one reproduction to the next. Many engineering software tools interface with CAD systems to address this process. At the completion of design and engineering, a numerical control tool-path is then developed to drive machine tools and fabricate a replica. Although multi-axis equipment exists which can mill large prefabricated masonry blocks, a more cost-effective approach is to machine a master mold from an appropriate tooling material. In this way, multiple copies of the replica may be produced. Not only does this mitigate against accidents, mistakes in finish-out and other production challenges, it also offers the opportunity to distribute the cost of production.

Upon completion of a mold, then, several techniques may be employed in the casting of the replica. Interior, sheltered applications may argue for the use of any of several lightweight materials. Expanded polystyrene, for example, can be finished with an appropriate appearance but also enjoys the advantages of easy shipment, storage and installation. For outdoor display, however, a material such as glass fiber reinforced concrete (GFRC) is more appropriate. GFRC is a well-established construction material already used in the fabrication of intricate building exteriors. Because of its high strength, cast panels are thin, lightweight and durable. Not only can GFRC be integrally pigmented, it can be stained in a variety of colors. Another engineering requirement GFRC meets is that its vapor permeability can be controlled to exacting standards with various additives. Vapor permeability reduces the destructive effects of moisture being trapped against the original facade, a central reason materials such as fiberglass are inappropriate for conservation reasons.

Planning for the future

It must be stressed that the appropriate configuration of an imaging system is a product of carefully defining archaeological and conservation-related goals. Part of this specification, of course, deals with the processes that take place *after* imaging, the manipulation and output of various work-products. Project goals, however, also directly affect the imaging process itself because there are several other types of data that can be captured beyond three-dimensional coordinates. The acquisition of these additional images, then, can offer significant advantages at later stages in the image manipulation process. For example, a full-color image of the monument would not only be useful as a reference in the reproduction

process but the color image can also be mapped or merged with the three-dimensional geometries. In this manner, the original colors and textures of the monument's surface can be presented in a three-dimensional model, thus delivering richer information than computer-generated colors and textures.

Other general classes of data that influences both current and future research include specialized imaging techniques involving quantitative color analysis, color fluorescence, ultraviolet reflectance, infrared, infrared luminescence and infrared false-color image capture. Some imaging technologies even involve physical stress analysis that may be useful in assessing corrective measures to prevent the structural failure of a monument.

Finally, the importance of emphasizing both high-resolution and broad-spectrum imaging must be addressed. Given the many constraints facing conservation efforts it is obvious that over the next few years all or parts of many facades will be lost forever. Rather than serving as baseline images for future conservation and research, then, the images captured by this project may be the only comprehensive record of these monuments. It is therefore important to appreciate that the expense of mobilizing equipment and personnel argues for the broadest capture of data possible.

The emergence of conservation imaging

From the 19th-century illustrations of Frederick Catherwood to the early 20th-century works of Adela Breton, thorough and exacting reproduction of Mesoamerican art continue to support serious research. In an ominous portent for the future, however, the more recent contributions of Merle Greene Robertson and Ian Graham, among many others, have quickly become the only detailed records of the works now seriously compromised or lost forever. The dimensional expression of sculptural form, then, is a type of documentation that has been unavailable until very recently. The production of a replica, therefore, should be no more than the starting point in the use of these datasets. For example, a library of three-dimensional iconographic elements presents many research opportunities when combined with the digital image-processing techniques already endorsed by some researchers (Wainwright 1990:75).

Due to widely varying circumstances involving individual sites, researchers, funding sources and governments, each imaging project must also adapt to unique objectives. The fabrication and installation of full-scale replicas may not, therefore, be appropriate for every imaged monument. Remote sites with vulnerable monuments, for example, may be priority candidates for imaging only. An initial task, then, is to broaden the discussion of target projects with interested researchers. Defining project objectives and the work-product to be produced for each monument helps the draft of a comprehensive technical specification, a definition of the equipment and techniques required. As a further guide to establishing the project, similar conservation efforts throughout the world represent valuable resources. Rock art projects, for example, have not had a compelling need to employ three-dimensional imaging but there are a number of shared concerns. Projects in

Canada (Wainwright 1990) and Australia (Ward 1992), as well as endeavors in the United States, are among those that may be profitably consulted.

Another conservation effort more directly involved with imaging, however, is the Conservation Imaging Consortium (CIC). Founded in 1991 and based at the Getty Conservation Institute, the CIC is concerned primarily with the electronic imaging and image processing of two-dimensional art. One particularly relevant effort of the consortium is the Conservation Imaging Agenda, which is designed to orient vendors, consultants, researchers and potential funding agents to the R&D priorities of imaging projects (Mazor 1993:41).

Conclusion

It is not difficult to imagine a day soon when the names Pacal and Shield Jaguar are as well known to school children as are the names Ramses and Tutankhamen. With the ongoing decipherment of Maya hieroglyphics and other advances in knowledge and understanding, public interest and awareness of the Maya and in archaeology's role in telling the story is growing. It is equally true, however, which within a few brief years many examples of Mesoamerican monumental art will be lost forever.

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