AVANT-GARDE STONEMASONS:

Collaborative Robots

O.MARÉ,
UNSW, Sydney, Australia
omare@marlor.com.au

Abstract.
In architecture, robotic assistance is typically associated with exploring novel methods of constructing complex forms. Less attention has been directed towards the opportunity for its use in remedial work. The knowledge required to complete remedial work on sensitive sites remain an essential trait that stone masons hold. This research explores the potential adoption of computational design skills with traditional 'artisan' methods. Skills of stone masons would be paired with the opportunities of working collaboratively with robotic assistance, allowing for efficiencies and modernisation within the trade. The method of allowing stone masons to adopt computational design tools was achieved through the creation of a robust script and workflow to autonomously read fed images of masonry walls to identify and translate data into a tooling path for a robotic arm to achieve accurate repointing. An evaluation of different types of brick pattern was documented and tested with analysis of liner and non-liner wall orientation. Understanding key relationships between existing methods of craft and computational techniques allowed for overlaps to be noted and addressed. From these relationships, a scope of the types of bond that could be a used for collaborative assistance and applied to was created; English Bond, Flemish Bond and Running Bond styles of brick bond was tested through the system. An underpinning question of computational designer's ability to transition stone masons into a modern context was asked. This research provided possible outcomes of the transition in architecture and stone masons to a digital space within the context of remedial work. This conclusion was reached through the use of robotic assistance on repointing masonic walls, with an autonomous system established to identify and correct repointing.

Keywords *Stone Masons, Collaborative Robots, KUKA + Architecture, Repointing, Grasshopper*

1. Introduction: Research Aims and Motivations

This paper will be exploring methods of achieving repointing on brick facades through the use of robotic fabrication, creating a possible workflow for stone masons to adopt into their array of tools.
In so, by doing this there could be the potential for the research implemented to see;
- a decrease in workplace injury
- a increase in attention given by stone masons to more complex task
- and an increase in cost savings and productivity

The process created must use an autonomous method of achieving the KUKAS tool path with minimal input from the user. Take a photo, Feed it into a script, Run the outputted code.

Why focus on stone masons and repointing brick walls?

As it stands, the state of robots in architecture mostly look at the creation of new, 'novel' forms in architecture. Brick stacking robots, carbon weaved structures, and robots that can pile rocks on top of each other. While all of these explorations have their merit, equal amount of attention must be also directed to remedial work, ensuring the relevance and maintenance of old architecture.

3. Research Questions

The research conducted in this paper wanted to explore the question, how could robotic fabrication in architecture be used as a tool for remedial work, resulting in a autonomous method of construction. The scope of the tool and remedial work was narrowed to look at repointing brick facades, with an end user identified as stone masons. The over arching question was to see the ability for computational tools to create a image based workflow of autonomy, allowing an end user, Stone masons, to use with no computational literacy.

4. Methodology

The research conducted explores the relationship between the built environment and computational design techniques to address remedial works on structures. A question of a digital fabrications relevance within the built environment was underpinning the exploration of repointing using robotic assistance within the research. A subset of questions were created alongside this, with a theoretical question of the role of computational designer's ability to extend their reach into new fields of practice.

A robust script and workflow was created in Grasshopper, a visual based scripting package, to autonomously read fed images of masonic walls to identify and translate data into a tooling path for a robotic arm to achieve accurate repointing. The script comprises of four key elements to successfully achieve autonomous outputs of tooling paths, or code, for the robotic arm to understand. These elements are, 1. Transforming variable free RGB images into grey scale images with pixel information into a narrowed range, 2. Evaluating the new pixel information into a new variable for further deconstruction of data, 3. Restructuring of data into a KUKA friendly language, 4. Orientation of new data into the environment with evaluation of simulation. These four key elements proved to successfully address the overarching question of the computational designer's ability to use learnt skills into a construction technique.

Four Key Elements

1. *RGB to Grey Scale*

   Images of masonic walls were taken from a fixed location on the KUKA robotic arm, outputting a captured image with RGB values. For clarity in data and removal of any possible variation and error, RGB values where flattened into a grey scale, allowing each pixel within the image to be given a value between 0-10. This processed allowed the data to be clearly processed into what would be brick or mortar.

2. *Transforming data*

   Once the image was flattened and transformed into its new values, a system of removal of all non-applicable data, the pixels corresponding to bricks, was undertaken. Once the removed data was expelled from the script,

3-4. *Restructuring of Data for KUKA PRC*

   Once the image was flattened and transformed into its new values, a system of removal of all non-applicable data, the pixels corresponding to bricks, was undertaken. Once the removed data was expelled from the script,

Using these methods of data extraction, manipulation and repurposing, a automated script was created to from tooling paths for a KUKA robot.

5. Background Research

"Compared with the car-industry, the level of automation in the building industry is low. This low level of automation is due to the fact that in the building industry each object is a unique object and each building site is a unique location. " - (Van der Zee, De Vries, Salet 2014, p. 459)

As the digital slowly consumes the analogue, traditional, manual processes are being evaluated for their application of autonomy. The tasks most commonly digitised are the ones with the most monotony. With digital fabrication technologies, a large focus has been placed on additive manufacturing, with little attention placed on remedial and/or maintenance of structures. Prototyping of designs and elements has typically the use of digital manufacturing. There are five main areas of additive manufacturing and three subtractive that are prevalent.

Additive:

1. Fused depositing modelling (FDM)
2. Stereo Lithography (SLA)
3. Selective Laser Sintering (SLS)
4. Laminated Object Manufacturing (LOM)
5. Electron Beam Modelling (EBM)

Subtractive:

1. CNC Milling
2. Laser Cutting
3. Wire Cutting

These additive and subtractive manufacturing processes are at the forefront of the assessment of analogue tasks for automation. For the purposes of this research, only subtractive manufacturing process will be assessed with a narrowed scope of 'remedial works' focused on.

The proposed works that have been undertaken through this research was the successful map a surface into a virtual space, with a generative tooling path created in each iteration. This tooling path was specific to each surfaced map, with definitions between grout and brick.

The process of repointing

Repointing is typically done on buildings every 20-50 years, or as required. The process involves evaluation of the condition of existing grout and assessment of the overall structural performance. If chipping and cracking is present, extra grout is allocated to the section of damage. The manual process can be time consuming, costly and an impedance on surrounding space.

Why is Automation not present?

There are various reasons proposed to why more automation is not present within masonic trades. This report proposes the main reason to why the adoption of robotic fabrication is not present in remedial masonic works is the push for adoption of parametric based modelling used to create previously unachievable structures with.

Van Der Zee, De Vries and Salet proposed a solution to the lack of automation within the building environment. They speculate that the unique nature of each task, with variables created each from each task to be a major influence.

6. Case Study

An exploratory research attitude was adopted for this paper, broken down into main stages to gauge and document the ability of the researcher to conclude their study. These three tasks were to;

1. *Explore methods of image sampling, translating images into autonomous KUKA tooling paths*
2. *Design, prototype and fabricate end effectors*
3. *Establish a workflow of exploratory tests*
4. *Experiment and establish non calibrated work surface*
5. *Test manual methods vs autonomous methods in creating tooling paths.*

Once each of the three stages were completed, notes and observations has been documents and evaluated.

1.1 Methods of translating images to tooling paths.

Four types of image sampling and image deconstruction had been chosen for evaluation in their ability to complete the task of translating images into tooling paths for a KUKA autonomously. These four types were, Thermal Imaging, 3d Scan data, Edge detection and image sampling (a component in Grasshopper).

1.2 Thermal

Thermal imaging was disregarded due to the unreliable data that could be present. Thermal bleed from brick to grout was noted when brick facades had been in exposed to direct sunlight for more than two hours. Similar results where seen when the façade had been exposed to prolonged periods of rain and dappled shade.

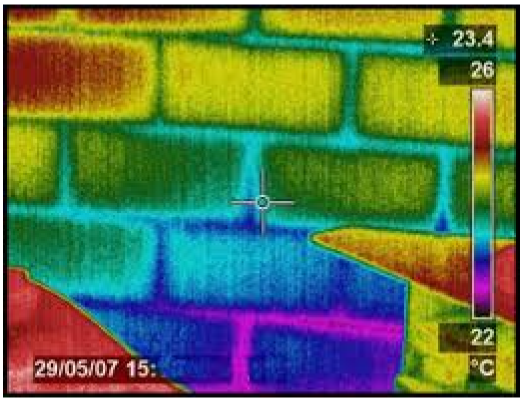


Image 1.

1.3 3d Scan data

3d scanned data provided a exhaustive summary of mapping a brick façade with the most potential for removing variability with the data. Unfortunately the method was un achievable as access to 3d scan machines was limited.

Image 2.

1.4 Edge Detection

Edge Detection alone proved to provide the least achievable outcomes. The required time to learn, test and implement along side the training and teaching required for a KUKA ensured the research to be unfeasible. However, from observations of the potential of its use, paired with the image sampling script created, notable importance of future exploration of its use must be made in future research.

Image 3.

1.5 Image Sampling within Grasshopper

Image sampling within grasshopper on its own provides the function of manipulating an image based on its colour pixel values. Breaking an image down into RGB, Alpha and Black and White for data to be extracted. For the purposes of this research, black and white pixel values where extracted. This was completed by flattening a RGB (colour) image into a gray scale image. The resulting data would provide the best definition of data for extracting correlation between grout and brick.

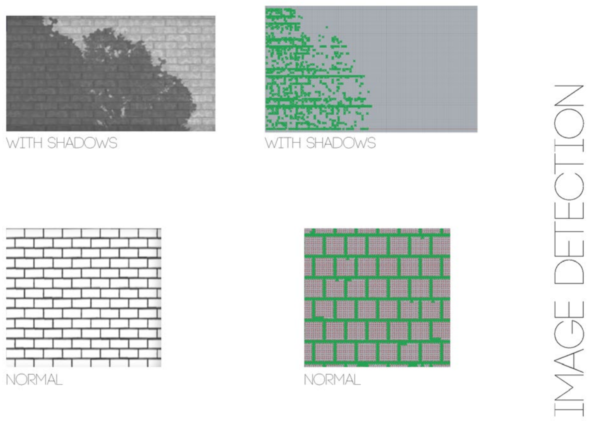


Image 4.

2.1 Design, prototype and fabricate end effectors

To clarify the term end effector and the use throughout this paper. The end effector is the part located on the end of the robots R6 rotational cuff. The end effector is not necessarily the part that holds the tool but can also be a mounted tool constructed for each task required. For the purpose of this research, the end effector is a tool holder that was used to mount a Dremel.

To explore the best end effector for my tasks, with the final task to repoint a brick façade, I explored different iterations of what the end effector could be. Image *5* displays the various iterations of designing and prototyping the end effector. Image *5* shows the initial design to mount a Dremel for the task. This design was however abandoned due to limitations and axis loss on R6. The orientation of the tool from R6 resulted in the tool rotating on itself, loosing the ability of R6 to rotate.

Image 5.

2.2 End Effector iteration II and III

Iterations two and three saw development of the fundamental ratios and overall design needed to access the full potential of the KUKA. To overcome the loss of rotation on R6, a 30 ° angle was implemented to the designs. This allowed the removal of any errors, previously seen in past simulations, with simulations and future tests. Alongside the offset was the implementation of a clamp system. This would prove to be valuable in the ability to change tools for different tests later. Iterations two and three shared a design theme that would be later abandoned in iteration four, the final design. This abandoned feature was the two stage system of head and coupling. This feature was observed to create 'wobble' and vibrations, limiting the overall stability of the end effector and effectiveness of the tool. The intended use of the two stage system was for ease in changing styles of tools for testing. This however was no longer necessary once the clamp system was incorporated into the design.

2.3 End Effector iteration IV – The final design

The final iteration of the design can be seen in image *6* It was created from a solid 3d printed piece. The angle offset was set at 30 ° for no loss of rotation on R6. A removable clamp for ease of tool change, and it was done with a rapid prototyping method, 3d printing. This design was successful in eliminating the vulnerabilities observed in previous iterations. Future iterations on the design would follow the fundamental ratios created with rapid prototyping methods translated into more structurally stable methods, such as CNC milled parts or solid cast pieces. Due to the limitations of a KUKA R6 700, maximum payload 6kg, it would be recommended that lightweight materials like aluminium be explored for production.

ITTERATION 4

Image 6.

3. Establish a workflow of exploratory tests

For an autonomous system to create a tooling path with in KUKA's PRC, a work flow was created for exploratory tests. The outline for the workflow can be seen in image 7. The steps to achieve a outputted tooling path are as follows;
Step 1, Take a image
Step 2, Feed the image into Grasshopper to be broken down into black and white pixel values, given a new data set and structure for each pixel. Lines and planes would then be created for the KUKA PRC commands to follow.
Step 3, Run the commands and observe the robots movements.

Image 7.

After the commands were loaded to the KUKA, it was noted that running a initial 'offset run' was recommended to ensure the correct orientation and accuracy of the commands. The initial tests observed some inaccuracies within the order and orientation of columns.

Once the workflow was established, a subset of tests were created to explore the relationship between simulation of commands within the KUKA PRC and physical outcomes. These were to;

- *Test manual methods vs autonomous methods in creating tooling paths and,*
- *Understand the mechanical functions of the KUKA (R6 700), its limitations and ability, through three making experiments, Drawing, Engraving and Repointing.*

4.1 Experiment and establish non calibrated work surface

Initial tests were conducted using a machine set calibration method. This would involve moving the KUKA to three points along a base. Although this process of calibration for a work surface was recommended with initial tests, the process was exchanged for a dynamic XYZ world space. This variation of calibration proved to resolve many of the 'WorkSpace Error's encountered from simulation to KUKA.

Using a XYZ coordinate system would involve manually moving the KUKA to three further most points on the work surface. By choosing to gather XYZ coordinates of the bounds of the work surface allowed the operator to understand if the KUKA was able to access full range of movements and identify any limitations of rotation within KUKA's PRC simulation but the code would be loaded. Image 8 shows the use of a roller board that was able to be moved to various locations from the KUKA's base.

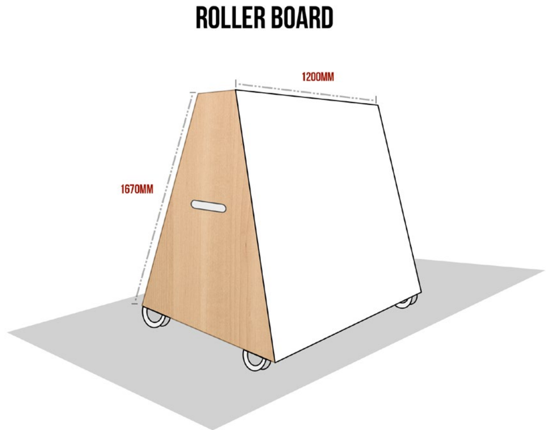


Image 8.

4.2 Limitations on a KUKA R6 700 on linear work surfaces.

This system would also allow the KUKA to gain full reach of its ability. For the KUKA used in this research, limitations and effective orientations were noted. For the task of repointing brick facades, the tooling paths would be a linear array of lines, horizontally and vertically orientated.

Unfortunately, a KUKA R6 700 will encounter a limitations when working with linear paths that are located directly in front of the KUKA. Image 9 shows the method used within this research to overcome these limitations and over ration of R4 to move to the extents of a linear line. By locating the workspace off to a 45 ° offset from the KUKAS home position, the KUKA was able to achieve its tasks without limitations of work space.

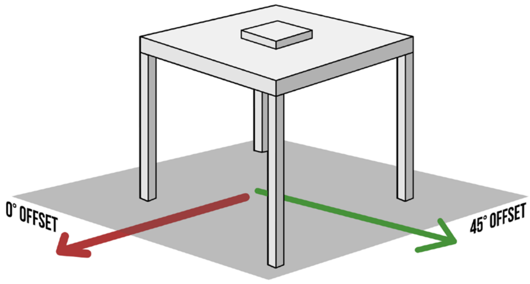


Image 9.

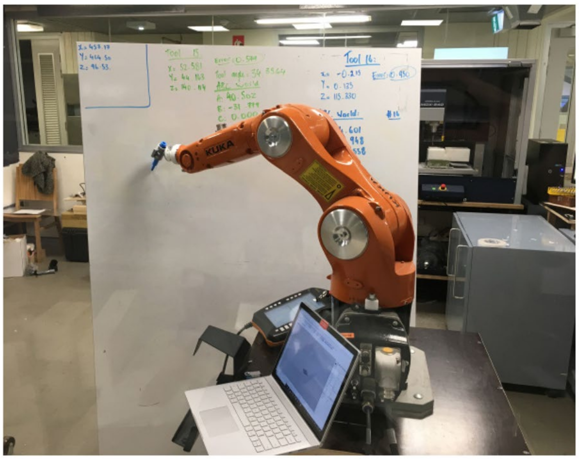
5.1 Test manual vs autonomous methods of creating tooling paths

To offer validity and gauge time to complete accurate repointing on brick facades with robotic fabrication, tests where conducted within Rhino and Grasshopper. To create tooling paths manually, by drawing lines from rows and columns obtained from an image, and to allow the image sampling script to decide and create tooling paths from a fed image. Both methods were run in KUKA's PRC simulation then outputted to the machine.

A drawing exercise discussed in 3.1.2 explores the methods of achieving tooling paths for the KUKA by drawing an image created in rhino. This exercise would offer fundamental setup sets to be taken with using a XYZ coridnate base work surface over a static base calibration from the machine.

5.2 Manual creation of KUKA tooling path

For this test, a line/vector based drawing was created in rhino. These lines would then be referenced into KUKA's PRC for tool path creation. This test was conducted to understand the workings of the machine along with its limitations in workspace and paths. Design iteration three was used to explore the exercise using a moveable workspace discussed in 4.2.



DRAWING EXERSISE

Image 8.

5.3 Autonomous methods of creating tooling paths

The image sampling script created was used in three different exercises. These where;
-1. *Test the image sampling scripts outputted code on a foam board*
-2. *Use the image sampling script on a foam board on the same image used to create the tooling path*
-3. *Use the image sampling script on constructed brick walls, run commands on brick wall with tool mounted for 'destructive' tests*

Following each test, the results of accuracy, cutting depth, speed and XYZ workspace accuracy were noted and incorporated back into the script.

5.4 Test the image sampling scripts outputted code on a foam board

To test the image sampling scripts potential for successfully translating data obtained from a image to tooling paths, the initial image sampling test was to out put the code created. This was done on a foam board mounted to the roller board. Image 9 shows the end result of running the script.

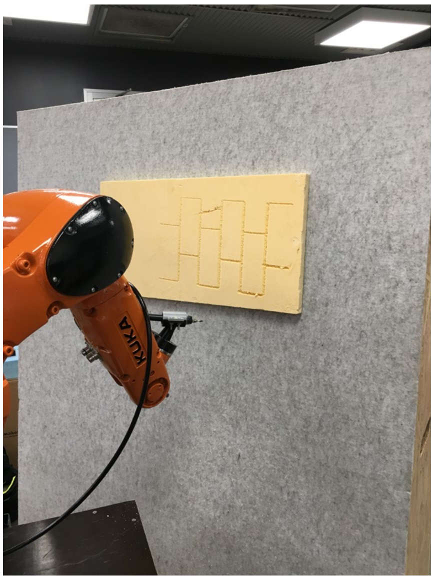


Image 9.

Through observations on this test, it was noted that without the addition of a rotational component within grasshopper, the outputted code for rows and columns was inaccurately rotated and mapped to its surface. This was noted and additions made to the script for future tests. Supplementary to the rotational error, the order of tooling paths was noted to be incorrect. Rows then columns had been noted to be a traditional hierarchy of repointing. Only once the rows had been addressed will the columns be undertaken. This was noted to be explored and corrected in the next stage of experiments and tests.

5.5 Use the image sampling script on a foam board on the same image used to create the tooling path

A similar method of experimentation from 5.4 was used, using the roller board work surface with XYZ calibration and foam board for documentation. The new task would include an updated script from observations of deficiencies in the previous task. The new test would see the addition of a 1:1 scale print of the same image used to create the tooling path, although the tooling path would still be obtained through a uploaded image, not taken on the surface. Image 10 show the initial offset tooling path from the work surface adopted.

Image 10.

This adoption of an offset run was a key ingredient before any destructive runs would be started. The offset run was a small sample of the commands to be run with no offset. An offset of 10mm was added to the commands to observe the accuracy and ensure the tooling path was correctly orientated.

5.6 Use the image sampling script on constructed brick walls, run commands on brick wall with tool mounted for 'destructive' tests

Two brick walls were created with the intention to fully repoint each variation. Each created had slight differences in their composition. Both used the image sampling script with slight variations on user input, cleaning and manipulation of the image in photo shop.

5.7 Brick Wall One

'Brick Wall One' consisted of several bricks stacked on top of each other with a 10mm grout thickness, 1:0 mortar to sand ratio and a MPA rating of 1.1. The grout was chosen for its common use in repointing, although not commonly used for structural purposes.

A initial offset run was used to observe the accuracy of the outputted code from the workflow established. The observed path was noted to be outside the bounds of exceptional use. This was noted to be from the improper formation of the wall. Unfortunately the grout applied was not to trade quality, the presence of grout overlapping onto brick. This lead to imperfections with the tooling path created in KUKA's PRC from the script.

Following this discovery, the bricks were painted white to assist the script in detecting what was grout and what was brick. This proved to help give definition, although the amount of manual input to ensure a proper tool path was created deviated from the research aim, “create an autonomous method of creating tooling paths for a KUKA”.

Brick wall one was abandoned and notes from the failures and deficiencies in the composition and construction would be used to create a new iteration of a brick wall.

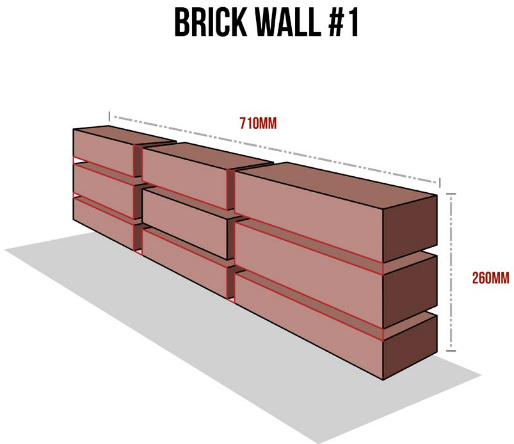


Image 11.

5.8 Brick Wall Two

‘Brick wall two’ consisted of several bricks in a running bond, 15mm grout thickness, 1:1 mortar to sand ratio and used a clay extruded holed brick. The MPA rating for the mortar was not calculated.

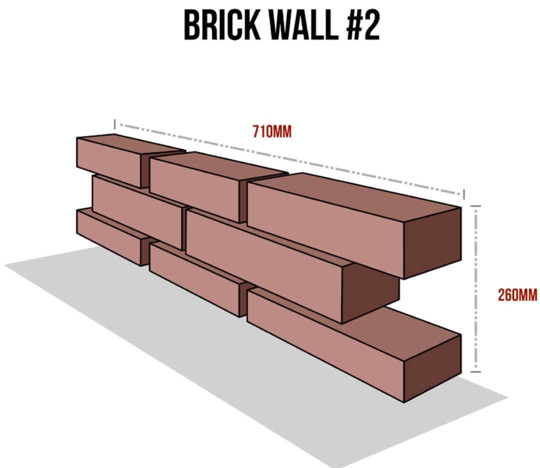


Image 12.

With notes on the previous test with building a brick wall and running the image sampling script on it, Brick Wall Two was created to test its ability to transform the data of an image to a KUKA tool path. The errors in construction and composition has been altered to address the necessary user input to gain a autonomous working script.

Once the new iteration on a brick wall was created, a image was taken of the brick wall and fed into the script. Image 13 shows the final version of the brick wall. The cleaner method of constructed ensured a clean and correct outputted tooling path.

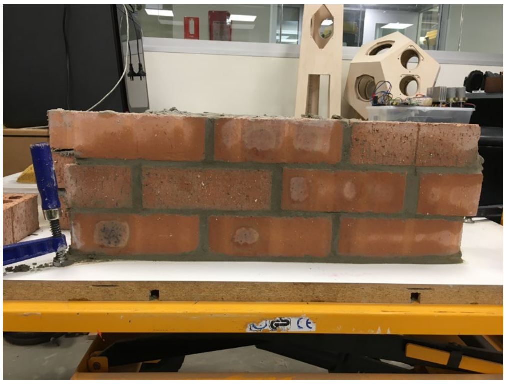


Image 13.

Once the image had been deconstructed and fed into the script, a outputted code was loaded onto the KUKA. The code had a 10mm offset from the work surface to observe accuracy and correct orientation with a movement speed of 0.4 m/s, a common speed used in manual methods of repointing.

The offset tooling path run was observed to be accurately orientated and positioned between the brick rows. The offset of 10mm from the work surface was removed and a 'destructive' path was loaded into the KUKA.

The initial speed of the KUKA showed to offer strain on R3 with warnings present on the machines display. The presence of these warning was noted to be a hardware issue to be resolved once the research was completed. The KUKA was able to remove approximately 40% of row one before a unresolvable issue was reached.

Unfortunately 'brick number three' along the first row was 5mm incorrectly placed. This resulted in the tooling path overlapping with the bricks edge seen in image 14.

Image 14.

Due to the KUKA having the absence of live tooling path corrections, a KUKA will continue on its path unaware of any obstacles that it may encounter. This resulted in the KUKA continuing on its preset tooling path. End effector iteration four was destroyed in the process. This paper would conclude that this issue would potentially be resolved with the pairing of additional methods of image deconstruction. Edge detection has been discussed and allocated for future application to remove the risk of this issue's presence.

Although the KUKA was unsuccessful in completing the task of fulling repointing a brick façade through the use of a autonomous tooling path script. It was successful in its ability to create a tooling path from a image given.

6. Key Notes

This research will list some of its key finding with the use a KUKA and KUKA's PRC in hopes this knowledge will be used in future applications.

- For use of linear work surfaces, it would be advisable to explore the use of XYZ coordinates in the KUKA space to reference the work surfaces into Grasshopper and Rhino. This research notes the effective use over recommend 3 point base calibration.

- If the tooling path shows linear consistency, offsetting the KUKA or the work surface to a 45° from the home position (0°) would be recommended. This offset removed over rotation and limitations of R4.

- The use of a 30° angle on the end effector allowed the rotation of R6. The removal of this angle will result in a loss of its axis.

- If repointing with a KUKA is intended, the use of a removable end effector would be recommended. This would ensure change of tools without the need for tool calibration each iteration.

- Movement speed of 0.4 m/s was noted to achieve a efficient method of repointing.

7. Significance of Research

From the completion of this research, the potential for a image based system of KUKA workflows was sucsefull. The ability to allow users with limited computational literacy the use of robotic fabrication. Although the complexity of the machine and the limitations found within this research was rarely documented, this paper ambitiously hopes to highlight and make interested parties aware. With the knowledge of efficiently setting up the variables of the calibration process, minimal errors proved to be present. The findings of this research would provide expedited progress to an otherwise timely exploration to the fundamentals of a KUKA's use.

The image based workflow's use has the potential for results in façade work, with a workflow of 'drawing to fabrication' established. A final version of the script must be paired with additional methods of image deconstruction. Edge detection has been advised. Coupled with the addition of edge detection, would be the creation of a front end system, eliminating any need for the use of Grasshopper.

An understanding of technical aspects in repointing would be advised. Although this paper did not outline the technical aspect of repointing masonry walls, the research conducted explored the variables and processes of repointing.

8. Evaluation of research project

The initial outcomes and objectives were as follow:

1. Explore the possible relationship that could be formed between computational designer/architect and stone mason
2. How stone masons could work collaboratively with robotic assistance by setting up a autonomous script
3. Setting up a workflow for a KUKA to reproduce the process of repointing
4. Understanding the limitations of working with in a digital space using traditional methods for repointing a brick wall. What can a KUKA achieve within the scope of remedial work and repointing.

Overall, all four objectives listed and outlined for exploration where met, although each had varying amounts of successes. The greatest strengths of the research were the adoption of orientation and restricting of data received from mapping brick wall façade from fed images. This achieved a error free and autonomous delivery of the KUKA's tool path. From the initial testing to final outputted task, a few fundamental practices of setting up the KUKA's working environment have been noted. This was the orientation of the work space which allowed for optimal rotation on the KUKA's elements. Alongside the orientation of the workspace was the offset angle of the end effector and tool. It was noted that with a 30 degree offset in the final rotational cuff (R6), the KUKA was able to access its full ability. Although a robust working script to autonomously create a tooling path for a KUKA to follow, the system and programming used would hinder any attempts by stone masons to resolve any errors. Arguably this may not be the case for traditional methods of the same task.

Future exploration into the task of repointing with robotic assistance must explore the ability to pair the image sampling script created with edge detection. This would ensure a more robust and stable workflow, with the decrease in risk of collation seen in the final test.

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- Cristina Ramos Jaime (UNSW, CoDe Associate Lecturer)

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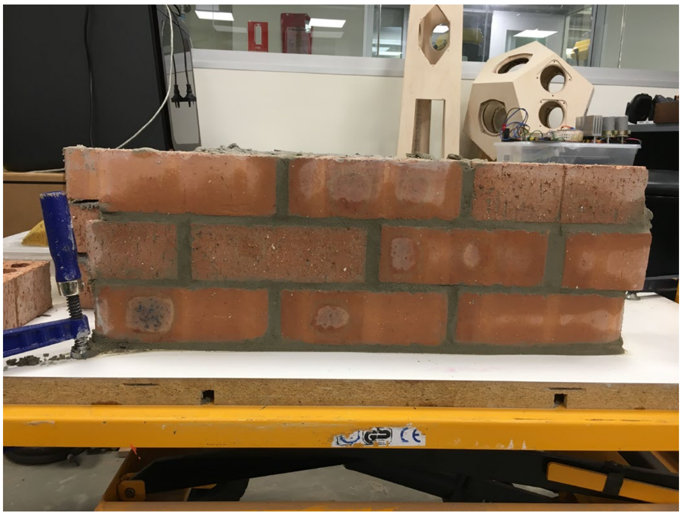
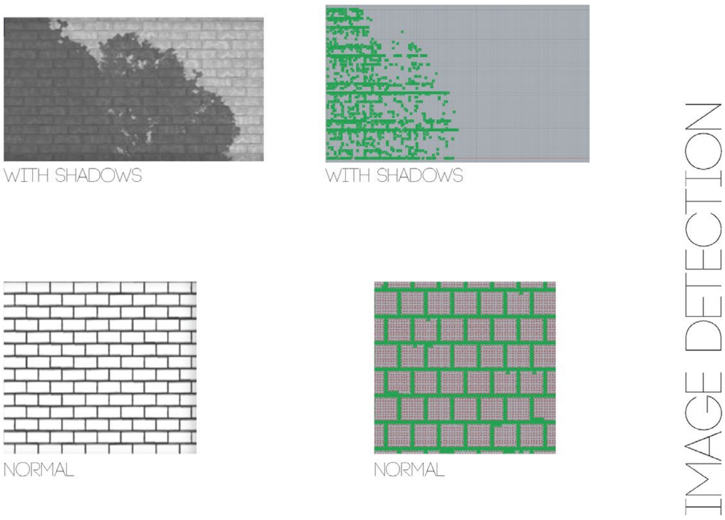
Appendix.

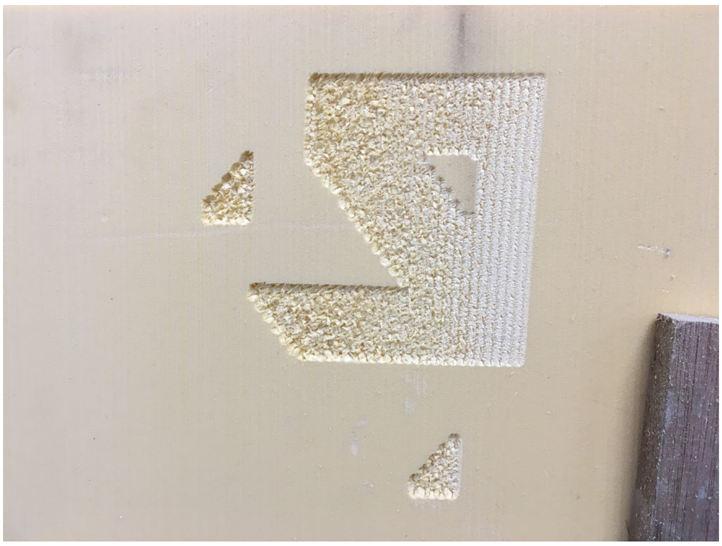


Brick Wall Two.

Tool Wear.



Before and After Image Sampling.



Engraving from fed image.