Self Replicating Robotic Strategies as a Catalyst for Autonomous Architectural Construction

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Abstract. The research explores examining future trends in robotics and how they can be applied to spatial interactive architectural environments. The strategy of using modular robotics of architectural space-making demonstrates an architecture whereby adaptation becomes much more holistic and operates at a very small scale. The strategy of using self replicating strategies as a catalyst for autonomous architectural construction was very much driven by the premise of an advanced architectural design studio. This paper highlights conceptual contributions by architecture students for alternative means of Martian Colonization through means creating architecture that creates itself. The parameters of the design project had three primary considerations including: The actual trajectory issues (how to get materials to the Mars), Chemical Processing (how to make materials on the Mars) and Space Manufacturing (how to fabricate and assemble/construct things on Mars). Of these central issues explored in this studio, the focus was primarily on Manufacturing as a process carried out by small modular robotics. The premise of the approach is that rather than sending a constructed architecture to space, we send tiny robotic modules that are capable of mobility and reproduction through automated fabrication techniques using in-situ materials. The modules with embedded sensors, self-healing composites, and responsive materials were designed to construct buildings aimed at adaptation. Such buildings could potentially respond in a humanlike way to counteract loads, reduce material and allow for active environmental adaptation. When enough of architecture of the colony has constructed itself – we send humans to inhabit it.Several examples by architecture students are highlighted whereby individual modules were created within the context of a space architecture design studio and applied to scenarios of space making at various scales. The design context primarily focused on the master plan of a colony for 10,000 inhabitants. The colony is an assembly of numerous discrete yet interconnected projects that include residential, public, civil, industrial, commercial, research, healthcare, and farming etc. The environment on mars was also seriously considered including: gravity, pressure, radiation, and the mass balance of resources and waste required for sustaining human life at such a scale. Students worked in teams of two to produce complete colony designs including the detailed development and a construction/ fabrication concept for one of the buildings. Students developed scaled prototypes of the system that successfully demonstrated the robotic aspects of their project. Physical models demonstrated actual robotics, structure and materials. Biomimetic strategies were employed as a means to satisfy adaptability in terms of form, processes, and systems. Central to biomimicry

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within the context of the work was an understanding of the process by which organisms grow and develop including includes growth, differentiation, and morphogenesis. In terms of adaptation, the area of morphogenesis was primarily studied as a means to create an architecture that ensures a continuous turnover of cellular-like robotic modules that dynamically ensure mechanical integrity similar to that of a living, evolving system.

The projects successfully demonstrate various strategies for mechanical design, locomotion and control.

Keywords: Modular Robotics, Architectural Construction, Space Architecture, Habitat Construction, Robotic Construction, Interactive Architecture.

1 Introduction

The strategy of using self replicating robotic strategies as a catalyst for autonomous architectural construction was very much driven by the premise of the advanced topic architectural design studio. Space Architecture is an ideal test bed to explore many of the basic interfaces which concern humans in a different way and that puts the subject of architectural construction into a different perspective. This particular was taught with collaborators from NASA JPL, JSC and Boeing and focused on automation and robotics in construction.

The focus of the design studio was to allow architecture students to make contributions to the conceptual design for alternative means of Habitat Construction on Mars through a means creating architecture that creates itself. The design project had three Primary Considerations including: The actual trajectory issues (how to get materials to the mars), Chemical Processing (how to make materials on the mars) and Space Manufacturing (how to fabricate and assemble/construct things on the mars). Of the central issues explored in this studio, research concentrated on Manufacturing as a process carried out by small modular robotics. Issues of Space Manufacturing, which is very much tied to chemical processing, therefore became paramount as carried out by small modular robotics at a variety of scales. Such systems were seen to demonstrate value for three primary reasons: 1) the required quantity of structural material resources is far in excess of what can be sensibly be launched from the Earth, 2) the required civil and structural engineering tasks dictate machinery requirements far in excess of what can be sensibly launched from Earth, and 3) the requirement of fabricating the components and building and maintaining the facilities.

The premise of the approach was that rather than sending a constructed architecture to space, we send tiny robotic modules that are capable of reproducing through automated fabrication techniques using in-situ materials. The modules with embedded sensors, self-healing composites, and responsive materials will construct buildings aimed at adaptation. Such constructed architecture could then also have the potential to respond to counteract loads and reduce material, change shape to block sunlight, allow for active ventilation and insulation, and prevent their own degradation. The general premise is that when enough of architecture of the habitat has constructed itself, we safely send humans to inhabit it.

2 Project Overview

The overall architectural designs primarily focused on the master plan of a self-sustaining settlement for 10,000 inhabitants. The settlement is an assembly of numerous discrete yet interconnected projects that include residential, public, civil, industrial, commercial, research, healthcare, and farming etc.

Students were required to develop hyper-efficient urban planning and architectural design which includes human and environmental interactions, sociology and psychology. Students worked either individually or in teams of two to produce complete designs of one component facility in the settlement including the detailed development and a construction/ fabrication concept. Students developed scaled prototypes of their systems that were required to demonstrate the robotic aspects of the project as integrated into the designs to optimize the performative aspects in terms of energy, mobility and robustness. Physical models were developed to simulate actual robotics, structure and materials. Issues of embedded computational control structures, communication and kinetic engineering were therefore paramount. The environment on the mars was seriously considered including: gravity, low atmospheric pressure, dust, radiation, and the mass balance of resources and waste required for sustaining human life at such a scale.

3 The Architectural Value of Modular Robotics

The idea of architectural building blocks with autonomous reconfigurable robotics is at the forefront of architectural robotics today. Designers in robotics are moving away from traditional (pick and place) uses of automated mechanical devices in architecture to transformable systems that are made up of a number of small robots. For many terrestrial applications ranging from cleaning carpets and windows to adjustable furniture, we are seeing a distancing from the precedent of figural humanoid robots to transformable discrete systems. The manufacturing technologies compounded with recent advancements in software (computational intelligence) for these systems allow robots to be increasingly smaller and smarter. Current advancements in evolutionary and self-assembling robots, specifically dealing with the scale of the building block and the amount of intelligent responsiveness that can be embedded in such modules, are setting new standards for robotics.

As architects and designers familiarize themselves with more diverse, responsive, and autonomous robotic systems, they are beginning to understand ways to apply them to dynamic situational activities and build them into systems that make up architectural space. Our furniture and entire spaces might someday be comprised of a multitude of interconnected assemblies of robotic modules that can reconfigure themselves for a variety of needs or desires. There are many important lessons to be learned in both distributed computation and small-scale robotics that can feed into a future paradigm of architectural space-making.

3.1 Performance Parameters and Precedent in Modular Robotics

Students in the context of this studio therefore needed to simultaneously consider the methods of movement, connection, geometry, and embedded intelligence of such small-scale robotic modules. In addressing the performance parameters of modular robotic design, concepts focused on several key strategies: 1) geometry 2) movement 3) connection 4) scale 5) materiality, and 5) embedded intelligence. The final objective of the approach was to create innovative designs that are minimally functional with the capability for evolving additional multi-functionality. An additional primary consideration is how modules can connect to each other with sufficient mechanical strength and then disconnect easily again without using too much energy. In addition to the tectonic objectives of the robotics listed above there are several architectural objectives that this project explores 1) It served as a vehicle for developing strategies for decentralized control dictating how individual parts of a collective system should behave and how local interactions between individual modules work in terms of forming structures and figuring out how to move them around. 2) It served to demonstrate the possibilities of architectural space-making with unprecedented levels of customization and adaptability.

The studio began with an inclusive overview of modular autonomous robotics that had architectural applicability including: The Biologically Inspired Robotics Group (BIRG) at the Swiss Federal Institute of Technology.[1] Modular reconfigurable robotics at the scale of furniture was also presented as developed at the Self-organizing System Research Group at Harvard University. Also, researchers at Caltech are developing robots made up of modular parts that work as a system to interpret and act upon information.[2] Hod Lipson and other scientists at the Cornell Computational Synthesis Lab have also begun developing multiple types of modular reconfigurable robots and evolutionary robots. These self-replicating prototypes were designed to allow for each object to be able to attach, detach, and reattach to different self-similar faces based on predetermined computational logic. These modular objects are able to connect to each other through electromagnetic connections, and the entire system has the ability to change its physical shape based on how it is programmed.

3.2 Component Module Design

The students began with a module design that geometrically satisfied the required performance parameters listed above in section 3.1. In these robotic modules developed by the students, the scale of the module was typically based on the size of the microprocessor board, battery, and mechanical parts that had to fit within each module. The architectural students' robotic explorations were limited by the current possibilities of manufacturing and of the inherent physical mechanics. The robotics were developed within the context of the studio and included an overview of electronics and tutorials of Audrino. Students developed a cursory understanding of basic circuitry and were able to apply a number of different sensors to their models.

For the most part the robotics was limited to a single module and that informed the parameters of the larger physical model. In most cases, designs were limited to practical extrapolations based on the development of a single module. Also informing

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[1] Roombots. http://birg.epfl.ch/page65721.html

[2] Chih-Han Yu, Francois-Xavier Willems, Donald Ingber and Radhika Nagpal. "Self-Organization of Environmentally-Adaptive Shapes on a Modular Robot." Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Nice, France, 2007.

the module development was a required diagram of their larger architectural strategy for in-situ resource allocation, fabrication and construction as well as how it can deal with water, air, and electrical. In the examples from the studio below, the students designed (and modelled) conceptually self-replicating models which would allow for each object to be able to attach, detach, and reconfigure according to predetermined computational logic. The projects successfully demonstrated various strategies for mechanical design, locomotion and control.

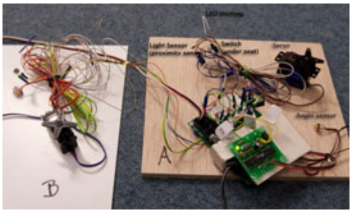

Fig. 1. Typical Robotic Module Electronic Components. Students used the Arduino developer kit and various sensors and actuators

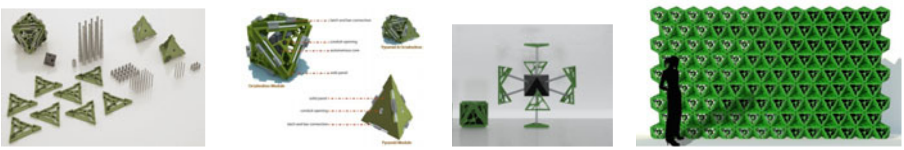

Fig. 2. This module used a panelized design with linear actuators for motion built around a dodecahedron hub

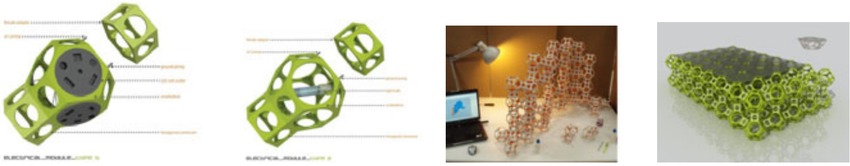

Fig. 3. This module used a male-female latching strategy and two separate complimentary modules

Fig. 4. This module used a six-pointed star with linear actuators on extending arms for motion and latching and a strategy for injection infill

Fig. 5. This module used a pendulum-based spherical strategy for motion which adhered with Velcro

3.3 Discrete Mechanical Assemblies and Decentralized Control

Understanding how to create architecture with autonomous reconfigurable robotics necessitates a clear understanding of a control structure. The important point is that each individual actuating module is controlled by a decentralized controller at a local level. This model of decentralized identification and control is based on neural networks and simplifies the implementation of the control algorithm. Decentralization is valuable on a number of points. In creating many self-similar parts, there is a redundancy in terms of control, an economic savings in terms of mass-production and an increased robustness to failure, in that if any single part fails, the system as a whole does not fail. When there are many unknown stimuli such as an exterior environment which is constantly changing, then decentralized intelligence is the obvious choice for being an effective way to handle the sensing and response (perception and action). Architectural robotics in a very general sense is built on the convergence of embedded computation (intelligence) and a physical counterpart (kinetics) that satisfies adaptation within the contextual framework of environmental interaction. The individual modules therefore can have a remarkable ability to communicate with each other even while being specifically task oriented. Decentralization then is a powerful control strategy for such systems of individually networked devices (in this case) whereby there is no central control system.

Most architectural applications are neither self-organizing nor do they have higher-level intelligence functions of heuristic and symbolic decision-making abilities. Most applications do, however, exhibit a behavior based on low-level intelligence functions of automatic response and communication. When a large architectural element is responding to a single factor then a centralized system can be effective in executing a command to a single agent, but when there are many unknown stimuli, or many small autonomous parts, then decentralized intelligence is the most effective way to handle the sensing and response. The more decentralized a system is, the more it relies on lateral relationships, and the less it can rely on overall commands. In a decentralized system there is normally no centralized control structure dictating how individual parts of a system should behave, local interactions between discrete systems therefore often lead to the emergence of global behavior. An emergent behavior can occur when a number of simple systems operate in an environment that forms more complex behaviors as a collective. The rules of response can be very simple and the rules for interaction between each system can be very simple but the combination can produce interactions that become emergent and very difficult to predict.

4 Biomimetics as Process Inspiration

As the overall designs necessitated a certain degree of dynamic response, biomimetic case studies were explored as a means to satisfy adaptability in terms of form, processes, and systems. Biomimetics studies systems, processes, and models in nature, and then imitates them to solve human problems. It lies at the intersection of design, biology, and computation. Put simply, nature is the largest laboratory that ever existed and ever will. Central to biomimicry within the context of this studio was an understanding of the process by which organisms grow and develop. This area of developmental biology includes growth, differentiation, and morphogenesis. In terms of adaptation, the area of morphogenesis was primarily studied as a means to create an architecture that ensures a continuous turnover of cellular-like robotic modules that dynamically ensure mechanical integrity similar to that of a living, evolving system.

Students performed case studies in modular autonomous robotics that had the potential to reproduce themselves. New available technologies like the fab@home 3-d printer which has the capacity to print with a wide palette of materials and mobile CNC routing robots became the inspiration for what might be possible architecturally with modular robotics. With the possibilities of such new CNC processes, students began to look at precedent in nature that was in-line with the adaptive issues that they were trying to solve. The heuristic approach is very bottom-up, in that you first design the brick (robotic module) and then the architectural possibilities are very much influenced by the inherent possibilities and limitations of that particular module. These modules then reference precedent in nature as an inspiration for how they could adapt.

The approach concerning biomimetics was to design architectural systems that could operate like an organism, directly analogous with the underlying design process of nature. Architectural robotics utilized at such a level could allow buildings to become adaptive much more holistically and naturally on a number of levels. Understanding the processes by which organisms grow, develop and reproduce then became an invaluable precedent for how such small mechanisms in an architectural environment could potentially operate.

5 Self Replication Strategies and ISRU

In terms of self-replication, students did a large amount of research on Martian in-situ materials resource utilization (ISRU) that could mined and used as building materials. There is a great wealth of materials that span the gamut of a necessary architectural palate. Numerous types of masonry bricks can be constructed using regolith[3]. As such a material has a low tensile strength and because views would be desired, the best strategy was to use masonry in combination with other materials such as glass

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[3] Mackenzie, Bruce, “Building Mars Habitats Using Local Materials” pg 575 in The Case for Mars III: Strategies for Exploration. Stoker, Carol ed., American Astronautical Society: Science & Technology Series v74, 1987.

which could also be fabricated with regolith materia[4]. In light of the material possibilities, the studio then looked as existing precedent such as the Fab@Home 3-d printer which allows for the creation of multi-material objects. This allows a printed object to be functional rather than static. The Fab@Home has the ability to print conductive silicone, epoxy and cement. By mixing these materials into interesting geometries, fluidic and electrical conduits have been printed. This enables the creation of structural bricks that contain an edifice's plumbing and wiring pre-installed. These systems can be seamlessly intertwined with conventional building systems[5]. Students then developed different scenarios which incorporated bricks which could also create other bricks. Each project developed ideas of fabrication and mobility so that the some of the bricks became miners, some fabricators and some static bricks.

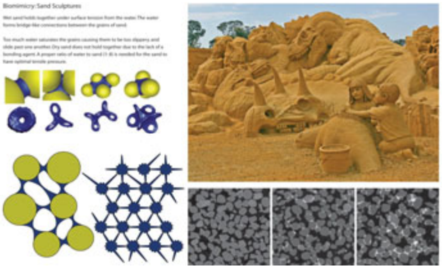

Fig. 6. Biomimetic Module, This module was articulated using the adhering properties of sand as a precedent for clustering

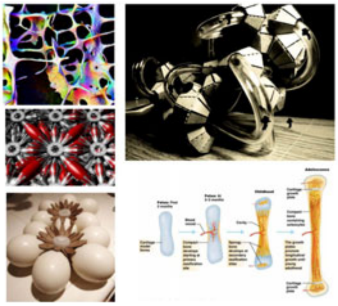

Fig. 7. Biomimetic Module. This module was articulated using the remodeling properties of bone as a precedent for growth.

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[4] Lansdorp, Bas; von Bengtson, Kristian (2009). Mars Habitat Using Locally Produced Materials. In A. S. Howe, B. Sherwood (Eds.), Out of This World: The New Field of Space Architecture (Chapter 23, p. 311-315). Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

[5] H. Lipson, "Principles of modularity, regularity, and hierarchy for scalable systems." Journal of Biological Physics and Chemistry 7, no. 4 (2007): 125–128.

An important aspect here is that such building systems reposition the role of the designer. As Gordon Pask states in his foreword to the book, An Evolutionary Architecture: "The role of the architect here, I think, is not so much to design a building or city as to catalyze them: to act that they may evolve." [6]

6 Creating Architectural Space

A primary goal of this studio was to make conceptual contributions to architectural systems that are made up of a number of small robots. In other words, students were required to conceive of futuristic architectural possibilities of this new direction in robotics. Manufacturing technologies compounded with recent advancements in software (computational intelligence) allow the robotic parts in these systems to be increasingly smaller and smarter. Current manufacturing technologies have allowed microprocessors to grow increasingly smaller, cheaper, and more powerful and we are seeing that we now have the potential to think of space itself as being organized in a computational network. These new standards are extremely exciting in light of the role of autocatalytic processes, defined here as a reaction product itself being the catalyst for its own reaction. In the context of modular reconfigurable robotics such processes describe how the pace of technological change is accelerating because of these processes. In other words, the process is "autocatalytic" in that smart, articulate machines are helping to build even smarter, more articulate ones. In the examples

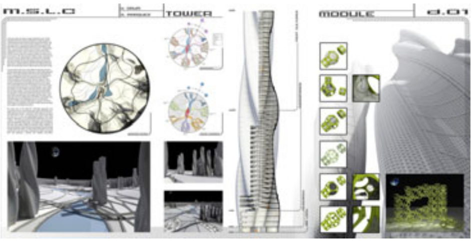

Fig. 8. Architectural Strategy Based on Module Design. These structures were developed with the module in Fig.3.

Fig. 9. Architectural Strategy Based on Module Design. These structure were developed with the module in Fig.4.

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[6] Introduction to: An Evolutionary Architecture, by J. Frazer (London: Architectural Association Publications, Themes VII, John Frazer and the Architectural Association, 1995).

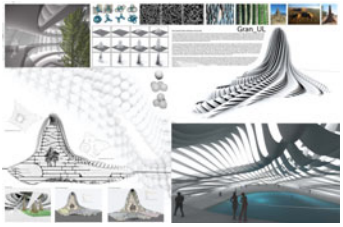

Fig. 10. Architectural Strategy Based on Module Design. These structure were developed with the biomimetic strategy in Fig 6.

Fig. 11. Architectural Strategy Based on Module Design. These structure were developed with the biomimetic strategy in Fig 6.

below, the students used their self-replicating module designs to construct the larger architectural environments. The projects successfully demonstrated various strategies for spatial adjacencies and relative scale. The designs also included site-planning of all buildings, transportation, access, emergency egress, and landscaping.

7 Conclusions

The research explores examining future trends in robotics and how they can be applied to spatial interactive architectural environments. The strategy of using modular robotics of architectural space-making demonstrates an architecture whereby adaptation becomes much more holistic and operates at a very small scale. This paper highlights conceptual contributions by architecture students for alternative means of Martian Colonization through means creating architecture that creates itself. This design project examines the value of self-reconfigurable robotics as basic architectural building blocks. The work was carried out in the context of an advanced topic architectural design studio. The design studio was successful in allowing architecture students to make contributions to the conceptual design for alternative means of settlement scenarios through means creating architecture that creates itself. The design project was carried out with three Primary Considerations including: The actual trajectory issues (how to get materials to the moon), Chemical Processing (how to make materials on the moon) and Space Manufacturing (how to fabricate and assemble/construct things on the moon). Of the central issues explored in this studio, the primary consideration was on Manufacturing. Several examples were highlighted whereby individual modules were created and applied to scenarios of space making at various scales. For architectural students, this was a highly research–intensive studio both in terms of Space issues and also robotics. Although the robotic aspects were very underdeveloped, the projects successfully demonstrated various strategies for mechanical design, locomotion and control. Biomimetic strategies were employed as a means to satisfy adaptability in terms of processes and systems that focused on growth scenarios that integrated self-replication.

We believe that this cursory exploration into architectural building blocks with modular autonomous robotics has great potential in space architectural applications. We also believe that there is a great amount of work to be done particularly in terms of scaling issues and in biomimetics. Such an extrapolation of advancements in both robotics and new materials demonstrates an architectural future whereby adaptation becomes much more holistic and operates on a very small internal scale.

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