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MUD Frontiers

Virginia San Fratello
San Jose State University, virginia.sanfratello@sjsu.edu

Ronald Rael
University of California, Berkeley

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BIO-MATERIALITY

MUD FRONTIERS

VIRGINIA SAN FRATELLO
EMERGING OBJECTS / SAN JOSE STATE UNIVERSITY
RONALD RAEL
EMERGING OBJECTS / THE UNIVERSITY OF CALIFORNIA BERKELEY

During the last 35 years, additive manufacturing has become commonplace within the realm of academic research as a tool for creating models and full scale working prototypes and, in very rare instances, it is used as a method of manufacture by specialists to fabricate custom componentry for buildings. However, additive manufacturing is still not close to being a commonplace method of manufacture within the construction industry due to the expense associated with the purchase of large, industrial 3D printers and robot arms. Additionally, many materials such as resins, bulk filament and pellets, and proprietary powders are expensive when used for large format printing and in instances where these materials must be shipped long distances. Finally, additive manufacturing requires expertise in 3D modelling and coding, which means additional costs and time must be spent mastering advanced software applications. For many end users, these obstacles have precluded the use of additive manufacturing as a way of building. This research aims to overcome these three obstacles through the development of a lightweight, inexpensive, and mobile robotic setup capable of 3D printing. The use of ubiquitous and free materials such as local soil for 3D printing, and the scripting of an easy to use g-code generator for developing 3D printable files, enables a more accessible, portable and ecological approach to additive manufacturing at the architectural scale (Fig. 1).

Context

The construction industry is one of the largest sectors in the world economy, representing up to 13% of global GDP and employing 7% of the world's population (World Economic Forum, 2016). It is also an industry with very low annual productivity increases, only 1% per year over the past 20 years, where less than 1% of revenues is invested in R&D, remarkably poor in comparison to other sectors such as the automotive or retail supply chain industries (Barbosa et al., 2017). Additionally, only 0.2% of all robots worldwide are sold to the construction industry compared to 55% sold to the automotive industry (Executive Summary World Robotics, 2018). To date, there are only a few examples where robots are predominantly used in the construction of entire buildings; some examples include: the Canal House Cabin by DUS Architects; the DFAB House by Gramazio and Kohler Research; and the Flotsam and Jetsam Pavilion by Branch Technologies. The mobile robot used as part of the MUD Frontiers project is designed to extrude traditional formulations of adobe

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and cob, made from clay, sand, silt, aggregate and chopped straw, with the capacity to print cement-based formulations as well. Other existing examples of robotic paste extrusion that can be found in the construction industry include: the Gaia 3D printed earth house by WASP; the Batiprint House, made of foam and cement; and several extruded cement 'showcase homes' by WinSun, ApisCor, and ICON. All of these buildings require specialised software knowledge by the designer and the builder. If more buildings are to be constructed using technologies such as 3D printing and robotics in the future, the industry will require either highly skilled digital talent to migrate to that sector, or a reduction in the skills required to use the requisite software and programming applications necessary to drive such new technologies.

The construction industry is the largest global consumer of raw materials, and accounts for 25 to 40% of the world's total carbon emissions (World Economic Forum, 2016). A return to mud as a building material attempts to correct the errors of a wasteful, polluting and consumptive industry. Ecological and sustainable issues are at the forefront of conversations surrounding the future of construction, and soil-based construction materials are the most 'earth friendly' materials that exist (Rael, 2009). Earth is a ubiquitous material and buildings made of local soils can be found in almost every region of the world. However, traditional and indigenous earth building knowledge is being lost in many parts of the world due, in part, to a shift from agrarian to capitalist societies. For the past 10,000 years until only recently, earth was the most widely used building material on the planet; but it has now been replaced by cement which is a contributor to 8% of the world's carbon dioxide emissions in its production (World Business Council for Sustainable Development, 2002). Nevertheless, there has been a worldwide movement to continue to build using unstabilised soils, in the form of rammed earth, adobe, cob, and the numerous other earth-based building technologies. A large number of earthen building codes, guidelines and standards have appeared around the world over the past two decades, based upon a considerable amount of research and field observations regarding the seismic, thermal and moisture durability performance of earthen structures opening the door for the nascent revival of building with earth.

Mobility: Portable Robotic 3D Printing

The MUD Frontier project is addressing the challenge of creating accessible robotics for construction through the development of a mobile and lightweight 3D printing set-up that can be transported easily to the field or jobsite. The scara robotic 3D printer that was developed for this endeavour is combined with a continuous flow hopper that can print wall sections and enclosures of up to 2200mm diameter circle and 2500 mm tall, structures considerably larger than the printer itself. The set up can be carried by 1-2 people and relocated in order to continue printing.

1. The fabrication setup.

2. High alpine 3D printing with local soils.

3. The fabrication setup.

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The robotic arm was developed for approximately $16,000, considerably less than the average price of a new industrial robot arm that costs $50,000 to $80,000 at this time, however it uses much of the same mechanical technology used in industrial robots.

Ubiquity: Local Earthen Materials

The printer is able to 3D print local soils directly from the work site in order to demonstrate the possibilities of sustainable and ecological construction in a two-phase project that explores traditional material craft at the scale of both architecture and pottery. The clays harvested for the projects are free, as they can be dug directly from the ground or surrounding region where the walls, enclosures and pottery are being printed. The material undergoes no chemical transformation, nor are any stabilisers, such as cement, added to the mixture.

Phase I of the MUD Frontier project took place along the U.S.-Mexico border in El Paso, Texas and Ciudad Juarez, Chihuahua, where earthen architecture and clay pottery of the Mogollon culture (A.D. 200-1450) define the archaeological history of the region. Excavated pit houses and above ground adobe structures defined the historic architecture of the region, and by A.D. 400 this region witnessed the development of a distinctive, indigenous coil-and-scrape pottery tradition known as Brownware.

Local, 'wild' clays were gathered from eight sites throughout the region and used to 3D print 170 ceramic vessels by local potters from both countries, reflecting current craft skills and recalling the coil pottery through additive manufacturing. A large 3D-printed adobe structure was also manufactured using largely the same material as the pots, but with the introduction of sand. The vessels reveal the nature of the local geology and the creativity of local ceramic artisans from the contemporary Jornada Mogollon region. The fired earthenware exposes a range of clay complexions: greens, browns, purples, wheat, pink and red colours that speak to the nature of mono, bi, and polychrome traditions that developed over time. The structure and vessels were produced with the intent of connecting the forefront of digital manufacturing with the traditional coiled pottery techniques, and subterranean and adobe architecture of the borderland regions between Texas and New Mexico in the United States and the state of Chihuahua in Mexico.

During Phase I, the robotic setup for printing the large structure was installed at the Rubin Center Gallery. The gallery was maintained at a constant temperature of approximately 20˚C. A mixture of five parts locally sourced clay and three parts sand was mixed with chopped straw and water and pumped through the printer. The layer height of each mud coil is 30mm and each coil is between 40 and 60mm wide. The overall structure is 213cm tall and 180cm wide and took seven days to print at approximately 300mm per day.

Phase II of the MUD Frontier project took place in the high alpine desert of the San Luis Valley which spans southern Colorado and northern New Mexico in the United States (Fig. 2). The second phase of the research reflects the earthen construction of the Indo-Hispano settlers of the valley and the local Rio-Grande pueblo culture. The 3D-printed and fired earthenware vessels from phase II take advantage of locally sourced, wild micaceous clay dug directly from the nearby mountains. The clay is used directly from the ground as both the clay body for printing and as a slip on top of the 3D-printed clay vessels. The vessels are fired in the 3D-printed kiln.

During phase II, the robotic setup was installed outside in the alpine desert of the San Luis Valley, Colorado (Fig. 3). The temperature of the valley floor fluctuated from a high of 30˚C during the day to 6˚C at night. The desert environment was sunny, windy with some rain over the sixty days of printing. It was observed that printing was most successful when the weather conditions were dry, sunny and most importantly, windy. The mud mixture used was wild, dug directly from the ground, sieved to a particle size of less than 6mm, and mixed with chopped straw and water. The clay/sand/loam mixture in this region has historically been used to make mud bricks and mud plaster for local buildings and there is a tacit understanding among the community about where to dig

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for the mud and how moist it should be. The mixture proved to be very well suited for 3D printing coiled mud structures. The layer height of each mud coil is on average 30mm and each coil is between 40 and 60mm wide. Four structures were printed of varying dimensions, however it was observed that under ideal weather conditions an average of 400mm in height could be printed every 24-hour period.

The research during phase II was conceptualised under four themes: The Hearth, Beacon, Lookout, and Kiln. The Hearth explores the decorative aspects of structure (Fig. 4). The structural reinforcement of double-layer earthen walls creates a simple interior environment and an exterior that has structural expressiveness. The thin mud wall construction is reinforced using local, rot-resistant juniper wood to hold the interior and exterior coiled walls together. The wood sticks extend beyond the walls of the structure on the outside, and are flush on the inside, referencing the cultural differences between the architectural traditions of Pueblo and Indo-Hispano buildings. It also recalls traditional African architecture such as the Mosque in Djenne, where the wood sticks protruding from the building are not only decorative but also used as scaffolding. The interior holds a 3D-printed *tarima*, or mud bench, surrounding a fireplace that burns the aromatic juniper (Fig. 5).

The Beacon is a study in lightness, both illumination and weight. It explores how texture and the undulation of the 3D-printed coil of mud can produce the thinnest possible structural solution for enclosure. These coils are then illuminated at night, contrasting the difference between the concave and convex curves that create the mud walls.

The Lookout is an exploration in structure; the 3D-printed staircase and mezzanine are made entirely of mud. A dense network of undulating mud coils is laid out to create a structure that can be walked on. This also demonstrates how wide yet airy walls can create interior enclosures that represent possibilities for insulation, especially in the harsh climate of the San Luis Valley which can drop below -29°C in winter (Figs 6, 7).

The Kiln explores several of the techniques discussed, including undulating/interlocking mud deposition to create structural and insulative walls. The Kiln is also used to enclose an area that draws in oxygen and keeps in heat to fire locally sourced clay with a juniper wood fire, which burns hot (Fig. 8).

Democracy: Software

Custom software, called Potterware, was created to be the underlying control for the 3D printer. In its most accessible form, it is used to design the ceramic vessels. A more robust version is employed to design the walls and enclosures created by the robotic 3D printer. The software is an intuitive design application for 3D printing, that runs in the cloud from a typical web browser, such as Google Chrome; it features easy-to-use sliders and automatically generates printable g-code files, alleviating the need to learn 3D modelling software, meaning instead that a novice user can quickly begin to create complex g-code to 3D print functional pottery or earthen environments. Objects, walls and enclosures, at the scale of rooms, can be designed and ready for printing within minutes.

4. The Hearth exterior viewed from the east.

5. The Hearth interior.

6. 3D printing The Lookout substructure.

7. The Lookout stair during construction.

8. The 3D printed kiln.

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Conclusion

The MUD Frontiers project re-examines and conceptually unearths traditional indigenous building traditions and materials using 21st century technology and craft coupled with local labour to explore new possibilities for ecological and local construction techniques. Based on the research so far, the robotic printing of local soils shows promise for the rapid creation of robotically-crafted, geometrically complex, buildings that are durable and structural, using wild clays that have historically proven successful in building construction. Further research is needed to understand how the surface of the 3D-printed mud will weather over time, but by studying traditional earthen buildings in the region, these structures' longevity will require only a roof and occasional maintenance to be viable as long-term enclosures. The current size limitation of the printer is a drawback and the creation of a new printer, with a longer arm, that can print larger 'rooms' is desirable. Next steps include creating 3D-printed mud buildings that can be fully sealed which means addressing how elements such as roofs and doors can be factored into the printing process. Upon their 40th anniversary, the *Smithsonian Magazine* announced the 40 most important things they believed one should know about the next 40 years. Number one on their list was that 'Sophisticated Buildings will be made of mud'. MUD Frontiers aims to see this prediction become a reality.

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