BENDING EXPECTATIONS

An efficient workflow to produce non-developable curved creases in sheet metal using a six-axis robotic arm and traditional tools.

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Abstract. Current metal forming processes used in fabrication are laborious and costly. Techniques such as pressing, moulding and punching are commonly used to form metal, but: are time-consuming; require the use of heavy machinery and trained technicians; the creasing patterns are limited; the quality of the final product relies mainly on the craftsmanship level of the manufacturer. Current computational design tools and digital fabrication techniques provide the opportunity to create manufacturing processes that can, not only overcome the limitations of the traditional tools, but also open up a whole field of new possibilities in metal design. This project develops an efficient workflow based on a novel collaboration between a six-axis robot arm and a bead roller tool to create curve patterns and freeform creases in sheet metal. This research combines parametric design with robotic fabrication, creating a digital tool that will allow to: simulate creasing patterns; predict and preview the final shape of the folded sheet metal; analyse the structural behaviour of the final product and generate the G-Code for the robot tool-paths for fabrication.

Two main processes are tested and evaluated, one being the robot's ability to feed to the metal through the bead roller itself and the second is modifying the bead roller to become an end effector for the robot arm. The project will develop a workflow that removes the need for heavy machinery, moulds, punching and pressing machines and replaces them with a robot arm improving accuracy and efficiency.

Keywords. Robotic Fabrication; Bead Roller; Sheet Metal; Curve-Creased Pattern;

1. Introduction: Research Aims and Motivations

Current metal forming fabrication processes are laborious and costly. Furthermore, techniques that are commonly used to form non-developable metal surfaces such as punches, presses and moulds often require the use of heavy machinery. Collectively, these factors can deter designers from exploring the opportunities of using metal for more complex forms and surfaces. However, recent digital fabrication techniques and computational tools suggest significant opportunities to develop new processes that can overcome existing limitations. More specifically, the research project described here aims to adapt computational methods to develop a new workflow that combines the processes of traditional metal forming with a bead roller tool and robotic fabrication in a collaborative context. The possibilities of forming metal into curve creased origami shapes is explored and add opportunities for these panel designs to be used for complex panelling systems for pavilion design, façade designs and even structural members such as columns.

The proposed workflow, combining parametric design and robotic fabrication, removes the limitations of the traditional tools for metal forming. It allows the reproduction of an original design without the constraint of having to adapt it to a specific fabrication tool. It provides a more accurate and efficient manufacturing process. It makes possible to simulate and predict results, giving an understanding of the outcomes before production, which is translated in time and cost saving: by creating a collection of digital models, comparing them and selecting just the optimum one for fabrication. The process allows replicating the final product with exact precision as many times as desired, minimising the manufacturing time.

Current metal forming techniques for non-developable curved surfaces include processes such as explosion forming and hydro-forming which use~~s~~ heavy machinery to force metal into the shape of the mould that has been developed. Explosion forming uses enclosed space and an explosive to force sheet metal into a mould, hydroforming, on the other hand, uses a high-pressure water chamber and a punch to form metal. When looking at designs that could use altering patterns throughout or complex shapes a mould would need to be developed for each panel which becomes an expensive, time-consuming process (Schodek ~~D~~,2005). Introducing the bead roller and robotic fabrication removes the need for dies and moulds. A bead roller is a traditional metal forming tool that uses two different shape dies to form metal through pressure and the movement of rolling. Although artisan metal formers would still refer to a mould when using the bead roller, the precision of robot fabrication would remove this necessity.

Regarding robotic fabrication, there is more research being conducted than ever before, Companies like Robofold LTD are developing software and ~~process~~ that can develop almost any curve folding pattern into sheet metal forms. Most of the project conducted by Robofold LTD use two or more robotic arms that use vacuum end effectors to carry out the sheet metal forming. “Robotic Bead Rolling” (~~J~~ Friedman, 2014) tests the way in which a modified bead rolling end effector can be used to imprint sheet metal and the effects of this process and demonstrates a range of opportunities that have yet to be discovered, showing how this area of sheet metal forming should be further explored. Although robot technology is becoming more prevalent, this research project aims to focus on the fabrication with one robot arm as they are still not highly available.

2. Research Objectives

Through formulating the basis of this research, some primary and secondary objectives have been set out to be achieved throughout the time frame of 13 weeks.

Primary Objective:
To develop a workflow for developing curve creases in sheet metal, from the digital to fabrication.

Secondary Objectives:

- Create a Grasshopper script that can simulate the folding process of different 2D curve creased patterns into 3D forms.
- By using the 2D patterns simulate and generate robotic arm tooling paths for fabrication.
- Test the folding capacities and limitations of the bead roller and assess ways this could be improved.
- Conduct Physical testing of two processes and analysis ways in which it could be improved in further testing.
- Compare and evaluate the two processes developed looking for qualities of efficiency and accuracy.

3. Research Questions

As this research paper aims to develop a workflow that could move a manual process into a digital environment for testing and use robotic fabrication for higher degrees of accuracy and control, these research questions were developed to aid the objective of the paper in discovering results:

To what degree can a computationally-modelled curved creased origami surface produced in the visual scripting program Grasshopper, be accurately fabricated by combining a metal bead rolling tool and six-axis robotic arm in a collaborative fabrication context?

In what ways can robotic fabrication combined with traditional metal forming tools enhance the metal fabrication outcomes?

4. Methodology

Action Research (AR) describes a process that aims to address a defined problem and propose a solution that adds value to every person involved. AR is an iterative process that has four key ideas; Planning, acting, observing and reflecting. A significant element of action research is on community or the focus on people, and this project will be developed through a group of people including students, supervisors, teachers and industry partners and aims for the results to add value to designers but also to the people involved in the research itself. The project will develop a workflow that connects design to the fabrication process, by using computational tools and robot fabrication following the course of AR. The first step of action research is clarifying the thesis idea by identifying a problem and researching other theories so that all decisions made, to define the topic, are informed and thoughtful. Considering the projects aim to create curve creased folds in sheet metal through robotic fabrication a workflow will then be developed by using grasshopper 3D, a visual scripting program, to design simulations and test the outcomes in a virtual space. The virtual simulation connects multiple audiences as it develops an understanding of robotic fabrication, tooling paths and the process of folding sheet metal, however, this is beneficial to designers in making informed decisions of the overall design showing possibilities and limitations. The next step in this project is to physically test prototypes of each curve creased panel and compare back to the simulations that were created in the virtual environment. The project will reflect on the results of physical prototyping and the comparison made in the previous step, allowing for the process of iteration to begin. AR uses an iterative process that aims to improves the workflow or the design to benefit people. The research being conducted is following this methodology as once reaching the iteration process, improvements in scripting, fabrication and the overall design allow for better user experience and result. These improvements aim to also benefit the user in a real environment as well through creating a cost-effective process removing costly machinery and processes that currently used.

5. Background Research

Advancements in robotic fabrication have opened the door for designers and architects, to explore complex and intricate forms and potentially fabricate them in less time, using fewer resources. Computational tools are key to realising the opportunities of robotic fabrication and allow design models to be quickly altered to explore multiple iterations and test ideas in a virtual space to minimise failure and time spent on fabricating. While the industrial six-axis robot arm has been a consistent feature of much high-end research, it is fast becoming a commonly accessible fabrication option for designers to utilise, so that design outcomes are not made to match fabrication techniques but benefit from them.

The bead roller is a traditional and manual tool that is used for sheet metal forming, commonly used in the automotive industry and for custom pieces. The tool uses two different dies that allow for grooves or different indentions to be developed in the sheet metal. Special forming dies can be used that will allow for folding up to a 90-degree angle. Although this has great potential, this tool is used by artisan craft’s people who have spent years perfecting the techniques needed to develop sheet metal, especially considering the development of 3D sheet metal forms. By moving this process into a robotic fabrication environment, it aims to develop higher degrees of control and reduce human error. Not only does this process hold great potential but it removes the necessity for dies and mould that are used into today's fabrication process for forming non-developable curved surfaces.

The combination of computational design tools with advanced fabrication robotics has meant that existing material folding techniques such as curve folding in origami design have also become the subject of more recent re-exploration and experimentation. While, paper folding techniques have been long-explored in architecture, such as the “Foldable Farm House for Farm Workers” designed in 1965 by Herbert Yates published in Life magazine, and traditional straight fold techniques (Koschitz 2014), translat~~ed~~ these ideas to a buildable architectural scale has remained a significant challenge. Given this, techniques such as curve creased folding remain relatively under-explored from an architectonic perspective. Curve fold sculptures can be ~~from~~ in

Bauhaus student's work dating back 1950s. It wasn't until David Huffman began studying this curve crease fold that we understood the ability and began to experiment with it computationally. Most non-developable surfaces using curve folding techniques in design are created by using casting, stamping and moulds that are expensive and use heavy machinery (Koschitz 2008). Exploring the potentials in robotic fabrication will allow this research to avoid the use of these processes to create a complex 3D form so that it can become a cost-effective outcome.

Projects such as “Robot Lattice Smock” (Saunders 2014) in partnership with RoboFold Ltd Designed a Curve folding panel system out of sheet metal and constructed it through the use of grasshopper plugins "King Kong" and "Godzilla" created by RoboFold Ltd, that simulate the folding process and then generates the code to control the robot arms. In the case of this project, they used three to four robot arms working together to fold each panel into its form. This is a valuable project as it shows the process and steps taken in order to create the panels which will help in defining a design process, but in terms of using less machinery and resources, it fails. While this research project intends to explore similar ideas, a key aim is to find ways to achieve these forms using one six-axis robotic arm instead of multiple arms.

Another project that explores the use of a robotic arm and sheet metal is “Robotic Bead Rolling” (Friedman ~~J~~ et al, 2014). They modify the novel tool of the metal Bead Roller that can imprint and shape metal as an end effector for a robot arm to design metal panels. This project aims to transfer a manual process into a robotic work environment to gain more control and improve the fabrication process. This study points to the ways that imprinting patterns into the metal sheets can impact the structural properties of the sheet metal for stressed architectural skins, and particularly how the bead roller causes sheet deformation. This could be used to either create the curve folds and resulting 3D forms by modifying the bead roller, if control can be achieved or the novel tool could be used in collaboration to imprint curves into the metal to aid the automated folding by the robotic arm.

Alternatively, in a project undertaken by J Lavalee (2011) a CNC press punch is used to create folding patterns in sheet metal and a press brake is used to fold curve creased into metal panels for column design. Significantly, although this project explores the effects of curve folding on metal, the process allows room for human error by using a press brake to possibly vary results each time it is used. Whereas this research project is exploration automation processes and how robotic fabrication could eliminate these errors and create a more efficient fabrication process.

The last important component that needs to be considered in framing this research project is the computational tools that are being used to control the design process. Plugins for grasshopper such as Kangaroo, King Kong and KUKA|PRC allow the simulation of different~~ly~~ folding patterns (Kangaroo and King Kong), tooling paths for robotic fabrication (KUKA|PRC)¬ “Adaptive Robot Control” (Braumann et al. 2015) Analysis KUKA|PRC software plug-in for grasshopper, noting that the software is able to “Quickly define and prototype robotic process”. An important aspect of the KUKA|PRC software is that once a working simulation is complete, it outputs code in terms (Braumann et al. 2015) of this research project this also will add value in robot fabrication as the code does not need to be written, it is automatically generated and can be quickly altered in the parametric software.

6. Case Study

6.1 COMPUTATIONAL TOOLS:

Grasshopper 3D is a parametric software tool that allows for designers to create, analysis properties and simulate results. For this research project, the computational tools have allowed for the development of the curve crease design, simulations predicting the folded form, the generation of robotic tooling paths and code.

King Kong developed by Robofold LTD, is an open source plugin for grasshopper that is used to predict the outcomes of 3D sheet metal forms using 2D curve crease patterns input by the user. This was used in the development of different curve crease patterns for this project. An issue that occurred in the development of curve crease patterns is that it wouldn’t work on radial patterns (Figure 1), so in development, kangaroo the plugin that King Kong relies on was used to develop these patterns instead. This is not ideal as it needs more manual scripting whereas King Kong is a more automated process.

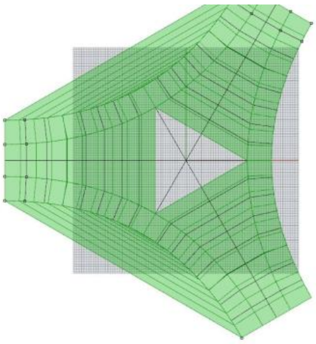

Figure 1 - Screenshot of a radial curve folding pattern from King King that would not work in the desired manner.

Once the design has been visualised (Figure 2) by King Kong and Kangaroo, the designs were translated into KUKAPRC where the robotic tooling paths can be simulated, analysed and generated and transferred to the robot arm for fabrication.

Figure 2 - Three screenshot from the grasshopper that represent the output of the folding process created by kangaroo. This shows the different stages from flat sheet metal to a 3D form.

KUKAPRC has many features that became highly important in customising the tooling paths for each panel. The software allows for a real-time visualisation of the movement of each axis (Figure 3) that and changes colour to red if any rotational limitations are reached and at which part of the simulations which allows the user to understand the exact coordinates or movements that are not possible, this becomes crucial in understanding how to achieve the results desired within the limitations of the robot arm.

KUKAPRC is important in the development of the fabrication process as you can enter the end effectors position in the XYZ world in relation to the robot arm and you can define a workspace that matches the coordinates in the real world. This allows for an extremely accuracy process having less than a 0.5mm error margin.

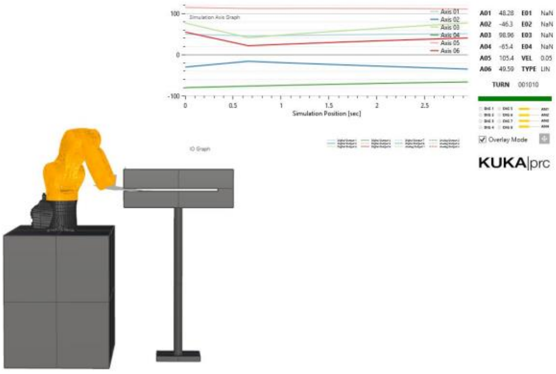

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Figure 3 - Screenshot of the KUKAPRC simulation representing process one and outputting real time analysis of each of the six-axis rotational values.

For this research, process one used offsets of the curve patterns and process two used direct curve fold patterns to generate robotic tooling paths in KUKAPRC which then outputted the necessary code (KUKA Sunrise) to program the Aglius r6 700. Although Code could not be altered in real time within this project if issues were to occur, adjusting code was a short process as the scripts are parametric and the code is generated rapidly.

6.2 FABRICATION TOOLS:

The KUKA Aglius r6 700 is the industrial six-axis robotic arm that was used for testing throughout this research ~~paper.~~ Understanding the capacities and limitations of the robot arm was crucial for developing simulations in grasshopper 3D and the physical prototyping. The robot arm has rotational extremes that define the extents of movement (Figure 4). This is crucial as it also determines the reachability of the arm and defines the workable area where the testing can take place. It is important to note that the payload of the robot arm is six kilograms and if this is exceeded can result in emergency braking and errors to avoid dangerous situations.

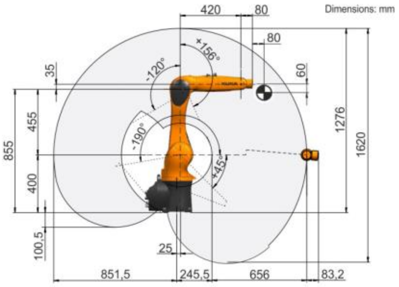


Figure 4 - A diagram showing the rotational values of each axis of the robot arm and the reachability of the arm.

The bead roller that was used for process one was a floor mounted bead roller that has a 22mm shaft and used forming dies that had a 22mm inner circumference. For this process forming dies needed to be used, this included a lower polyurethane die and an upper knife edge tipping die.(Figure 5)

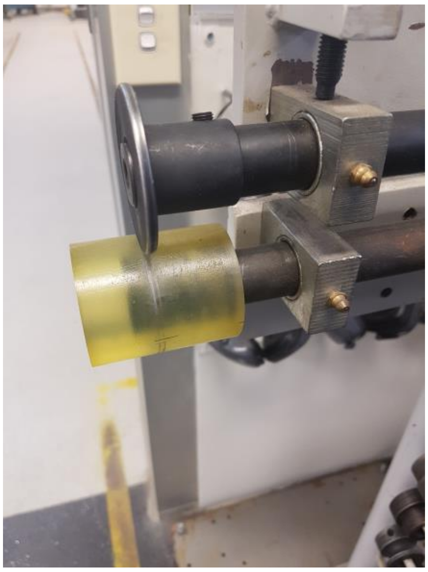


Figure 5 - The forming dies that were used in both process one and two for folding metal up to a 90-degree angle.

6.3 BENCHMARK MODELS:

Initially it was important to test the bead roller itself with a participant that had never used a bead roller to form metal. Multiple experiments ~~would be~~ undertaken to develop an understanding of the elements required to create curve creases and introduce the folding at the same time. The first test that was under taken (Figure 6) is just a straight line to understand the pressure needed, the speed of the movement and the pressure that the participant needed to apply to the sheet metal in order for it to fold. As seen in figure 6 the line did not remain straight in both the first and second attempt.

Attempting curve creased folds added more complexity to the movement, the participant need to be able to roll the dies, follow the curve path and apply enough pressure to causing the folding effect. The products produced (Figure 6-9) show that the average person does not hold the level of skill to produce this types of models unlike a trained metal artisan. Through this experimentation a basic understanding of the process was developed that could be translated into process one and two and the basic movement that would need to be replicated by the robotic arm.

Figure 6 - First benchmark model attempt of two straight line folds.

Figure 7 - Benchmark model first attempts at curve crease folding.

Figure 8 - Benchmark model attempting two curve crease folds together. Between the two folds the metal warped due to tension within the metal.

Figure 9 - Am image of a bench mark model that aimed to developed four curve creases.

6.4 END EFFECTORS:

Before testing the capacities and limitations of using a robot arm in collaboration with the bead roller custom end effectors needed to be developed. For process one, in order to attach the metal onto the robot arm, the design consisted of a piece of 1.5mm aluminium that was folded at a 90 angle so that it was able to be bolted to the robot arm and also have a surface area to attach the sheet metal onto it. This design allowed for the sheet metal pieces to be changed quickly.

The second end effector developed was based off end effector used “Robotic Bead Rolling” (Friedman 2014). This end effector developed not contain the Arduino kit like the Robotic Bead Rolling end effector (Friedman 2014), but used a similar shape and design to construct the frame and set up the dies inside the frame. The end effector frame used 3mm aluminium to add to the sturdiness of the structure to reduce any potential wobble.

Figure 10 - On the left is the end effector used in process one, which is a simple L shape for attached the sheet metal onto the robot arm. The right image is the end effector developed in Jared Friedman's "Robotic Bead Rolling" used in process two to form metal.

6.5 FABRICATION ENVIRONMENT:

At the beginning of process one, it did not need any extra special considerations for the environment other than having enough space around the robot arm and bead roller to allow for all movements needed to be reached without any collisions. The environment needed to be further developed throughout the iterations to accommodate for the torsional force of the robot arm, where the bead roller was weighed down with 100kg.

Process two needed to take into consideration more environmental factors as the sheet metal needed to be clamped into place. A small wooden table was clamped into place to remove the possibility of any movement or sliding effect similar to process one. On top of the table two Metal L shape braces were bolted into to the table so that the sheet metal that was being used was secure and could not be moved out of position.

6.6: ROBOTIC FABRICATION:

Process One:

Once the digital models had been developed, robotic tooling paths were generated that represented an offset of the curve crease. The curve crease fold was offset for the tooling path as the robot arm needs to make a larger movement then the curve fold itself so that the metal folds the same curve crease in the virtual world. Six iterations of the process were undertaken to observe the process.

Figure 11 - Image showing the starting position of each robot tooling path for fabrication in process one.

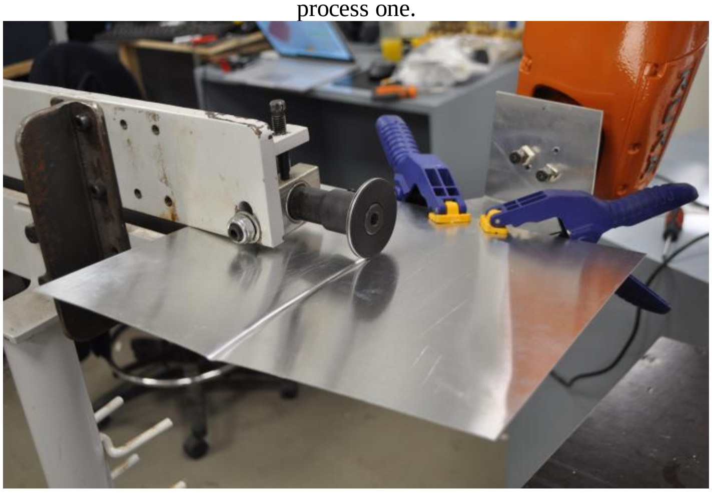


Figure 12 - Image showing the end result of iteration 1.

Iteration 1:

The first iteration considered a straight line as the robot tooling path to test exactly what would happen when feeding sheet metal through the bead roller. The starting time of the roller from the participant and the robot arm weren’t in sync which would cause precision and accuracy issues. Although, The first tooling path show~~ing~~ the accuracy of the movement in comparison to the benchmark models as the imprints did not run off the path like the handmade models.

Iteration 2:
The second iteration attempted to follow a curved tooling path. The attempt was unsuccessful as the pressure from the dies on the sheet metal was greater than the force of the clamp and the metal shifted out of place as the robot arm moved through the tooling path.

Iteration 3:
The third iteration attempted to follow the same tooling path as iteration 2 but in this version, the dies pressure was loosened in attempted to allow for a more flexible movement. The clamps still did not have enough force to hold the metal in place, and the resulting imprint did not match the tooling path that was desired.

Iteration 4-6:
To start iteration 4, the end effector was altered slightly. Instead of clamping the metal to the end effector it was bolted on instead so that it could not slide out of position as the robot arm followed the tooling path. The iteration encountered a new problem as there was a torsional force between the bead roller and the robot arm. As the robot's axis changed to follow the curvature of the tooling path, the arm was pulling the bead roller closer towards it, resulting in the tooling path to be incorrect in relation to the virtual model.

For Iteration five the bead roller was weight down with approximately 45 kilograms and the same tooling path as iteration four was attempted. Again the bead roller starting shifting inwards towards the robot base due to torsional force.

For iteration six to try and counteract the torsional force the bead roller was weighed down using weights equalling 96 kg. The same tooling path was used and again the same issue was occurring. Another issue that was observed is that the speed of the robot arm to the rotations of the cogs on the bead roller tool ~~cannot~~ be estimate correctly. In further experiments an automated device would needed to be used to maintain accuracy of the fabrication process.

In conclusion, process one developed unexpected results. The type of bead roller being a floor mounted bead roller allowed for too much torsional force when developing curve creases, in further research a table mounted bead roller would be beneficial as it would reduce the lack of stability, adding to the accuracy of the process. Prototyping a device that could automate the pressure applied on the dies would also benefit this process as it is too hard for the human eye to estimate the same pressure for each panel using only a bolt.

Figure 13 - Image of panel tested in iteration one.

Figure 14 - Image of panel tested in iteration 5.

Process Two:

Process two which is the development of an end effector that takes some of the key elements of a bead roller and compacts it’s into something smaller that can be mounted to a robot arm. This presents new opportunities compared to process one. The aim of this process is to have even more control and degrees of freedom in movement as it reduces the amount of axis extremes and has reduced wobble and flex of the sheet metal adding accuracy in comparison to process one. Multiple iterations were tested to develop this process and grow the understanding of movement.

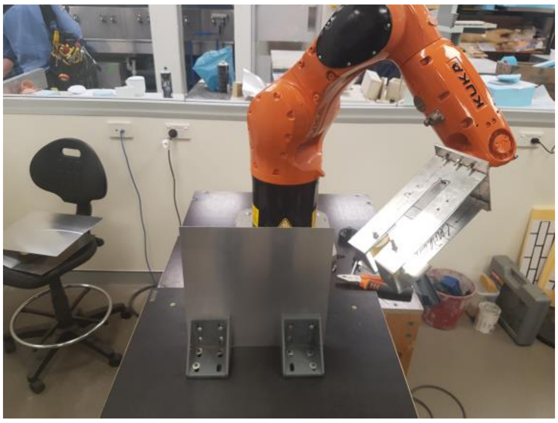
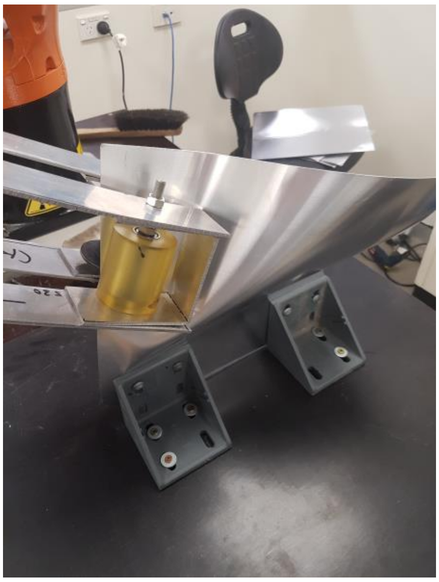


Figure 15 - Image depicting the fabrication environment of process two.

Iteration 1:
The first iteration was just a straight line across the middle of the sheet metal to test the process and any potential hazards. This movement was successful, but the bead rolling dies did not roll appropriately along the metal due to the angle of the A5 axis on the robot arm.

Iteration 2:
This process was tested using the same tooling path but change A5 axis to position the beads correctly and a change of A6 axis to rotation of 110 degrees to test the bending capacities of the end effector. The angle that was generated in the tooling path became too high as it moved from point to point this caused the end effector to collide with the robot arm itself coming to an emergency brake.

Iteration 3:
Iteration 3 aimed to complete the same tooling path as iteration 2 but reduced the rotation of A5 axis in its starting position to avoid collisions between the robotic arm and the end effector itself. In this iteration the robot arm was successfully able to run through each point in the tooling path but did not leave much of an indentation on the metal as the far corner of the end effector has dragged along the metal reducing the rolling effect of the dies.



Iteration 4:

Iteration 4 aimed to complete a tooling path generated that represented a curve crease around the corner of the sheet metal. This was unsuccessful as the dies did not roll properly across the metal but dragged instead this results in the end effector pulling the sheet metal upwards and the robot stopped the movement as the payload of the robot arm exceeded 6 kilograms.

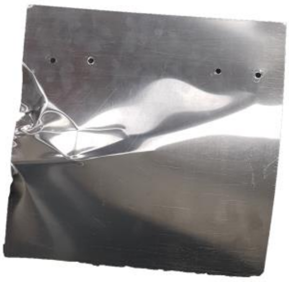


Figure 16 - Image of resulting panel when the end effector in process two got caught on the metal due to bulkiness.

Figure 17 - Image of resulting panel after two iteration test one, success the second iteration, the metal got damaged by the end effector.

In comparison to process one, process two require less human intervention as it was a more automated process. It show great potential for further developed if a second end effector was developed, leading to a fabrication technique that would not need to rely on the use of moulds and heavy machinery.

7. Significance of Research

The two processes that have been conducted throughout this research paper, although not successful yet, have ~~open~~ the door to further explore robotic fabrication techniques for sheet metal forming. As robotic fabrication becomes more accessible and easier to use the more opportunities there are to change the manufacturing process of sheet metal. The paper has enabled a new set of questions to be answered and a new objective to further adapt these processes.

Process two deemed the most promising of the processes as it had the least amount of human intervention which could be further developed into an autonomous process which would reduce the need for human labor and reduces human error. With an improved end effector that include features such as reduction in material, to reduce the size and weight of the end effector and an increased throat depth to allow for increased folding capacity. The use of process one and two allow for the removable of heavy machinery and the use of dies and moulds that opens up opportunities for complex designs. The potential of this research project could lead to the development of intricate panel design through a relatively simple and cost effective process allowing designers to create complex systems for façade design, pavilions and even structural members such as columns instead of altering design to conform to the current manufacturing process that are available.

8. Evaluation of research project

When considering the primary objectives of this research to develop a process that allowed for collaboration between, computational tools, robotic fabrication and traditional metal forming tool this paper has been successful.

The scripts developed using Kangaroo and King Kong to simulate the folding process, and the deformation of different 2D patterns into the resulting 3D forms have been successful in visualising potential results that could occur, giving the user a clear understanding of their design before beginning physical prototyping. This adds to the value to the use of computational tools as fewer materials will need to be used to understanding the structural changes in metal and the designs that are achievable.

The translation from the folding patterns into robotic tooling paths in KUKA|PRC is a simple and useful process; the parametric scripts were developed and altered quickly between each different iteration that was tested, showing the power of computational design tools to generate code for the fabrication process rapidly.

Conducting an iterative process by attempting to test curve creases with the robotic arm and bead roller developed a better understanding of this new process and ways to improve in the future. From iteration one is it clear that the robot arm holds higher accuracy and precision compared to the benchmark model completed by a person who had never formed metal in a bead roller, as the robotic tooling path did not run off track, whereas the benchmark model goes off track several times. This further emphasises that robots can learn a process that would take years to be master by an artisan, creating a quicker alternative to forming metal.

The process still needs further development as the bead roller dies have to be tightened and loosened for each tooling path that has been completed before starting the next. This is an issue it is impossible to estimate the same pressure applied to each panel, reducing the accuracy of the process. This could be improved in process two by developing an automated device that could control the pressure applied to the dies.

Overall the research conducted could become a more cost-effective process as it removes the bead roller from the equation, but also allow for more intricate panel design that achieved within the limitations of the bead roller. Overall this paper has achieved the primary and secondary objectives of the paper and has opened the door to further research into the area of robotic fabrication of sheet metal panels.

Acknowledgements

I would like to thank James Stevenson and Aaron Coats at Bates Smart, the staff at the design futures lab and supervisors Nicole Gardener, Alessandra Fabbri and Hank Haeusler.

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