Fusing design and construction as speculative articulations for the built environment

Stig Anton Nielsen[1], Alexandru Dancu[1]

[1]Chalmers University of Technology, Dept. of Architecture, Göteborg, Sweden

ABSTRACT: Dry stone constructions date as far back as 9000 BC and are associated with the first stable human settlements in the cradle of human civilization. Agricultural tools and permanent settlements led to sustained domestication of crops, and consequently a continuous co-evolution of humans and their environment.

The tools adopted widely by contemporary society are related to processing and visualizing information. It has been suggested that based on the information gathered from the environment, architecture itself could become responsive to the real environment.

This research seeks to attain a constant modification of the built environment on a small scale, rather than a large scale stepwise engagement. We suggest that representations of information should be closely coupled with the built environment, and that the built environment should be conjoined in real-time communication with multiple different representations, enabling sense-making and suggesting potential future states.

Through physical construction and design experimentation, representations of potential modifications, or articulations, are overlaid onto the environment. It is however important that these articulations be in constant flux based on the ongoing communication between environment and representations of it.

We propose a computational material supported by a framework that would link computation and environment in constant bi-directional communication and continuous, stepwise development.

We propose a methodology composed of scanning the environment, real-time computation, guidance, and construction visualization that would lead to a new approach of evolving the digital into a new physical reality. Future mixed reality architecture applications could make use of computational composites in order to fuse design and construction.

KEYWORDS: Dry Stone, Mixed Reality, Computational Composite, 3D Scanning, Augmentation

INTRODUCTION

Dry stone constructions are found throughout history and date as far back as 9000 BC (Schmidt, 2000). They have been associated with the Fertile Crescent and the first human settlements, as the source for human civilization transitioning to a society with stable settlements. The agricultural tools and permanent communities led to sustained domestication of crops, and consequently a continuous co-evolution of humans with their environment. (Brown, 2009) (Harris, 1989). The most influential tools adopted widely by society today are related to processing and visualizing information. Architecture has not been ignored by the information processing revolution. It has been suggested that based on information gathered from the environment, architecture could become “responsive to evolving in not just a virtual but a real environment” (Frazer, 1995).

In this paper, we suggest linking physical environments, based on their optical properties, to digital processing capabilities with the purpose of fusing design with construction. We exemplify how to achieve this by implementing a framework that supports the construction of dry stone walls on site in real time. The construction process requires natural stones of any size, a mobile display, a depth sensor, and a computing device.

We obtain insights and find the requirements needed to build a dry stone wall through an experiment that employs human skills that could in future be replaced by computational capabilities. As the design and construction process becomes augmented by sensors and computation, we speculate on distinct types of articulations and communications that could occur. Material and visual articulations both become embodied in the fabric of the environment.

Societies and cultures change rapidly, and computation can be used in the built environment to follow, articulate, and accommodate constantly changing needs at the speed which they arise. If indeed our future condition will be that of energy and material scarcity, the construction industry—starting with architects—should consider the standing building stock as their main matter to work upon and modify, upgrade and accommodate to changing needs. Rather than large scale interventions, where demolitions are necessary to make way for entirely new constructions, small scale iterations should constantly improve and adapt spaces, buildings, urban space, and city parts.

As such an approach requires a vast understanding of existing spaces, buildings, and the spaces in between, we need systems and techniques to modify the high complexity of the existing built environment. In addition, as this approach would lead to an increase in the number of interventions at different locations, we must invent tools to manage these multiplicities both locally and city-wide. In order to link computation and environment, representations must be closely overlaid with the natural and the built environment in constant communication with the computation system. Through sensors, representations, and articulations, computation can become embodied within the environment.

Cognition in changing environments and the handling of non-uniform objects is not a trivial task. In 1991 Rodney Brooks published the article '*Intelligence without representation.'* He proposed constructing robots using a type of cognition system different from traditional AI, which tries to create for the robot an internal cognitive model of its surrounding environment. Instead, Brooks' robots successfully use the environment as its own model (Brooks, 1991). Additionally, Christopher Alexander's research on vernacular architecture suggests that using the environment and matter as its own model has actually been performed successfully over centuries. Immediate interactions between users and the built environment have been the driving forces behind the vernacular traditions (Alexander, 1964).

In this paper we will discuss an experiment relying on multiple computational processes that guide a physical construction. We will discuss how potential modifications and articulations can be overlaid onto the environment and how to achieve a bi-directional communication between the virtual and the physical.

1.0 Mixed reality in architecture

Augmented Reality Aided Design has been proposed for architecture because it could enhance decision making, assist in the understanding of complex spatial arrangements, and offer information that would be "*displayed where it occurs*" (Seichter, 2003). Seichter focuses on design sketching in augmented environments, pointing out the importance of representation and interaction for "*perceptive performance.*" More recent work in immersive projected environments is the embodied interface for collaborative 3D sketching (Dorta, 2014). Novel interaction and visualization techniques have been proposed for use in architecture sketching.

Abboud identifies opportunities and obstacles for mobile augmented reality (MAR) in design, construction, and post-completion, supported by a number of use cases for each phase (Abboud, 2014). Opportunities identified for MAR are: overlaying a site with the intended virtual design, scale and clash detection can be explored by overlaying virtual objects on top of physical markers, augmented physical presentation media would overlay 4D data, such as traffic flows, shadow studies, and wind flows to inform the design process, communicating architectural narratives, and as a new interface between the virtual and the real. The latter opportunity does not present a use case, but the author suggests that

> *AR will continue to alter this understanding and perception of the built environment. Architects would do well to consider the possibilities enabled by AR, and seek to involve themselves in the design of future places that straddle the digital and real.*

In this paper, we overlay a site with virtual objects by using inherent markers, but also create a new interface between the virtual and the physical. The overlay was enabled by using a depth sensor and a state-of-the-art real-time reconstruction software (Niessner, 2013) that enables scanning the environment and the granite. The new interface is created by fusing design and construction, and proposes a new use case that, to our knowledge, has not been yet identified or explored, namely assisting real-time dry stone wall construction based on locally available materials. For these reasons, we would not call our work Augmented Reality, but rather Mixed Reality on the continuum between the virtual and what is, or becomes physical (Yuichi and Tamura, 1999; Tamura, 2001).

1.1. Computational composites

Vallgårda and Redström introduce the concept of the computational composite, which suggests using computation as a material and how this should be combined with other physical materials (Vallgårda and Redström, 2007). In order to develop a computational composite useful in dry wall construction, the experiment needs to have a source of input, data computation, and a way of directing the output data to the correct position in the environment. We do not create these systems from the ground, instead we employ low-cost hardware and state-of-the-art open source components to make up our framework.

When creating physical material composites the amount of each component as well as the contact method determines the success of the composite in attaining the intended properties. In our experiment, the computational component is inherent and ingrained to the surface of the stones. We use the visual appearance of the granite as a strong, accurate “glue” for the computation to adhere to. The surfaces are good for the purpose, because they are different for each side of the stone and unique for each stone. Consequently, the computer vision system is able to attach to them accurately because it can identify each unique surface. As non-embedded sensor systems usually need orientation within global cartesian coordinates, this visual adhesion effectively manages a bi-directional flow of information, and lets the matter and computation become embodied as a composite.

1.2. Fieldstone and dry stone walls

Among the first permanent human settlements are those associated with the Fertile Crescent dating back as far as 9000 BC (Schmidt, 2000). With the emergence of stable settlements using dry stone, the ground was set for human civilization. Setting dry stone constructions does not require mortar, but rather works by carefully selecting stones that interlock with each other to create a stable body. This selection process is not trivial, so it led to carving stones symmetrically so they would be easy to assemble. Carving requires tools, intense time and energy. In this paper, we propose minimizing the stone fitting selection process through machine computation.

Fieldstone is the common natural stone found in the surface soil of farmlands and forests. The structure and properties are different depending on the local geological conditions. For centuries farmers have been ridding their lands of stones for the purpose of farming, creating dykes from the piled stones. Dykes and dry stonewalls can have many purposes and degrees of sophistication. Walls can containing livestock, or secure soil from erosion, and are often seen holding terraced fields in place. Common among them all is that they do not use mortar, relying on compression forces, and in some cases built with a technique using interlocking stones. The advantages of the permeable structure of a drystone wall are many, for example water drainage and habitation, encouraging biodiversity (Thompson, 2006).

As our experiment was based in Sweden where the ground is rich with granite, we found this a natural choice of material. Most historical structures of fortification in Sweden used granite, but for modern constructions only the foundations are set in granite. For our experiment we found large amounts of chopped granite available near the university campus. Because granite contains different minerals, the surface texture is often very distinct and full of contrast, unique for each stone and every side of the stone. This makes it well suited for state-of-the-art pattern recognition.



Figure 1: A natural granite stone with scale markings on three sides.
Figure 2: The pattern of the side marked B.
Figure 3: This seemingly homogenous pattern of another granite stone also used for pattern recognition.

Figure 4: Galloway dyke on Fetlar, Shetland Islands, UK.
Figure 5: The Lion Gate of the Mycenae acropolis is a dry wall.

2.0 EXPERIMENT

2.1. Building a natural stone wall

Building good solid dry stone constructions requires a high level of skill, and the process is inherently indeterminate. Normally it is not possible to plan more than a few stones ahead, and the structures will be asymmetric and are never the same. Despite the repetitious process of placing stones the situation is constantly changing, unlike the process of bricklaying masonry. The experiment focuses on some aspects within automation which are already defined as difficult, namely that of uncharted changing environments and the handling of differentiated elements (Benedict and Osborne, 2013). The difficulties of constructing with natural materials in a constantly changing environment makes it an intriguing challenge.

An architecture student shared his experience and the difficulties involved in building a stone wall, using naturally shaped granite stone and mortar, as part of his Masters thesis. Figures 6, 7 and 8 show one of his walls under construction. His first hand description follows:

> *The hardest part was finding a good fit for the stones, and searching for a good shape. Also if you arrange a few stones that fit together on the wall, you have to remove them in order to apply the mortar. And then you immediately lose track to where they fitted.*
> *We built a concrete block wall of the same size in around 4-6 hours. But I am an amateur builder of course, and only have good technical knowledge of masonry. Although we did try to hire professional masons, they didn't know how they would do it with irregular stones. And they were really reluctant to give it a try.*
> *So it's hard and time consuming, but it seemed like a good idea at the time to use the material on site.*

Figures 6, 7 and 8: The natural stone wall here is not a dry wall, but rather bound by mortar.

2.2. Insights and building steps

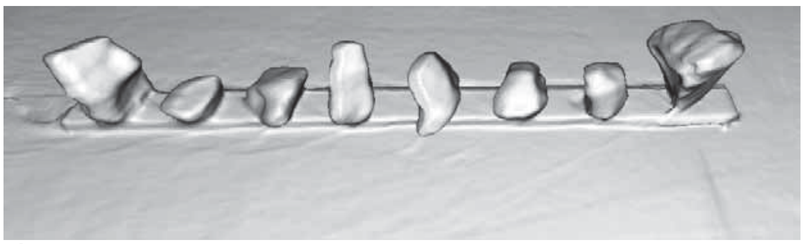
To list the difficulties: A) Choosing a stone, B) Finding a suitable location for that stone, C) Applying the mortar, and D) placing the stone in the same location on the wall after applying mortar.

Then the procedure A through D is repeated until the wall is finished. The unskilled builder describes several difficulties, firstly step B: Finding a good fit for the stone and secondly, step D: replacing the stone after applying mortar. Of course if one chooses to build a dry stone wall, the replacement step is eliminated, but when studying videos demonstrating craftsmen building dry stone walls, it is clear that the most time consuming part is moving the stone around until it fits in a stable position (Switzer, 2011).

We need to describe the steps in the process in order to construct a computational composite, therefore we need to break it down into three computational steps.

i) Scan the physical environment and granite using an off-the-shelf depth sensor (Kinect) and state-of-the-art reconstruction/scanning/mesh software, to label the granite.
ii) Stepwise computation and positioning of the granite to satisfy certain criteria and predict/propose the next placement (step) in the construction process.
iii) Real-time visualization and feedback of the state of construction.

Firstly we use a state-of-the-art 3D reconstruction method, to scan and represent the stones in a virtual physics simulation. We used a commonly available game engine with physics simulation and were able to iteratively test different placements of the stone. Once a good fit is found, the location is passed to the static surfaces or trackers which we know are existing in the environment. This way, through the use of pattern recognition, we are able to identify a relative location in the environment and present the different possible locations for the stone using augmented reality on a smartphone, tablet, or laptop. The next sections will describe these steps in more detail.



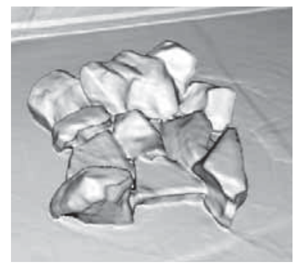


Figure 9: Individual scanned stones.
Figure 10: Scanned buildup.

2.3. Scanning environment and granite

The scanning process consists of two main parts: scanning the initial environment where rocks will be placed (Figure 10) and scanning individual stones (Figure 9). The state-of-the art reconstruction method used for scanning (Niessner, 2013) proved to be robust in tracking and allowed us to acquire large environments. In our setup, we fixed the stones in styrofoam and scanned them all at once and then in post processing cut and patched the meshes.
The rock meshes were processed using the Meshlab software version 1.3.4. Individual stones from the large mesh containing 6 stones were cut by deleting the vertices of the other stones.
Then, based on the remaining vertices, the operation was run by selecting in Meshlab: Filters > Normals, Curvature and Orientation > Compute Normals from point sets (Neighbour number = 10, Smooth iteration = 0). To fill the holes that originated from deleting the base vertices, Poisson reconstruction was performed by the operation: Filters > Remeshing, Simplification, and Reconstruction > Surface Reconstruction: Poisson (Octree: 6, Solver Divide: 6, Samples per node: 1, Surface offsetting: 1), followed by a mesh reduction of polygons through the operation Quadratic Edge Collapse Decimation (Target number of faces: 255).

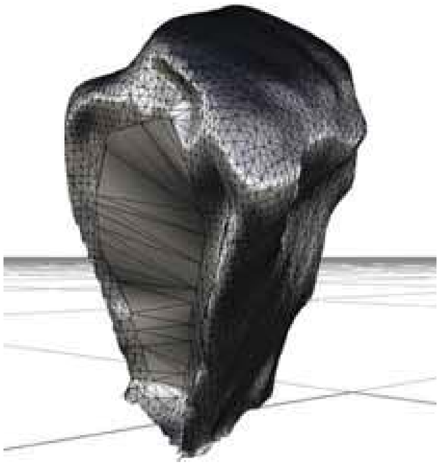


Figure 11: Mesh model of a scanned stone before of mesh processing.

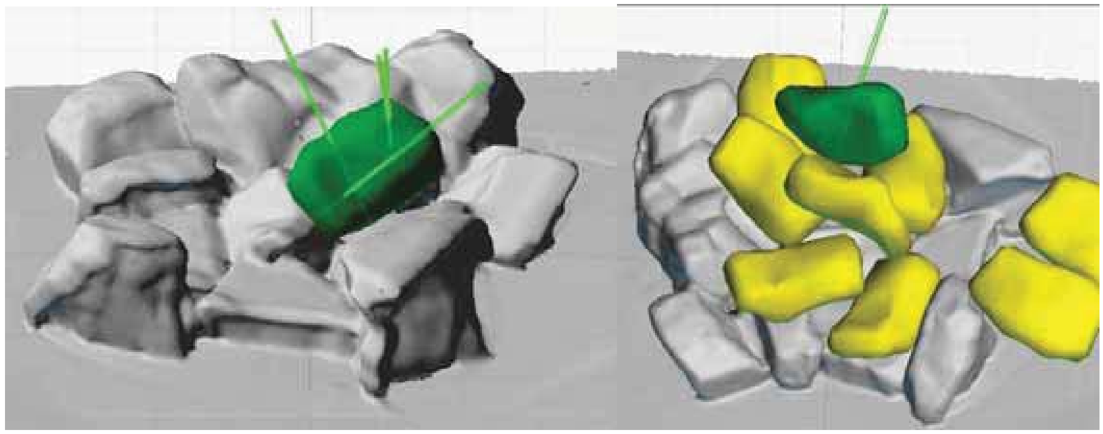
2.4. Stepwise computation and placement of the granite

Placing and arranging a rock was implemented through a virtual physics engine, Unity, which can define meshes as objects with physical properties. Such objects will collide with each other and, based on the settings of their physical material properties, they can simulate bouncing elasticity and set the friction level. We implemented a script for dropping stones from different locations, with different rotations over the existing wall, and based on a set of criteria, decide whether it obtained a good placement or not. By manipulating the timescale in the Unity game engine, many iterations can be rapidly calculated.

A stone wall can have different purposes, but the main criterion is always that it should be stable and robust. The criteria for which we evaluate the position of the stone were therefore that the stone should be placed on the existing stones with well distributed points of contact, and that the surfaces of the connection should all be as horizontal as possible to lead the forces down and not to let the stone act as a wedge splitting the wall apart. Many other criteria can be important, such as to plane front alignment with intended front surface, as well as solidity.

The physics engine allows for opportunities entirely different from the physical world, and we made use of this in a few ways. Because the physics engine can change simulated physical properties of both environment and the stone instantly, we were able to create a stone that was slightly slippery and not bouncy in order to let it quickly find a good position. Then once a position that satisfied the two criteria is found, we can instantly stop its movement and change its physical properties to that of a real stone, so that friction would hold it in place and its mass would let it lie undisturbed by a newly instantiated stone that would then try to find its position iteratively.

We have not yet implemented criteria for creating a smooth outer surface of the wall or for optimizing volume or space fill, but the physics engine certainly can facilitate these opportunities.



Figures 12 and 13: A stone finding its place, while the game engine evaluates the criteria for the normals and contact points.

2.5. Visualization and construction guidance

The 3D models of the granite were overlaid and aligned using the pattern recognition and extended mapping capabilities of the physics engine Unity and the augmented reality software platform Qualcomm Vuforia. Having a suitable placement of the granite rock in the virtual environment, we need to go ahead and place it in the actual environment. For this procedure we make use of a combination of commonly available hardware, namely an Android smartphone running Vuforia. This software allows us to assign flat surfaces from the stones as three dimensional placeholders. As all the stones have natural and unique patterns on the surface, we can let the pattern recognition of the Qualcomm software track them. As mentioned previously, the natural pattern of the granite stone has good properties for being recognized by this software.

We traced a scale on several flat surfaces of each stone, and photographed each of them perpendicular to the surface. These images were then placed in correct scale on the virtual mesh model of the stone within Unity, using the plugin for Qualcomm Vuforia. When recognizing the image tracker, the software can orient and scale an associated model in relation to the camera on the smartphone, and the three dimensional model is rendered on top of the camera image, appearing as if placed statically in the real-time video. As either the camera or the image tracker, i.e. the surface of the stone, is turned, the 3D model is updated with the new position in space, allowing us to fully explore the 3D position of the model in relation to the physical environment

Figure 14: Augmented mesh model of stone shown on top of existing conglomerate of stones.



Figure 15: A sample stone.
Figure 16: The tracker from the surface of the sample stone.
Figure 17: View through the camera with the sample stone overlaid by the mesh model and following the movement of the stone in free air, as if it is draped over the stone.

3.0. DISCUSSION

Humans have always adapted successfully to their environment. Currently, their development happens in parallel with the advancement of widely adopted information technology. The digital environment shapes the way we think and the way we live. We can draw a parallel to the first permanent human settlements constructed from dry stone, which led to the beginning of civilized life for early societies. Similarly, computational materials like the one proposed in this paper, can lead to a new approach of evolving the digital into a new physical reality.

When using virtually overlaid models correctly positioned in the environment, we are able to both guide and change the next step instantly. The gap between design and construction is being closed, and the design phase does not need to stop as construction commences. But if we are supposed to make these technologies act in an urban setting where actual needs must be met and slightly larger scale modifications are made, we could ask if real time is in fact sufficient or if we may need to forecast and predict near future events and necessities.

There are also other considerations of environmental interest in that we make use of locally available materials, which can significantly reduce the environmental impact of buildings. Currently the use of natural stone presents more disadvantages that the additional cost of fabrication and transport of homogenous materials, although smart use of technologies may change this. 3D reconstruction software has limitations. It may lose track of the camera position if there are not enough features to track in the image. In this case, scanning needs to be restarted because the obtained mesh is broken.

CONCLUSION AND FUTURE WORK

We showed the potential for using mixed reality and closely linked representations in a real-time computational construction process. For this particular computational composite, it turned out that the aspects of non-uniform natural materials was a good way to bind the computation to the matter by using pattern recognition. Natural materials such as granite are comprehended better by visual recognition systems than more conventional modern homogenous materials. We experimented with the variable aspects of a physics engine that was used to compute and augment human construction skills. Future mixed reality architecture applications could make use of computational composites in order to fuse design and construction.

REFERENCES

Brooks, Rodney A. 1991. "Intelligence without representation." Artificial intelligence 47.1: 139-159.

Rieffel, Marc A. 1995. “Induced representations of C* algebras”, Advances in Mathematics 13.2: 176-257.

Alexander, C. 1964. “The synthesis of form."

Vallgårda, A. and Redström, J. 2007. “Computational composites” Proceedings of the SIGCHI confere Human factors in computing systems. ACM.

Switzers Nursery & Landscaping (2011) https://www.youtube.com/watch?v=owTnhZ_TOx8

Frey, Carl Benedikt, and Michael A. Osborne. 2013. "The future of employment: how susceptible are jobs to computerization?."

Abboud, Rana. 2014. "Architecture in an Age of Augmented Reality."

Thompson, A. 2006. “The Character of a Wall. The changing construction of agricultural walls on the island of Gozo” Omertaa Journal of applied anthropology

Wilson, Michael R. 1980 "Granite types in Sweden." *GFF* 102.2: 167-176.

Unity, 2014. http://unity3d.com/unity/download (The Pro version was not required in our experimentation)

Unity Extension - Vuforia v3.0, 2014. https://developer.vuforia.com/resources/sdk/unity

Brown, Terence A., et al., 2009. "The complex origins of domesticated crops in the Fertile Crescent." *Trends in Ecology & Evolution* 24.2: 103-109.

Schmidt, Klaus, 2000. "Göbekli Tepe, southeastern Turkey: A preliminary report on the 1995-1999 excavations." *Paléorient*: 45-54.

Harris, David R., 1989. "An evolutionary continuum of people-plant interaction." *Foraging and farming: the evolution of plant exploitation*: 11-26.

Frazer, John, 1995. "An evolutionary architecture."

Seichter, Hartmut, 2003. "Augmented reality aided design." *International Journal of Architectural Computing* 1.4: 449-460.

Dorta, Tomas, Gokce Kinayoglu, and Michael Hoffmann, 2014. "Hyve-3D: a new embodied interface for immersive collaborative 3D sketching." *ACM SIGGRAPH 2014 Studio*. ACM.

Abboud, Rana, 2014. "Architecture in an Age of Augmented Reality."

Milgram, Paul, and Fumio Kishino, 1994. "A taxonomy of mixed reality visual displays." *IEICE TRANSACTIONS on Information and Systems* 77.12: 1321-1329.

Tamura, Hideyuki, Hiroyuki Yamamoto, and Akihiro Katayama, 2001. "Mixed reality: Future dreams seen at the border between real and virtual worlds." *Computer Graphics and Applications, IEEE* 21.6: 64-70.

Niessner, Matthias, et al, 2013. "Real-time 3d reconstruction at scale using voxel hashing." *ACM Transactions on Graphics (TOG)* 32.6: 169.

Collins, Brian, et al. 1995. "The Dresden Frauenkirche-rebuilding the past." *BAR International Series* 598: 19-19.