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A role-based conceptual framework for teaching robotic construction technologies to architects

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Abstract

In the last 30 years, there has been increasing interest in the adoption of robotics in the construction industry and more recently in architecture. Cutting edge technologies are often pioneered in industries such as automotive, aeronautical and ship building, and take decades to filter into the hands of architects. If this is to change, architects need to be better educated in the field of robotic construction technology.

This research catalogues robotic construction technology currently being used by architects and discusses the motivations that drive architects to use this technology. This catalogue includes an interview with architect Dr Simon Weir and investigates his motivation for using robotic construction technologies on a project for an Aboriginal community in central Australia.

Existing frameworks for classifying robotic construction technologies are reviewed and assessed for their suitability for use teaching architecture students about these technologies. This leads to the development of a new conceptual framework for teaching architecture students about robotic construction technology. This conceptual framework classifies the technology according to the role it plays in the construction process, which makes the information more accessible to architects.

The developed conceptual framework is implemented by teaching a class of students from the Master of Architecture course at the University of Sydney. Results from this class reveal outcomes for further development of the implementation of the framework into the classroom. A revised course structure is presented along with an appropriate hybrid robotic system for teaching architecture students about robotic construction technology.

Glossary of Terms

3D Printing	A process for manufacturing three-dimensional objects through successive deposition of layers of material.
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CNC	Computer numerical control
IDE	Integrated development environment

Table of Contents

1 Introduction

In the last 30 years, there has been increasing interest in the adoption of robotics in the construction industry and more recently in architecture. As can be seen from the background information below, cutting edge technologies are often pioneered in industries such as automotive, aeronautical and ship building, and take decades to filter into the construction industry. Architects are sufficiently removed from the on-site construction of buildings that it takes them even longer to engage with these technologies. If this is to change, architects need to be better educated in the field of robotic construction technology.

1.1 Background

In 1908 the Ford Motor company began production of its revolutionary Model T automobile. Prior to this date, cars were too expensive for the average person to afford due to the large amount of specialised labour required to produce them. To reduce the cost of cars and to increase their production speed, Henry Ford developed moving assembly line production. Each worker specialised in one task and the car moved along the line of workers until it was completed. By 1925, the process had been refined so that a car was being produced every 3 minutes and a single car took only 93 minutes to construct. Previous methods required about 12.5 hours to create a single automobile. This reduced the cost of the car to $240 (approximately $2700 today). Ford said at the time, “no man making a good salary will be unable to own one”. (Ford, 1922)

The first applications of assembly line construction in architecture responded to the post-war housing shortage in America in the 1940s. One such example is Case Study House No. 8, which was designed and constructed by Charles Eames. (Steele, 2002) Completed in 1949, it aimed to present an inexpensive, prefabricated house that could be rapidly assembled from readily available parts. In order to achieve this, Eames borrowed ideas from the automotive industry. Components of the proposed houses could be efficiently mass produced in a factory assembly line, reducing their cost and fabrication time.

The assembly line concept is still being applied to architecture today as a way of minimising cost, increasing accuracy and reducing production time. A contemporary example can be seen at the Stelumar Plant opened by Mattamy Homes in Canada. (Hanes, 2008) In 2007, this factory began mass producing houses in a similar way to Ford’s Model T automobile. A skidding system moves the houses between ten different work stations as various parts of the house are constructed. Even the cabinetry, light fixtures, electrical systems, plumbing, and paint finishes are added in the factory in Milton. The houses have a maximum floor area of 300m^2 and weigh up to 30 tonnes. The completed houses are transported on a specialised truck to a nearby plot. Using this method, one house can be produced every day and a single house takes only 10 days to construct and deliver.

Mass produced houses constructed by Mattamy Homes (Alter, 2007)

Another parallel can be seen between the automotive and construction industries with the introduction of robotic automation. In 1961, General Motors installed the first robot in their die-casting factory in New Jersey. (Munson, 2010) Developed by Unimation, the robot was intended for industrial applications that were dangerous and repetitive such as die-casting, forging and spray painting.

An early adoption of robotic automation in architecture was made by German housing company, Huf Haus. (Huf Haus, 2011) In 1958, they began developing a commitment for prefabricated timber structures and built 12 emergency churches for the Düsseldorf Protestant Church. Now the company pre-fabricates entire houses in their factory in Hartenfels. Teams of workers assemble sections of the house up to 15m long, complete with glazing, door handles, blinds and security systems. Each team has a specific role and the part moves along an assembly line until it is completed.

Machines made by German company Hundegger have been installed along the Huf Haus assembly line to automate the cutting of the timber frame components. Hundegger has been manufacturing robotic machines capable of fabricating complex timber joinery since 1981. (Hans Hundegger, 2010) The machines contain robotic gripping arms as well as several computer controlled tools, including circular saws, drills and routers. Dovetail joints and mortise and tenon joints can be created out of nearly any size or profile of timber. Additional machines can be used to automatically pick up timber and feed it into the cutting machine, and remove the finished pieces and stack them.

Once Huf Haus has fabricated all of the parts, they are driven to site where they can be quickly assembled. Prefabricating the parts ensures that a high level of accuracy, quality and speed is achievable. According to their website, “the production process is not driven by quantity but by the semi-automated pre-fabrication and pre-assembly of the components that results in a quality standard that could never be achieved through manual, predominately on-site, assembly.”[1]

A Hundegger machine and some timber joinery produced by it (Hans Hundegger, 2010)

This modularisation of a design into smaller components has been used extensively in the automotive, aerospace and ship building industries. For example, the ship building industry breaks the ship down into discreet ‘chunks’, which are then simultaneously designed and fabricated, sometimes off-site, and only brought together at the final point of assembly. Kieran and Timberlake (2004) have proposed that a similar model would increase efficiency in the construction industry; “instead of having all parts arrive at the final point of assembly, the tiers gradually build up collections of parts to supply modules or integrated component assemblies to the original equipment manufacturer.”

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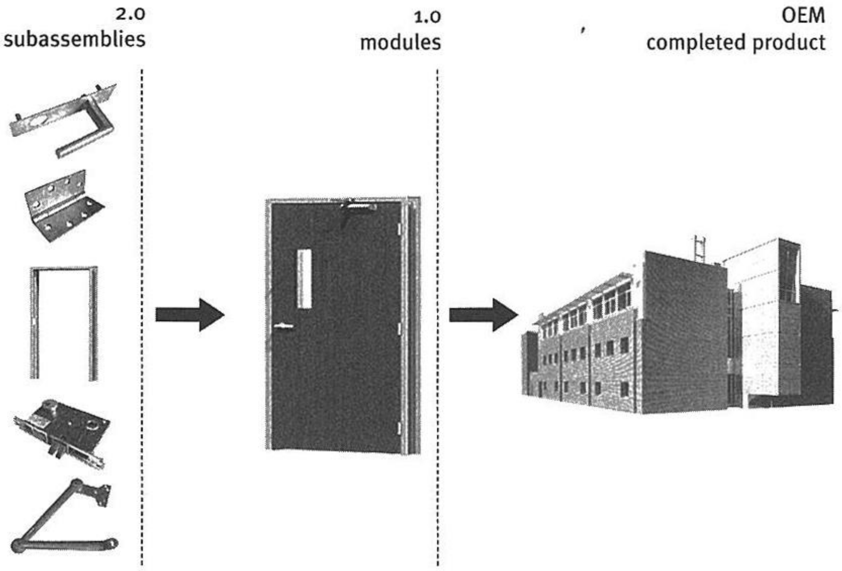
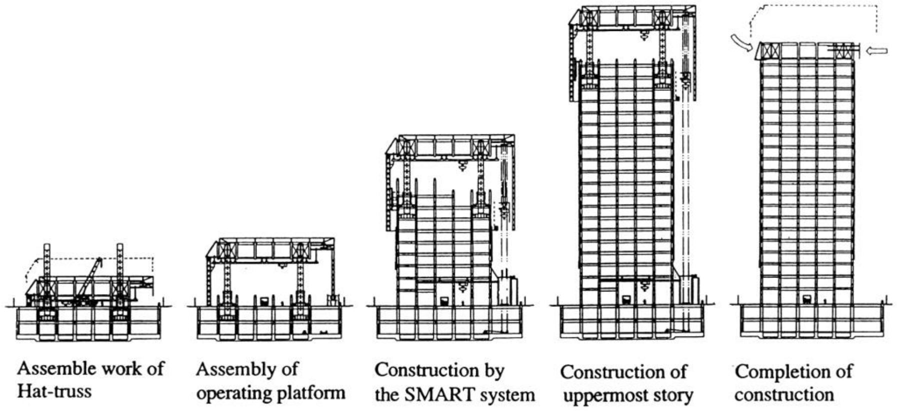
[1] http://www.huf-haus.com/en/the-company/worth-knowing.html



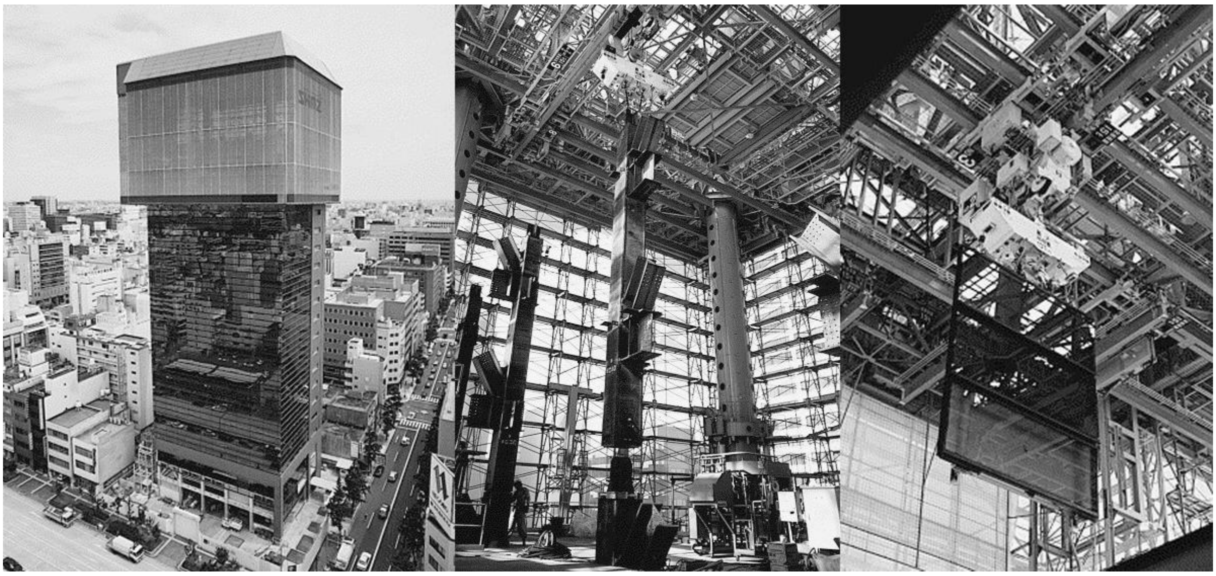
Modular construction as described by Kieran & Timberlake (2004)

Japanese construction companies have attempted to bypass modularisation and prefabrication altogether and creating entire automated construction sites. One of the best examples of these automated systems is the Shimizu Corporation's SMART (Shimizu Manufacturing system by Advanced Robotics Technology), which constructs a whole floor of the building before raising it into position and beginning work on the next floor.



A diagram showing the construction sequence of the Shimizu SMART system (Yamazaki & Maeda, 1998)

From 1991 to 1994, Shimizu used their SMART system to construct the 20-storey Juroku Bank Building in Nagoya. It automated the erection and welding of the steel frame structure, placement of concrete floor panels and installation of exterior and interior wall panels. (Cousineau, 1998) Other examples of similar Japanese automated construction systems include the Obayashi ABCS (Automated Building Construction System), which constructed the ten-storey Riverside Sumida Bachelor Dormitory in Tokyo; and the Taisei Corporation and Mitsubishi Heavy Industries T-UP (Totally Mechanised Construction System), which constructed the 34-storey Mitsubishi Heavy Industries Yokohama Building. (Cousineau & Miura, 1998)



Shimizu SMART system constructing the Juroku Bank Building (left),
automated steel erection (centre) and automated panel transport system (right)
(Yamazaki & Maeda, 1998)

1.2 Motivation for Research

As robotics increased in popularity, it has been incorporated into various educational syllabi. As early as 1993, Seymour Papert used a wheeled drawing robot to teach children principles of computer programming and problem solving. As these technologies slowly make their way into architecture schools, it is important to ensure that the way they are taught aligns with the goals of the architects who will be using them.

Despite the robotic construction systems above being used in the construction industry for over 30 years, and in other industries even longer, they have not yet gained widespread recognition within architectural education. Branco Kolarevic (2003) asserts that it is the architecture schools that are responsible for addressing the deficiency in architects' knowledge of digital technologies, "Educational institutions are the ones who have the power (and, hopefully, the foresight) to prepare future generations of professionals for the emerging practices of the digital age. We need to start training architects to be master builders again, to understand and reengage the processes of building through digital technologies."

Mark Burry agrees that the lack of engagement with digital technologies can be traced back to architectural education, "I am sure there is a deeper and richer body of theory including technology that could be added to the syllabus. But at the schools I have taught at, the syllabus is effectively still the same... There must be a lot of room for a completely renovated architectural education." (Kolarevic, 2003) Burry and Kolarevic have established a need to improve architectural education and close the technological gap that exists between architecture, construction and related disciplines.

1.3 Research Questions

The research presented in this dissertation has been motivated by the following research questions:

How are architects engaging with robotic construction technology?
How can robotic construction technologies be introduced to architecture students?

1.4 Aim

To explore these research questions the research presented here addresses the following aim:

The aim of the research is to develop a framework and appropriate technology for teaching architecture students about robotic construction technology.

1.5 Objectives

To achieve this aim the following objectives were set:

1. Conduct a literature review of robotic construction technologies used by architects.

2. Conduct an interview with a practicing architect who is using robotic construction technology.

3. Review existing conceptual frameworks for classifying robotic construction technology.

4. Develop a conceptual framework to aid the teaching of a class of architecture students.

5. Implement the conceptual framework by teaching a class of architecture students about robotic construction technologies.

6. Assess the outcomes of teaching a class of architecture students about robotic construction technologies using the conceptual framework.

7. Develop a small-scale robotic construction system appropriate for teaching architecture students about robotic construction technologies.

1.6 Significance

The research contributes a conceptual framework for teaching architecture students about robotic construction technologies. This conceptual framework aims to be more appropriate for architects than existing frameworks by responding to their motivations for engaging with robotic construction technology, as opposed to those of engineers and other professionals involved in the construction industry. The framework is significant because it will give architects a better understanding of robotic construction technologies, which will assist them in creating new architectural forms, building higher performance buildings, and increasing their level of control over the construction process.

The research will also develop appropriate technology to teach architecture students about hybrid robotic construction systems based on the developed, role-based conceptual framework. This will permit architects to think about the technology in terms of this classification and allow them to develop novel robotic construction processes based on these roles.

2 Literature Review

Architects currently engage with robotic construction technologies in a number of different ways: to use technology to rationalise a design they have already conceived; to experiment with the technology and allow it to inform their design process; or to develop new technologies to address limitations or extend the capability of existing technologies. This literature review will reveal the underlying motivations driving these architects to use robotic construction technologies.

2.1 Architects using robotic technology to solve existing design problems

In the last 25 years, there has been significant interest in the use of robotic systems for architectural applications. As the designs of major architects increase in complexity, the use of robotic fabrication tools is sometimes essential. Architects such as Norman Foster, Frank Gehry and Zaha Hadid use a range of robotic technologies to achieve the freeform geometries of their proposals. Companies such as *Designtoproduction* are often consulted to find a suitable robotic fabrication process to realise an existing design idea.

2.1.1 Frank Gehry is an architect who designed the Guggenheim Museum in Bilbao. Opened in October 1997, the building consists of a series of intersecting sculptural forms clad in titanium. Located in a once thriving port town, the museum was commissioned by the local government in an attempt to rejuvenate decaying district. The museum was designed around a large, light-filled atrium with views to the surrounding estuary. (Gehry, 1999)

In order to design and construct the complex geometry of the museum, Gehry employed many cutting edge digital technologies. A concept model was first produced by hand out of paper and laser-scanned into the computer. Software called CATIA, which was pioneered by the aerospace industry, was used to build the surfaces digitally. This model was then used to rapid prototype scale models of the form, in order to iterate the design. (Mitchell, 2001)

Once the digital model was completed, it was also used to calculate the shape of each of the titanium panels. Data was also sent directly to robots and other machines fabricating the parts of the building. The same model was also given to the structural steel contractor, who used software called BOCAD to automatically generate the steel connections. (LeCuyer, 1997)

Bilbao Guggenheim Museum: digital model in CATIA software (left) (Mitchell & McCullough, 1995), the unclad steel frame (centre)[2], the completed museum (right)[3]

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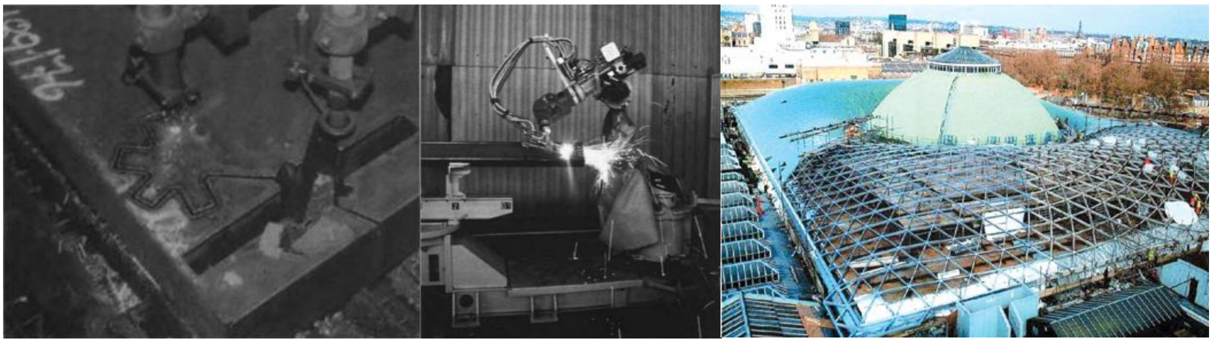
[2] http://eliinbar.files.wordpress.com/2011/12/scan_doc0026.jpg

[3] http://www.mirohotelbilbao.com/content/imgsxml/en/fondos/diruna-con-nubes-1-hd.jpg

2.1.2 Norman Foster is an architect who designed a new roof for the Great Court of the British Museum in London. Opened in December 2000, the new roof spans from the rectangular perimeter of the courtyard to the circular reading room in the centre of the courtyard. It is 95m long and 74m wide and has a maximum arched span of 28.8m on the north side of the reading room. The structure is made from a network of 4878 steel members connected at 1566 nodes. Triangular glass panels, each of which is unique, are fitted on top of this structure. The final structural design was developed by Buro Happold using a computational form-finding process. (Barnes & Dickson, 2000)

The fabrication of the steel members and nodes was undertaken by Waagner Biro of Vienna. Given that each node is unique and the angles between members range from 26 degrees to 110 degrees, it was decided that no manual method could be used in the fabrication process. The star-shaped nodes were generated automatically from a 3D model and arranged on to panels based on the construction sequence. They were then cut from steel plates with a CNC flame-cutter. The nominal centre was marked and each node numbered during the cutting procedure.

The fabrication of the steel members was also automated as much as possible. Box sections of non-standard hot rolled flanges and webs were preassembled and tack welded. These elements were produced slightly too long and the end treatment completed using an adapted welding-robot. The parts were fixed on a turntable and the end in front of the robot cut using data generated from the 3D model. The member was then turned 180 degrees and the second end prepared.



Flame-cutting the steel nodes (left), welding robot cutting steel members (centre) (Barnes & Dickson, 2000), the roof under construction (right)[4]

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[4] http://www.qualterhall.co.uk/media/uploads/qh_1248093566172_museum-roof.jpg

2.1.3 Zaha Hadid and Patrik Schumacher are the architects who designed the Nordpark Cable Railway Stations in Innsbruck, Austria. Completed in 2007, the project comprised four stations (Congress, Löwenhaus, Alpenzoo and Hungerburg), two 24m pylons and a steel cable-stayed suspension bridge spanning the River Inn. Once the complex form of the stations had been finalised by the structural engineers, a German company called *designtoproduction* was used to design the production logic. Specialising in digital manufacturing, the company includes computer scientist Fabian Scheurer and his two partners Christoph Schindler and Arnold Walz, who are both architects. Scheurer views the projects in terms of the complexity of the information embedded in a system and its components. He explains that if more complicated building blocks are fabricated, some of the complexity can be shifted from the assembly to the fabrication of the component and time on site is saved. (Weinstock, 2008)

Once the manufacturing method had been established for the glass panels, each uniquely shaped, and an appropriate construction method developed for the load bearing steel structure, the way in which they were to be joined was considered. The usual method would be to design and fabricate adjustable metal joints, an expensive process that also requires every single joint to be adjusted before the panels are mounted, resulting in extensive measuring and fine tuning during the assembly process.

The solution used an inexpensive material which was simple to manufacture, and required no on-site adjustment. Individual profiles, each cut from polyethylene boards to its own specific angle, site on the steel support ribs, and metal strips are glued to the glass panels and fixed to the profiles with simple screws. The geometry of the profiles was defined through spline-curves in a Computer Aided Design (CAD) model, and scripts were written to automate the production of the profiles, the placement of drill holes, the nesting of the profiles for the most economical use of the material in cutting, and the generation of the machine code for the five-axis CNC router. A unique identification code was also automatically generated for each component. More than 2500 individually shaped parts were prefabricated, each fitting at the correct angle without further adjustments.

Profiles mounted to the steel structure at Löwenhaus Station (left),
Glass panels being mounted to the profiles at the Alpenzoo Station (right) (Weinstock, 2008)

2.2 Architects experimenting with robotic technology to find new architectural possibilities

Robotic technologies are also opening up new possibilities in architectural expression. Architects such as Greg Lynn, Neri Oxman and Regine Leibinger are experimenting with robotic fabrication processes in order to achieve novel forms. The robotic process itself is explored in order to develop their design ideas.

2.2.1 Barkow Leibinger (Frank Barkow & Regine Leibinger) is a German architecture practice which has been designing buildings for the machine-tool company *Trumpf* in Stuttgart since 1998. This relationship has allowed the practice to research CNC fabrication techniques developed by *Trumpf* including laser-cutting, bending, welding and inflating of steel sheet and tubes. (Barkow, 2010)

Steel tubes cut by Barkow Leibinger using a Trumpf laser-cutter (Barkow, 2010)

2.2.2 Neri Oxman is an architect who is developing a process called *Variable Property Design*, which allows materials with continuously varying properties to be 3D printed. These properties can simultaneously respond to multiple conditions such as structural, environmental and corporeal constraints. This concept has been developed by studying natural structures such as bones, which vary their density according to multiple conditions. In 2009, Oxman used this process to create a prototype for a Carpel Tunnel Syndrome Splint. (Oxman, 2010)

'Chaise Lounge' 3D printed by Neri Oxman (Oxman, 2010)

2.2.3 Greg Lynn is an architect who has developed a free-form modular blob, which aims to reinvent the traditional brick. The module is designed using a combination of digital and physical models, and fabricated out of plastic polymer using rotational moulding. The modules are then arranged into walls and arches in the 3D design software and the intersections calculated. The physical modules are then cut by a company called *Machineous* using a 5-axis CNC router. Finally, the cut modules are fitted together and welded along the seams using a soldering iron. In 2006, Greg Lynn used this process to create a Pavilion called *Blobwall*. (Ziger/Snead, 2009)

Robot arm used to cut pieces for Blobwall (left)[5] *and the completed Blobwall (right)*[6]

2.2.4 FACIT is a London-based design and construction firm, which uses a CNC router to fabricate high-precision building modules out of plywood. The design is broken down into light-weight blocks using custom computer software. Each of these blocks is cut by the machine before being assembled by hand and delivered to site. FACIT claims that this digital method of construction is easier for clients because the exact cost is known before construction commences. Each design is highly customisable and is cheaper, faster to construct and more accurate than traditional methods. This technology was launched at The Architecture Foundation Exhibition in 2007 and was used to create the UK’s first fully digitally fabricated house. (Goodeve, 2010)

A CNC router used to create prefabricated modules (left,
and the modules being assembled on site (right) (Goodeven, 2010)

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[5] https://www.youtube.com/watch?v=tDbr4WYgP3o

[6] http://blobwallpavillion.wordpress.com/

2.3 Architectural research developing new robotic technologies

The following examples look at limitations of current robotic systems and develop specific solutions to address them. Gramazio and Kohler (2008) explain that it is necessary for architects to design their own robotic tools to meet the requirements of designs that are “characterized by an unusually large number of precisely arranged elements, a sophisticated level of detail, and the simultaneous presence of different scales of formation”.

As well as problems of complexity, precision and scale, there is research into the issue of moving robotic technologies out of controlled environments and on to the construction site. This introduces technical obstacles such as vision systems to map local surroundings, working within construction tolerances, operating around humans safely and adapting to changing site conditions.

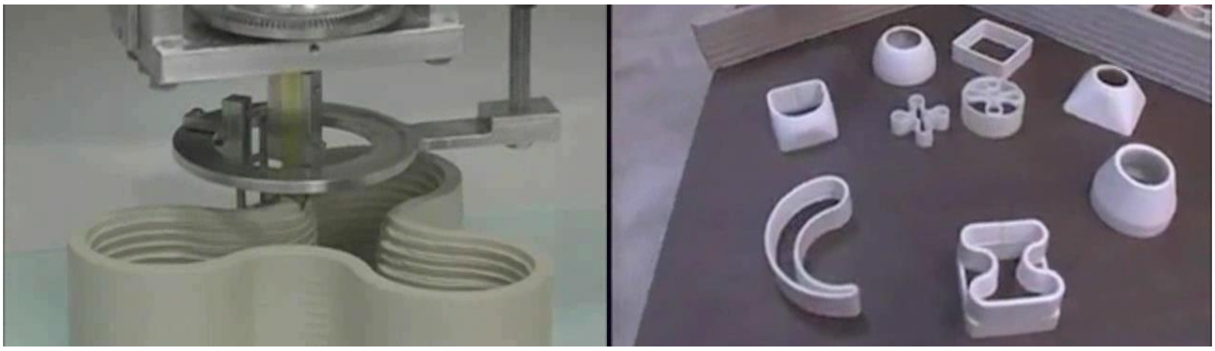
2.3.1 d_shape is a construction system developed by UK company *Monolite* in 2007. It is a large 3d printer which builds up three-dimensional spaces using 10mm layers of sandstone combined with an inorganic binder. The printer can print a maximum area of 6x6m and to a maximum height of 18m. The desired space is first designed using 3d modelling software. Information from this model is then used to control the 3d printing head. After completion, the rough shape needs to be hand ground to remove excess material. (Dini, 2010)

The d_shape printer (left) and pavilion printed with it (right) (Dini, 2010)

2.3.2 Solar Sinter Project is being developed by Markus Kayser, a research student at the Royal College of Art. The project uses the sun to melt sand and turn it into glass objects. This is similar to the process of Selective Laser Sintering, where a laser is used to fuse layers of powdered material into three-dimensional objects. In Kayser’s project, layers of sand are poured into the machine at regular intervals and melted by the sun. Sunlight is focused into a beam using a Fresnel lens. The path of this beam is controlled by several motors connected to a computer. (Kayser, 2011)

The Solar Sinter machine (left) and one of its creations (right) (Kayser, 2011)

2.3.3 Contour Crafting is a layered fabrication technology developed by Dr. Behrokh Khoshnevis of the University of Southern California. It uses a robotic arm to extrude a square tube of cement along a curve. Once it completes each layer, the arm moves up and extrudes the next layer on top of the previous one. In 2004, this system was used to build the first wall ever to be constructed entirely by machine. While it is limited to creating extruded profiles, it is much faster than the 3d printer described above. For architectural applications, where the building plan is the shape to be extruded, the extruder is a mobile robot which extrudes concrete as it drives around the site. Upon completion of each layer, it climbs on to the partial wall and begins the next layer. (Khoshnevis, 2010)

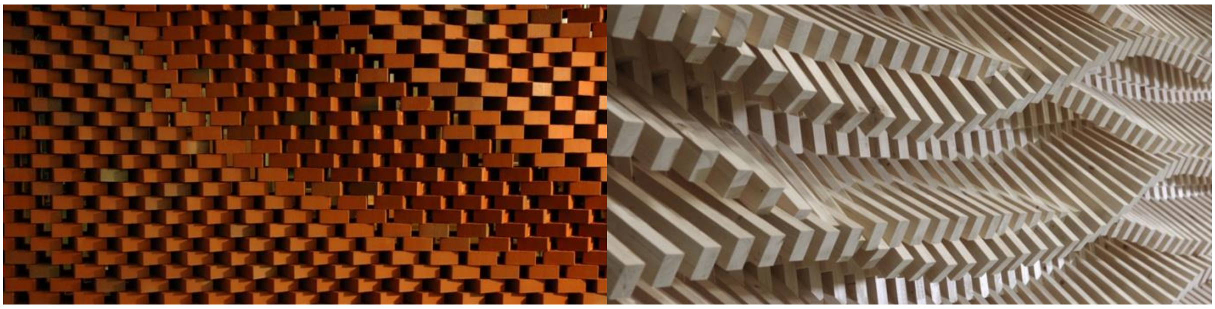


The Contour Crafting machine (left) and some objects fabricated using it (right) (Khoshnevis, 2010)

2.3.4 The Freeform Construction Project is a 3D concrete printing technology being developed by Richard Buswell at Loughborough University in the UK. It uses a gantry style CNC machine with an extruding head to deposit layers of cement. The machine is capable of manufacturing components inside a build volume of 2x2.5x5m and has produced a reinforced concrete architectural piece weighing roughly one tonne. (Buswell, 2010)

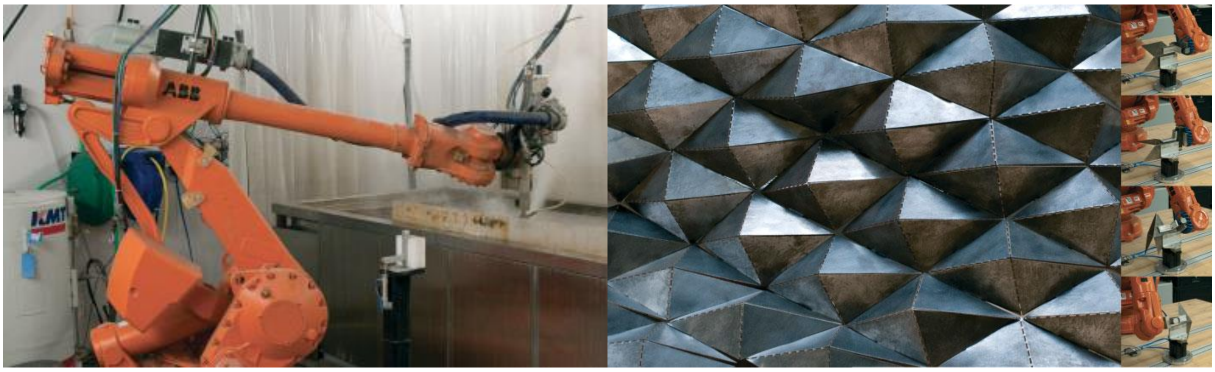
The 3D Concrete Printing Machine (left) and four panels fabricated with it (right) (Buswell, 2010)

2.3.5 Eidgenössische Technische Hochschule (ETH) has acquired an industrial robot named R-O-B to allow students to construct complex assemblies of bricks, timber battens, and concrete and foam blocks. The research is conducted under the direction of Zürich-based architects Fabio Gramazio & Matthias Kohler. In 2006, the architects programmed the robot to construct the complex brick wall panels for the Gantenbein Vineyard Facade in Fläsch, Switzerland. (Gramazio & Kohler, 2010)



Brick (left) and timber (right) walls assembled by a robotic arm (Gramazio & Kohler, 2010)

2.3.6 Harvard Graduate School of Design (GSD) has been using a robotic arm to bend steel sheet to form complex metal surfaces. The same robot was also used to cut patterns of angled holes in a concrete wall in 2009. The research at this school has been focusing on parametric methods of programming the fabrication process. (Bechthold, 2010)



The industrial robot used at Harvard University to create a folded metal ceiling (Bechthold, 2010)

2.3.7 Harvard Graduate School of Design (GSD) with funding from the Spanish Ceramic Tile Manufacturers Association (ASCER) has been developing the *Ceramic Futures Project* under the direction of Martin Bechthold and Christoph Reinhart. The project uses a combination of three robotic processes to fabricate curved ceramic tiles. A variable pin mould is robotically set to the correct shape, the ceramic slurry is 3D printed using a robotic extruder and finally the surface is robotically milled to the correct shape. This process aims to minimise waste often associated with ceramic tile manufacture. (Bechthold & Reinhart, 2011)

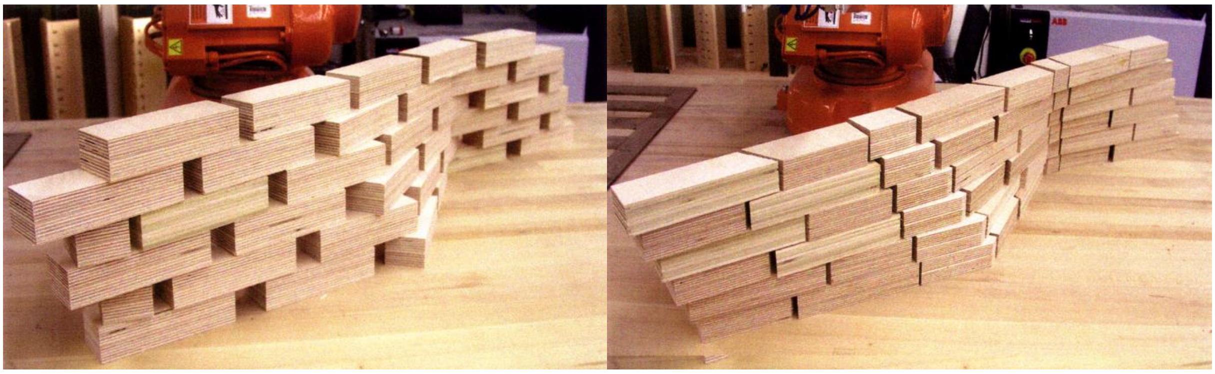
Robotically setting the pin mould (left), 3D printing ceramic slurry (centre)
and robotically milling the surface (right) (Bechthold & Reinhart, 2011)

2.3.8 Stuttgart University's Institute for Computational Design (ICD) and Institute of Building Structures and Structural Design (ITKE) has used a large industrial robot arm to fabricate the ICD|ITKE Pavilion, 2011. The research was led by architect Achim Menges, who programmed the 7-axis robot to cut complex finger joints in plywood panels. The freeform surfaces of the pavilion were divided into hexagonal 'cells' using an algorithm. The software then resolved the geometry of the figure joints along the edges of these cells. The final pavilion used more than 850 unique components and over 100,000 finger joints. A custom-designed rotary saw tool was developed for use with the specific cutting paths used to create the finger joints. (Menges, 2011)

The industrial robot cutting complex finger joints (left) and the completed ICD|ITKE Pavilion (right) (Menges, 2011)

2.3.9 Massachusetts Institute of Technology research student Yuchen Liu developed a digital fabrication strategy for freeform masonry construction. In his thesis *Robotic Design Construction,* he explains that currently "architects have to make their design to fit the machine's operations, that means, to some extent, architects design for machines." Liu argues that this predetermination of existing CNC processes has "resulted in the difficulty in applying digital fabrication to construction on different sites, and architects are required to design a new process to release them from the limitation of the old digital fabrication process." (Liu, 2009)

The research aimed to automate the design, fabrication and construction phases of the process. A freeform wall was designed parametrically using CAD software. Moulds for the bricks were CNC routed out of plywood sheets. Once the bricks had been poured and set, the robotic arm at Harvard GSD was used to stack the bricks into the correct formation. This process was first tested on bricks or uniform size and later repeated of bricks with non-uniform lengths.

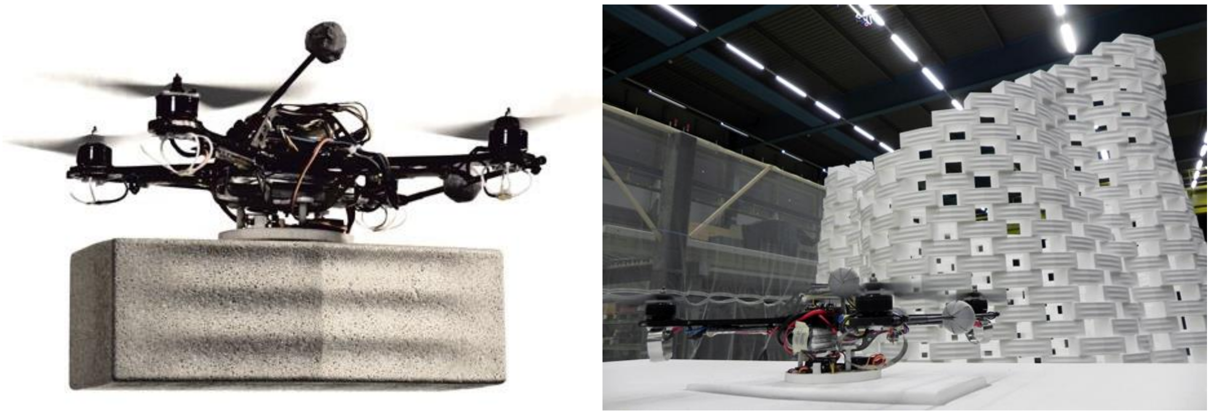


Freeform walls created at MIT using uniform (left) and non-uniform (right) bricks (Liu, 2009)

2.3.10 University of Pennsylvania GRASP Lab has used teams of quadrotor robots to autonomously assemble tower-like structures. The towers are constructed from modular parts with magnetic connectors. The robots are able to determine whether a part has been placed successfully and retry if necessary until the part is connected correctly. Further research has been conducted by this lab to use multiple quadrotor robots to lift heavier parts by working together. (Lindsey, Mellinger & Kumar, 2011)

A team of three quadrotor robots used at Pennsylvania University to construct towers
(Lindsey, Mellinger & Kumar, 2011)

2.3.11 Flight Assembled Architecture is an installation built by quadrotor robots. It is a tower 6m high and 3.5m in diameter, made up of 1500 prefabricated polystyrene foam modules. The tower was assembled by the flying machines between the 2nd December 2011 and the 19th February 2012 at the FRAC Centre in France. The installation was a collaboration between Gramazio & Kohler Architects who have been researching digital design and fabrication; and Raffaello D'Andrea who has completed work in autonomous systems design. They imagine the installation as a scale model of a "vertical village" 600m high and housing 30000 people. (Gramazio & Kohler, 2011b)



A quadrotor carrying a polystyrene module (left)[7] *and a tower constructed from the modules (right)*[8]

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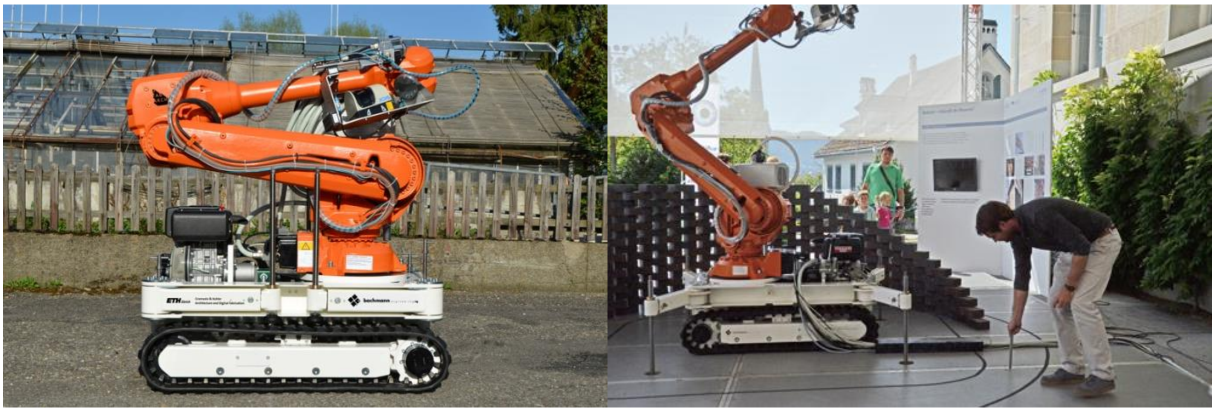
[7] http://www.dezeen.com/?p=175914

[8] http://www.designisthis.com/images/uploads/2012/03/flight-assembled-architecture-FRAC-gramazio-kohler-raffaello-dandrea.jpeg

2.3.12 Harvard Self-organising Systems Research (SSR) Group has used an autonomous robot named ‘kali’ to construct staircases and other structures from modular components. Part of the *Termes Project*, the robot is able to pick up one piece at a time, navigate along the top of previous pieces and place it in the correct location. Simulations have also been run to show how a team of such robots might work together to build larger structures. (Petersen, Nagpal & Werfel, 2011)

The autonomous robot used at Harvard University to constructs a staircase
(Petersen, Nagpal & Werfel, 2011)

2.3.13 dimRob is a research experiment being conducted at the Eidgenössische Technische Hochschule (ETH) in Zürich as part of the ECHORD project. Coordinated by Gramazio & Kohler, it examines strategies for using robotics on a construction site. To demonstrate these strategies, an industrial robot arm was mounted on a custom track system developed in conjunction with Bachmann Engineering AG. The mobile robot has sensors that allow it to locate assembly objects, locate its own position on site and adapt autonomously to changing conditions. By the end of 2011, the robot was able to watch a person draw an imaginary line on the site and then get to work building a brick wall along this line. (Gramazio & Kohler, 2011a)



The dimRob robot packed (left)[9] *and constructing a wall on site (right) (Gramazio & Kohler, 2011a)*

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[9] http://www.dfab.arch.ethz.ch/data/bilder/03_Thumbs/111/110408_111_ECHORD_001_Setup_TB.jpg

2.4 Discussion of the Literature Review

From the literature review above, we can see that architects are interested in becoming involved in the paradigm shift towards using robotic technologies for architectural applications. Three motives in particular drive this enthusiasm:

2.4.1 The first is a desire to create new Architectural forms that were previously impossible or difficult to create.

After conceiving a curvaceous or complex form, architects can represent this form using CAD software. Not only can their ideas be digitally represented, but data from this representation can be used to control the digital fabrication and assembly of the building's components. It is therefore robotic construction technologies that enable architects to create new forms, which were previously difficult or impossible to construct.

Frank Gehry was one of the first architects to explore the potential of this technology to achieve more adventurous architectural geometries. For example, his Vitra Furniture Museum in Germany consists of a series of intersecting sculptural forms, which "pushed the use of conventional design and construction to the limit." (Abel, 2004) In 1987, Gehry was commissioned to design the Walt Disney Concert Hall in Los Angeles. This design was much more complex than the Vitra Museum and he soon came up against resistance from the executive Architects responsible for creating the construction documents, who found the design too difficult to document using traditional two-dimensional drafting techniques.

Realising that he would need to depart from traditional construction methods if he were to get anything built, he hired Jim Glymph in 1989 to help increase the technical expertise of his office. Glymph immediately insisted that all future projects be documented in house to avoid problems being encountered on the Walt Disney Concert Hall project. He also discovered that the aerospace industry was using software called CATIA, developed by Dassault Systemes, to translate complex geometry involved in automobile and aircraft design into digital models suitable for fabrication and manufacture.

Gehry's office immediately began using CATIA on the Villa Olimpica Fish Sculpture project in Barcelona. The software was used for design development, structural analysis and as a replacement for traditional construction drawings. The success of this project paved the way for all of Gehry's later projects, including the completion of the Walt Disney Concert Hall and his more famous Guggenheim Museum in Bilbao.

The software aided in the fabrication of the complex metal skin covering Gehry's buildings. The design could be broken down into small patches and sent to the fabricator for direct CNC cutting and bending. Each piece was labelled with a bar-code and marked with the nodes of intersection with adjacent layers of structure. It could then be scanned by the builder on site to see its location within the design. Laser-surveying equipment linked to the CATIA model enabled each piece to be precisely placed in its final position on the building. Stone cladding was also directly fabricated using information from the digital model using a 3-axis milling machine, which was installed by the subcontractor on site in a tent. (LeCuyer, 1997) Without the aid of this technology it would have been impossible for Gehry to translate his freeform design models into reality.

2.4.2 The second is to deliver a higher performance architectural product.

Attaining a higher performance building requires higher precision of the building components. Digital fabrication machines allow the architect to meet these demands for higher tolerance building components, while simultaneously reducing the manual labour required to create the building. Norman Foster is an architect with a commitment to designing low-energy, high-performance architecture. In order to deliver this performance, he collaborates closely with consultants, who expose him to technologies available in other fields, such as digital fabrication.

The brightly painted, exposed steel structure on the Renault Distribution Centre (1980-82) was developed in close collaboration with structural engineers at Ove Arup & Partners. The exterior mast and tension cable system reduced the weight of the structure and allowed for an uninterrupted span within the interior spaces. Material was further reduced by using CAD/CAM techniques to cut patterns of circular holes in the webs of the I-beams.

Digital fabrication technologies were utilised to an even greater extent on Foster's Hong Kong Bank Building (1979-86). Chris Abel (2004) described the building as "a wholly machine-crafted building. Crafted, moreover, with combined CAD/CAM technologies, including robot welders and computerised numerically controlled (CNC) metal cutting machinery, the like of which had never been used on the same scale in the construction industry before."

For his more free-form projects, such as the Swiss Re Tower (1997-2004), Greater London Authority Headquarters (1998-2002) and the British Museum Great Court Roof (1994-2000), Foster used custom software called the SMG (Specialist Modelling Group) Template. The software was written under the direction of Hugh Whitehead in order to rationalise free-form curves into a series of arcs with known centre points and radii. This reduced the computing power required to generate the curves, allowing the software to run on all of the company's workstations and their consultant's computers. The software also allowed for simple exporting of the geometric data to Excel spreadsheets, which simplified the process of preparing the design for digital fabrication.

The development of the SMG Template within Foster's office marked an important conceptual change in his relationship with robotic technology. No longer is this technology simply being used by his consultants and contractors to meet the performance demands of his designs; but he is now actively driving the use of the technology for the benefit of his buildings. The development of these software tools allows Foster's consultants to analyse his digital design models and his contractors to generating data to control the CNC machines fabricating elements of his buildings.

2.4.3 The third is to bestow the architect with more control over the design and construction process and reassert the role of the architect as *Master Builder*.

While Gehry first became interested in robotic construction technologies out of necessity to realise his complex sculptural designs, he has since recognised that they have even greater implications for architects. This technology enables architects to gain more control of the construction process. His partner, Jim Glymph says, "It's the old image of the architect as master builder". (Gehry, 1999) Gehry's digital process is thus designed to capture his artistic intent in minute detail and preserve this intent during construction of the building.

Jim Glymph adds to this philosophy that "architecture needs to return to a more direct association between the material, craft, the physical reality of the building and its own design process." (Kolarevic, 2003) The implication is that architects should expand their knowledge of these fields in order to reassert their role as *Master Builders.* Robotic technologies allow architects to carry their design intentions through to the construction of the building, without having their ideas compromised by engineering consultants or builders.

In stark contrast to Gehry viewing engineers as a threat to his design intent, Foster's office is more interested in a tight collaboration with his consultants. By working closely with environmental, structural and fabrication consultants, he is able to integrate their valuable input early into the building's design and thus produce higher performance architecture. His interest in robotic technology is not merely a way of maintaining the quality of the architecture but also the only realistic way to fabricate the curves of a structurally or formally performative design.

Gramazio and Kohler add more depth to the discussion of the architect as *Master Builder* by describing a shift in the *role* of the architect. "From now on, we are no longer designing the form that will ultimately be produced, but the production process itself". (G&K, 2008) In this role, the architect actually relaxes the top-down control sought after by Gehry, and gains a bottom-up control of the way the architecture is created through an understanding of the robotic technology.

Kolarevic has extrapolated this idea to its logical conclusion where architects will have complete control not only of the fabrication of the elements of a building, but also of their assembly on site through robotic means. "It is conceivable that in the not so distant future architects will directly transmit the design information to a construction machine that will automatically assembly a complete building." (Kolarevic, 2003) In fact this type of automated construction system has already been implemented by Japanese construction companies such as Shimizu (Section 1.1). These systems, however, have not been widely embraced by architects because they are not aligned with the motives described above. Rather than offering freedom, performance and control to the architect, they impose severe limitations on the design possibilities. If such a system were to be invented in light of the above discussion, it would need to be more flexible in order not stifle the architect's creative process.

3 Case Study 1: Interview with Dr Simon Weir

In order to gain a deeper understanding of an architect's motivations for using robotic construction technology, Dr Simon Weir was interviewed. Weir is a Sydney-based designer, and a lecturer at the Faculty of Architecture, Design and Planning at The University of Sydney. He was questioned about an architectural project he is currently involved with, for which he has determined the use of robotic systems would be essential. Prior to the commencement of this project, Weir had little knowledge of the capability of robotic technologies, so he provides a unique opportunity to investigate the motivations of a designer to use these technologies outside of the robotic architecture movement presented in the literature above. The interview examines the reasons Weir has found such technology necessary and how his choice to use it has impacted his design process.

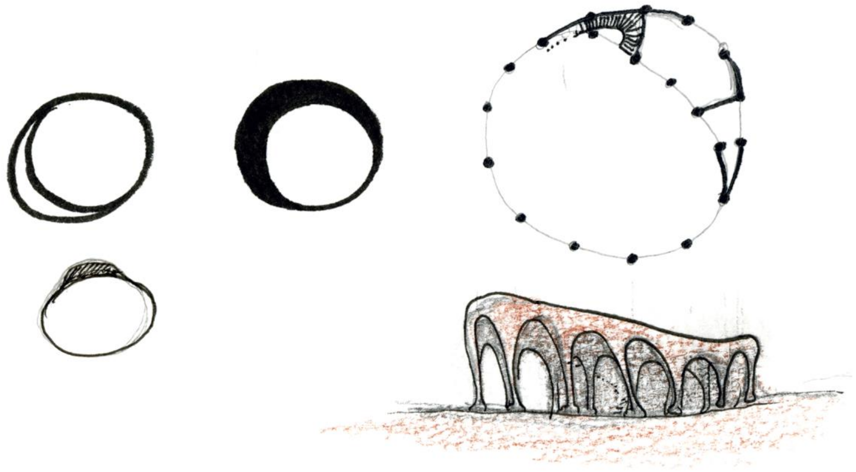
Dr Simon Weir has been engaged to design a series of buildings for the Yankunytjatjara tribe of the Uluru area in central Australia. The nearest town to the site is called Yulara and it is within sight of Ulura (Ayers Rock) and Kata Tjuta (Mount Olga). Currently the local indigenous people are running a wilderness tourism operation which allows people to sleep on the land and eat foods traditionally eaten by the people of the area. As the business grows in popularity, the indigenous elders have decided to create a more permanent infrastructure from which to run the operation. The elders also travel internationally to pass on their knowledge to other indigenous people, but would like to create a place for people to visit them and discuss their ideas.

Dr Weir is designing buildings that will show consideration for traditional Aboriginal beliefs. The Aboriginal people of Australia have a strong spiritual connection to the land. Galarrwuy Yunupingu (1990) asserts that the easiest way for him to talk about Aboriginal Spirituality is for him to talk about the relationship that Aboriginal people have with the land. The two concepts are inseparable. He says, "We all come from the land and that is where we will go back to when we die. My bones will join those of my Ancestors". He goes on to describe the Aboriginal relationship with the land as similar to a relationship between family members, "It is very strong and there's no breaking it". Aboriginal people can even feel sorry for the land, like you would feel sorry for someone who is hurt. He adds that the land "gives life to our people and gives a place for our Spirits to live".

Dr Weir is aware of the challenges he will face when designing a building that respects these traditional Aboriginal beliefs. Not only must the buildings meet the programmatic needs of the community, they must also minimise their impact on the land, be constructed in ways that are sustainable and run sustainably for their lifetime.

3.1 Design Inspiration

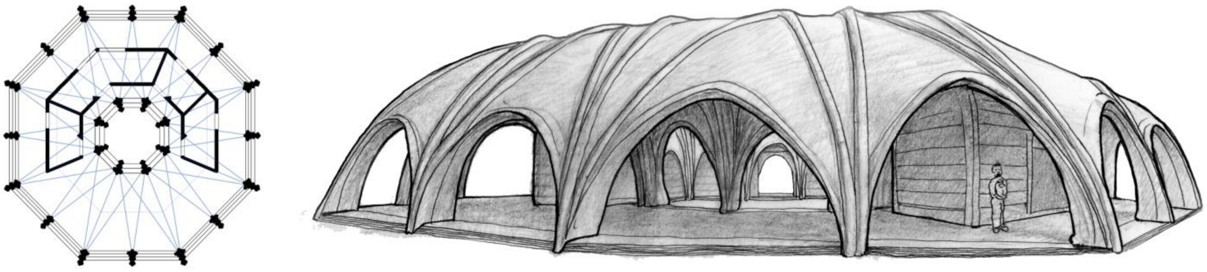
The design is inspired by the structure of the Spinifex plant, which is found in the local area. When sliced across the stem, one can see a crescent shaped spine, which supports the rest of the plant. Weir has taken inspiration from the logic behind the structure of this plant, and designed his buildings to incorporate a more rigid spine, which bends over and supports the roof, before branching and touching the ground as a series of columns around the building perimeter.



Sketches of the Spinifex plant stem cross-section (left) and an initial design concept (right)

3.2 Design Proposal

Dr Weir imagines each building as a ring of stone arches, with a secondary layer of structure underneath the exterior shell to provide more protection. This would give the inhabitants a smoother transition from outside, through the partially protected veranda, to the completely enclosed interior. Dr Weir hopes this will provide the Aboriginal people with a stronger connection to the land surrounding the buildings.



A design iteration with two rings of stone arches; plan (left) and perspective (right)

Weir has proposed that the local stone is the most sensible construction material for the buildings. Blocks of this stone could be cut from a nearby quarry and stacked to form the main structure of the buildings. This would minimise the amount of material transported to the remote site and would fit more closely with the traditional Aboriginal concept of the local land providing everything that they need.

> *If the building is actually constructed from materials that are already there, then a large part of the architecture is a reorganisation of existing things, rather than an importation of new things. (Weir, 2011)*

Weir maintains that another advantage of using a hard-wearing stone is that the building will last a long time and therefore have a lower impact on the environment. In such a remote area, building a lightweight structure would mean replacing the building more regularly, creating waste, which would need to be transported away and disposed of.

> *We can't build things that end up in the tip because the tip is the site. Whatever rubbish we produce will stay on our site forever. It does for everyone, but Western architectural culture pretends that that doesn't matter and we produce large tips. But it does matter more to the Aboriginal people because that's where animals or where plants or where water is. To spoil it has serious consequences and we have to minimise that.*

Unlike Gehry's purely sculptural endeavours, Weir's freeform stone vaults have emerged in response to a variety of design considerations. The forms arise from a combination of programmatic requirements, a sustainable view to reduce waste and increase building longevity, and a sensitivity for the Aboriginal client's spiritual beliefs.

3.3 Construction Methodology

In order to realise his design proposal, Dr Weir has been investigating a number of non-standard construction methods. The process he is developing will incorporate a several advanced digital technologies. The process begins by building a database of the available stone, including a visual scan to determine the colour of the stones as well as a computerised formal scan to collect information about the shape of each piece. Once this data has been collated, the available pieces will be compared to a digital model of the building to determine its final location within the design. An industrial robot arm fitted with a water jet cutter will then be used to cut each of the pieces to the correct shape. Notably, Weir goes on to discuss the possibility of also using robotic assembly to complete the construction process:

> *The other question would be the degree of the influence of robotic assembly techniques. If all the arches are standardised, we could use a single piece of formwork to assemble each arch, but if the arches are different then there'll be an enormous amount of formwork, which is a waste of material. In that situation, using a robotic arm or a pair of robotic arms as mobile, transferrable formwork would be of real benefit.*

On one hand, Weir's use of robotic construction technology is driven by a similar motivation to that in Gehry's office. The technology simply provides a method of realising the complex, freeform design. Weir admits:

> *The only other way of doing it would be the old fashioned way where masons get there with hammers and chisels and knock the stuff up. This would be profoundly slow unless you have an enormous number of workers.*

However, the deeper motivation for utilising this robotic technology is a cultural one. Weir realises that this project presents a valuable opportunity to increase education and practical skill set of the local Aboriginal community.

> *If we're going to train indigenous people to work on the project, we have to decide what skills will be most beneficial to them in the long run. I imagine learning some more sophisticated techniques like equipment maintenance, and software integration, would be more beneficial.*

Weir has been discussing this idea with the Aboriginal elders and they are also keen to use this project as an opportunity to inspire the younger generation of Aboriginal people to learn about construction technology. He says:

> *They want to use the construction industry itself as a way of incentivising people ... to learn a trade. Building this robotic construction system and quarrying local stone in a very high-tech fashion ... could be an ongoing process. [It] can actually be a sustainable business model that seems to be appropriate for indigenous people. For them to be able to ... provide the highest quality, longest lasting architectural workmanship available on the planet. What they can promote as their skill, is building better architecture.*

This ambitious vision is significant because it identifies a motivation for using robotic construction technologies not investigated by any of the architects or researchers discussed in the literature review above. Weir is not driven by a need to reconnect architects with the construction process through digital media. While his use of the technology will allow the creation of new architectural forms and improve structural and environmental performance of the buildings, these come second to the philanthropic desire to empower the indigenous Australian population through the mastery of robotic construction technologies.

3.4 Monitoring the Construction Process

Typically, digital fabrication does not require vision feedback. Data from the digital model is sent to the machine as a series of commands. In robotics, this is referred to as an open-loop system, because there is no feedback from sensors that would close the loop between actions and consequences. It is for this reason, that these machines are usually housed in controlled environments (referred to as structured environments) so that the user can tightly control the results. However, given that the stone Dr Weir is planning to cut is not homogenous in its composition and the water-jet cutting process has unpredictable results when making larger cuts, such an open-loop system would not be appropriate for this application. In this case, an iterative, closed-loop cutting process might be necessary. The robot could remove a small amount of material and then scan the work piece to check whether it is within tolerance and then cut some more material. Weir acknowledges that:

> *We definitely need an ongoing visual scan of the cutting process because it is not super-accurate at the scales that we're operating in. The precision of a water-jet diminishes with distance.*

Similar closed-loop systems are already in use in the construction industry. In the Netherlands, a computer controlled robotic nozzle with a laser guidance system has been used to spray concrete to form 28,000m^2 of rail tunnel. The system measures the existing profile of a tunnel to within 5mm using a laser scanner. Using this profile information, the robot then controls the sprayed concrete pump operation and nozzle orientation to vary the thickness of concrete that is applied. (Jones, 2008)

Coping with the settlement of the building as it is being built will also require the use of feedback loops in the robotic construction systems. A scan will identify any deviation of the half-finished building from the digital model.

> *The ongoing measurement is a key part of it. The building's going to weigh a couple of hundred tonnes, which is to say five times more than a normal building of that size. So we are going to get foundation settlement, which we're going to need to keep track of to a very fine tolerance. We are going to need some agility in the process.*

To achieve this agility, minor adjustments could be made to the geometry of the blocks that are next-in-line to be cut and placed on the building to compensate for the settlement. This means that the shape of the final blocks is not known until all of the blocks below have been laid. To achieve this level of flexibility, the blocks must be cut as they are needed, rather than all at once at the beginning of the construction process.

Compensating for building settlement is just one example of the benefit an agile robotic construction system. It would also allow the accuracy of the robot's workmanship to be monitored and corrected if necessary. Flawed stones could be recut. Unexpected obstacles on the site (such as humans) could be avoided.

This leads us to a shift in thinking about the construction process, which can be paralleled to the field robotics in the 1980's. The first mobile robots attempted to scan their surrounding environment completely, assess which path they would take through this environment and finally execute this path carefully, hoping that nothing had changed in the meantime and that nothing would go wrong during the execution. In 1990, Rodney Brooks published a paper titled *Elephants Don't Play Chess*, in which he described a new method for controlling robots in non-structured environments. The described method involved building up simple layers of feedback between the sensors and the motors, and having certain layers take priority over (subsuming) others. Robots could now cope with changes to their environment and adapt if something unexpected happened. As computing power increased, robots were able to gather and process larger amounts of data in real-time, making better informed on-the-fly decisions. Instead of reacting to simple sensors such as SONAR, they could now react to footage captured by cameras. Sebastian Thrun (2003) and the Stanford University Racing Team used such a system (in this case a Simultaneous Localisation and Mapping or SLAM system) to manoeuvre an autonomous vehicle, winning the 2005 DARPA Grand Challenge.

In a similar way, transposing robotic construction technologies from the factory and on to the construction site calls for flexibility in the robotic system so that it can adapt to its surroundings in real-time. Gramazio & Kohler (2008) discuss the architect's role as designing the production process, not the finished form of the building. However, designing a rigid construction sequence will not allow the level of flexibility discussed above. It will not be possible to pre-plan the entire construction process once robotic construction technologies become active on real construction sites. The architect will also need to design feedback loops and layers of subsumption within the construction process, as described by Brooks (1990).

In their more recent installation, *Flight Assembled Architecture*, Gramazio & Kohler (2011b) in collaboration with Raffaello D'Andrea (2011) is the first step towards creating a flexible robotic construction system. (Section 2.3.11) Gramazio & Kohler designed a 6m tall tower out of foam bricks. D'Andrea then programmed a high-level construction sequence to control a series of quadcopters to pick up the bricks, transport them to the correct location and place them on the structure. However, he has also programmed in low-level behaviours, such as object avoidance and compensation for airflow. While each quadcopter is instructed where to place each brick, they are autonomously decide how they will go about executing this instruction within their environment. The installation is inside a large exhibition space, which limits the number of uncontrollable environmental factors.

3.5 Conclusion

Architects have a variety of motivations for learning about robotic construction technologies. Frank Gehry is primarily motivated to create flowing, sculptural forms, which push the boundaries of the construction industry. Norman Foster is driven by an aspiration to produce high performance architecture. Many architects are also motivated by a desire to reinstate architects as master builders. They see robotic construction technology as a way of regaining control of the construction process. Dr Simon Weir presents more sensitive social and cultural motivations. On a cultural level, he responds to the spiritual connection between his Aboriginal client and their land. He also reacts to the social needs of the Aboriginal community by involving them in the construction process and providing them with a new source of income through a mastery of this technology.

None of these architects are driven purely by an aspiration to understand the technology. They have all become interested in how the technology can help them achieve their design goals. It is therefore worthwhile to develop a conceptual framework to introduce architects to robotic construction technology in a way that is appropriate to their architectural motivation. This will allow architects to more easily engage with the technology and assess how it can play a role in their design process.

4 Conceptual Framework

The literature review and interview with Dr Simon Weir above highlight the need to introduce architects to robotic construction technologies. As mentioned in Section 1.1, Kolarevic (2003) insists that it is the responsibility of educational institutions to teach architects about these technologies. He argues that increased knowledge of these technologies will give architects greater control of the construction process.

In order to effectively integrate these concepts into an architectural classroom, they need to be classified in a way that will allow students to understand the greater context of robotic construction and how it can be applied to their own design process. This classification will lead to the development of a framework for teaching architecture students about robotic construction technologies.

4.1 Existing Classifications

Many architects writing on topics such as digital design and fabrication have already attempted to classify the available robotic construction technologies; this chapter presents several of them. The aim of these classifications is to comprehend the significance of these new technologies and asses their role in the future of architectural design and construction. Several of these existing classifications are presented below in chronological order and with examples from the text. The classifications are then assessed for their suitability as the foundation for a framework for teaching architecture students about robotic construction technologies.

4.1.1 Mitchell & McCullough

In their book, *Digital Design Media*, Mitchell and McCullough (1995) describe a range of digital tools available to architects and reveal some of their potential applications through example projects. In a chapter titled *Prototyping*, they present one of the earliest classifications of robotic construction technologies. The divide the technologies into the following:

- Weaving and Embroidering (eg Jacquard loom and carpet weaving machines)
- Printed Patterns (eg laser and inkjet printers used to print patterns on materials)
- Plotted Templates (eg printers and plotters used to print templates)
- Computer-controlled Cutters (eg laser and water jet cutters)
- Multi-Axis Milling (eg CNC mills and lathes)
- Incremental Forming (eg laminated object manufacture, fused deposition modelling, stereolithography, laser sintering and 3D printing machines)
- Reshaping (eg heat-induction bending machines and pin-moulds for glass)
- Reproducing: Moulds and Dies (eg 3D printed ceramic moulds)
- Assembling (eg Shimizu Insulation Spray Robot and Kajima Reinforcing Bar Arranging Robot)

Mitchell and McCullough identify potential applications for these technologies as: producing small-scale physical models, producing full-size construction components, and positioning and assembling components. They go on to list advantages of these technologies such as: cutting costs, shortening schedules, reducing dependence on standardised construction components, allowing fabrication of complex shapes, and making short production runs feasible. They conclude by saying that CAD/CAM technology “bridges the gap between designing and producing that opened up when designers began to make drawings.” (Mitchell, 1995)

4.1.2 Kolarevic

In his book, *Architecture in the Digital Age: Design and Manufacturing*, Kolarevic (2003) collates a number of essays by and interviews with well-known architects who are in the process of adopting digital technologies into their design process. In his own chapter titled *Digital Production*, Kolarevic presents a classification of the technologies, which appears to be a simplified version of Mitchell & McCullough's classification. Following the heading *Digital Fabrication: From Digital to Physical*, where he quotes William Mitchell, he goes on to classify the technologies as:

- 2D Fabrication (eg plasma, laser and water jet cutters)
- Subtractive Fabrication (eg CNC lathes and mills)
- Additive Fabrication (eg stereolithography, selective laser sintering, 3D printing, laminated object manufacture, fused deposition modelling, and multi-jet manufacture machines)
- Formative Fabrication (eg pipe bending machines and pin-moulds)
- Assembly (eg laser surveying equipment and Shimizu SMART system)

In later chapters, Kolarevic explores how these technologies can be incorporated into an architectural firm's design process. He transcribes a panel discussion with prominent architectural figures such as Mark Burry, Bernard Cache, James Glymph and William Macfarlane. Each of these architects also contributes an essay describing in detail some projects which utilised digital technologies.

4.1.3 Schodek, Bechthold, Griggs, Kao & Steinberg

In their book, *Digital Design and Manufacturing*, Schodek et al. (2005) focus on manufacturing technologies for industrial designers but there are also numerous examples of how this technology can be applied to architectural design. There is much discussion on how manufacturing processes are combined to form production lines and the impact of the process on the achievable volume of production.

In a chapter titled *Computer Numerical Control (CNC) Technologies*, Schodek suggests that it might be useful for designers to categorise these technologies based on 'the shapes able to be produced', however, he quickly continues to divide the technologies into the following 'process-based categories' instead:

- Machining or Material Removal (eg laser, water jet and plasma cutters; CNC mills and lathes)
- Deformation, Moulding & Casting (eg injection moulding, and metal tube bending machines)
- Fabrication or Addition of Elements (eg CNC welders and rapid prototyping machines)

This chapter goes on to give a detailed description of the various machines in each category. The descriptions are technical descriptions of what the machines are capable of and do not include architectural examples as in the descriptions given by Mitchell & McCullough or Kolarevic above.

It is significant that while Schodek et al. discuss industrial robot arms (including robotic welders) later in their book, they do not include them here in the chapter on CNC technologies. Under a section titled *Material Handling, Assembly, and Other Systems*, they say these systems "play primarily supportive roles in the production process. Computer control is common. They are not, however, "CNC" machines in the sense discussed in this book."

It is also interesting that they have merged 2D cutting technologies and 3D milling technologies into the category of 'machining or material removal'. This classification is also used by Bonwetsch, Gramazio & Kohler (2006) under the term 'subtractive fabrication'.

4.1.4 Bonwetsch, Gramazio & Kohler

In a report titled *The Informed Wall*, Bonwetsch, Gramazio & Kohler (2006) present the results of "a four week design studio with graduate students as part of a broader research project investigating digital additive fabrication processes and their implications on architectural design." As part of the research, they situate their work within the field of digital fabrication, which they classify into 'three main principles of digital fabrication':

- Additive (eg stereolithography machines)
- Subtractive (eg CNC milling machines)
- Formative (eg press brake machines)

It is particularly notable that Bonwetsch, Gramazio & Kohler exclude assembly from their list of processes, given that their own process involves stacking regular bricks into complex patterns using six-axis industrial robot arm. They refer to this process as 'digital additive fabrication' and equate it to other 3D printing methods but with relatively coarse resolution and faster production speed.

4.1.5 Pottmann, Asperl, Hofer & Kilian

In their book, *Architectural Geometry*, Pottmann et al. (2007) focus on descriptive geometry, mathematics and CAD software techniques for architects. In a chapter titled *Digital Prototyping and Fabrication*, they present a classification of robotic technologies:

- Cutting Based Processes (eg laser, plasma and water jet cutters)
- Additive Processes: Layered Fabrication (eg fused deposition modelling, 3D printing and stereolithography machines)
- Subtractive Techniques (eg CNC mills, routers, foam cutters and robotic machining)
- Assembly: Robotic Assembly (eg Gramazio & Kohler's brick stacking robot)

In each of the sections above, the focus is on the impact of these technologies on digital modelling processes. Modelling methods and the limitations of transforming a digital model into physical reality are discussed. The chapter concludes with a section titled *Assembly*, where they discuss 'fastener-based assemblies', 'geometry-based assemblies' and, finally, 'robotic assembly'. The focus of this final chapter is how digital fabrication techniques are improving the precision with which fastening methods can be executed. Only a single paragraph on the last page of the chapter is devoted to the discussion of the potential of robotic assembly.

4.1.6 Dunn

In his book, *Digital Fabrication in Architecture*, Dunn (2012) provides architects and students with a resource on the rapidly evolving digital technologies in their field. Divided into three sections, it covers digital design tools (CAD), digital fabrication techniques (CAM) and finally how and why these technologies can be applied to architecture. In a chapter titled *Digital Fabrication Principles*, Dunn provides a categorisation of the technologies based on Kolarevic's classification above:

- Cutting (eg laser, plasma and water jet cutters)
- Subtraction (eg CNC mills and routers)

- Addition (eg rapid prototyping machines)
- Formation (no example given)

Later in the chapter Dunn also includes a case study titled *Robotic Fabrication of Architecture*, where he discusses the work of Gramazio and Kohler on their Gantenbein Vineyard Facade in Switzerland. By separating this example as a case study at the end of the chapter, the implication is that it does not easily fit into Dunn's described classification.

4.2 Analysis of Existing Classifications

Significant in the classifications above is a gradually declining emphasis on robotic assembly. Mitchell and McCullough (1995) devote a chapter to the topic of robotic assembly, where they discuss technologies being developed in the construction industry in Japan, such as the Shimizu Might Jack, the Kajima Reinforcing Bar Arranging Robot, the Obayashi Gumi Concrete Placer and several others. A year after the publication of *Digital Design Media*, McCullough (1996) published a book titled *Abstracting Craft: The Practiced Digital Hand*, where he again discussed the potential for robotic assembly by saying, "The background for CAD/CAM comes from the broader disciplinary context of industrial engineering. Fabrication is just one component of this discipline. For example, although it was less significant in traditional artisanry, assembly, too is most essential to industry. Indeed, the archetypal image of industry is the assembly line."

Kolarevic (2003) follows suit and over several pages describes how Gehry used various technologies to assist with the on-site assembly of his projects. Specifically, he describes the use of bar codes and laser surveying equipment during the construction of the Guggenheim Museum in Bilbao and the EMP project in Seattle. Kolarevic goes on to describe advances in the Japanese construction industry, such as Shimizu's SMART system, which he describes as "the world's first digitally-driven, automated construction system". He concludes by saying these experiments in Japan are "harbingers of the inevitable digital evolution in the building industry."

From this point on, however, there appears to be a reluctance in the literature to discuss robotic assembly. Only Pottmann et al. (2007) retain a section on 'robotic assembly', but it has been reduced to a short paragraph at the end of a lengthy chapter titled *Digital Prototyping and Fabrication*. Indeed even Bonwetsch, Gramazio & Kohler (2006) themselves refer to their robotic process as 'digital additive fabrication'. Dunn (2012) also discusses the innovative work of Bonwetsch, Gramazio & Kohler, but it is included as a case study at the end of a chapter about digital fabrication technologies. Architects have acquired an obsession with the fabrication of building modules but have resigned the assembly of these modules to traditional means.

Perhaps this shift in emphasis is a result of the way these technologies have been discussed in the literature. All of the classifications above focus on the processes within each machine and classify them accordingly. Schodek et al. (2005) briefly allude to the idea of reclassifying the machines based on the forms they can produce, but do not dwell on this.

The following section proposes a framework that categorises the technology based on the conceptual role it plays in the construction process, rather than the technical process used within the machine, in an attempt to make the information more accessible to architects and help architecture students understand how the technology can enhance their own creation practice.

Table 4.1 Summary of Classifications

Mitchell & McCullough	Kolarevic	Schodek et al.	Bonwetsch, Gramazio & Kohler	Pottmann et al.	Dunn
Weaving + Embroidering					
Printed Patterns					
Plotted Templates					
CNC Cutters	2D Fabrication	Machining or Material Removal	Subtractive	Cutting Based Processes	Cutting
Multi-Axis Milling	Subtractive Fabrication			Subtractive Techniques	Subtraction
Incremental Forming	Additive Fabrication	Defomation, Moulding & Casting	Additive	Additive Processes: Layered Fabrication	Addition
Reshaping	Formative Fabrication	Fabrication or Addition of Elements	Formative		Formation
Reproducing: Moulds and Dies					
Assembling	Assembly			Assembly: Robotic Assembly	

4.3 A Role-Based Conceptual Framework

If architects are to create new architectural forms, build higher performance buildings, and increase their level of control over the construction process, they need to concern themselves with both digital fabrication and robotic assembly of building components. A robotic arm stacking bricks replaces the role of a builder, not a fabricator. Therefore, classifying this technology as ‘digital fabrication’ limits architects because it ignores the conceptual role the technology has played in the construction process. The robotic construction technologies presented in the literature review above can be reclassified according to their role as *Fabricators* or *Assemblers*.

4.3.1 Fabricators

Fabricators create components by transforming a base material by cutting, bending, drilling or welding until the desired form is left. Examples of fabricators include the Hundegger machines used by Huf Haus to accurately cut timber joinery, the laser-cutters used by Barkow Leibinger to cut patterns into stainless steel pipes, the CNC routers used by FACIT to cut plywood housing modules, and the 6-axis robot arm being used at the Harvard GSD to bend sheet metal into panels.

4.3.2 Assemblers

Assemblers arrange these components into larger assemblies. Examples of assemblers include the robotic arm programmed by Gramazio and Kohler to stack bricks and timber battens into complex patterned walls and columns, Harvard SSR’s Kali robot, which arranges foam modules to form staircases and other structures, and the quadcopter robots used to create a tower of foam bricks by Gramazio, Kohler and D’Andrea.

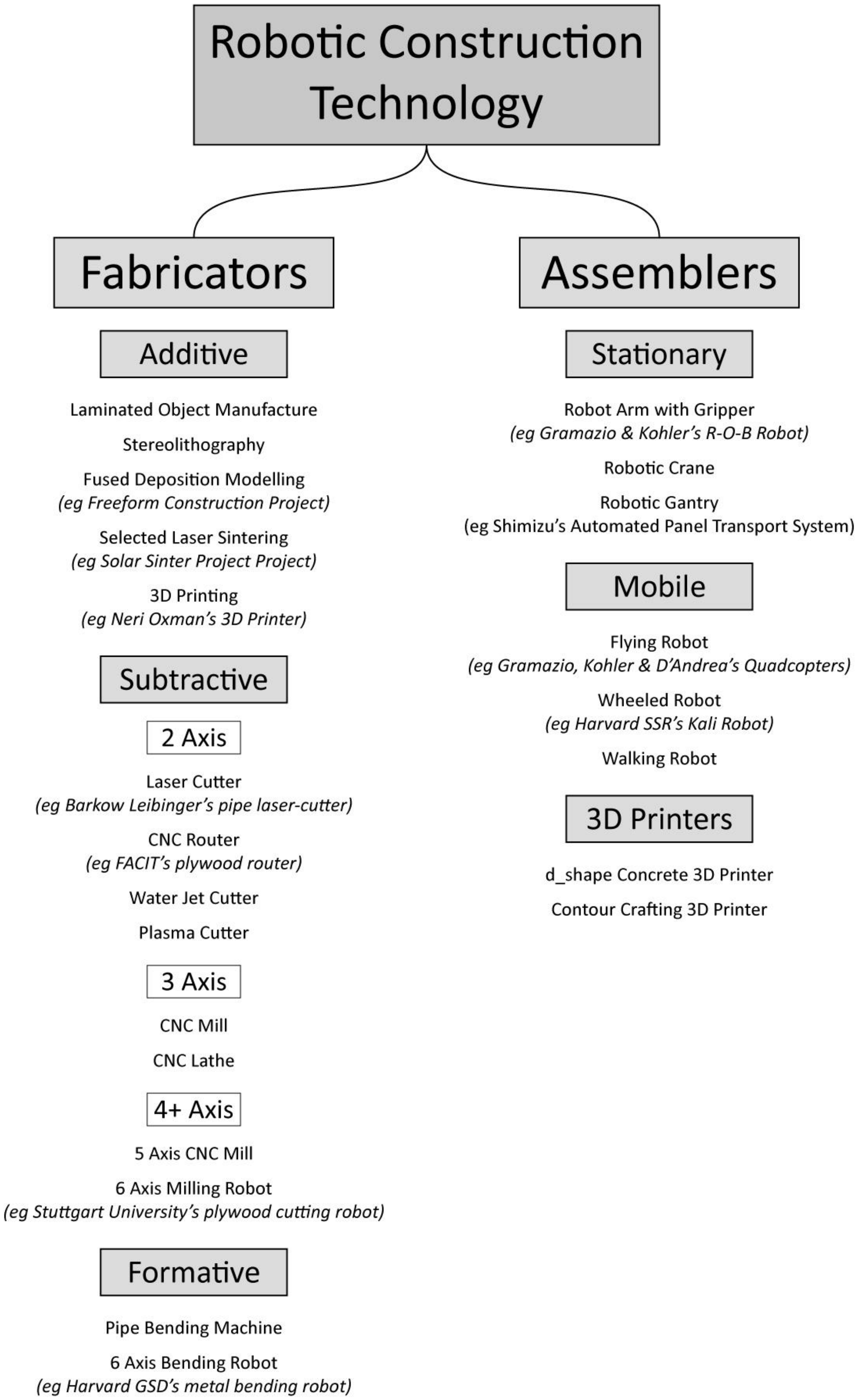
The existing classifications presented above can be remapped into the proposed classification as a second tier below the general division into *fabricators* and *assemblers*. Categories of ‘subtractive’ and ‘formative’ fabrication would now fall exclusively under the classification of fabricators. The ‘additive’ category could, however, be classified as either fabricator or assembler depending on the type of task it is carrying out. Figure 4.1 summarises how the existing classifications relate to the proposed framework.

4.3.3 Classifying 3D Printers

The 3D printing systems in the literature review above do not obviously fit into either category. These include the d_shape machine (Section 2.3.1), which ‘prints’ thousands of layers of sandstone and binder to create complex architectural forms, and the Contour Crafting system (Section 2.3.3) which extrudes layers of cement to form walls.

The classification of these machines will depend on the conceptual role it plays in a particular project. If the machine is ‘printing’ an entire building it should be classified as an assembler because it is arranging tiny modules (the grains of sandstone or cement) to form larger objects. However, if the machine is used to ‘print’ building components such as wall panels or columns, it should be classified as a fabricator.

Figure 4.1 Role-based Conceptual Framework

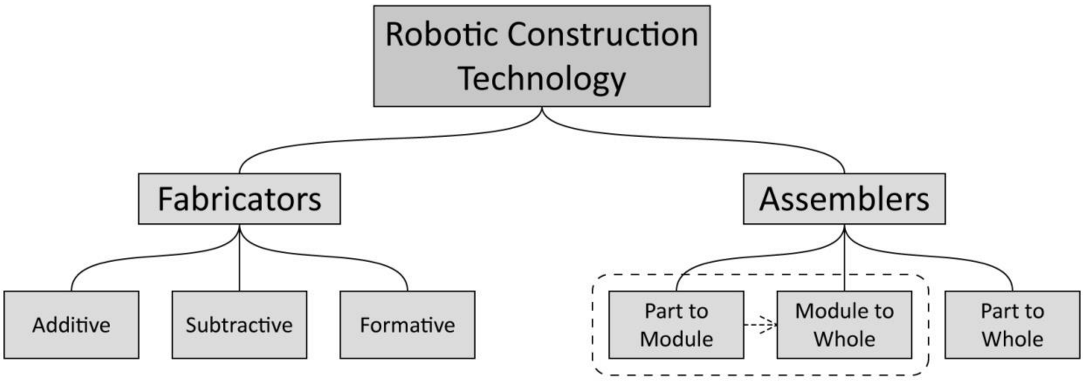


4.3.4 Modular Construction

As discussed in Section 1.1, in industries such as automotive, aeronautical and ship building, the finished product is divided into a number of modules, which are further divided into sub-assemblies (or parts).

In this way, the assembly of the finished product is broken down into a number of more manageable stages. This exposes the opportunity for expanding the classification of the Assembler in the framework presented above. Applying this same principle to divide assemblers we can arrive at three sub-classes:

- *Part-to-Module Assembler*: assembles simples components to produce more complex ones;
- *Module-to-Whole Assembler*: assembles complex components to produce a complete structure; and,
- *Part-to-Whole Assembler*: assembles simple components to produce the complete structure directly.



Gramazio & Kohler's brick laying robot (Section 2.3.5) would now be classified as a *Part-to-Module Assembler*. In their Gantenbein Vineyard Facade project, bricks (the sub-assemblies) were assembled into whole wall sections (modules), which were then delivered to site for traditional positioning on the building. The robotic quadcopters in their Flight Assembled Architecture installation (Section 2.3.11) would now be classified as *Part-to-Whole Assemblers*. Each of the assemblers chooses a foam brick and places it in its final location on the completed tower. MIT research student Yuchen Liu's robotic arm stacking laser-cut bricks (Section 2.3.9) would also be considered a *Part-to-Module Assembler*, except that his bricks are all unique shapes, whereas Gramazio & Kohler use bricks that are all the same.

An interesting implication of this framework is that all of the 3D Printing systems would now be classified as assemblers of some sort. The d_shape 3D printing system would be classified as a *Part-to-Whole Assembler* because it aims to print the entire building for tiny grains of sandstone. The Freeform Construction Project Concrete 3D Printer would be classified as a *Part-to-Module Assembler* because it is used to print building components such as wall panels.

The robotic assembly of *Module-to-Whole* has not yet been explored by architects. Construction companies such as Mattamy Homes (Section 1.1) assemble building modules by hand in their factory and Huf Haus (Section 1.1) assembled modules by hand on site.

4.3.5 On-site versus Off-site Construction

In the introduction of this dissertation, several models of on-site / off-site construction were presented. Mattamy Homes fabricates parts and assembles them in an off-site factory, delivering the house to the site as a complete unit. Huf Haus fabricates parts and assembles them into modules in a factory, before delivering them to site and assembling them into the completed house. The automated Japanese construction systems fabricate and assemble parts on-site, constructing a whole level of the building, before moving on to the next.

The new framework for classifying robotic construction technologies presented above, allows architects to reimagine the construction process as a series of automated fabrication and assembly processes. Each of these processes can be reconceptualised as either on-site or off-site.

4.3.6 Hybrid Robotic Construction Systems

The framework also allows architects and students to conceive ways of combining fabricator and assemblers into novel construction systems. The literature review presented several projects where multiple systems were combined.

The *Ceramic Futures* project led by Martin Bechthold and Christoph Reinhart (2011) combined three different fabrication processes to minimise waste in the creation of curved ceramic tiles. This system utilised three *Fabricators*: one formative, one additive and one subtractive.

The *Flight Assembled Architecture* installation Gramazio & Kohler (2011) uses multiple robotic quadcopters acting collaboratively to construct a tower of foam bricks. This system utilised several *Part-to-Whole Assemblers* to decrease construction time of the tower. The *Termes Project* at the Harvard GSD also contemplated the use of multiple *Part-to-Whole Assemblers* to decrease construction time; however, this ‘swarm’ approach was only simulated in software. Research conducted by Yuchen Liu of MIT used a CNC milled mould to create masonry blocks, which were then stacked into a wall by a robotic arm. This process utilises a subtractive *Fabricator* and a *Part-to-Module Assembler*.

The hybrid robotic construction systems presented above highlight the importance of reconceptualising robotic construction technologies. By situating these examples within a framework where the role of the technology is clear, architects are able to understand the function of this technology in the design and construction process. The framework also aids the research of countless new hybrid systems based on these roles.

5 Case Study 2: Design Experiment with Students

In order to assess the suitability of the role-based conceptual framework for teaching architecture students about robotic construction technology, a course structure was developed based on this framework and delivered to a class of 17 students from the Master of Architecture degree at the University of Sydney. At the beginning of the course, the students had little exposure to the robotic technology being introduced and limited digital design skills.[10]

This implementation of the conceptual framework divided the course into two parts; one to teach the students about *fabricators* and another to teach them about *assemblers*. Associated with each of the two parts was a design task, which allowed the students to apply their new technical knowledge to their design process.

The first design task involved designing and fabricating a modular, architectural component. The components were to be designed using the CAD software, *Rhinoceros* and physical prototypes created using one of three fabricators available to the students in the faculty; a laser-cutter, a CNC mill, or a 3D printer. By introducing these machines as fabricators, the students could focus on the *role* of the machine in their design process, rather than the technical process within the machines. The performance of each prototype iteration was to be tested against a list of design constraints (Section 5.1).

The second design task asked the students to arrange up to 100 of their modules from the first task into an “interesting assembly”. The assembly sequence was to be programmed into the student’s digital models and carried out by an assembler. The assembler used by the students was a small, 4-axis robot arm with a reach of 60cm, constructed for the purpose of the course.

Students were given an outline of both assignments at the beginning of the course. Continuity between the two tasks was achieved by reusing the component fabricated during Task 1 in the assembly of Task 2. It was anticipated that the students would thus perceive the fabricator and assembler to be working together as part of a hybrid robotic construction system with either an Additive, 2 Axis Subtractive or 3 Axis Subtractive Fabricator combined with a *Part-to-Whole Assembler*.

The aim of the course was to encourage students to explore the potential of robotic fabrication and assembly technologies and to question the role these might play in their regular iterative design process.

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[10] The course structure was developed and implemented by the author. The content was approved by the course coordinator to ensure it satisfied the pedagogical framework of the degree.

5.1 Design Task 1: Designing and Fabricating a Modular Architectural Component

Students were asked to design and fabricate a number of physical prototypes according to the following constraints:

Fabrication constraints:

- The components must all be identical.
- They should have overall dimensions less than 50x50x50mm.
- They can be fabricated from any combination of materials.
- They should be mass-producible using fabrication techniques available (eg laser-cutting, CNC milling, 3D printing)

Assembly Constraints:

- The components should fit together easily.
- They should be designed in such a way that the robotic arm can pick them up and stack them.
- They should be self-supporting when stacked.

Design Constraints:

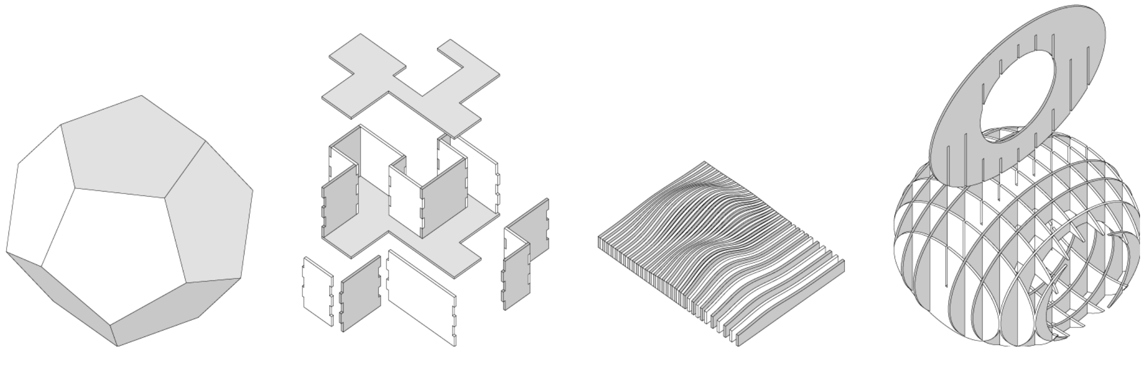
- The components should be visually appealing.
- They should have the potential to be stacked into interesting assemblies.

Students were given demonstrations of how to operate each of the fabricators and allowed to book sessions to use them, and develop their components.

5.1.1 Laser-cutting Demonstration

Students were introduced to many techniques for fabricating complex objects using the laser-cutter. These included unfolding the surfaces of an object to obtain its flattened net; creating notches and finger joints along the edges of surfaces to allow adjacent pieces to fit snugly together; and taking multiple sections through a complex object, cutting each layer and stacking or notching them together to approximate free-form surfaces.

The diagram below shows the four laser-cutting fabrication strategies shown to the students during class. Each model was designed to demonstrate advantages and potential pitfalls of the technique:



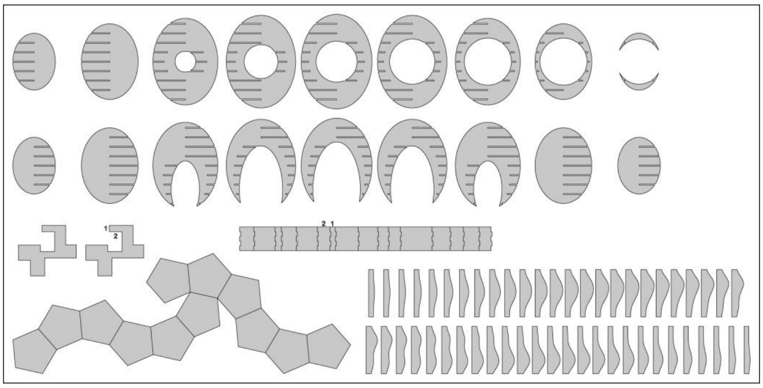
Left to right: Dodecahedron, Orthogonal Prism, Freeform Surface, Hollow Ellipsoid

Dodecahedron: Unfolding Technique
The dodecahedron is the simplest to laser-cut, only requiring that the surfaces of the digital model be unfolded to produce a 2D net, which can be folded to form the 3D object. As the laser-cutter cannot mitre the edges of the material, this technique requires consideration of how the edges of each surface will meet. In a dodecahedron, the faces meet at approximately 116 degrees, so the laser-cut pieces will not meet flush at the edges.

Orthogonal Prism: Finger-joint Technique
The second example was an orthogonal prism, made of 18 flat surfaces. The edges were finger jointed for ease of assembly. The thickness of the material must be taken into consideration so that the pieces do not overhang the base and so that the object does not end up taller than the original model.

Freeform Surface: Sectioning Technique
The third example was a freeform surface that was divided into a number of sections, based on the thickness of the material. In this case, 51 1mm section were cut and glued together. While this is an easy method of representing freeform geometry using the laser-cutter, it requires a lot of material compared to the other techniques and gives a stepped profile to curved surfaces.

Hollow Ellipsoid: Notched Waffle Technique
The fourth example was an ellipsoid with a second ellipsoid subtracted from inside. This model was sliced in both directions at regular intervals and notches were added to each piece so that the pieces would fit together. This model highlighted the necessity to consider the assembly sequence when using this technique. In this case, many of the pieces were impossible to insert into the model due to the complex geometry.



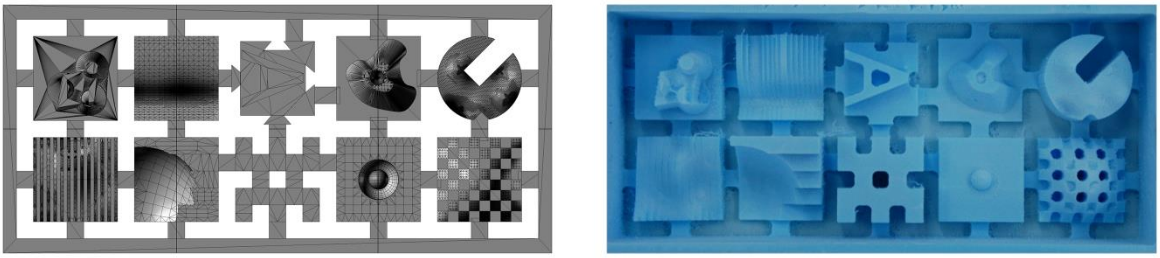
The laser-cutting profile sheet for the four example models

The students were taught about laser-cutting best practises such as numbering pieces or setting them out in a logical order on the cutting profile sheet to make construction of the modules simpler. They layout of pieces also effects the amount of material wastage. In the demonstration, all four example models were fit on to a single sheet of 1mm cardboard 800x400mm to reduce waste.

5.1.2 CNC Milling Demonstration

Students were asked to create small digital models to fabricated using a 3-axis CNC mill out of high-density foam. These models helped to outline the limitations of the milling process. These limitations include those imposed by using a 3-axis machine (no overhanging parts can be created without manually turning the part); as well as the trade-off between cutting-path accuracy and milling time; and also the relative advantages and disadvantages of different sized and shaped cutting tools.

A total of ten student models were milled to demonstrate the limitations of the milling process. In the images below, a number of these limitations can be seen:



The digital models created in Rhino (left) and the physical models milled out of foam (right)

Overhanging Geometry
The milling machine being used had 3-axes of movement. It can move the cutting tool left, right, forward and backward (x and y axes) and up and down (z axis), but cannot change the orientation angle of the tool. Material below overhanging geometry cannot be removed because the cutting tool can only approach the model from above. The fourth model in the second row contained a sphere suspended from below by a small cylinder. The top of the sphere was cut accurately, but the material underneath the sphere could not be removed.

Step-over Accuracy vs. Cutting time
In order to cut the desired geometry, the milling machine moves the cutting tool back and forth over the model. The user can decide whether they cutting passes will be along the x-axis or the y-axis and can also specify the distance between each of the passes. This distance is referred to as the 'step-over'; a small step-over will increase the accuracy of the final object, but will increase the amount of time required to complete the job.

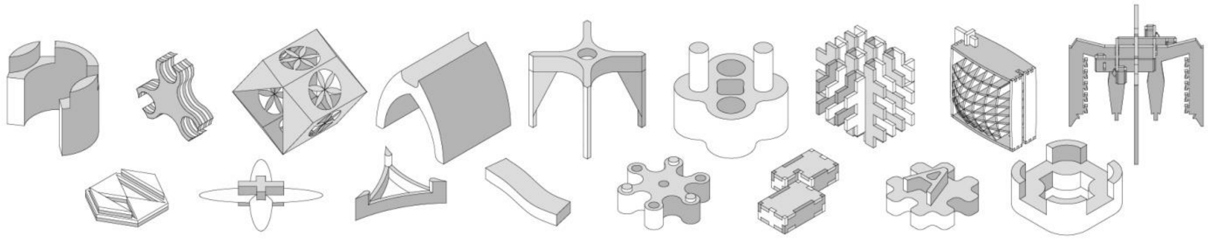
Geometry of the cutting tool
Most of the issues encountered by students were caused by the geometry of the cutting tool. Before the job begins, the user can select from a wide range of cutting tool. For the job above, a small 6mm diameter cutting tool was used. The first model in the second row contained strips of curved geometry with 2mm channels cut between them. As the cutting tool was wider than the channel, it could not fit inside to remove this material and the channels were not cut.

In many of the models, the radius of the cutting tool also diminished the accuracy of the finished part. The third model in the second row contained square holes with sharp corners, however, on the final object the radius of the tool caused the corners to be filleted, giving an undesired result.

The user can also decide on the geometry of the cutting tool, including tools with squared off ends or ones with ball-nosed ends. Generally, ball-nosed cutters are used to cut free-form profiles and square ends are used to obtain flat surfaces. The milling process above used a square end cutter as most of the models contained flat top-surfaces.

5.1.3 Task 1 Results

Students submitted images and the digital model of their modules and received feedback based on how successfully they considered the design constraints. They were also assessed based on how well they incorporated the new digital fabrication technologies into their design process.



Completed Student Modules

Students were also required to complete a report describing their design process, any issues they encountered during the fabrication of their prototypes and how they resolved these with each design iteration. Typical design issues included the following:

Fabrication Issues

- Level of detail too high to reproduce by the fabricator
- Incorrect tool choice, e.g. diameter of cutter too large to fit inside holes
- Incorrect machine settings, e.g. direction or step-over of cutting passes
- Material too thin to hold the desired shape
- Material too thick to bend into the desired shape
- Modules take too long to construct
- Modules are too difficult to construct

Assembly Issues

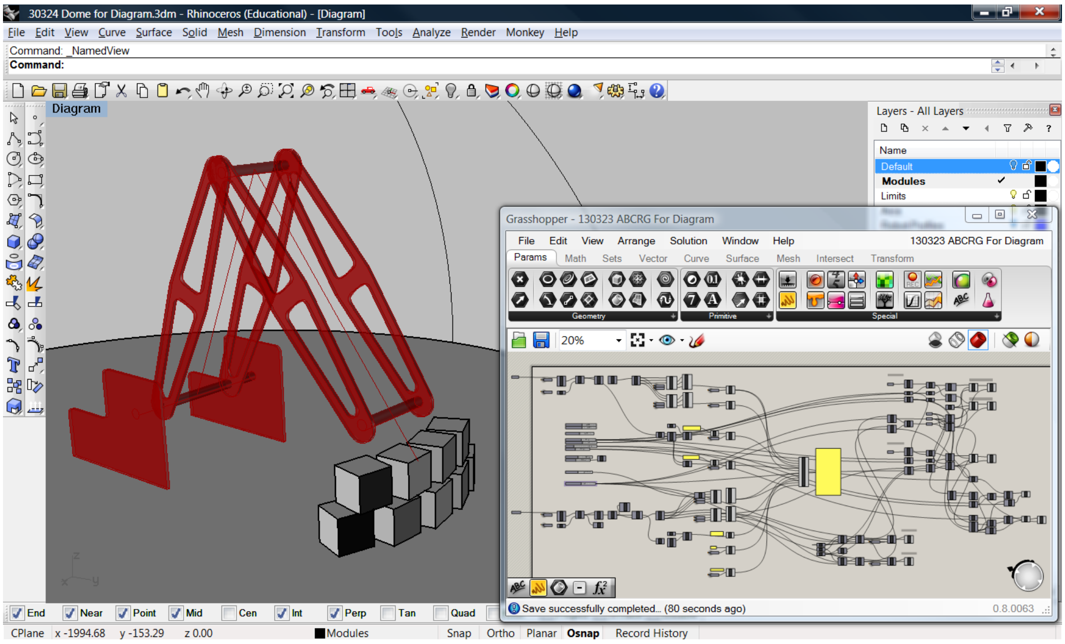
- Modules do not interlock properly
- Modules cannot be handled by the assembler
- Modules are structurally unstable when stacked

5.2 Design Task 2: Arranging the modules into an Assembly

Students were asked to create an interesting assembly using up to 100 of the modules designed in Task 1. The modules were to be arranged in a CAD model, which would then be interpreted by a custom script written using *Grasshopper*, a visual scripting and parametric design plug-in for Rhinoceros. The script locates each of the modules in the assembly and calculates the angles of the robot arm necessary to place the module at that location. This information is then converted into instructions to control the movement of the actual robot as well as providing a visualisation of the generated movements within the CAD environment.

5.2.1 Simulating the Robot's Motion

The students were given the simulation script to test their assembly design and make sure the robot could actually achieve the intended result. This simulation provides real-time feedback about the motions of the robot allowing students to make adjustments to their assembly before finalising and uploading instructions to the actual robot.



30324 Dome for Diagram.3dm - Rhinoceros (Educational) - [Diagram]

Command: _NamedView

Command:

Grasshopper - 130323 ABCRG For Diagram

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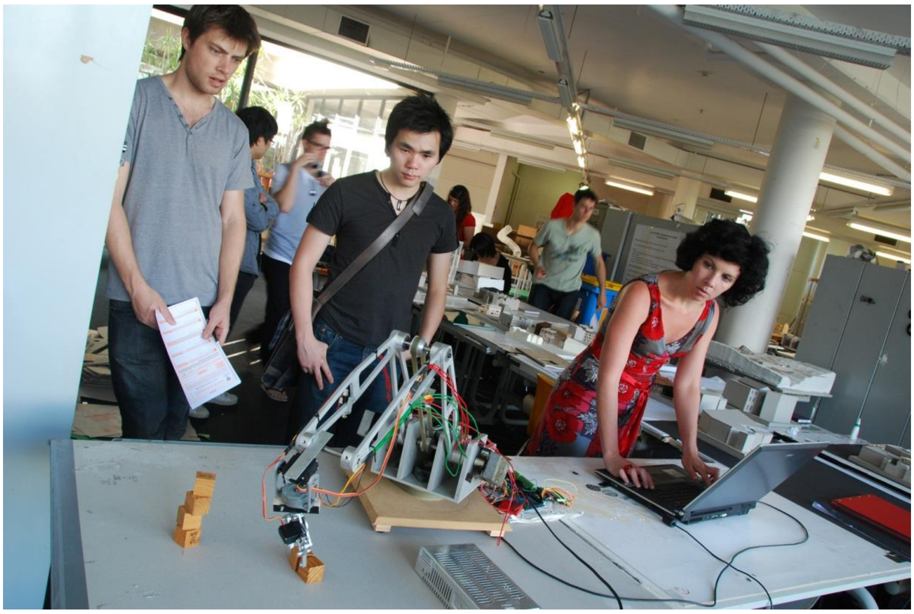
CPlane x -1994.68 y -153.29 z 0.00

Screenshot showing the custom script and simulated robot arm

5.2.2 Manually Controlling the Robot

Students were also introduced to examples from the literature review above, including videos of Gramazio and Kohler's brick stacking robot. Students were also shown how to control the robot using a laptop keyboard to manually stack some wooden blocks. This allowed them to understand how the robot operates and what motions it is capable of.

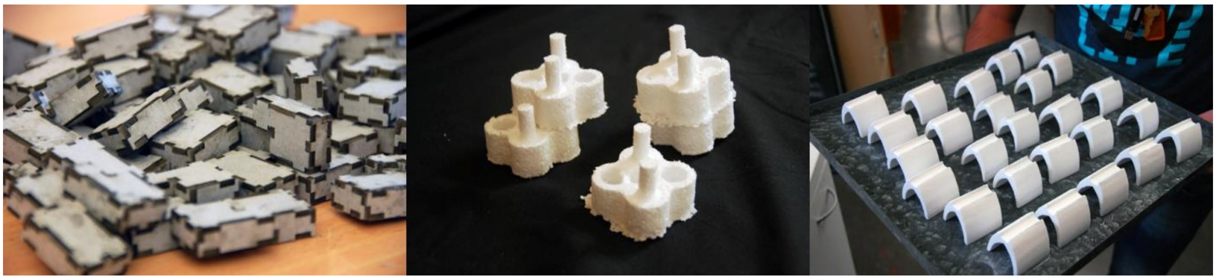


Some students manually controlling the robot arm

5.2.3 Mass-production of Modules

Three of the student module designs were selected to be mass-produced and assembled by the robot arm. The first module consisted of two intersecting rectangular prisms, which were laser-cut out of cardboard. The second was a square module with two pegs on top and two matching holes underneath, CNC milled out of foam. The third was a stackable arch, which was 3D printed. The students worked in teams to fabricate and construct the modules.

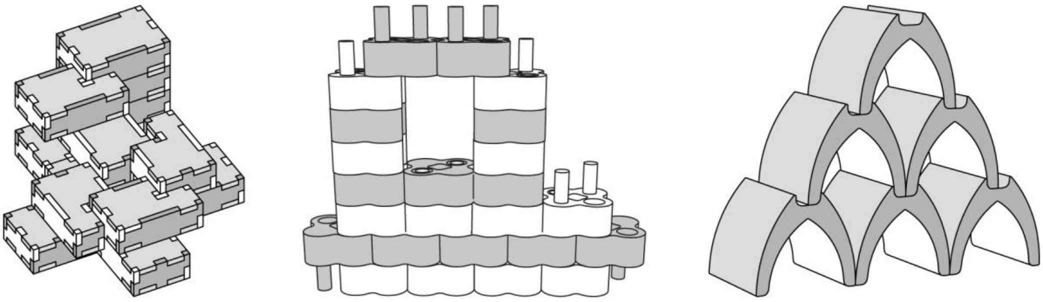
Students assembling laser-cut modules (left), removing excess powder from 3D printed modules (centre), and sanding 3D printed modules (right)



Completed modules: laser-cut (left), CNC milled (centre, 3D printed (right)

5.2.4 Task 2 Results

Once the modules had been constructed, the student's assembly designs were used to generate instructions for the robot arm to follow.

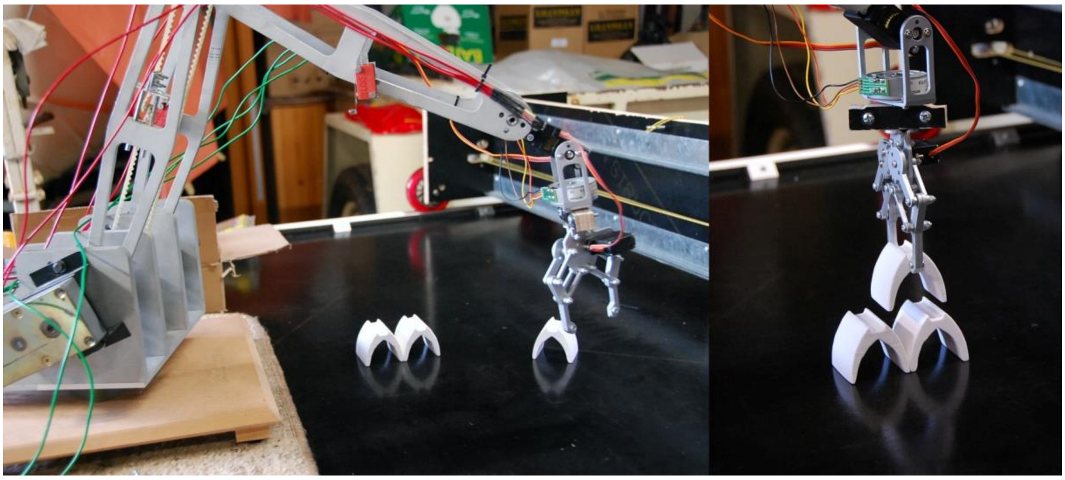


Small assemblies of the modules; laser-cut (left), CNC milled (centre), 3D printed (right)

Each model was loaded into the simulation script, which generated a text file containing all of the instructions for the assembly process. A typical instruction to pick up a module and place it in position would look like the following:

```
M600,908,453            Move to point 60mm above the next module
R90                     Rotate the gripper to the correct angle
M600,866,446            Move down to pick up next module
G40                     Close the gripper
M600,908,453            Move up 60mm
M253,771,606            Move to a point 60mm above the destination
R82                     Rotate the gripper to the correct angle
M253,674,598            Lower the module into place
G50                     Open the gripper
M253,771,606            Move up 60mm
**********
M600,908,453            Repeat the process...
```

Each instruction begins with a letter to describe the type of instruction to be carried out, including moving to a point, rotating the gripper, or opening/closing the gripper. Due to time limitations in class, only the simplest assembly with the 3D printed modules was actually executed using the robot.



The robot stacking the first few modules of the 3D printed module assembly

5.3 Discussion of Case Study 2

The results of the design experiment were analysed to see how successful the implemented framework was in teaching architecture students about robotic construction technologies. Students were asked to present a report describing their design process. These reports were used to assess how well the student understood the theoretical concepts of the role-based framework, whether they were able to technically master the use of the robotic construction system and to what level were able to innovate while designing architectural modules for the system.

Whilst all students were able to achieve reasonable technical competence with the robotic construction system, the level of design innovation across the course was not particularly high. The most notable observation from the results above was that 14 of the 17 students designed clipping mechanisms into their modules to allow them to interlock. Typically, this system consisted of a peg on the bottom of the module and a matching hole on the top to accommodate the peg of the module above. This system limits the possible arrangements of the modules to rectangular or hexagonal grids. The students were not specifically asked to incorporate such a system, so the fact that so many students arrived at this result is significant. By embedding this logic into the modules, the students have made them simpler for a human to stack, without realising that this is not necessary when a robotic assembler is used.

One explanation for this result might be that the students were unfamiliar with the capabilities of the assembler and therefore could not explore the full potential of the system while designing their modules. While manually testing the assembler to pick up and stack some wooden blocks, many students were surprised at how easy it was to control. One student compared it to the ‘claw’ machines in game arcades, but said the assembler gives you more control. Had the students been introduced to the assembler earlier in the design process, they may have felt more comfortable pushing the boundaries of what it was capable of assembling.

Dividing the course into separate fabrication and assembly tasks was intended to allow the students to focus on each of the roles in the robotic construction process without overwhelming them with new information. However, from the above results, it is clear that this created a disconnect between the two processes so a more integrated introduction to robotic construction technology would be preferable. Students spent much time refining their modules for the fabrication phase, but if they discovered further issues during the assembly phase, it was inconvenient to go back and fix them.

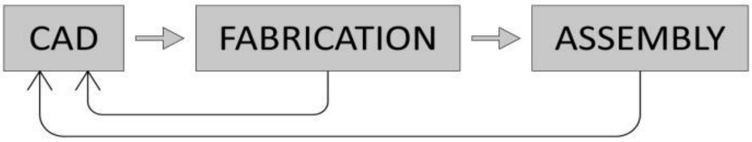
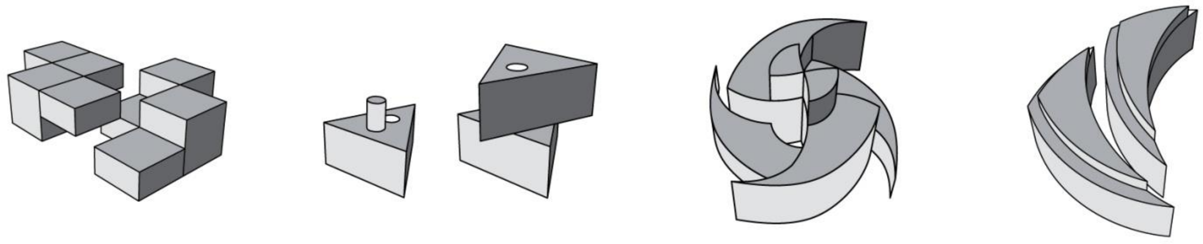


Figure 5.1 *Separating the fabrication and assembly phases makes it difficult for students to respond to design issues that arise during the assembly phase.*

Of the three students who did not use pegs to connect their modules, one was a hexagonal module that could only be stacked in two-dimensional arrangements. The second consisted of two intersecting boxes, and provided much freedom for stacking into different assemblies. The third is of most interest, as the student discusses their design process in their report and gives some insight into their reaction to this new process. Interestingly this student also began with a peg-and-hole design, but soon questioned this approach:

> *The way the bricks would connect was my first concern in this stage. How can you connect the elements without giving up too much freedom? Different forms were created. But they all had some sort of connection mechanism which limited the stacking possibilities or which were just impossible to stack. A connection should not be that forced. The bricks do have their own weight which will keep them in place.*

The sketches below illustrate the student's process of understanding what the robot is capable of and not limiting the stacking possibilities.



Student's initial sketch models

By continuously considering the entire robotic construction process the modules would undergo, this student was able to avoid the limitations inherent in the majority of the student's designs. In order to improve the results of the other students in future, a more tightly integrated robotic construction system is required. This will encourage students to simultaneously consider both the fabrication and assembly. The drawback to this approach would be that the students have twice as many design constraints to consider from the outset.

The next chapter will propose a revised course structure based on the discussion above. It will also develop a hybrid robotic construction system with a more closely integrated fabricator and assembler. This system will be appropriate for teaching architecture students about robotic construction technology.

6 Discussion

In the last 25 years, robotic construction technology has been gaining popularity with architects as they look to this technology to help them solve their design challenges. This shift is motivated by a number of factors including the desire to create more complex architectural forms, an aspiration to produce higher performance buildings, and the drive to engage more directly with the construction process. An interview with Dr Simon Weir also highlighted cultural and social motivations for engaging with this technology.

Many architects, such as Mark Burry (Kolarevic, 2003), argue that it is the responsibility of the architecture schools to revise their syllabi and educate future architects about robotic technologies. In order to integrate these technologies into the architectural classroom, an appropriate framework for discussing these technologies must be developed. Many classifications of robotic construction technology already exist, but they focus on the technical processes of the machines, which is disconnected from the way architects engage with the technology to solve design problems.

A conceptual framework was developed for classifying robotic construction technology according to the role it plays in the construction process, which is a more instinctive way for architects to contemplate this technology. The framework was then investigated by teaching a class of students from the Master of Architecture course at the University of Sydney about robotic construction technology. From the results of this course, a new course structure is outlined below and a suitable hybrid robotic construction technology for use in this course is proposed.

6.1 A Small-Scale Hybrid Robotic Construction System to aid the Teaching of Architecture Students

This section proposes a course structure to overcome limitations uncovered in the Discussion of Case Study 2 (Section 5.3). It then develops a small-scale robotic construction system more appropriate for this proposed course structure. The system will be low-cost and easily adaptable to encourage widespread adoption of the course structure.

6.1.1 Proposed Course Structure

One of the greatest limitations identified in the course structure implemented in Case Study 2 was the lack of a process which integrated the use of both the fabricator and the assembler. A potential solution to this would be to divide the course into two tasks of increasing complexity; both of which would encompass the whole fabrication and assembly process. This would allow the students to gain an understanding of the whole robotic system while designing relatively simple modules in the first task, and to experiment more freely in the second task once they have more of a thorough knowledge of the robotic system.

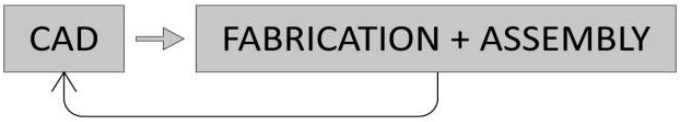


Figure 6.1 *Integration of both fabrication and assembly processes within each design task would allow students to easily respond to design issues that arise during the assembly phase.*

Part 1
In the first part, students could design a simple repeating module to gain an understanding of the opportunities and limitations of the specific fabricator and assembler being used. The module could be modelled in a CAD application such as *Rhinoceros* and interpreted by a custom script similar to the one described in Section 5.2. The student would only need to focus on the design of a single module and the construction sequence used to stack the module into an assembly.

Part 2
In the second part the students could design more complex, non-modular components with the system. This would open up opportunities to introduce students to parametric design concepts to illustrate how the amount of CAD modelling can be reduced when designing more complex assemblies. In this part, the student would focus on developing a parametric module, which could be morphed according to its local position within an assembly. The construction sequence would also need to be more closely controlled by the student to ensure a successful assembly.

6.1.2 Development of a low-cost Hybrid Robotic Construction System for the Architectural Classroom

To complement the proposed course structure in Section 6.1.1, a suitable robotic construction system was developed. This system would consist of a small-scale fabricator and assembler integrated tightly with the inclusion of a sensory feedback system. Control software would also be necessary to coordinate the various elements of this hybrid system.

In order to allow the teaching of robotic construction technology in as many architecture schools as possible, the total cost of the system should be kept under $1000 so that it can fit comfortably within the budget of a university course. To keep the cost of the system as low as possible, a combination of off-the-shelf and purpose built parts will be considered for the creation of the robotic hardware. Data for the fabricator will be generated within an existing low-cost CAD application and control software for the system will be written using an open-source development environment.

Finally, it would be advantageous for this hybrid system to build on existing research conducted in this field. Gramazio and Kohler have already presented a robot arm stacking standard bricks, which was subsequently used to assemble the facade of a real project (Section 2.3.5). Research by Yuchen Liu developed this idea further by presenting the possibility of using a robot arm to stack non-standard modules (Section 2.3.9). Gramazio and Kohler have also begun investigating the potential of using mobile robots to extend the scope of construction compared to a tethered robot arm. This research uses an industrial robot arm mounted on a custom track system to move freely around a construction site. (Section 2.3.13) Cameras and 3D scanners have been integrated into the robot to allow it to calculate its own position on the site and assemble complex walls in the correct relative location. The robot is also capable of interacting with construction workers, who can draw lines on the ground while the robot is watching and then have the robot construct walls along these lines.

In order to showcase these possibilities to students, the hybrid robotic construction system should be able to fabricate custom modules that look like real building elements; it should be able to assemble these custom modules; and it should be mobile in order to show the possibility of these robots one day participating in on-site construction.

Fabricator Design

One obvious solution for the fabricator part of the hybrid system would be to use one or more of the fabricators from Case Study 2 (Section 5). These included a laser-cutter, a CNC mill and a 3D printer all available in the workshop at the Faculty of Architecture at the University of Sydney.

However, there are two practical reasons for not using any of these fabricators for the hybrid system. The first is that not every architecture school has access to these machines and this would limit the potential for the system to be adapted and used widely to teach architecture students. The second is that it is difficult to automate the removal of parts from these machines and therefore human intervention would be required to remove, prepare and supply them to the assembler. This is not as conceptually strong as having the assembler directly interact with the fabricator in a unified system. Having the two robots physically interacting allows students to understand the difference in the roles of fabricator and assembler.

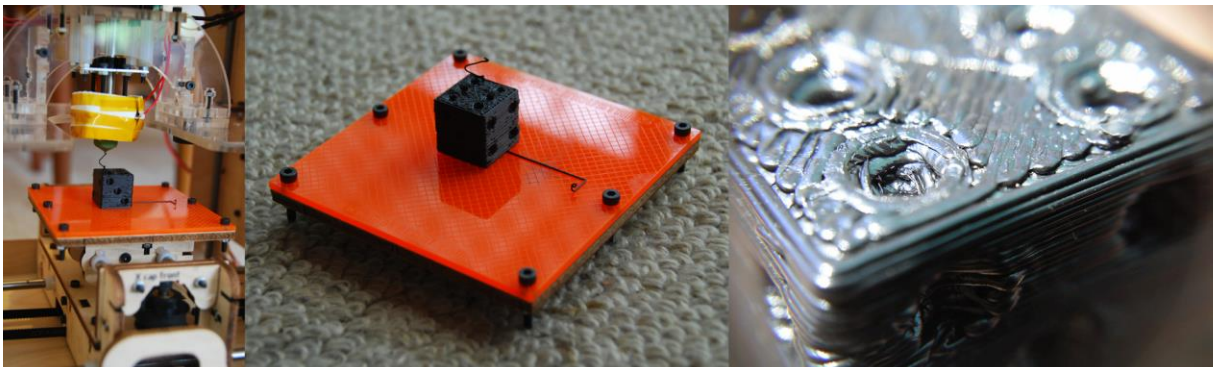
There are also many preconceptions about how these fabrication machines should be used and the sort of forms that can be produced using them. Students are likely to have used some or all of these machines to create scale models for their architectural design courses, which may detract from the roles of these machines in the proposed course structure.

MakerBot

Another potential candidate for the role of fabricator in the robotic system was the Cupcake CNC 3D Printer from MakerBot Industries. This is an open-source fused-deposition 3D printer, which works by melting ABS plastic and extruding it through a nozzle. By extruding many layers of plastic, it is able to build up parts with a maximum size of 100x100x130mm.

In August 2010, MakerBot Industries ran a promotion called the ‘MakerBot Teacher Giveaway’. The promotion involved giving away 10 MakerBot Cupcake CNC Deluxe Kits to teachers around the world to help increase awareness of 3D printing. An application was submitted in response to this promotion asking for a 3D printer to use as part of a robotic construction system to teach Architecture students at the University of Sydney. MakerBot responded and arranged to send one of their 3D printers.

The 3D printer arrives as a flat-packed kit and is relatively low-cost, making it perfect for use in a classroom. However, there were a number of limitations that made this 3D printer difficult to implement as the fabricator in the hybrid robotic system. Most significantly, the part is fabricated on an etched Perspex build platform, which provides the necessary adhesion so the part does not move during fabrication. Once fabrication is complete, the part requires much physical force to remove and often needs cleaning up with a knife and sandpaper. This would be practically impossible to automate using an assembler robot without drastically increasing the cost and complexity of the whole system. Besides this, the 3D printer required much setup and calibration time and was found to give unpredictable fabrication results.

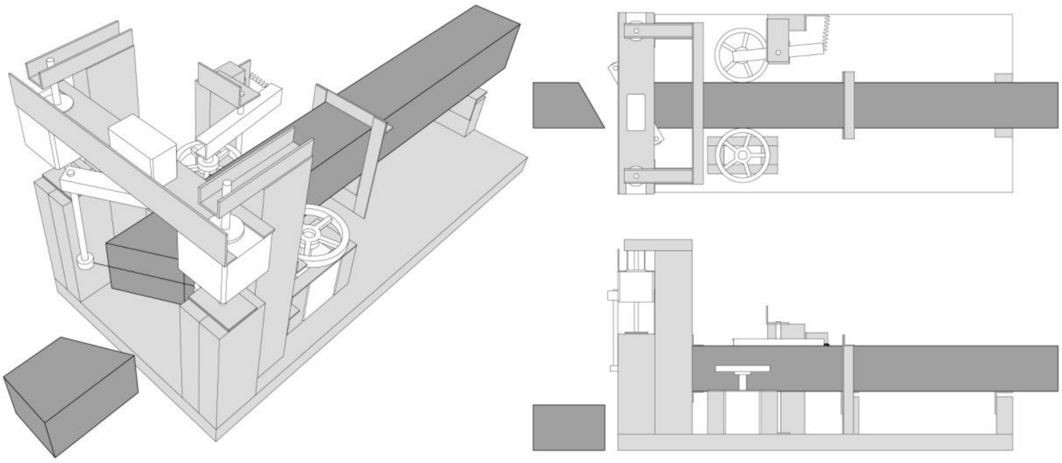


The MakerBot Cupcake CNC 3D Printer (left),
a finished part attached to the build platform (centre), and a close-up of the part (right)

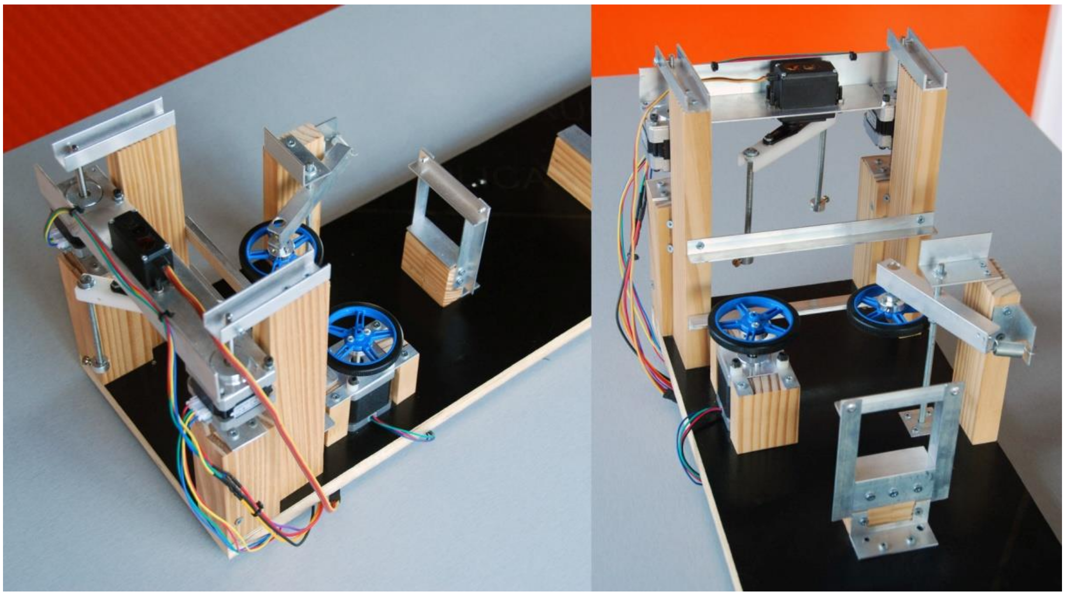
Custom Hot-wire Cutter

Due to the unsuitability of existing fabrication robots, the fabricator was purpose built to ensure it would meet the requirements of the hybrid system. The fabricator took the form of a hot wire-cutting robot, designed to cut custom blocks from a square tube of high-density foam 50x50mm. The robot has three controllable axes, including the angle of the cut, the depth of the cut, and the feed of the supply material. Based on this design, the fabricator is similar in capability to a compound mitre saw cutting a length of timber 50x50mm. This similarity gives the robot integrity as a scale version of a real fabrication process.

The fabricator was constructed from lengths of timber, standard aluminium angle and off-the-shelf drive components including stepper and servo motors. The motors are driven by a three axis stepper motor diver board, which is controlled by an *Arduino* microprocessor. The total cost of the fabricator, including electronic drive components was approximately AU$350.



Hot wire-cutting fabricator: perspective view (left),
top view (upper right), side view (lower right)



Photographs of the built hot wire-cutting fabricator

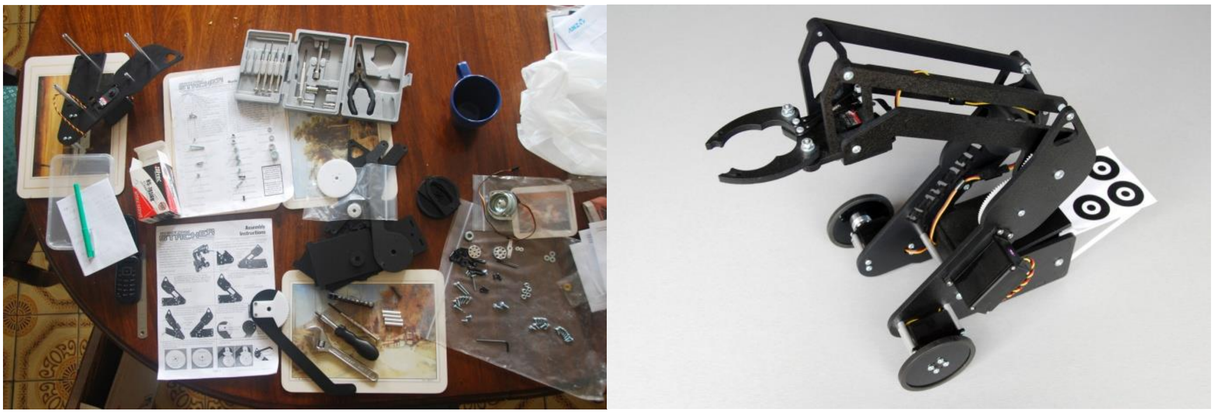
Assembler Design

A suitable assembler for the hybrid robotic system should be able to manipulate parts fabricated by the wire-cutting robot constructed above. While the small 4-axis robot arm used for Case Study 2 would be able to achieve this, it would not showcase to students the possibility of using mobile robots on construction sites. To meet this requirement, a search was conducted for low-cost mobile robotics platforms. Flying, walking and wheeled robots were all considered.

Many platforms were available off-the-shelf and provided a mobile base, motor controllers, batteries and some elementary proximity sensors. These were mostly aimed at robotics researchers, and thus did not have built-in manipulators. This would mean buying or constructing a manipulator and interfacing it with the mobile platform, which would add expense and complexity to the system.

A suitable assembler solution was eventually found; the *Stacker Robot* produced by ServoCity. (ServoCity, 2011) This robot has two independently controllable front wheels allowing it to drive forwards, backwards and turn on the spot. Mounted on top of the robot is a gripper, which can grip objects up to 100mm wide, making it perfect for grasping the 50x50mm blocks from the fabricator. The gripper can also be raised and lowered from 40-330mm, making it possible to stack up to seven blocks high. This functionality allows the robot to pick up objects, drive them to a specific location on the site, raise them to the correct height, and release them, making it similar in capability to a forklift. This similarity gives the robot integrity as a scale version of a real assembly process.

The Stacker Robot arrives as a flat-packed kit, which can be assembled in a few hours. The total cost of the assembler robot, including the Stacker Robot, four servo motors, an *Arduino* microcontroller to drive the motors and two *XBee* Wireless shields to transmit signals from a laptop was about $350.

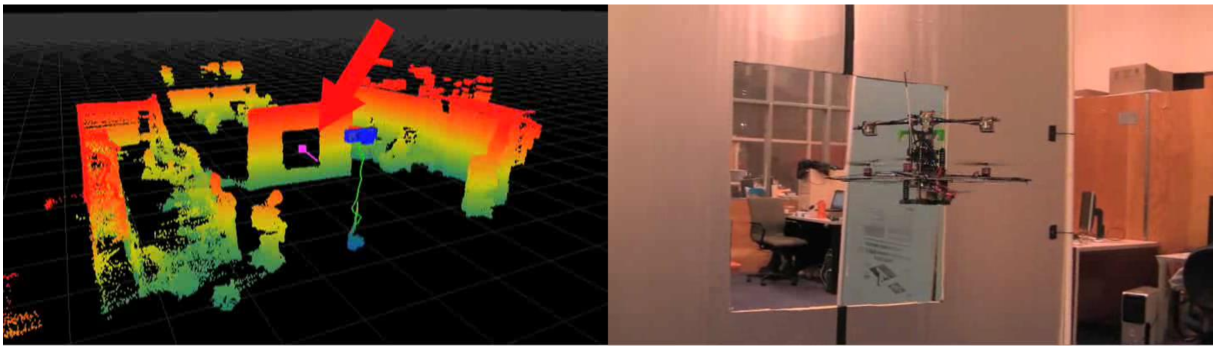


Stacker Robot kit (left) and completed robot (right)

Vision System Research

The use of a mobile assembler adds the requirement for tracking its position over a wide area. This could be achieved using a range of sensory feedback systems; however, only vision systems were investigated here due to their simplicity for use in the classroom. As with the fabricator and assembler robots, the students do not need to understand the technical workings of the vision system, only the role it plays in tracking the assembler. This vision system should therefore be seen as interchangeable with any other mapping technologies capable of performing the same role.

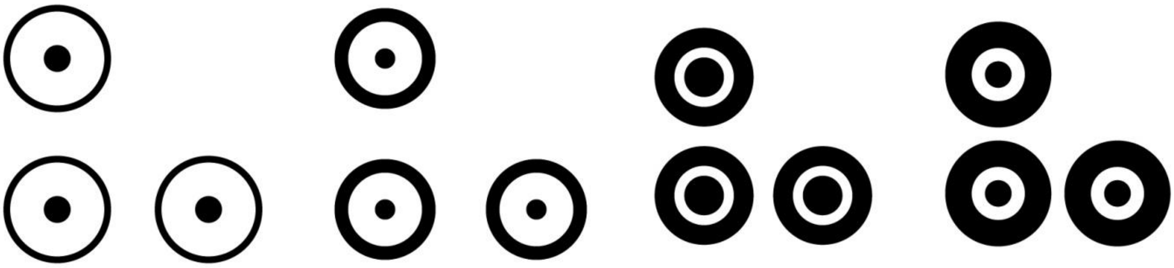
Many existing mobile robotic systems use laser-scanners to capture 3D data about their environment and a SLAM system to record and update this data in real-time. The data can be transformed into a 3D model, which can then be used to calculate a path through the environment. A team led by Nick Roy at the Massachusetts Institute of Technology developed such a system called RANGE to autonomously navigate a quadcopter robot through a series of spaces to win the AUVSI 2009 International Aerial Robotics Competition. (Roy, 2009)



MIT's RANGE system; mapping its environment (left and navigating through this environment (right)

The laser-scanners used in MIT's RANGE system proved unsuitable for use in the hybrid robotic construction system due to their cost of several thousand dollars per unit. Low-cost versions of this laser-scanner such as the David Laser Scanner (Winkelbach & Molkenstruck, 2010) were also investigated. These systems are designed to scan small objects using a laser line, and are not suitable for mapping environments. This would mean making many adjustments and increasing the complexity of the system unnecessarily. The Microsoft Kinect was also considered because it uses a structured pattern of infrared light to scan an entire room. This system also proved unsuitable because it cannot detect objects closer to the camera than 40cm, which makes it incompatible with the scale of the current fabricator and assembler.

To keep the cost and complexity of the system down, a simpler approach to the vision system was evaluated. Using a low-cost webcam, well-established augmented reality (AR) tag tracking algorithms could be used to locate black and white symbols in a three-dimensional environment. In order to supply high quality images, a high-end Logitech HD Pro C910 webcam with 5 megapixel resolution and autofocusing was used. While slightly more expensive than some available webcams (approximately AU$120), this ensured accurate control of the assembler and still came in cheaper than any of the other sensory feedback systems.

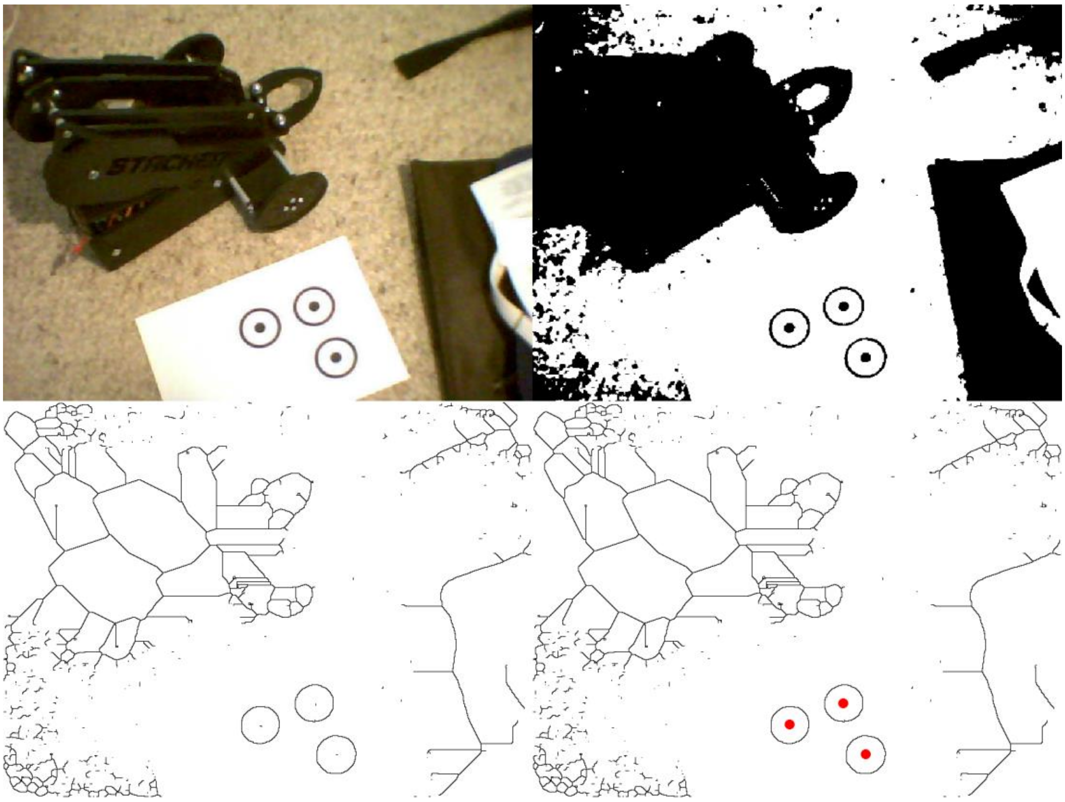


Examples of AR tags; increasing in visibility from left to right

Some existing AR tag tracking software available on the internet was investigated. However, this software is typically aimed at tracking tags in real-time (30 frames per second) in a relatively low-resolution video stream and was not capable of analysing high-resolution static images such as the 5MP images from the Logitech webcam. To address this deficiency and to give more control over the integration with the system, a simple AR tag finding algorithm was developed using the open-source programming language, *Processing*.

The first iteration of this algorithm used the following steps to find the location of the AR tag in the webcam image:

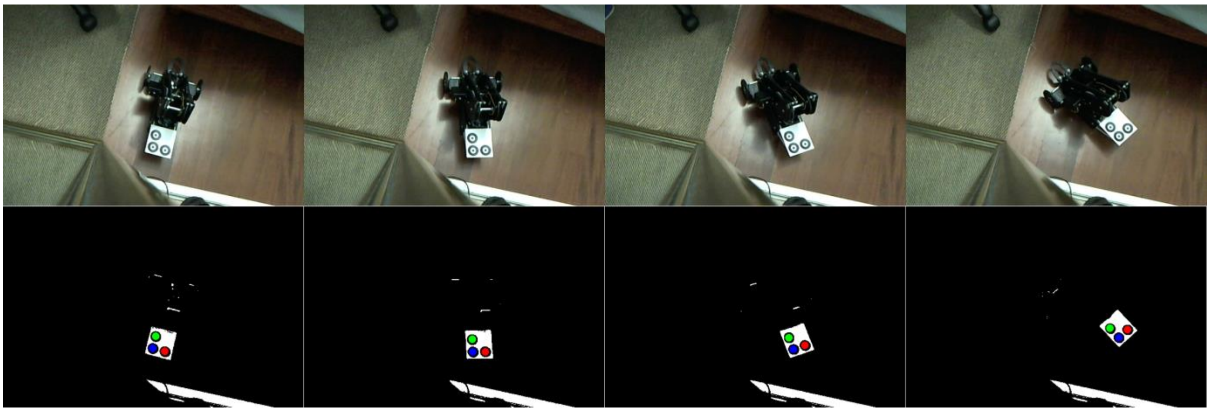
1. The image is captured from the webcam
2. This image is converted to a black and white image
3. The black areas of the image are thinned using a thinning algorithm (Ng, Zhou & Quek, 1994)
4. The black areas are identified as separate 'blobs' (Robotix, 2012), and the AR tag is found by searching for blobs of a certain size and arrangement.



Screenshots showing steps involved with in AR tag tracking algorithm

The thinning part of the algorithm (step 3) was found to be unnecessary and was removed from the second version of the algorithm.

An AR tag was fixed to the assembler robot to allow its position to be tracked. Controlling the assembler is accomplished by incrementally rotating and moving the robot towards the target location, checking its location using the algorithm and repeating the process until it has arrived at the target.



Sequence showing the assembler robot turning to face a target.
The top row shows the image captured from the webcam,
the bottom row shows the identified tag

Coordination software

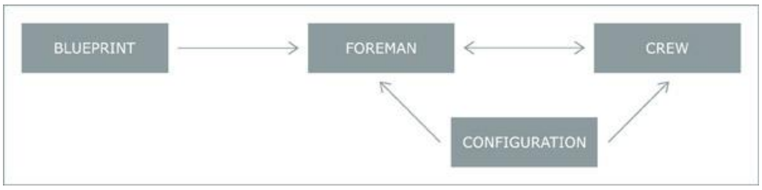
The final element of the hybrid robotic construction system is the coordination software. In the *Flight Assembled Architecture* exhibition, Gramazio and Kohler worked closely with Raffaello D'Andrea, who was responsible for creating the software to coordinate the quadcopters constructing the tower. This software was called *The Foreman* and is described by D'Andrea; "The Foreman manages the overall construction process by interpreting the blueprint, issuing build-orders to the Crew, and tracking the construction progress based on their feedback." (D'Andrea, 2011)

The coordination software for the hybrid robotic construction system plays a similar role to D'Andrea's *Foreman*. It sends instructions to the fabricator and assembler in sequence and uses data collected from the webcam to check the position of the assembler and monitor the overall construction progress. Instructions contain information to identify which machine should carry out the action, what type of action the machine should carry out, and finally some numerical data to control the amount of action to be carried out. For example, the following series of instruction tells the fabricator to make a 45 degree cut and the assembler to move forward, close its gripper and move backward:

`FF  50`	*Fabricator: feed material 50mm*
`FA  45`	*Fabricator: set angle to 45 degrees*
`FC -50`	*Fabricator: cut down 50mm*
`AF  100`	*Assembler: move forward 100mm*
`AG  0`	*Assembler: close gripper*
`AB -100`	*Assembler: move backward 100mm*

System Architecture

D'Andrea deconstructs his quadcopter construction system into a number of roles, which he refers to as "The Blueprint" (the design model), "The Foreman" (the coordination software), and "The Crew" (the quadcopter assemblers). He presents the following diagram to describe the system:



System Architecture diagram for the Flight Assembled Architecture Project (D'Andrea, 2011)

The system architecture for the hybrid robotic construction system builds on the architecture presented by D'Andrea for the Flight Assembled Architecture exhibition. A 3D digital model is translated into a construction sequence by a custom *Grasshopper* script. This sequence is then loaded into the coordination software, which issues instruction to the fabricator and assembler accordingly. (Figure 6.1, Table 6.1)

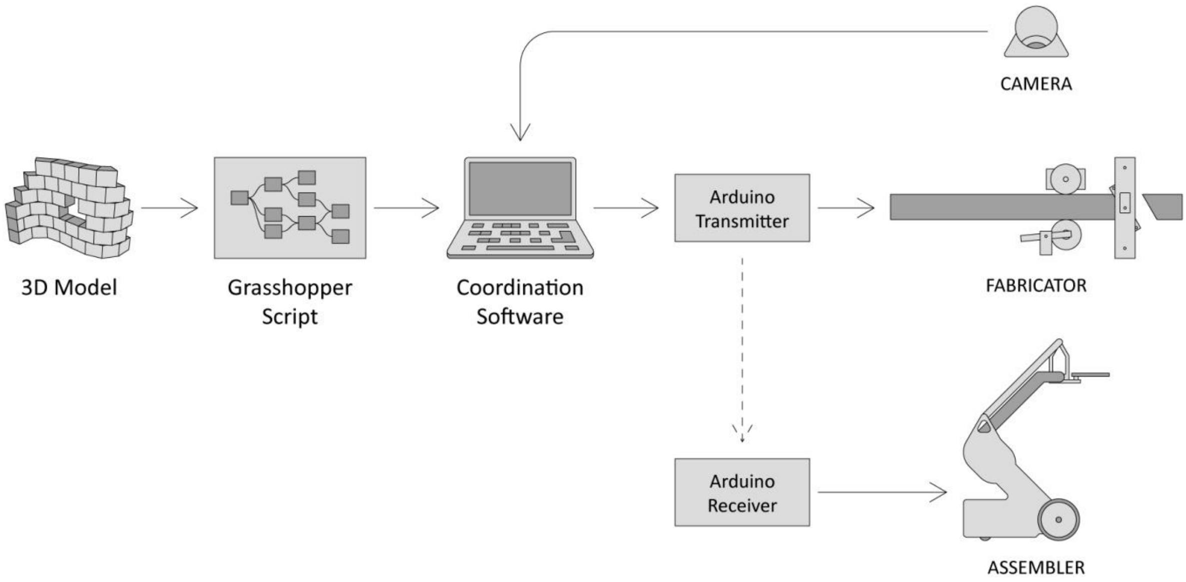


Figure 6.1 *System Architecture for the Hybrid Robotic Construction System*

Software	
Rhinoceros	CAD software to generate 3D digital model
Grasshopper	Scripting language to translate 3D model into construction sequence
Processing IDE	Coordination software to Issue instructions to the Arduinos
Arduino IDE	To upload software to the Arduinos
Hardware	
Computer	Running Windows and the software listed above
2x Arduino Uno	Interpret instructions and control the Fabricator and Assembler robots
2x Arduino XBee	Allow wireless communication between the Arduinos
Fabricator Robot	Custom-built hot-wire cutting robot
Assembler Robot	Stacker Robot Kit purchased from servocity.com
USB Webcam	With HD resolution or better

Table 6.1 *Summary of Software and Hardware required for the Hybrid Robotic Construction System*

6.2 Future Work

Future research would involve implementing the revised course structure and developed hybrid robotic construction system into an architectural classroom to assess its validity. The results of such a class trial would reveal whether the hybrid system would give students a better understanding of the role of fabricators and assemblers in the construction process. There are numerous other concepts that could be included in an architectural course on robotic construction technologies; several of these are discussed below.

6.2.1 Introducing Students to Sensory Feedback Systems

Integrating the robotic fabrication and assembly tasks necessitated the introduction of a feedback system to track the assembler. This presents an opportunity to educate architecture students about different types of sensor and vision systems, which could be utilised in construction robots. With an understanding of sensory feedback systems, students would not only be able to design the 'production process' as described by Gramazio & Kohler (Section 2.4), but they would also be able to design subsumption logic into this production process as described by Brooks (Section 3.4). This low-level awareness would increase the students' control over the construction process.

Dr Simon Weir recognised the importance of monitoring the water jet cutting of stone for his project in Central Australian. (Section 3.4) Due to the inaccuracies of the cutting process and unpredictability of the stone material, he speculated that an automated visual inspection of the fabricated parts would identify defects and rectify the problem by recutting the part. Similarly, if the assembling robot places a component in the wrong place, it could attempt to rectify the problem by making the required adjustments.

6.2.2 Cooperative Robotic Construction Systems

As robotic construction technologies gain popularity, there is a need to update architects' knowledge by introducing cutting-edge concepts to the classroom. The future of robotic construction technologies will likely involve several cooperative assembly robots working together to increase efficiency of the construction of buildings. Gramazio and Kohler's *Flight Assembled Architecture* exhibition (Section 2.3.11) and the Harvard SSR Group's *Termes Project* are examples of swarms of assemblers working towards a common goal. The small-scale hybrid robotic construction system developed above could be expanded to include multiple assemblers to showcase this possibility to architecture students.

As well as using multiple assemblers to decrease the construction time, there is potential for assemblers to cooperate on tasks that would be impossible with only a single assembler. For example, Dr Simon Weir discussed using multiple robot arms to build an arch without the need for separate formwork. A robot arm could be used to hold each stone block in position on the arch until the final keystone is place, securing the structure and allowing the arms to start work on the next arch. This could lead to specific classes aimed at allowing students to experiment with novel assembly sequences that would have been previously impossible.

Multiple fabricators could also be added together to create new hybrid systems. For example, Harvard GSD's *Ceramic Futures Project* has already combined three fabricators in a new manufacturing process for freeform ceramic tiles. There is much potential for architecture students to research new fabrication processes based on new combinations of fabrication machines.

Using the role-based framework presented above, there is also potential to experiment with the placement of the fabricators and assemblers in innovative combinations of off-site and on-site. New models of construction can be imagined, opening up an exciting future of architectural research.

7 Conclusion

The research has satisfied its aim of developing a framework and suitable technology for teaching architecture students about robotic construction technology.

To achieve this aim, a literature review was conducted to catalogue robotic construction technology being used by architects. The literature review revealed three reasons architects are motivated to engage with this technology. The first is a desire to create new architectural forms, which would be difficult or impossible to create without access to robotic technology. The second is a commitment to building higher performance architecture; achieving a higher production tolerance and reducing manual labour required for construction. The third is a drive to bestow the architect with more control over the construction process by generating data for the fabrication and assembly of the building directly from the architect's design model.

An interview was conducted with Dr Simon Weir to investigate his motivation for using robotic construction technologies on a project for an Aboriginal community in central Australia. While Weir was interested in creating new architectural forms and improving the quality of the buildings, these were not the main drivers for using the technology. He presented both a cultural and a social motivation for using robotic technology, not seen in any of the other examples in the literature. A respect for the Aboriginal people's spiritual connection to the land led to the idea of using local stone as the main material for the buildings. This material choice would require robotic analysis, cutting and placement of the stone blocks. Weir also responds to the needs of the local Aboriginal community by involving them in the construction process and aiming to provide a new source of income for the community through a mastery of this technology

A need to teach architects about this technology was also revealed through the literature review and interview with Dr Simon Weir. In order the teach architecture students about the available robotic construction technologies, existing classification frameworks were reviewed and assessed for their suitability for use in the classroom. These existing frameworks were found to focus on the technical processes utilised by the technology, which does not correspond to the way architects are engaging with the technology.

A conceptual framework was developed, classifying robotic construction technology based on its role in the construction process as either a *fabricator* of building elements or an *assembler* of these elements. The framework was further extended to classify assemblers as *Part-to-Module*, *Module-to-Whole* or *Part-to-Whole* assemblers and to merge existing frameworks into the developed framework. This conceptual framework allows architects to more naturally contemplate robotic construction technologies based on their role in the construction process, rather than their technical process within the machine.

This role-based conceptual framework was implemented by teaching a class of students from the Master of Architecture course at the University of Sydney. The course was divided into two parts; the first taught students about robotic fabrication, and the second taught them about robotic assembly. The first part required the students to design and fabricate a small-scale architectural module and the second part asked them to design an assembly using these modules. Despite the link between the two parts of the course, the results from the class indicated that a more direct integration of the fabricator and assembler would be beneficial.

An assessment of the results from the class revealed a number of outcomes for further development of the implementation of the framework into the classroom. As well as requiring tighter integration between the fabrication and assembly tasks, it was found that the technology used to during the class must be carefully considered in order to demonstrate the role-based nature of the framework. Specifically, the robotic system should represent a small-scale version of real robotic fabrication and assembly processes, should introduce students to feedback systems to control and monitor these processes, and should also reveal the potential of using mobile robots for on-site assembly.

Taking these outcomes into consideration, a hybrid robotic construction system was developed. The system needed to be low-cost in order to encourage the introduction of similar systems to as many architecture schools as possible. The hybrid system included a small-scale hot wire-cutting fabricator, similar in capability to a compound mitre saw; and a mobile assembler, similar to a forklift. A camera was introduced to provide the necessary feedback on the progress of construction and coordination of the fabricator and assembler. System architecture and fundamental control software for the system was also developed to coordinate the various elements of this hybrid system.

The research contributes a conceptual framework for teaching architecture students about robotic construction technologies. This conceptual framework is more appropriate for architects than existing frameworks because it responds to their motivation to solve design problems. It does this by classifying the technology based on its role in the construction process, rather than the technical process it employs.

The research also develops appropriate technology to teach architecture students about hybrid robotic construction systems based on the developed, role-based conceptual framework. This permits architects to think about the technology in terms of this classification and should allow for novel experimentation in robotic construction in the future.

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Appendix A: Transcript of Interview with Dr Simon Weir

Interview conducted on the 7th June 2011.

Steven Janssen is in italic font
Simon Weir is in regular font

Maybe you could start by describing the project a little bit? (0:43)

That's a tricky one, out of nowhere, how to describe a project? Formally it's just trying to construct purely stone buildings using local stone on site, so have a quarry and a milling and a construction process all on one site, essentially.

Who is the client and what have they asked for? (1:10)

The client is a group of indigenous elders from the Yankunytjatjara and the Pitjantjatjara area around Uluru. It's the Yankunytjatjara tribe and that's the name of their language as well, is the actual group that belong to the Uluru area itself. But one of the larger neighbouring language groups is the Pitjantjatjara and apparently their languages aren't that much different there. I don't know that much about that.

So they can understand each other? (1:40)

Well, they're all multi-lingual and the people who live there have been brought up there, were brought up with four languages, plus English, if they choose to learn English, so it's just natural that you learn your language and the other people's language at the same time.

And what have they asked you to design for them? (1:58)

So they're currently running this really intense wilderness tourist operation. Where people can come in and sleep on the land and eat foods that they catch and dig up on the site. And it's possible already to do that with small groups of people but as the elders get older and a little bit more fragile, and the number of people who want to visit gets larger, the initial step is just to increase some of the infrastructure and the basic facilities. The longer term plan is that when the elders get much older and more enfeebled. At the moment they travel internationally and nationally quite a lot as part of just being who they are, but as they start to get older, they want to travel less and we'd have people come to them.

Will they have new elders, who rise up through the ranks? How does the system work? (2:52)

It's always the eldest who has the most seniority so there are currently three or four generations living there, but the elders are in their eighties and they're still pretty strong.

So you would design accommodation or a tourist information centre of a sort? (3:09)

No, it's not for the tourist information so much. It runs a dual purpose, you bring in tourists, people who just blow in and get the experience and leave some money and go home again, but there's also the idea that it's going to be a place where the indigenous people from around the country come for indigenous training by indigenous people. A lot of people around here, for example, have their roots in this area, but all the heritage is gone, all those people have died and the knowledge has been destroyed, so they still yearn for some kind of connection to the landscape, and they can get that in part, even though it's dislocated, through the indigenous elders who still live on their own land in central Australia. So they go there for that as well. So it can often be that the elder here would go and see the elder out there, who is older.

What sort of things do they discuss in these meetings? (4:09)

There's a whole list of that kind of thing, I'm certainly not enough of an expert to give you a proper list, but not only how to work with the land physically but get a better appreciation of the principles behind living with each other, and living with the land, so that it's a smooth communal process, rather than a battling kind of process. There's something kind of combative with our western relationship to the land. It's full of predators and we're continuously fighting back, but they don't have that quite such a hostile relationship. I mean, the land is still deadly and everything, you can't pretend that it's something overly friendly. It's about acting in such a way that what you do is both for your benefit and for the benefit of other people around you and also for the people in the past and in the future. They consider all of these layers through time as part of their immediate family. You know what you're going to do, as long as you know what you're doing will leave behind, because that is what you're doing. Even though you might think about things step-at-a-time, you need to see the bigger picture into which it falls.

So how are you going to propose an architecture that fits in with this mentality? (5:35)

Well, the principal things are, there's really two levels, it's really maximising local materials so that there's less stuff shipped in, less foreign materials brought in. I mean there will always be a certain amount, they want some of the western comforts, just like we do, we all benefit from heaters at night and electricity and Macs and internet connections and everyone benefits from that kind of stuff. We're not trying to somehow architecturalise the pre-industrial object, but we figure if the building is actually constructed from materials that are already there, that a large part of the architecture is a reorganisation of existing things, rather than an importation of new things. More like that. So that's the first step, which also works not only at the local level that the indigenous people and people who visit there will see that building belongs to the place if only materially. What we can't do is like we do in regular Wester architecture is build things that end up in the tip because the tip is the site. So whatever rubbish that we produce will stay on our site forever. It does for everyone, but we, Western architectural culture, pretends that that doesn't matter, that we produce large tips. But it does matter more to them because that's where animals or where plants and where water is. So to despoil it by throwing in tons and tons of junk means that not only us humans, but all the other animals and all the other plants have less space forever, or at least for tens of thousands of years because of that action. And that, because it's a really serious consequence, we have to minimise that.

What sort of materials are available on the site? (7:29)

There's pretty much only three, I guess. There's the dirt itself, but it's very sandy, there's not much clay in there for any kind of pise construction. There is the stone of course, which we're using and there's a lot of Spinifex and you can make a super-strong glue out of the end where the Spinifex touches the ground, that connection between the blade of the Spinifex and the earth; the major chunk of the plant. I don't know whether we're going to be able to use that, but we'd like to as part of the bonding materials, but I don't know enough about it at the moment, I've got to learn how to produce it and see how reliable it is and that kind of thing.

Are you thinking you can make a mortar to join the stone out of this Spinifex glue? (8:16)

That's the idea that's out there, yeah. Or to use it to mix with the sand itself to make an earth block, or something.

Is the idea that this architecture then will dissolve back into the land and then be rebuilt or that it will simply last forever? (8:30)

The second one doesn't make any sense. I guess forever is too long. Nothing will last forever. Essentially, yes, it will dissolve back into the earth itself, even if that takes 1000 years, that will be the end process.

Is that the sort of timeframe you think these structures will last? (8:59)

We're going to aim for as long as possible. If we're using the stone itself, well we don't know until we get some erosion figures on the stone, how long it will last out in the rain before it just naturally starts to fall apart. As long as possible.

How did you get involved with this project? (9:18)

It's really just the usual way; a friend of a friend.

And who is your friend in the project? (9:28)

There's a group of people I know, that I was friends with in the Southern Highlands, ten years ago, or 15 years ago we met. And they are friends with Bob Randall. And Bob Randall is the more public figure amongst this group. And Barbara is also as well, these are outstanding figures in the community but Bob is more active in the English speaking community than Barbara is. So he gives talks around the world and around the country about Kanyini is the particular principle that he talks about the most and his car has a Kanyini number plate, the umbrella company that we're working under is Kanyini strategic enterprises. And he has a movie out called *Kanyini*, which Melanie Hogan made and there's a few of these terms, Kanyini and xxx and these other things I can't remember off the top of my head. But Kanyini is essentially what he calls "unconditional love but with the responsibility". And that's one of the principles he talks about that's fundamental to the indigenous way of life that would be good if it was also part of the Westerner's way of life as well. There seems to be a split, I think, culturally or psychologically about that issue. We seem to think that perhaps unconditional love is a very airy fairy bliss state. We have this Western conception of love like it's all in the moment, so that 'being in the moment', all these kinds of expressions, which is really anathema to a long term responsibility for your actions. It's a form of psychological denial of the consequences of what you're doing. That kind of Kanyini involves something about that intense presence in the moment, but also caring about the emotional and psychological responses that you have with people while you're with them, while also taking seriously into consideration and modifying everything based on your knowledge of how far in direction and time your actions do effect. And to think about those kinds of decisions while you're acting with love.

That sounds really complex. And this is the sort of mentality you're using for the architecture of this project? (12:02)

Yeah, exactly because we have to think about making nice buildings in the short term; it's not about making ugly things only thinking of the future; but producing things that will satisfy all the demands of the present and as many of the demands of the future as we can anticipate, which there is really quite a lot, I mean, architectural needs don't change very much, so why should we build something that will need to be demolished in a couple of decades when it will always be wanted? But that's not the way we build here; we build things for 20 years, hoping to get 50 out of them. But we knock it over and start again; that's always the plan. Rather than thinking why should we build stuff over and over again, let's do it right the first time and it can keep itself alive indefinitely.

We've touched on this already a little bit, but what is your proposed construction method for the project? (12:58)

Well there's two that we're currently investigating, which would be either making earthen blocks out of the combination of the sand and the Spinifex, so that's very experimental. Or the most immediate plan that we're working on is to take the local stone from the site and cutting it on site and constructing buildings that are as made of stone, there is as much stone as is possible in the construction of them. So there would be stone walls and stone vaults as roof ceiling materials and stone floors. And you can fit out with some of the more convenient materials which would be replaceable, but the shell itself should be there.

And how would you propose constructing these stone blocks and cutting them or transporting them the site? (13:49)

At the moment it's what we've been talking about, though this plan is bound to change, but to remove the stone from its current location and assemble it into an enormous pile and do some kind of preliminary cutting to see the exact colour of the pieces of stone themselves because they're all slightly different because the amount of oxide changes. And then using some kind of visual scan or computerised formal scan of the stone itself in order to orient whereabouts in the construction it will be located. So we'll have a full three-dimensional map of the building and all the pieces of stone in advance as a digital map and then we'll have a robotic-controlled water-jet cutter slice the pieces of stone precisely to the requirements in the three-dimensional model.

And as well as preparing all of the stone, you mentioned this robotic system would also assemble the pieces on site. (14:54)

The extent to which the robots will assist assembly is not something I'm not really clear about at the moment. There's still quite a lot of variables in between. Like the maximum size of the harvestable stone from the quarry site. If it ends up being quite small then a manual production would make sense. But larger would be better, and certainly we'd need some kind of robotic or electric assistance for that part of the process.

And what other construction techniques are you considering for the cutting and stacking of the stone blocks? (15:35)

Well the only other way of doing it really would be the old fashioned way where masons get there with hammers and chisels and knock the stuff up.

And for what reasons have you decided to go against that traditional approach? (15:53)

On the one hand it sounds profoundly slow unless you have an enormous number of workers. And the training is going to be an issue. We have to decide, if we're going to train indigenous people to work on the project, what skills will be most beneficial to them in the long run, rather than the short run. And I imagine learning some more sophisticated techniques like equipment maintenance, rather than just stone cutting and hammer and chisel maintenance, or maybe there's software integration or the connectivity between whatever information supply there is, whether it's back here or in the cloud, getting that into the systems will be more beneficial to them in the long run than just teaching them hammer and chisel stuff. Because there will be both, essentially, there will be no way around this without hammer and chiselling a lot of stuff at the last minute, you know, fixes and details can be manually sized.

And I guess the other question would be the degree of the influence of robotic assembly techniques. There is a fair degree of reasons for both of these things and I don't know which way to go. If we had all the arches standardised so they were essentially the same as each other, we could use a single steel piece of formwork, which we could use for assembly of each arch. But one or two or three steel arches, steel trusses would serve as the formwork for all the arch construction if the arch was the same. But if the arches are different and they're going to keep moving in section as you work around different parts of the building then there'll be an enormous amount of formwork, which is essentially waste material. And we can find a way to reuse some of them, but if we end up needing a different formwork for every span, we'd have like a thousand different trusses required, which is clearly crazy. And in that situation, actually using a robotic or a pair of robotic arms as mobile, transferrable formwork would be of some real benefit because they could just hold the pieces while we wait and hold whatever shape next.

Were there any other requirements that led you to choose this robotic system? You mentioned, for example, speed. If it was done manually, it would take a lot longer. Were there any other factors that would make it beneficial to use robotic systems to assist the construction process? (18:52)

There's a few parts with it I don't know how else to do them, so I don't really have reasons for it, other than I have no idea how else to it. Like, how else would you make this sequence of shifting vault forms where there is no continuity? What kind of formwork system do you use?

Is accuracy another important factor? (19:31)

Yeah, the ongoing measurement instance is also a really key part of it. The building's going to weigh maybe a couple of hundred tonnes, which is to say five times more than a normal building of that size. So we are going to get foundation settlement, which we're going to need to keep track of to a very fine tolerance. A timber structure, that can wobble quite a bit and no one will ever really notice.

So as it is even being built, the building will be moving. As you're adding blocks, you'll need to reassess the new blocks so that they fit into the settled form of the foundations? (20:03)

Exactly, yeah, we're going to need some kind of agility in the form process.

Do you think then not only the rocks will need to be scanned for their colour, but the building will need to be scanned as you're building it in order to update the model and produce new blocks. This implies that instead of cutting all of the pieces to begin with and then assembling them, you have to cut a piece at a time as it's needed and then insert it into the building. (20:21)

Yeah, I think so. Just thinking about it structurally, it only makes sense to build the whole building at once from the ground up. But the difficulty of that is that we end up needing all the formwork up at once, which becomes extremely expensive and the robotic option becomes out of the question, because we'd need a thousand robot arms, until the last step. And you put them all in and they're all finished with, which seems really wasteful. But you don't actually need robot arms because they'll go into position and they won't move for two years. You'll need them to get there, but once they're there you can let go of them forever.

This is an interesting architectural question because the Architect's role is no longer just creating the final form of the building but also creating the entire process of how every block is laid and how each one is cut and then assembled in order to save the amount of scaffolding needed or the amount of robotic arms needed to hold everything in place. Do you consider yourself a pioneer in this methodology of design, or do you have any similar precedents? (21:37)

I don't know about it in terms of this methodology of design, but I'm certainly inventing a design construction system, which I guess all architects do to a small amount. But there is less of the existing stuff to begin from with this. Who else has done work like this designing construction systems? I guess Gaudi is the person who started a lot of that. I don't know that many other people who've worked in this, not that there aren't, possibly. Like some of Ross Lovegrove's work, or something, but they're often looking at scale of furniture, inventing new construction systems in order to make particularly cool new things. But I've never seen it quite on this scale before.

What reactions have you been getting from the Aboriginal clients regarding this proposal? (23:11)

It's what they wanted, to a large extent. I mean, we haven't gone over every little particular detail of the construction process that has been proposed. It really came out of the first meeting. I always tell the same story: I was sitting with Bob Randall in Mutitjulu, which is the community right beside Aires Rock. It's pretty ramshackle and there's a lot of these metal box buildings. Like we do these temporary buildings or those demountables, things like that. So they're basically these metal boxes with square rooms and square windows. So I was sitting there, supposed to be playing architect for the day and I said to Bob that, "it looks to me like all of these buildings here are actually hostile to your way of life. It's not only not what you should want, but this actually is really working against you and if we're going to do something out here, I think we need to do something completely different". And he just said, "good, that's what we need". And after going out on site and finding that there is stone there, I thought, "we have to build from stone, it's the only option, it's the only way to do it". And they both agreed. All the indigenous people that I spoke to agreed so quickly as if that was their idea as well. It wasn't a surprise to them. They went, "oh yes, that's right".

Traditionally do they build from stone? (24:48)

They have built some stone things along the way, but they haven't had that much of a tradition of staying in the same places all that frequently. Because they have the same problems like we do. The reason we need to keep moving on is because as humans, we don't like being around our own poo too much. But if you walk away from a place for a couple of months, or a couple of years, it really is as good as new. So you avoid that kind of repetitiveness. Though often there have been situations where I've seen photographs and I've heard stories, they've built some very small stone shelters because it is warmer to stay in at night. They don't seem to have been designed to be there very long. Like, you might do a month or something and then you move on. And you don't need the building to last any longer. So we have all sorts of little remnants of the base couple of layers of some of the larger pieces of stone still in situ. You can build a lot of timber structures and shelters there. They've always built timber shelters for themselves.

Out of the Spinifex, or are there other trees available? (25:58)

There is Desert Ash and there are a couple of the occasional other tree you'll get there. Like a newly dead tree, or a newly dead tree next to a living tree. You can kind of bang them together, lean them into each other and cover it in some Spinifex.

So they would never cut down a living tree? (26:14)

I don't know. The termites get to it so quickly that it doesn't last very long at all, but that's cool. And occasionally a fire or the ember; you have the fire right next to it occasionally, it'll just burn, doesn't matter, you just make another one.

How does your proposal fit in with this idea of moving from place to place and allowing the land to revitalise? Or is that no longer relevant to the way they live? (26:53)

No, not really. That is the thing that is different about the way we live and the way they're getting accustomed to living as they spend more time with us. Which means we've got toilets. The toilet changes everything. And having a water supply to a tap, rather than find your water supply where you dig it. So that brings people back to the same places. So we do have what we call "waste issues". But human waste issues, it's not toxic waste. It's just nutrient rich waste and it's a very nutrient poor soil. So we will end up with these gardens of plants that aren't normally there as a consequence of the nutrient density we're going to get out of the toilet. But we can make that work for us just by putting food plants in there and using the extra water in there to make some trees grow a bit faster in order just to produce firewood. We're just going to use it like a permaculture system rather than avoid the problem. We're just going to embed it into the system that we're going to produce.

How will the local people become involved with the project? (28:17)

Depends on what scale you really mean by "the project". It's run by the people, for the people.

I should say the construction of the project, first of all. (28:27)

Well, we have a mandate from them to hire as many family members as possible because they want everyone to feel involved in it. And also it is in itself an opportunity to drive education. That is one of the key aspects of what the whole thing's for. It's not only so indigenous people can come and learn indigenous law from indigenous elders but that it gives an incentive, this is the plan, that it will, by having these businesses, the tourism businesses run by indigenous people, by dual- or tri-lingual indigenous people, people who are really good at English, but also good at Pitjantjatjara and Yankunytjatjara, like their three first languages. There's a lot of kids growing up who still live with their parents and they speak Pitjantjatjara and they don't... It's hard to speak for someone else, I'm worried that I'm speaking out of context about something that I maybe don't know enough about... but there is sense that there is not much of an incentive for these young people to learn English because what would they do with it? And the answer isn't much. Or it means leave their family and leave the life that they've grown up in and go to a really foreign world. So there is a big psychological investment on whether or not to learn English. And there really is a sense of loyalty to the family by refusal to do that. And I mean that in a positive sense that they're going to continue living this way with their parents the way they've always lived and why would we go off and go and fraternise with the other side. So by producing these businesses where the dual language capacity is both obviously beneficial to them but it's not at the cost of their indigenous awareness because they'll still be with indigenous elders, so they'll have this dual-cultural thing going on at the same time.

So it's running like that. That's part of the bigger sense that the project is trying to fulfil. And the construction side will be involved in that. They want to use the construction industry itself as a way of incentivising people to come along and earn some dollars and also learn a trade at the same time. Those that are more skilled at it will go to the local school, which we're going to try and get a TAFE connection with, so we can... If the building site becomes large enough, which if we run both projects simultaneously, it will be. It will be dozens and dozens of workers. Then we can actually run a TAFE certificate, well we won't run it, but it will be possible for the TAFE to run tradesman certificates and contractor certificates out of the local school to feed back into the job. So if the construction project runs for long enough, which it should do if we go from beginning all the way to the end, ten or 12 or 15 years, then it's time for kids to decide "ok, I will finish high school and I will get a job with my elders here and I'll go to TAFE and I'll work on the construction or the hospitality at this business" that will always be there to incentivise the education process. There's a real "what am I doing this for, I'm doing this so that I can go do that" with Uncle Bob and with Barbara and with Dorothea and the important people of the community, rather than "I will go and learn English so that I can work for all the Westerners at the resort", which is much more of a foreigner's foreign world, no indigenous leadership, or very little indigenous leadership, and it's a safer path for the parents, I think, to say "you should go, try that out, see what happens".

So it is important that this construction takes place over long time-span then? (32:18)

Ideally, the whole project will be almost perpetually ongoing.

Do you mean expanding or repairing? (32:32)

Expanding. We've got five houses for the first one and the second project is much larger again. It's the equivalent of... it's hard to count them, they stop being houses being larger buildings... but the equivalent of five times the size. And if that becomes successful, there'd be no reason not to expand that one. Either way we're up to a ten year plus construction just to get us to that stage where we'd start thinking about repairs and expansions. Which is why building this robotic construction system and quarrying local stone in a very high-tech fashion, it could be an ongoing process. So to train indigenous people to use these robotic machinery. If there is a string of 15 buildings in front of them, it makes more sense to really figure it out then as soon as you've finished what you're doing it's over forever. And it's really hard to bother.

So this is a sub-business that could allow the indigenous people with the skills to operate this machinery and the robotic systems to travel around and do similar projects elsewhere. (33:32)

Exactly, that's the philanthropic angle of it, which we haven't completely worked out into the business plan as we're discussing it with the charities that we're working with. But that is essentially the idea that we'll give them these robotic water-jet cutters.

And train them so that they can maintain them and use them? (34:02)

Yeah, exactly. So they will run them for our project and when our project expires they can keep it. And they know how to use it, and hopefully it should all still be working, or they'll at least know how to do the repairs and the expansions and they can transfer that exact construction anywhere else. And they can actually be a sustainable business model that seems to be appropriate for indigenous people. For them to be able to go and provide the highest quality, longest lasting architectural workmanship available on the planet. Indigenous people, what they can promote as their skill is building better architecture, more longer lasting architecture, than anyone else. It's exactly what an indigenous person maybe should be doing, or would want to do, I can't really talk into their mouths too much there. They'd certainly seem to have a much longer viewpoint than what Western architects plan for.

Do you think they would be able to apply this technology to other fields apart from architecture? (35:11)

I guess so, I don't know. I guess there's no reason why not though. But then you start this question of what is and what isn't architecture?

Maybe a better way of phrasing that then is: the system that you develop and the training that goes along with that; do you think that could be applied to other situations? (35:35)

It just depends on what level you think that we're going to say that the project is operating in. From what I've explained already, the project operates at lots of scales simultaneously. Both from the very long time scale, to the medium time-scale, to the short time-scale. And each of those things is transferrable differently to other industries. Essentially once this starts going it necessarily spawns other industries, like all large projects do. They either spawn or the feed subsidiary enterprises that become possible because the infrastructure is now in place, or because there are so many workers in one place, or because there's some attention brought to it and there's more tourists and therefore all these other things open up as a consequence.

The Bilbao effect? (36:47)

I guess so. I guess so.

What do you hope to learn by participating in this project? (36:53)

What do I hope to learn? I don't know. Stuff that I don't know that I don't know.

What technical challenges do you anticipate facing? (37:09)

It's just endless. I could give you technical problems till the clouds stop appearing in the sky. Like all the problems with using the stone itself. The compressive and the erosion and the tensile strength of the existing stone. How consistent it is. How do you measure the consistency of the stone? How far is it going to move after we do a building. No one's every done a building anything like this. Certainly in that 1000 square kilometres. Maybe in even that million square kilometres no one's tried anything like this before. So we don't know what to expect. There is no precedence. We need to be continuously aware of looking out for things that we don't know that we need to look out for. That's some of the technical challenges. Like maintaining robotic equipment 3500km away from any kind of expert.

That's going to lead to a lot of data management problems, where you have a 3D model of the building. You also have information about all of the stone that is available on the site, its colour, its properties, whether it's structural or not, how big it is, how it can be cut, and then how each of these pieces will fit into the assembly, the exact assembly process. This is a lot of data to manage. How are you proposing to deal with all of this? (38:06)

Any suggestions?

I guess that's what we can talk through a little bit. How could a working prototype of this system help your project? (38:41)

What does the working prototype mean? And what is this system? There's a lot of levels to this, isn't there? Does it mean we have a 3D model that is a BIM model at the same time, and a construction model, and a cost model, and a cutting model. So we have one 3D model that everything gets run through. So what part will be prototyped? As in just the construction/assembly piece, the cutting piece, the scanning side?

Which of these subsystems do you think would be more useful for the architect? (39:51)

I imagine we're going to need to do revisions of all of these systems at some stage.

Is it important how these systems link together or only that you have each of the systems working as a prototype before you try to create the whole thing? (40:04)

It sounds like there's going to be both, isn't there. Like prototypes of the components and then prototypes of their combination. Ideally, if we're going to need to do an agile system, we're going to say in advance, "here's the model, but I know that the top half of the model will need to change because the bottom half of the construction site will move". Then we do need to make sure we can be actively tracking foundational movement, which will correlate to structural transformation, which will correlate to different cutting maps. And ideally that will be a single system for the cutting assembly. But also if there is robotic cutting assistance, that will need to know as well. It will all need to come, hopefully, from a single map, rather than needing lots of models, which need to be updated over and over again. That sounds like a cause for a lot of time, it's a very risky process, I think. I'm hoping that the different systems talk to each other, having a single database of knowledge that everything draws from live. Rather than the robotic cutter is working on last month's map, because that's the piece of software it's got, and the construction assistance is working on one right from the beginning, because that's the only time it's been updated. That stuff sounds like a nightmare. 3D chips in each of the machine and they just talk to the server, "now, give us the latest". I mean, that would be the ideal situation. I've never heard of anything like this being available, but that's what we have to design.

A similar sort of thing is available in large architectural projects where the BIM model will be on a server of the software company and then the engineers and the architects and everyone will be able to login to it and change it and update it and whenever you login, you get the most up-to-date version unless someone is simultaneously working on it elsewhere. So you could have a similar server where the model resides, and that has everything about all of the pieces, it has the database of the stone and then the robots which are cutting can take information about what pieces they should be cutting, the robots which are assembling can take information about which pieces are about to arrive and can be assembled, and then similarly there'll be data flowing back from each of these machines, "ok, I've just finished this piece, update the model and let the other machines know that this pieces is now ready to be moved into place or whatever". (42:04)

What do you think would be a most useful first prototype for your project? Which of these intricate systems would be most useful to see in action as a proof of concept for you? (43:05)

I don't know. Again I just feel like asking, "what's your suggestion"? I mean the first thing I've got to do is to get out on site and make some tests; have pieces of stone taken to engineers to get compressive strength tests, to have some idea of the formal capacity. And after that is done, I need to work out what inputs the robotic controlled water-jet cutters need. To check that if I've build a formal sketch model, what kind of software will be appropriate. And then I'd have to talk to engineers to make sure that they can do the structural calculations on the same model. The colour scanning and the matching stuff and the structural testing and then the ground shifting models I don't know even know where to start on those two things. Until I get a sense of that and the overall budget, I'm not really sure I'll need to go with single, simple form formwork, which can be repeated endlessly or whether the way to design a system doesn't require that and how that would go.

It could be that you start off very simple on the first five houses that you mentioned; all with the same arch, but still with the complex system in place with the server and the robots, but essentially being quite redundant where you move the robot into position, you tell it that there is stone here, it cuts it, it moves it moves it into this very simple arch, then you move the robot around to the next side and it builds another simple arch exactly the same. Once you have that working absolutely perfectly for the first five houses, then you might consider uping the complexity of the system to do any form that you want or any form of arch and changing along the section. (44:31)

I think the easiest prototype to build would be the one which assembles the pieces on site and also perhaps one of the most important because then it would need a vision feedback to know that what it had done was correct and to test if where is was going was moving slowly over time, so that it can adapt. And this is the difference between an open-loop system and a close-loop system. In an open-loop system, you will just tell the robot there are these pieces in these exact locations, stack them in this arrangement and hope everything goes correctly. And if anything goes slightly wrong the robot doesn't know and it start making things worse, or grabbing pieces, which don't exist and so on. So with a vision system it's now a closed-loop system, so it will only pick up the piece if the piece exists, so it will look for the piece and if it can't find it, it won't pick it up. Or if it puts a piece down and then the whole wall topples over, it'll do a scan and say, "the wall doesn't look like what I expect it to look like, I need to either call for help, or be really intelligent and fix up what's gone wrong." So that system would be one that is quite challenging and interesting to see working, because then you can actually have the architecture actually being constructed by a prototype. (45:11)

But probably more important is the one that actually cuts the pieces because as a last resort if you had a system, which cut with a water-jet, all the pieces to the right size, then you could have labourers with a crane arranging them manually. It wouldn't be so important that a robot was doing it or not. The accuracy would come from the shape of pieces all locking together. (46:36)

Yeah, you should be able to do a visual check. This must go here because that means the lines line up. There's a possibility the assembly is not so difficult. But we definitely will need, from what I've heard from the robotics company, an ongoing visual scan of the cutting process. Because the cutting process is not super-accurate at the scales that we're operating in. The precision of a water-jet diminishes with distance, so we always have that middle bit. It's actually like a blurry circle in section; that is the shape of the cutting blade, a blurry circle. So we need to actually check really how they're fitting together, by looking at the stone as it's cut. Rather than presuming we're going to get like you get a piece of cardboard off a laser-cutter, which really will be accurate, but once you get to big scales, we've lost that.

How you think my research is going to help your project, or how would you like my research to help your project? (48:22)

Either of those things that we're talking about, they're things that I need to research and invent a solution, so whatever part of it you think you can do, or you're interesting in doing would be helpful, because I'll have to do all of it eventually.

I guess the water-cutter part needs to be done at 1:1 because, like you said, you're working with real material. You can't cut a piece of stone, which is 5cm cubed and with a water-jet and then say, "ok, therefore we can do it 20 times bigger". You actually need to get a water-jet and cut a large piece of stone and see what happens. So that would be a working 1:1 prototype, which would eventually become the water-jet robotic cutter used on site. Whereas the other prototypes can, to a certain extent, be built at a smaller scale and certain things have to be taken into consideration. So obviously the construction robot still won't be the same at a small scale because the friction and other factors *will be different and gravity doesn't scale but these are things, which you can imagine working at a larger scale. (48:47)*

Yeah, but the formal recognition process might be identical.

Exactly. And the visual systems can be developed in almost exactly the same way. You just need larger cameras, larger scanners, larger amounts of data, stronger arms, but essentially the processing is the same. So I'm thinking at this stage that will be one which I could tackle. (49:44)

We could probably throw together a three-dimensional model of a few arches that belong to a vault. And you could try a construction robotic system to assemble. Because we could laser-cut them, or route out the pieces so they are complex, but predetermined complex pieces. So there will be correct orientations that won't be necessarily hugely obvious. We could figure it out, but we ourselves would have to pick it up and go, "oh, it's that way , or it's that way". Things slightly taper, so you could test that kind of formal recognition realistically. There's also the thing about... this is the fantasy object; I imagine this is just too complicated, as an object it just won't work well enough... but something like an octopus, which has eight arms, so it can hold six pieces of stone while it puts the seventh and the eighth into place. Because if a vault really is leaning, you have to hold all of it as you keep going up.

Unless the arm is really strong and it can lay one, a second arm lays another, the first one lets go and lays the third and pushes down. Then you're talking about a very strong arm though. (51:14)

Yeah and then the four of them, so there's two on each side, it works symmetrically and builds up like that.

And then the final one, a fifth robot places the keystone and then all the robots let go and hope for the best (51:30)

It sounds like we could figure out a way to do that, but would it be possible if while it's doing it, the ground moved a few millimetres? And for it to know.

And this is what interests me. You have a pile of pieces, which are already cut (and at some stage you would have to link that to another system instead of just providing them), but they arrive in a random order and orientation so there's a scanning process to see which piece is which, where are they? Ok, I'm going to work with this piece, how do I pick it up and then where has it got to go? Once it places it, it then has to do a scan and check that everything's going how it thinks it should have gone. So there's this double scanning process and then it goes for the next piece, checks that it's still there, no one has moved it, and then when it comes back, places it and then does another scan to update its own idea of what it thinks is going on. (51:56)

Yeah, to find the new top surface.

So it never is working absolutely, because then errors will multiply and by the time you get to the top, if it was only a millimetre out each time, then suddenly all of the stones are sinking down and you're 200 millimetres out at the top. But if it scans the new surface each time then it knows where to place it. And in fact, it could even then give information saying, "this next piece isn't going to fit due to the fact that everything has settled a little bit". (52:42)

You talked about the extent of the robotics being used before. You may discover actually by building some of these prototypes that it's not feasible for some of them to exist. So the cutting of the stone *may prove just to be too difficult and that it's better to be done manually, or the visual analysis might be too impractical so someone might just check each piece manually and then tell the robot, "yes, it's ok". So you might discover that instead of being a complete system where you walk on site and turn the machine on and then five weeks later come back to their finished house, it might be several systems, which don't quite link together and that's where the people fit in. (53:46)*

I'm pretty sure we'll have to go with the robotic cutting process. We might be able to do visual scans, like this is the right kind of colour but still every piece is going to be completely different because it's naturally shaped. We definitely need the robotic water-jet cutter to be able to have a look at the object before it makes its first cut. Because I have no idea how else we could pretend to be able to do anything. The manual, intellectual project is still not all that easy. To be able to look at a lump of stone that's this wobbly object and think to yourself, "I think that piece in the book will fit in there and therefore if I stick it in the machine exactly here and rotate it here and all this kind of stuff", then if you move it a centimetre too much and you end up with a bit missing because it didn't line up properly. I imagine we'd lose three-quarters of them through manual error. If the robot can't scan and go, "yes, it will fit in here like this, therefore our cutting model needs to be here, not here", where the stone is just sitting there.

Yeah, actually the analysis and cutting of the pieces is the one which really does need to be done robotically. It could be the construction, which may not actually be necessary robotically. You may find some temporary formwork that bolts together out of steel and can be adapted. Then the people can manually assemble each arch with a crane, remove the scaffolding, assemble the scaffolding in a different configuration but it's a very laborious process. But you have a long time-span. (55:43)

There's good reasons for both, isn't there? The speed of it is useful, but it also depends on the degree of participation they want on site, whether speed comes first, or participation comes second or whether we won't get participation until a couple of buildings are built. Because everyone will be like, "I don't reckon it's really going to happen". But once it's going it'll draw attention. I have reasons to suspect that these complicated robotic machinery won't have a good lifespan out there in the dessert, where it's tough as shit all the time. And sand and grit is going to get into everything all the time.

You may need to build a temporary structure around them to protect them, which would kind of defeat the purpose a little bit. (57:03)

It does a little, but then maybe not entirely. You got to do what you got to do.

You may discover if the assembly is too difficult with robotic assistance then the pieces need to be designed in such a way that they're almost like LEGO bricks and they just slot together and you have a more complex cutting process. You'll need to discover what the limitations of the cutting process are. Maybe that sort of detail is ridiculous. Maybe what this robot does is cut them down to size and then a stone mason still needs to clean them up so that they take five millimetres off every surface and make sure they're absolutely flat. But then you're limiting yourself; you have to make sure the design only uses pieces which have flat sides, which can then be done by a human. (57:13)

There's some sense to that though. I suspect that producing a too rough, slightly too large cutting model, which can be chiselled, is probably a nice way to go, because it means the building will be structurally calculated digitally. But it is a hand-finished building, which will show hand marks and will show human error and human folly and human whimsy on its surface. Which will also be a means of covering any robotic errors, should there be some. It gives us a degree of tolerance.

And if it's hand-finished then maybe the system that you really need is scanning the finished pieces and telling the stone mason who's finishing them that yes, in fact they're done. There is a similar concrete project where they built a concrete shell and wanted it to be so many inches thick. They were doing it by squirting concrete on to a surface and they had no way of telling when it was two inches thick. So they had a laser-scanner scan and tell them with a colour diagram this area needs a lot more concrete, this area doesn't. They would then spray more concrete, scan it again and it would tell them they were getting closer and closer until it was within a certain tolerance of what they wanted. This sort of thing could be done too, where the robot cuts it down to size, the stone mason cuts one of the surfaces, a scanner accurately scans what he has done and says, "this area need a little bit more work", and he keeps going. Maybe that's one of the most efficient ways you could do it if it's impossible for a robot to completely finish the pieces. (58:44)

I'm not quite sure what part of it you're interested in. I know you're construction robotic stuff is going on there but I'm still thinking about the actual robotic cutting process. Is that difficult, or is that very simple for a computer to be given a rough, blobby shape and have a database full of geometric shapes and deciding what fits optimally into the blobby shape?

That sort of thing has been done a lot, I think. You've got a library of parts, selecting which piece will have the least wastage. It's computationally quite heavy, but it can be done. And even deciding how to cut it is quite straightforward as long as the pieces aren't completely bizarre. As long as they're similar in shape then the cutter can do similar things each time. If it's completely freeform then the cutter has to just keep taking off a millimetre all over until it ends up the correct shape. Whereas if they have some logic behind them it can be done more efficiently. (60:27)

Yeah, that's the thing. I've been getting the impression from the guy I've been speaking to that there is a real efficiency in just trimming it. Because you use the shortest, most powerful part of the blade every time. So it can actually cut quite quickly if you're just going to shave stuff off. As opposed to doing the big straight line through something, which could twist or do whatever you like. That could be really long and slow and you're using the weak part of the blade if you do a really long cut. So adding up those two variables sounds like something we could use some mathematical assistance with.

Have you got a water-jet cutter that you're going to use and a robot arm that you're going to put it on? (62:01)

Yeah, I guess so. I don't know what the model is, but I told him that's what we wanted and he's putting those two things together, so I guess he has one in mind.

Maybe if you have access to that system then maybe that's something I could develop. If you had the system and you needed someone to develop software for it and see what was possible and what wasn't. And take some stone and cut it and show you what can be done, then that's something I could also focus my research on. And it really makes sense that that would be the first step as opposed to the construction of the blocks. I could build a prototype, which takes objects, which are already cut and assembles them. But if you discover that the pieces aren't possible to make then you may have wasted time building this prototype. (62:20)

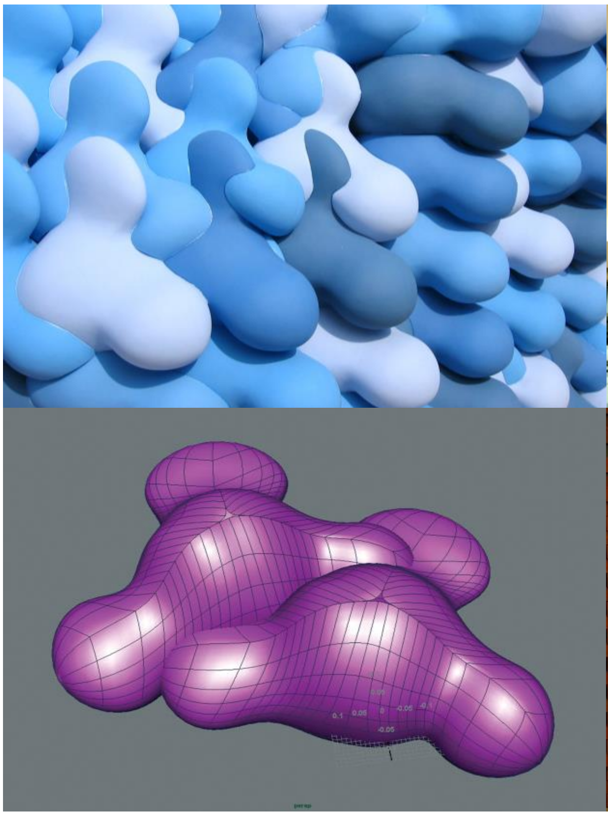
It's when we have a good sense how large the pieces of stone are going to be, what's the maximum size piece of stone we can get, and the construction robotics are a little bit up in the air. Because if we can get really large pieces, we'll make an arch out of six pieces. Which means maybe we can just have six arms. But if it's going to be out of 60 pieces...

Appendix B: Course Material from Case Study 2

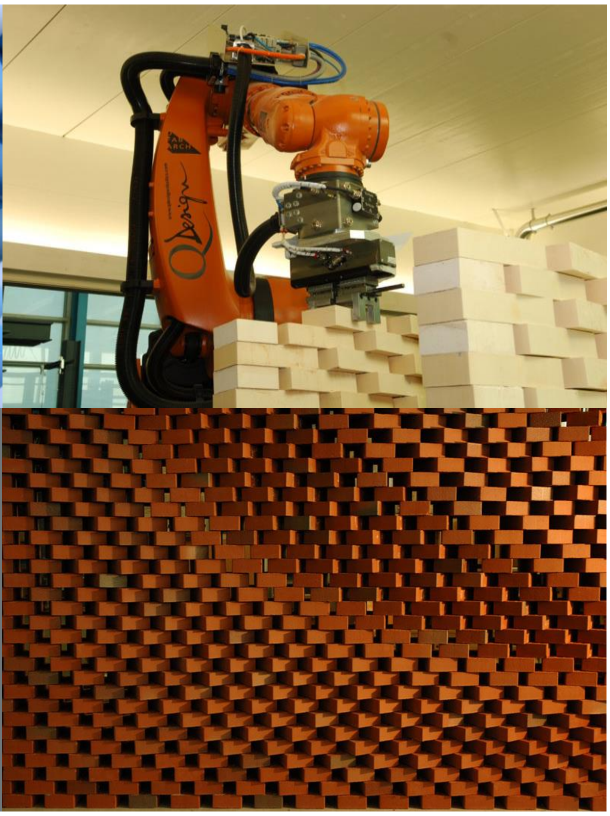
MARC6102
3D Computer Design Modelling

THE UNIVERSITY OF SYDNEY

Course Outline



Greg Lynn, "Blobwall" (2006-08)



Gramazio & Kohler, "The Programmed Wall" (2006)

Aims
This unit of study consolidates students' knowledge of advanced concepts in digital modelling and visualization media available for architectural design. The unit develops conceptual understanding and practical application of these techniques, using commercial modelling and rendering packages.

Format
The course will take place in a computer lab. Concepts and techniques will be explored through design exercises.

Outcomes
It will help students: generate sophisticated 3D modelling through pre-packaged techniques and scripting processes, assign colour and texture information, generate complex photorealistic images and develop transferable conceptual skills that apply across different 3D packages and for different contexts such as modeling, animation, games assets, and photorealistic rendering.

At the conclusion of this unit students should be conversant with 3D modeling and photo-rendering terminology and have the ability to produce sophisticated digital models and photorealistic images.

Contact Hours

3 hours/week, assessment preparation 8 hours/semester

Wilkinson 526 PG Computer Laboratory

Week	Date	Session	Exercise	Assignment	Additional Comments
1	28th July	Wed 15:00-18:00	Introduction		
2	4th Aug		**Basic Modelling**		**Tutorial:** Rhino Basics 01 2D and 3D curves, Simple Surfaces
3	11th Aug		**Adv. Modelling**		**Tutorial:** Rhino Basics 02 Surfaces and Polysurfaces
4	18th Aug		**Rendering**		**Tutorial:** Rendering in Kerkythea
5	25th Aug		**Adv. Rendering + Photoshop**	**ASSIGNMENT ONE** **DUE 24:00 31st AUG**	**Tutorial:** Advanced Rendering + Photoshop Techniques
6	1st Sept		**Laser Cutting**		**Tutorial:** Laser Cutting Techniques
7	8th Sept		**Solid Modelling +** **CNC Exporting**		**Tutorial:** Solid Modelling + Preparing models for CNC Milling
8	15th Sept		**CNC Model Techniques**		**Workshop:** CNC milling + Laser Cutting demonstration
9	22nd Sept		**Individual Tutorials**		**Workshop:** Consultation time to discuss individual submissions
	29th Sept	BREAK		**ASSIGNMENT TWO** **DUE 24:00 8th OCT**	
10	6th Oct		**Illustrator**		**Tutorial:** Creating 2D drawings in Rhino + Exporting to Illustrator
11	13th Oct		**Robotic Construction**	**ASSIGNMENT THREE** **DUE 24:00 19th OCT**	**Tutorial:** Introduction to Robotic Construction + Grasshopper
12	20th Oct		**Digital Fabrication**	**10% GRADE FOR PARTICIPATION**	**Workshop:** Mass-production of 3-4 proposed modules
13	27th Oct		**Robotic Construction**		**Workshop:** Robotic Construction

Web Based Resources

Rhino:

- **Rhino video tutorials < http://www.digitaltoolbox.info/>**
- Overview of Software Training resources <http://www.rhino3d.com/training.htm>
- Guide to reference books <http://www2.rhino3d.com/resources/default.asp?show=Book&search=&language=en>
- Online video tutorials <http://www.rhino3d.tv/>
- Para Cloud (parametric software plug-in for RHINO) <http://www.paracloud.com/>

Grasshopper:

- **Grasshopper video tutorials < http://www.digitaltoolbox.info/>**
- Grasshopper <http://www.grasshopper3d.com>
- Understanding Vectors <http://chortle.ccsu.edu/VectorLessons/vectorIndex.html#01>
- Dumo blog <http://dumo.tumblr.com/tagged/grasshopper>
- Live components blog <http://livecomponents-ny.com/>
- Giulio Piacentino blog <http://www.giuliopiacentino.com/grasshopper-tools>
- Pinupspace <http://www.tedngai.net/category/experiments>
- Nathan Miller blog <http://nmillerarch.blogspot.com/>

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MARC6102
3D Computer Design Modelling

Assignment 1

Value: 30%
Due: Midnight, 27th August 2010
To be submitted digitally via the Faculty Dropbox (address to be advised)

Task:

Choose an architectural space which has an interesting 'atmosphere'. This space might be glamorous, grotesque, lively, lonely, sterile, sublime, sombre, ethereal, homely, tense, comforting, alluring etc.

Model this space using the Rhinoceros 3D modelling software. You will then produce a rendered image of the space which **captures the mood of your chosen space** using lighting and camera techniques. You should *not* use complex textures. You may alter the basic material properties such as colour, transparency and reflectivity. Simple displacement maps may also be used. Emphasis will be placed on the quality of light achieved and the composition of the image.

You may use any rendering software you like. However, it is recommended that you use one of the following "unbiased" rendering engines:

- **Kerkythea** (which we will use in class)
- Thea Render (www.thearender.com)
- Maxwell (www.maxwellrender.com)
- Fryrender (www.randomcontrol.com/fryrender)
- Indigo (www.indigorenderer.com)
- Lux Render (www.luxrender.net)
- V-Ray (only if you are very confident with rendering)

You are encouraged to enhance the rendered image using the Photoshop postproduction techniques discussed in class.

Submission:

- The final image (no less than 1 Megapixel, in png format)
- No more than 3 source images of the chosen space
- The Rhino file containing the modelled space
- The rendering file (for example, the kzx file from Kerkythea)

You will be assessed on how well you employ the modelling, rendering and postproduction techniques learnt in class to capture the mood of your chosen space.

MARC6102
3D Computer Design Modelling

Assignment 2

Value: 35%
Due: Midnight, 5th October 2010
To be submitted either digitally via WebCT or physically via CD in the assignment slot on Level 4.

Task:

The aim of this assignment is to develop modular components, which can be a stacked using a 4-axis robotic arm.

The component should first be designed using Rhinoceros 3D modelling software. This 3D model should then be used to fabricate 3 identical prototypes of the component.

These first prototypes should be considered against the ‘design constraints’ listed below. Modifications should then be made to your 3D model based on what you discover with the prototypes.

This will be an iterative design process where you design in rhino, then fabricate some prototypes, then go back and modify the design in rhino and then fabricate some more prototypes and so on...

Once you are satisfied with your component, you will document the design/fabrication process using screenshots, photos and a *small* amount of text. This document will be divided into 2 parts. This first will present all of the iterations you went through to arrive at the final prototype. The second part will show every step of the final fabrication process. This part should be set out as an instruction manual for someone who might want to fabricate these components.

Design Constraints:

The components must all be identical.
They should have overall dimensions less than 50x50x50mm.
They can be fabricated from any combination of materials.
They should fit together easily
They should have the potential to be stacked into interesting assemblies.
They should be visually appealing.
They should be self-supporting when stacked.

They should be designed in such a way that the robotic arm can pick them up and stack them.
They should be mass-producible using fabrication techniques available to you.
Fabrication of the components should involve *at least* one digital technique
(eg Laser-cutting, CNC Milling, 3D Printing, or 2D Printing of templates)

Submission:

- A Rhino file containing a 3D model of the module
- A PDF file presenting your design iterations and your fabrication process
- Any laser-cutting, CNC milling or 3D Printing files used in the fabrication process

Files should be named like this:
Surname_GivenName_Rhino.3dm
Surname_GivenName_Process.pdf
Surname_GivenName_LaserCutting.dwg
Surname_GivenName_Milling.stl

Assessment:

The following is a breakdown of the marks for this assessment:

5% 3D Model
  - Quality of the surfaces
  - Design iterations organised logically into layers

5% Ingenuity of the fabrication process
  - How cleverly you combine digital and analogue techniques to fabricate a successful modular component

10% Clarity of the PDF file
  - Clearly organised Layout
  - Sharp, well composed photos
  - Concise, Insightful text

15% Consideration of the 'Design Constraints' listed above

MARC6102
3D Computer Design Modelling

Assignment 3

Value: 35%
Due: Midnight, 19th October 2010
To be submitted either digitally via WebCT or physically via CD in the assignment slot on Level 4.
Fabrication Workshop: 3-6pm 20th October 2010

Task:

For the first part of Assignment 3, convert the Rhino component you developed in Assignment 2 into a 'block' in Rhino. Insert and arrange copies of this 'block' component to form an interesting 3D assembly. This assembly should contain at least 100 components.

Once you have finalised the form of your assembly, use Rhino's *make2d* command in combination with Adobe Illustrator to produce vector diagrams of the construction sequence. This 'instruction manual' should have a similar aesthetic to the examples shown on the next pages.

From the submitted assignments, I will select 3 or 4 modules to be mass-produced during our fabrication workshop on the 20th October. The modules will be chosen based on ease of construction and potential for robotic assembly.

Submission:

- A Rhino file containing a 3D model of the assembly (using blocks)
- A PDF file presenting the vector diagrams of the construction sequence

Assessment:

The following is a breakdown of the marks for this assessment:

10% 3D Model
- Accurately modelled using blocks
- Beauty of the proposed assembly

15% PDF File
- Clear, well organised series of vector diagrams showing the how the modules are stacked into an assembly
- Text used sparingly (for headings)

10% Fabrication Workshop
- Participation during the workshop on 20th October