PAVING THE WAY

Exploring robotics in parametric brick wall prototypes using computational form finding techniques

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Abstract. Over the past two decades, rapid advancements in technology have introduced a wide range of benefits in the field of robotics. Repetitive tasks such as brick laying has seen the implementation of robotics to automate processes, however, has this been at the cost of design? This research paper investigates computational design as a solution to integrate design with robotics in the creation of brick wall prototypes. It serves as a model in showcasing the power of modern computational tools to those with limited computational literacy, by adding a physical element of implementing linework to allow for the quick, iterative design process of brick walls. This allows users to engage with the process of design to fabrication, which can motivate an individual to study computational design. With simulations of robotic movements integrated in computational tools nowadays, the ease of configuring set ups, tool pathing and collision states becomes noticeably apparent compared to the early 2000's. By using an action research approach, this paper explores the iterative process to test, analyse and gradually refine methods for achieving the fabrication of a brick wall using robotics. Ultimately, a thorough explanation of computational tools will highlight the benefits of robotics in construction, facilitating a greater presence of parametric masonry design principles in the wider built environment.

Keywords. Robotic Fabrication; Parametric Brick Wall; Collaborative Robot; Linework to Surface

Introduction

Over the past two decades, technology has advanced significantly, aiding in the development of the built environment. In the late 90's, architects moved from using pencils and paper to creating drawings on the computer, a way of making processes more efficient and more suitable for the time period. Fast forward a few decades, where a new breed of computational designers now have access to powerful tools such as Rhino and Grasshopper, complex parametric brick wall design and construction are easily achievable and configurable to the client's needs (Sousa, 2017). More specifically, this research project will explore possibilities of implementing physical linework into grasshopper to create brick wall structures and also delve into robotic fabrication to see the possibilities of creating these structures using a Kuka LBR iiwa 14 R820 robotic arm.

Whilst bricks have been one of the oldest materials used in construction to date, there has rarely been any changes in its structure, resulting in repetitive building designs that are seen far too often in the built environment (Lourenco, 2013). One factor contributing to this is that fact that this methodology in masonry works has always worked, so there has been no initiative for change. It is also hard for humans to replicate bricks that are offset or rotated for example in a drawing, hence the hesitation for innovation in parametric brick wall designs. With more research being placed into robotics in construction, this may be a thing of the past, as they have the capabilities to eliminate repetitive manual handling processes which will result in structures being built to tighter tolerances.

The extent to which robotics in architecture has the potential to bring out real change globally and influence the quality of the wider built environment can be seen in Gramazio and Kohler's research works (Gramazio & Kohler, 2014). This research takes inspiration from their winery façade built in 2006, which was a breakthrough at the time for implementing robotics in the construction of a parametric brick wall façade. It serves as a benchmark in comparing results of time efficiency and complexity in the design of a parametric brick wall as well as the use of robotics in the construction phase of this wall. Gramazio & Kohlers generation started with little technology and had to build their software from scratch with code in being able to achieve their façade design. Using the 13-year age gap, this research paper shows the power of computational tools nowadays in developing a script that allow users with limited computation literacy to engage in the robotic fabrication of a brick wall designed by the user.

Innovation is a term that is often excites and inspires others to increase and push their knowledge to create things that can be helpful to society. This research papers sets out to test if physical linework can be implemented into computational tools to create brick wall structures. Incorporating a physical element to this script can create a sense of motivation in modelling computational design to those with limited computation literacy such as the average high school student transitioning to university, in engaging in the robotic fabrication of a parametric brick wall prototype. With the of use of computational tools such as Grasshopper, this research shows the ease to which a user can create a brick wall. All that is needed from the user is the importation of at least two lines and changes in a few sliders to adjust the brick layout, making this process straight forward.

Research Aims

Th overarching aim for this project is to develop a workflow that enables users with limited computational literacy to engage with the robotic fabrication of a parametric brick wall. With limited time and complications with previous work, some primary and secondary aims are set for a 5-week working period:

Primary:

1. Implement physical linework into Grasshopper and experiment with different line works in brick wall designs.
2. Simulate movements of KUKA robotic arm based off current environment with KUKA PRC.

Secondary:

1. Extract toolpaths to KUKA Sunrise for physical testing.
2. Incorporate structural analysis in brick wall script to gauge if structure is able to stand if built.

Research Question

As this research paper aims to develop a more efficient workflow in creating parametric brick wall structures using a robotic arm in its construction to explore possibilities and benefits of this technology in the future, the following research question was developed as a benchmark for the overall paper:

How can the power of computational tools be exhibited to those with limited computational literacy as motivation for describing how far technology has come in the past two decades in the robotic fabrication of brick walls?

Methodology

The methodology used throughout this research project describes that of action research. Action research is a practice-based methodology consisting of four main phases: Plan, Action, Analyse and Reflect (Figure 1). It allows for the analysis and reflection of each cycle of an iterative process so multiple iterations are able to be explored and thus solutions can be reached effectively though a means of trial and error.

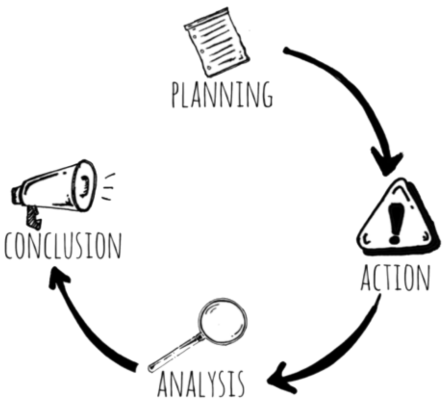

Figure 1. Action Research Process.

Phase one includes planning for research, where a specific research question is defined, and literature reviews are conducted to gain a deeper understanding of the related research. With analysis of existing literature, this research paper looks into developing new workflows to show the innovations of technology in computational design as well as the implementation of robotics in construction as a path for educating high schooler's transitioning to university, as well as creating more complex geometries in the built environment.

Phase two is action, which moves into the design process where data methods and workflows are planned, ethical issues are considered, and deadlines are set. This is where the experimentation occurs, and data collection is gathered. With this, a working period of 5 weeks was set, and workflows were created to document the process of the research. With two main objectives of design and construction, the workflow of this research is broken down into the creation of a brick wall from physical linework and construction of the brick wall using a robotic arm. Experimentations are set out in both, where qualitative data of observations are gathered for analysis.

Phase three includes analysis of results, where data is organized with charts, graphs and images of processes. As this research project primarily consists of observational results, problems identified in previous design stages are noted and isolated in images before the next step of the process is documented.

Finally, phase four is the conclusion of the research in which the research is shared to the general public. Reflections on the practices involved in the research are noted in this final phase, leading to new questions being asked and further works being stated.

Background Research

As the start of the revolution of the computer began to rise in the 20th century, researchers have constantly been trying to configure new ways of using robotics to aid with the burden of completing repetitive tasks. In particular, selected technologies could assist processes in brick laying, and also paired with advancements in computational design, could see the ability of creating more complex brick wall designs while educating the newer generation of tech savvy students. First of all, “in order for robotics to begin having a greater impact in construction it will be necessary to acquire a sound understanding of past, current and projected technological developments in several discipline areas” (Paulson 1985).

This research in particular, looks into a case study of the Gantenbein Vineyard, with the brick wall façade designed and built by Gramazio & Kohler Architects in 2006. Being a facility in storing wine barrels, the clients wanted a façade that incorporated grapes in its design. It would be achieved by digitally filling an open rectangular box with spheres of all sizes to represent grapes. An image was then taken of each side view, which is how the design would be created, and the visual of grapes in the physical façade would be created by the rotation of certain bricks. This research aims to replicate this geometric pattern using modern computational tools while adding another level of complexity by introducing curvature to compare between the technological gap.

Over the last two decades, the names of Fabio Gramazio and Matthias Kohler have become synonymous with robotics in architecture. They point out that robotics in architecture has the potential to reimagine the entire field of practice: “the modern division between intellectual work and manual production, between design and realisation, is being rendered obsolete” (Gramazio & Kohler, 2014). They wanted to be the beneficiaries in creating a new breed of architect-programmers, so they founded their firm in 2000 and 6 years later, built the façade of the Gatenbein Vineyard, using a robotic arm in its construction. This was a breakthrough for the technology at the time, however in the 6 years of figuring out how robotics could be used in construction, they had many issues with data manipulation, memory issues, hardware issues and the list goes on and on, being primarily due to barriers in the technology at the time, making it hard to sort and store data. In the current day situation, Gramazio & Kohler's occupational label of the architect-programmer title can now be known as a computational designer. Designs that took the pair years to create and construct can now be configured in a matter of weeks with ease. Gramazio & Kohler started with the simple building blocks of their software and had to code their way up to achieve the construction of the brick wall using a robotic arm. In comparison, advancements in software have created powerful computational tools such as Grasshopper, which incorporates all the code in the background, being visualized through nodes and easily understood with inputs and outputs. Using this time gap of 13 years and its jump in technological advancements, this research papers explores possibilities of computational design by implementing physical linework into structures and ties it back with robotics to compare how easy processes and workflows are nowadays vs the 6 years Gramazio & Kohler took to figure it out.

Fabio Gramazio states that "as architects, we need to engage directly with machines" (Dorfler, Sandy, Giftthaler, Gramazio, Kohler, Buchi, 2016). This is important to understand in engaging one's motivation, as it can allow for new designs that would not be possible without machines. In particular, Dakhli and Lafhaj's 'Robotic mechanical design for bricklaying automation', looks into more efficient workflows though the use of robotics in masonry works. They agree that with more complex geometries, robotics would have to be implemented into the construction sector to be able to keep up with the demand of the architects designs. As they delved into previous research of already existing robots in construction such as the 'SAM100' from Construction Robotics and 'Hadrian X' robot from Australian company FBR, they realized that a functional all in one masonry robot had not yet been thought of, where the robot could do both laying bricks and applying adhesive to the bricks efficiently. This is crucial to the final design outcome as there is no point in using robotics in construction if it is not going to be an efficient system. This research takes this notion of efficiency into account and uses computational tools to map out an efficient workflow where many designs and iterations of brick walls are able to be designed and built with a robotic arm. Most research into robotics in brick laying focus on the robotic side of things while disregarding the design. As mentioned by Fabio Gramazio, "the robot needs us as much as we need the robot" (Gramazio, 2014), meaning there has to be a sense of collaboration between the two, instead of the typical thought process of 'build along this axis x amount length and x amount height'.

With researchers currently focusing on the robot itself, planar designs that are seen far too often will continue to occur as the ongoing issue of repetitive work is only being solved with automation. With such dramatic technologic advancements, designs can easily be implemented into robotics itself and visualized and analysed digitally for construction. This research paper showcases an innovative quick way of designing brick walls while implementing its construction in a robotic arm. It sends coordinates of each brick to the robot from each layer in an ascending order so the robot can visualise the wall before it is built and judge if the toolpath is optimal or will cause a collision. It further showcases the power of computational tools to allow users the capability of implementing design directly into the robot for prototyping, to test whether or not a structure will work in its full scale.

As the invention of the computer has aided in complex design geometries, robotics cannot automatically understand design unless taught so though the iteration process. Villalon, Lieberman and Sass's 'Breaking down brick walls: Design, construction and porotype fabrication knowledge in architecture' aims to break the design barrier between architecture and construction by creating a program that incorporates both fields knowledge and imputing it into robotic software to create physical prototypes, particularly brick walls. By implementing a 'Design knowledge database', they can input it to a user interface that will draw actions and return concepts, which will then be ran directly to the robot, so it understands exactly what the user wants. As the research was undertaken over 10 years ago, improvements in user interfaces and interactivity between user and software as well as programming have come a long way, in which this research paper will demonstrate with the experimentation of implementing physical linework into current computation tools to create brick wall structures. It describes how interfaces in Grasshopper have improved dramatically, with all the code being stored in the background and visualized with input and output nodes, making the creation of parametric surfaces comparatively easier than 10 years ago.

Case Study

As the workflow for this research focuses on creating a structure from physical lines to then building this structure with a robotic arm, the case study will be broken down into two main topics:

6.1 The first to demonstrate if physical linework can be implemented into grasshopper to form geometries, from which a parametric brick wall can be modeled.

6.2 The second to delve into robotic fabrication and explore whether or not these brick wall structures can be built using a KUKA iiwa robotic arm.

6.1.1 Physical Linework Implementation

To obtain our physical linework, it would be drawn digitally in MS Paint, a tool that is located on every Microsoft computer, to show that the script didn’t need any other fancy programs other than Rhino/Grasshopper. This image can then be saved as a PNG file and imported into grasshopper using IS ‘Image Sampler’. The IS settings are changed to display values through brightness, where white represents 0 and black represents 1, with all shades in-between scaling from 0 to 1.

Iteration 1

With the first attempt at trying to implement physical linework into grasshopper, more emphasis was placed on gathering points closest to the values in the IS. Using ‘Dispatch’ allowed for the sorting of points closest to the line from which could be sorted vertically to create the line. However, issues with line weight played a major factor in this iteration, as a thick line would create multiple values on the x axis, meaning that the line would be too jagged and pointy, which is not optimal for creating smooth surfaces. This could be tweaked by using a very thin line; however, it would not be versatile enough for real world applications where there are several line weights being used.

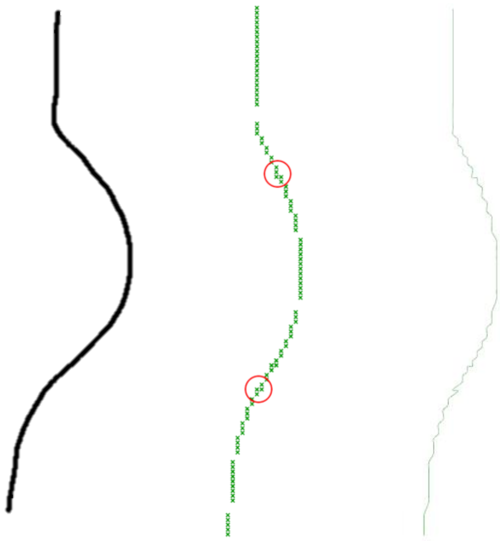

Figure 2. Iteration One.

Iteration 2

For the second iteration, a different direction was taken in placing more emphasis on the outline of the image. This was created using a mesh as a base, with the IS affecting this mesh by cutting it through a plane. With this outline, a bounding box is created and divided into segments, so intersections can be made. From these intersections, the start and end points can be used to map out the midpoints from which the line will be created. The midpoints are then sorted through the y-axis and 'Interpolate' is used to create the curve as per the image. Using this approach made the script more versatile as any line weight could be used.

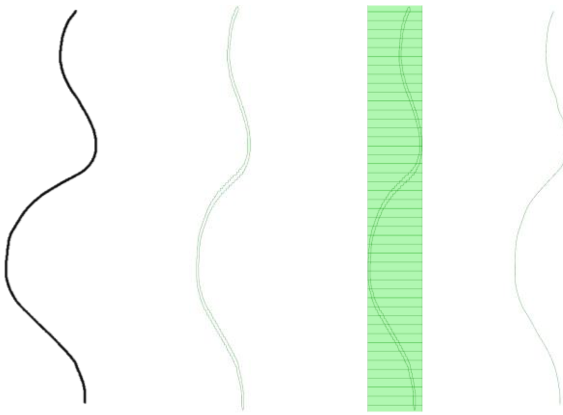

Figure 3. Iteration Two.

However, there was an issue with this method. That being that as the midpoints are sorted through the y-axis to construct the line (Figure 4), it had to be in a more linear format when it is drawn by the user. This means that there can't be any overlapping of y values, otherwise it misinterprets the overlap as a long line, which will result in the wrong midpoint being mapped.

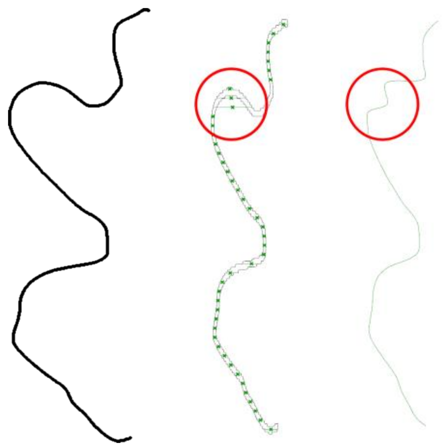

Figure 4. Iteration Two Problem.

6.1.2 Lines to Surface

The next step of the process is to then import another line or more depending on the design outcomes, to create the surface (Figure 5). Using 'Move' with the z-axis determines the overall height of the wall and this is easily configured to the design outcome. Loft is then used to join the curves to create the geometry.

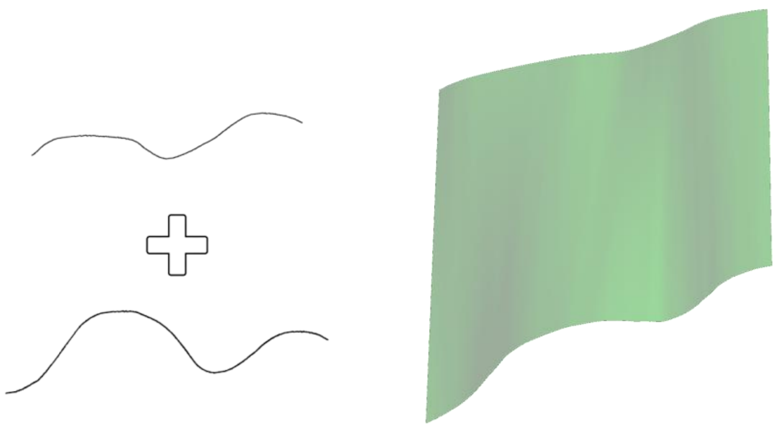

Figure 5. Lines to Surface.

6.1.3 Surface to Brick Wall

Using this geometry, the brick wall can be constructed and configured using realistic dimensions (Figure 6). To create the brick wall, the lofted surface is divided vertically using ‘Contour’. Each contour is then divided horizontally using ‘Horizontal Frames’, which can be adjusted to determine how many bricks sit on each layer. Using these horizontal points, the brick is mapped using ‘Center Box’, which places the brick in the middle of each point. This node can be adjusted to determine overall length, width and height of each brick. Finally, ‘Cull Pattern’ is used to remove every second brick, creating the overlapping effect that makes the wall structural in real world applications.

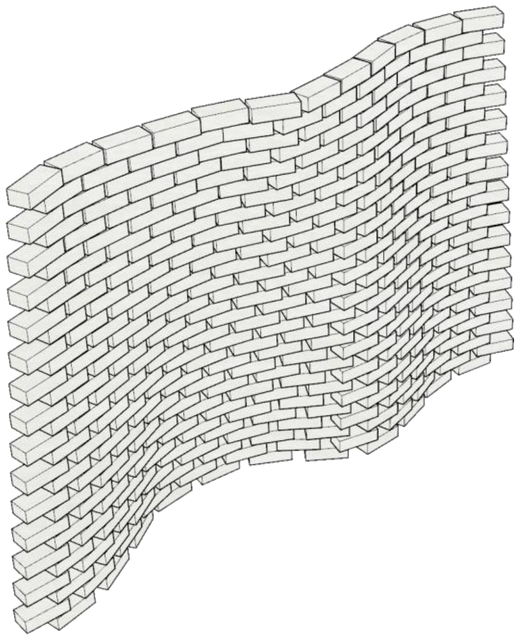

Figure 6. Surface to Brick Wall.

6.1.4 Gramazio & Kohler Effect

Drawing from Gramazio & Kohlers winery façade design in 2006, a goal of rotating certain bricks based off a pattern was set up to demonstrate and compare how far technology has come in the past couple decades with regards to time and complexity.

To achieve this, the desired pattern is loaded into an IS and ‘Surface

Closest Point' is used to grab values that represent the values in the image sampler. These values are then remapped to the surface and rotated to the desired angle. With just a few nodes used in grasshopper, the same effect that took Gramazio and Kohler years to figure out is achieved in just a matter of minutes. This is possible due to advancements in technology where Gramazio and Kohler had to write all the code and algorithms by hand back in 2006, whereas nowadays it is all visualized and easier to understand in grasshopper.

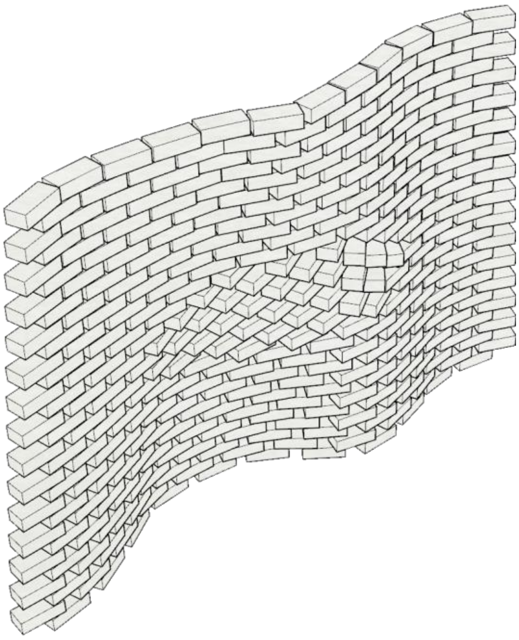

Figure 7. Gramazio & Kohler Effect.

6.2.1 KUKA LBR iiwa

The robotic arm used in this research is the KUKA LBR iiwa 14 R820. It falls under the collaborative 'side' of robotic arms, making it safer for use with humans for prototyping and experimental uses. However, it still has the potential to cause harm, so understanding the basics of its capacities and limitations is a must before operation. It has 7 axis of rotation, 4 vertical and 3 horizontal making it very versatile in its movements. Has a wide working space of 270 degrees, however, should be kept in the working range of 180 degrees to avoid damaging its joints (Figure 8). Finally, its load capacity ranges from 8kg to 14kg depending on how far it moves from its base, so with all this in mind, the KUKA robotic arm was not designed with the intent of using it from the handling of bricks. This is why this research focuses more towards prototyping, with the brick walls scaled down to suit the robot's capabilities.

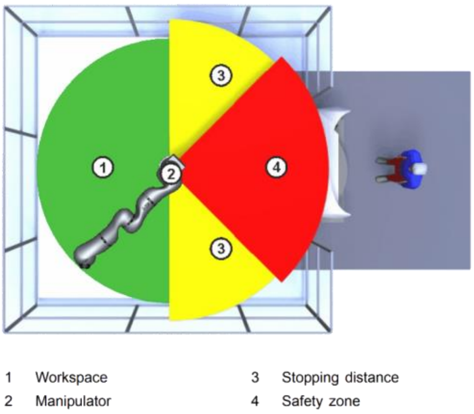

Figure 8. KUKA iiwa Overview.

6.2.2 Environment Set Up

The way in which the robot moves is based off commands set by the user in KUKA PRC, which is an add-on to Grasshopper that comes with the purchase of the robot. As these commands are specific, the environment plays a major role, both in the real and digital world. The setup of the robot in Rhino is crucial and must be replicated from the existing area of where the robot is situated in the real world, to avoid collisions with either stationary objects or the robot itself. With this, the robot is modelled in the center of a table 630x630x500mm high, just how it is in the real world (Figure 9).

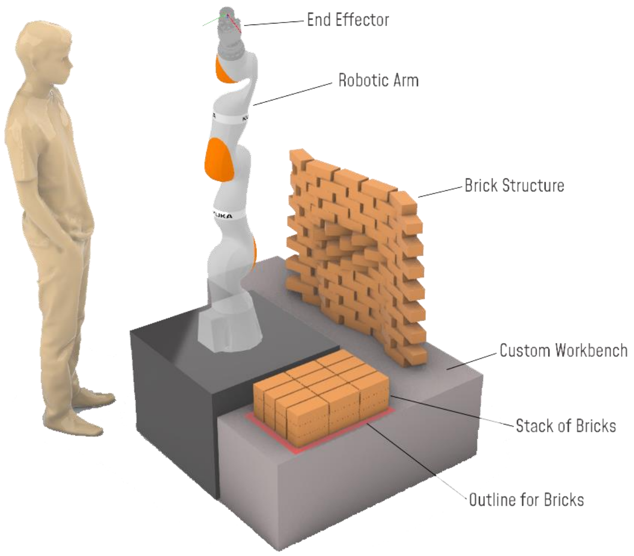

Figure 9. KUKA iiwa Set Up.

With the table housing the robot being quite small, a new table would have to be built to house both the brick wall structure and the stack of bricks it is to pick up. The L shape as seen in figure _ made the most sense in keeping to the 180-degree limitation while separating the two brick areas. Also, with the commands being set, tolerances are tight in placing the stack of bricks where the robot is to pick them up from, so an outline was created for guidance. The L shaped table was also lowered 100mm to allow for more of the structure to be built.

6.2.3 Robotic Arm Reach

To help future users who chose to use this script, a dome was built to signify the robot's max reachability (Figure 10). The dome is created using the maximum toolpath range during simulation and is beneficial in determining whether a structure could be built or whether its height needed to be modified to suit the robot's limitations.

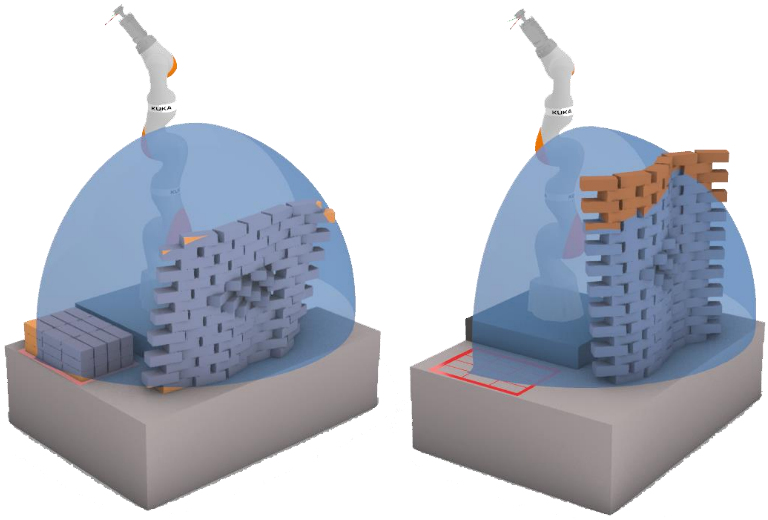

Figure 10. KUKA iiwa Reachability.

6.2.4 KUKA PRC

As the script is designed for versatility in the creation of the brick wall structures, commands set in KUKA PRC also had to be versatile in being compatible to all designs (Figure 11). Using the ‘List” function, points can be allocated in ascending order. With these points being sorted, they can be placed into commands to create the overall toolpath of the build. This means that once the initial script is set up in listing all these points, all changes to structures will work.

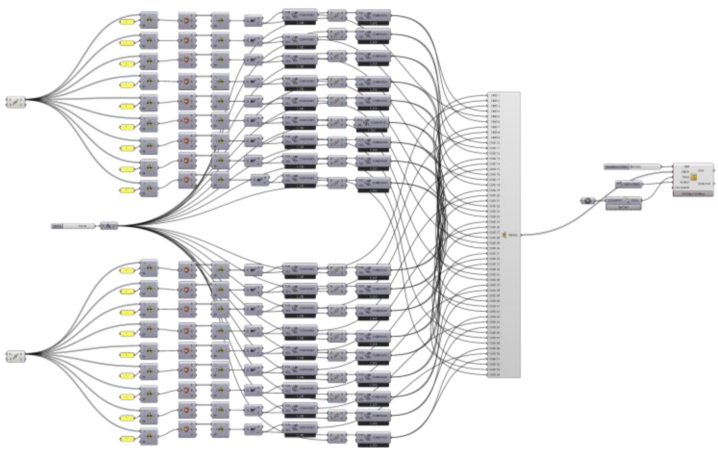

Figure 11. KUKA PRC Script.

Being geared towards high school leavers who will have no knowledge of grasshopper, let alone robotics, this script will make tasks a lot easier for them in visualising what they are doing, as all that's required is to import a couple of lines and change a few sliders to configure dimensions of the bricks. Figure 12 shows variations of brick walls that were constructed from users with limited computational literacy as a test to see how easy the script was to use. KUKA PRC was also used to see if the initial setup (Figure 11) would work for any brick wall and was successful in adapting to each wall, making physical testing a matter of sending these commands to KUKA Sunrise without any changes in the script.

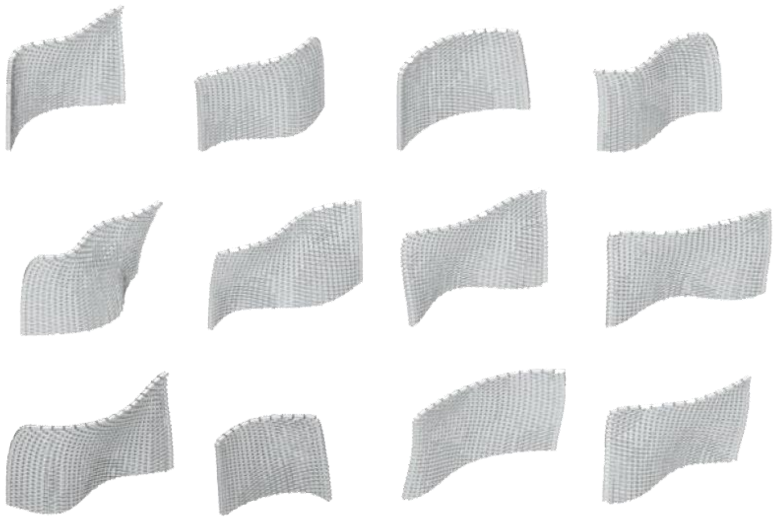

Figure 12. Variations of Brick Walls.

Discussion

With the overall aim of this research being to develop a script that has the ability to allow users with limited computational literacy to engage in the use of robotic fabrication of a parametric brick wall prototype, this paper has been mostly successful.

The objective of the first part in this case study was to demonstrate if physical linework could be implemented into grasshopper to then form a brick wall structure. With this, the final design outcome becomes more unpredictable and also brings a sense of life and personality into a structure. By testing multiple routes in figuring how this could be achievable, a solution was found that was highly versatile in adapting to all line weights and designs. A surface can then be created using these lines, from which a brick wall could be built and configured with multiple settings such as bricks per layer, angle of bricks and dimensions of bricks. This demonstrates how far computational design has come in the past two decades from which Gramazio & Kohler spent copious amounts of time developing workflows that can be completed in far less time and effort nowadays.

The objective of the second part in this case study is to build parametric brick wall prototypes using the KUKA iiwa robotic arm. Understanding the robotic software was a challenge in itself with KUKA PRC allowing for the creation of toolpaths and KUKA Sunrise for running commands to the robot arm. With limitations in coding skills and time, this research focused more towards KUKA PRC, experimenting with maximum and optimal tooling paths. Simulating the robot’s movements digitally has been successful in visualizing collisions, as well as the overall workflow of physical works. It gives the user a clear understanding of what is going to happen, adding to the value of computational tools. Simulation digitally is one thing, however there must also be physical works to test and validify if the digital is accurate. Further works into KUKA Sunrise and sending the set toolpaths to the robotic arm is the next step of this research in obtaining results, from which could be compared against Gramazio & Kohler’s work to really see how the complexity of working with robotic arms differs 13 years ago to now.

By breaking this research into these two main objectives of design and construction, this research proves how beneficial computational design is to the architectural, engineering and construction industry. Further work into structural analysis would reinforce this, as it would show the one script having all three industries involved in the formation of a structure all in the one file. It has become apparent in this space of the past decade, that open source collaboration can only benefit society, therefore, by creating versatile scripts like these that are easily manipulatable, more interesting masonry forms are able to be configured easily which can influence the quality of the wider built environment.

Conclusion

Developing computational workflows for integrating robotics in the construction of brick walls can be beneficial in motivating a new generation of technology enthusiasts with little knowledge of Grasshopper. This research shows how computational design has developed over the past two decades in robotic fabrication and creates an innovative solution to quick parametric brick wall design. It refers directly to Gramazio & Kohlers work in 2006 as a benchmark for innovation in the field, while adding another level of complexity in brick wall designs. Using modern computational tools, simulations of robotic movements allow for predictions of the final results, as well as the optimization of its toolpaths and collision states. This shows the versatility of modern computation tools available nowadays, adding value to computational design as a medium in the AEC industry.

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Appendix: Design Process

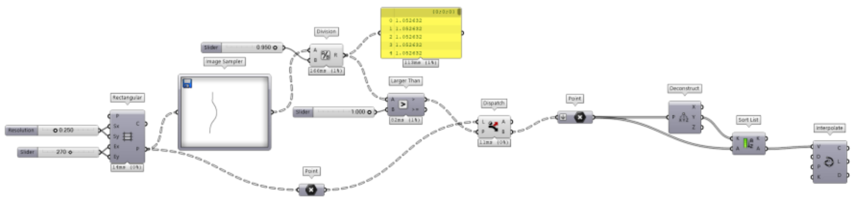

Figure 13. Iteration one.

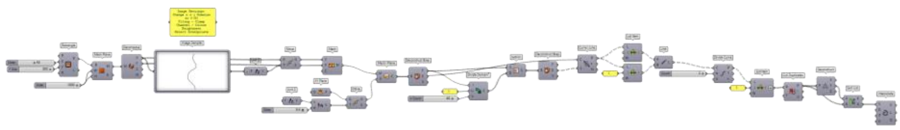

Figure 14. Iteration Two.

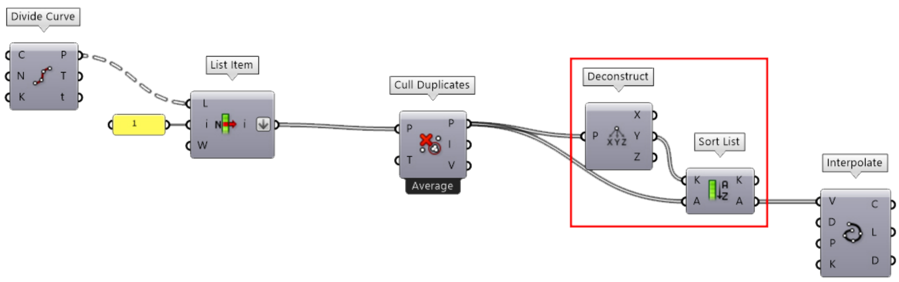

Figure 15. Iteration Two Problem.

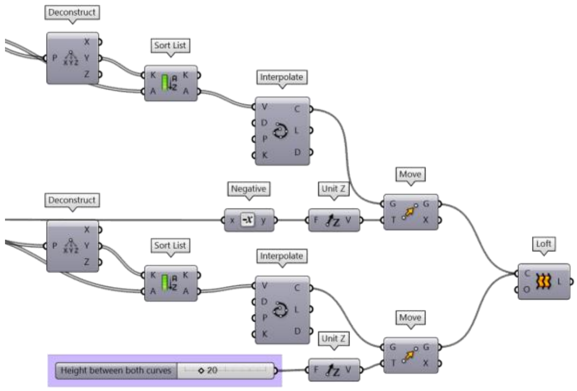

Figure 16. Lines to Surface.

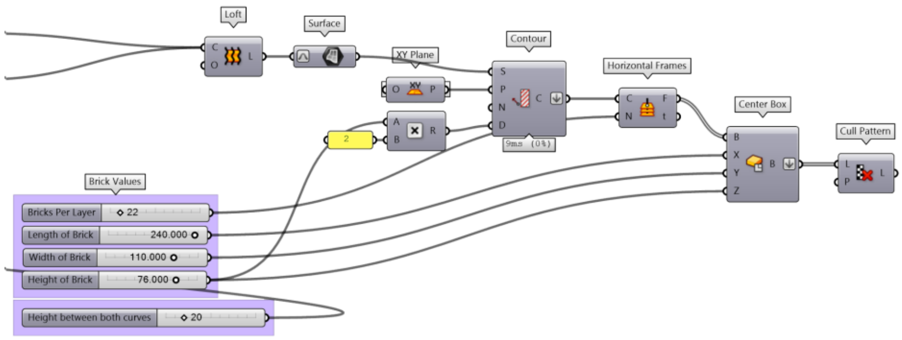

Figure 17. Surface to Brick Wall.

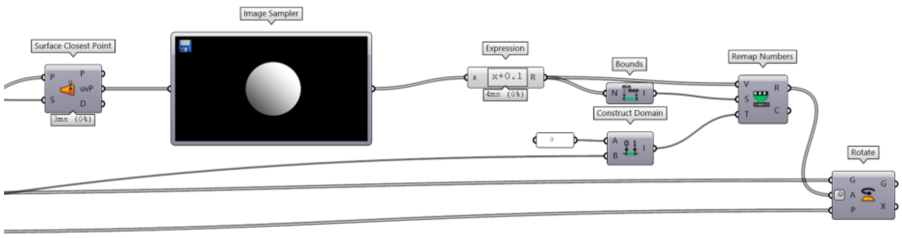

Figure 18. Gramazio Effect.

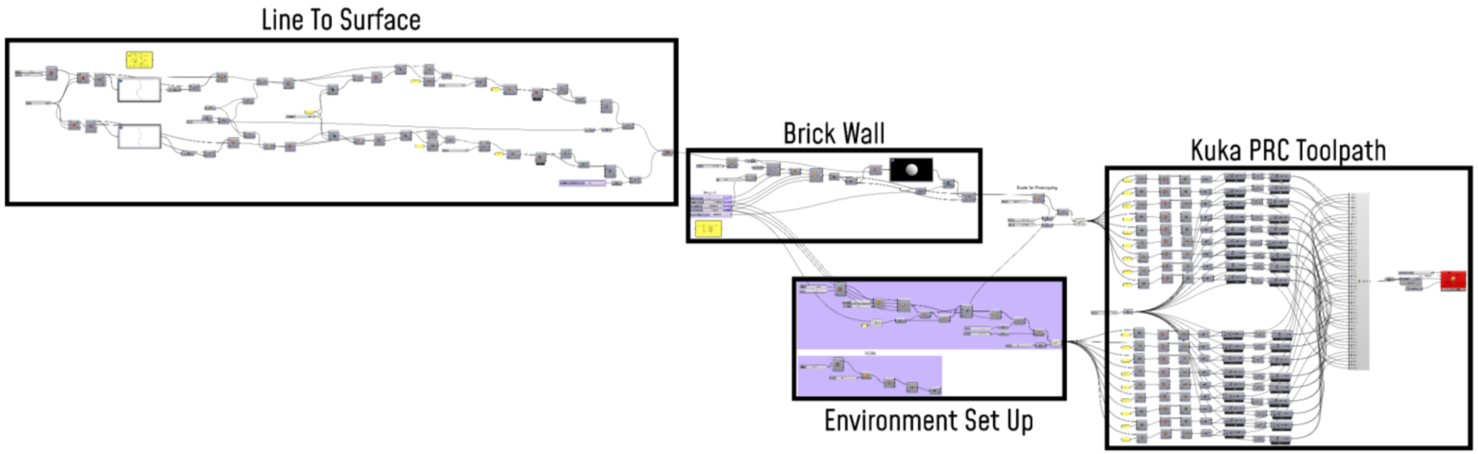

Figure 19. Overall Script.