Abstract. Casting is one of the most widely used construction techniques. Complex geometries produced via computational design processes are not easily achievable through traditional rigid formwork and are subject to increase material waste. More suitable casting techniques are required to efficiently represent digital design output. This paper presents a variable fabric formwork developed to work in conjunction with a 6-axis robotic arm for casting doubly curved panels based on hyperbolic paraboloid geometry. The variable formwork is designed to be extendable in length and width so it is able to produce a wide range of outcome within a single formwork. The interface established in the workflow allows the physical formwork and digital design to influence each other. This variable fabric formwork reduces construction waste and is a more sustainable method of casting complex geometries.

Keywords. Digital fabrication; Robotic production; fabric casting.

1. Introduction
Casting is one of the most widely used construction techniques (Lloret et al. 2013) in architecture. With emerging complex geometry in computational designs, traditional casting methods using rigid formwork is limited in responding to the demand of customisable geometry. Recent research in casting using digital fabrication mainly utilises CNC milling as either sacrificial formwork (Lavery 2013) or in-situ mould (Sousa et al. 2016). A number of flexible mould designs for precast concrete have been explored using robotic slip forming techniques (Lloret et al. 2013) and multi-point systems (Adapa 2016). Traditional rigid formwork can be replaced with flexible fabric; such techniques were explored by various researchers (Pedreschi & Chandler 2007; Thomas 2015; Kallegias & Erdine 2015) as well as in commercial applications (Fab-form 2016). The appeal of the system is in its fluid aesthetic quality and the potential to re-use formwork, thereby reducing
waste in the mould design. However, there is limited research in the exploration of fabric casting with robotic arms to produce varied geometric panels using a single mould design.

This paper discusses the design and fabrication of a variable fabric formwork that incorporated the use of a robotic arm. The project, titled HYPAR, is the result of a 12-week research based design studio at the University of Melbourne lead by the third and fourth authors. The studio encourages a bottom up material approach to design, where the team investigated fabrication techniques for the design of a pavilion structure. The team explored a variable casting mould system and the potential of using non-planar quadrilateral panelised system based on the geometric principle of hyperbolic paraboloid. The outcome was a series of cast panels (figure 1) using moulding plaster; plaster was used instead of concrete for ease of casting and reduced weight in the fabrication process. This naturally made the panels more fragile and less robust compared to a concrete cast. In this paper, the design team focuses on the fabrication workflow, material effects and geometric outcome of the test panels.

![Figure 1. Plaster cast hyperbolic paraboloid panels.](image)

2. Background

Soft and transformable formwork in casting has been explored by numerous practitioners. Pneumatically supported tubular formwork systems were used as early as 1938 to construct water pipe lines (Sobek 1986). In the 1960s, Bini established a method of casting concrete shells with inflated membranes (Roessler & Bini 1986). Unlike conventional rigid formworks, soft formworks have the capacity to cast more complex geometries; namely doubly curved surfaces. The results are typically of thinner shells which are structurally more efficient.

Most soft and transformable formwork utilises fabric as the key material. Significant developments in fabric formwork were made in the late 18th and the 19th century as a result of the Industrial Revolution (Veenendaal 2011). While traditionally seen as utilitarian application for its simplicity and cost effectiveness, it was not until the 1950’s that fabric formwork was used and explored in architectural projects by Miguel Fisac and later by Mark West (CAST 2016) and Kenzo
Unno. Veenendaal (2011) outlined the limitation of research in this field and identified the key challenges, for example the double curvature geometry is implicit to the fabric formwork and this tends to limit its application in traditional design.

2.1. USE OF ROBOTICS IN CASTING TECHNIQUES

Recent research projects in casting explored the use of industrial robotic arms to manipulate variable formworks to explore novel techniques and material expressions. While the research in this field is limited, there are two key projects that are relevant to our discussion. First, the Robotic Slipforming project conducted at ETH Zurich, which used a robotic arm to manipulate a cylindrical formwork, which was rotated and extended in height to form “double curved” columns (Lloret et al. 2013). The second project is Fabric Form developed at UCLA which utilised two robotic arms to stretch a truncated fabric formwork to a scripted geometry, resulting in concrete components that could be accumulated to form a lattice structure (Culver et al. 2016). Both projects utilized the robotic arm as the primary device to produce trajectory for the formwork in order to move it from its start to rest position. Here, the choreography of the production process conditioned by the anatomy of the robotic arm delivered a set of dynamic rules which could become a driver for design (Ameijde et al. 2012). As Gramazio and Kohler (2008) pointed out, “We design a behavior”.

2.2. RULED SURFACE GEOMETRY

The geometries produced by HYPAR are based on hyperbolic paraboloid, a doubly curved saddle-like ruled surface. In architectural design, this geometry has been widely used, most notably in the geometric development of Sagrada Família (Burry 2011A). Similar geometry is also deployed in the roof structure of St Mary’s Cathedral, San Francisco by Nervi. Here, eight hyperbolic paraboloids are used to generate the spatial transformation from a square on plan to a cross at the apex of the roof. The assembly of the roof is made possible by utilising a straight timber plank as scaffolding to support the triangulated pre-cast concrete panels (Nervi 1965); it demonstrates the advantage of deploying ruled surface in the construction of a complex doubly curved roof.

There are three key characteristics of the hyperbolic paraboloid that is critical to the project. Firstly, for any ruled surface, a single straight line lying on that surface will pass through a given point lying on that surface (Burry 2011B). The straight line is referred to as ruling. For hyperbolic paraboloid, every point on the surface has two lines passing, making it a doubly ruled surface. This geometric property makes hyperbolic paraboloid load-resistant in two directions (Farshad 1992) but more importantly, the ruling as straight line or edge can be articulated as physical material which is useful for the fabrication of the mould.

Second, it is important to note that not all ruled surface geometries are developable. Hyperbolic paraboloids explored in HYPAR are quadric surfaces which are non-developable; as the ruling consists of non-torsal generator where the tangent plane at any point on the surface is different from other points on the surface (Portmann et al. 2007). Despite the non-developable nature of the surface, it is
possible to define this “warped ruled surface” geometry by the four corners of the quadric surface. In HYPAR, we reduced the four corners into two opposite edges as the primary parameter.

Third, the nature of the geometry allows the possibility of joining hyperbolic paraboloid panels at their edges. The characteristic of this second order geometry as Burry (2011A) pointed out can be fragmented into individual components which when combined can still form a seamless surface. The complexity comes when the surface assume a thickness as in casting a panel. The four edge faces of the panel would also be ruled warped surfaces. These three characteristics of hyperbolic paraboloid are used as the primary parameters in the design and development of HYPAR.

3. Design and Fabrication of Variable Mould

HYPAR is designed as a variable fabric mould controlled using a 6-axis robotic arm. Figure 2 illustrates the design of the latest iteration of mould. This mould is used to cast a 300mm wide x 900mm length x 50mm thick panel. The mould consists of the following parts:

1. Bespoke end effector. The end effector attached to the robotic arm is a gripper with a pair of 3D printed ABS plastic teeth. A pair of negative teeth is screwed onto the top clamp (2). The end effector is driven by compressed air so the robotic arm could hold the mould in position and release the formwork after the curing process.

2. Top clamp. A CNC milled MDF panel with a pair of bespoke clamps where the fabric formwork and aluminium tubes are fixed to a horizontal plate. The width of the panel is pre-set but the mould can be adapted to increase or decrease its width.

3. Bottom clamp. A CNC milled MDF panel with a slot acting as a guide for the ruling aluminium tubes. The bottom width of the panel has potential to vary in width as per the top clamp.

4. Ruling. Consisting of 30 pieces of 1 meter long hollow aluminium tubes at 20mm centers. The tubes are pin jointed at the top clamp (2) but are not constrained at the bottom, which allows certain amount of movement and rotation. This allows for variation in length (L) to the panel, in this case the length constraint is $388mm < L < 900mm$. 

![Figure 2. Variable mould and diagram showing parts.](image-url)
5. Fabric formwork. The fabric used is a mixture of 95% polyester and 5% lycra, stitched with a sewing machine into a rectangular shaped pocket. It is placed in between the ruling and is only clamped from the top with an opening to allow the pouring of plaster.

6. Carcass. The carcass is CNC milled MDF and softwood timber framed supporting the bottom clamp. It does not support the weight of the cast which is primarily held up by the robotic arm.

7. Temporary frame. The frame is removed after the robotic arm engages with the mould via the end effector (1).

For individual casts, the bottom edge of the fabric formwork (5) is fixed at the same place at the bottom clamp (3), but the height, rotation and tilting of the top clamp (2) can vary for each cast, and thus generating variable formwork.

In the development of this variable fabric formwork, five iterations of the mould were made and improved over the 12 weeks’ period. The first mould was designed as a manual input device to attain the basic principle of hyperbolic paraboloid cast with the aid of elastic cables along the fabric to retain the ruling of the surface. Once a successful cast was made manually, the robotic interface was developed to pair the formwork with the 6-axis robotic arm. The research utilised an ABB IRB 1200-5/0.9 with a 901mm reach and 5kg payload.

A significant improvement to the system happened when the design team abandoned the elastic ruling in favour of a rigid tube system constrained in one direction. This minimised uncontrollable bulging of the fabric under hydrostatic pressure of the plaster.

Further improvements in the final iteration of the mould (figure 2) were made to increase the height and thickness of the cast, with this came the need for stronger ruling component along the side of the fabric to hold the cast. The design team also integrated pipes in the final cast and developed design opportunities for apertures; this is discussed in 4.2.

The main differences of HYPAR with the projects listed in section 2.2 are:

1. HYPAR is designed to produce non planar quadrilateral surface. The double curved nature of the fabric formwork highlighted in 2.1 is useful in the design and development of the surface.

2. Unlike Fabric Form by Culver et al. (2016), the fabric formwork utilised the “ruling” of the hyperbolic paraboloid surface as a principal to extend the length of the panel. In practice, the panel can vary in width and length.

3. If the length remains constant or within stretch limits of the fabric, the same fabric formwork can be reused to produce variable geometries.

3.1. FABRICATION WORKFLOW

The design team stimulated the making procedure on numerous occasions before using the robotic arm to engage with the mould. Figure 3 demonstrates the making procedure of the panels. Ten separate casts (figure 1) were made in order for the design team to acquire and develop the skill of casting; each getting progressively larger in size from 300mm to 900mm tall. The iterative procedure allows the
system to be refined, for example, in how to control leaks and poor workmanship issues in the mould.

![Figure 3. Fabrication workflow of HYPER.](image)

As discussed in 2.3, this second order geometry has a unique characteristic that enabled a doubly curved surface, for example a shell structure, to be panelized and combined together to form seamless curvature. The design team tested the hyperbolic paraboloid geometry onto a shell structure as a design response to the studio brief (figure 6-A). The geometry of various hyperbolic paraboloid panels as the outcome of the design were taken as the input to the digital workflow. A visual script was written in Grasshopper to generate a robot target frame for any hyperbolic paraboloid panels. As illustrated in figure 4-A, the panel is oriented to align with the bottom clamp (figure 2-3) of the mould in Rhino 3D. A plane is defined at the centre of each panel’s top edge and is offset to the top clamp (figure 2-2) position. It is referenced as one of the target frames for the robotic arm where the fabric mould is formed into the resulting hyperbolic paraboloid geometry. Other necessary target frames (figure 4-B) indicating the starting position of the robotic arm, its gripper closing position and temporary frame removing position are part of the movement information which translated into the trajectory of the arm for each corresponding form.

![Figure 4. Robotic workflow of HYPER.](image)

### 3.2. INTERACTIONS OF ROBOTIC ARM AND MOULD

The interface between the mould and the arm became a critical aspect in the fabrication process. While digital stimulation of the robotic arm was already undertaken
in RobotStudio 6.03.01, this only allowed the team to understand the trajectory of the arm without material constraints. There were other factors missing from this stimulation, for example, what was the reach limit in relationship with the ruling tubes? What was the maximum angle of rotation before the ruling starts to collide? Data collected from these questions allowed the team to feedback the information into the form generating Grasshopper script.

In order for the design team to develop and understand the limits of the mould with the robotic arm, the team tested and explored the limitations of the mould without any cast as physical simulation. Placed within the range of the robotic arm, the mould was jogged to its limitations along X, Y, and Z axis. A so called capability boundary can be recorded in this simulation process (figure 5) and it was used to mark out the geometry range in the robotic coding. Here, the interaction between the robotic arm and the mould constructed limits in the design. The mould is used to “teach” the robotic arm to understand the limits of the system; the information is written back into the form finding script to optimise the size of the panel subdivision.

Figure 5. Left, Robotic arm and mould interaction. Right, Capability boundary of the system.

4. Future Inquiry and Potential

Current research has identified limitations of the system. For example, the mould design is hindered by the pin joint of the ruling tube which limits the rotation of the robotic arm; this could be improved using rod end ball bearings. The robotic arm, however flexible and accurate, had a weight limit which was reached upon casting a 900mm tall cast; efforts to cast larger and wider panels would require robotic arms with larger payloads. Despite the limitation of research tools, the fabrication method explored in this paper provides a starting point towards a more sustainable way of casting multiple unique doubly curved panels.

The key challenge of the system was confronted when the panel assumed a thickness and individual panels needed to be butt jointed together edge to edge. In the current mould design, the edge is treated with aluminium tube ruling. However, because of the 50mm pre-set thickness of the panel, the ruling aluminium tube did not produce a sufficiently tight tolerance for the panel to be butt together as a male and female slot. This will continue to be investigated in future research.
4.1. DESIGN IMPLICATION AND POTENTIAL
As discussed in section 3.3 and 3.5, the team tested the geometrical possibility of HYPAR in a shell structure design. The limits of the system was identified through the interaction of the robotic arm and the mould provided the parameter for the architectural proposal (figure 6). Through the material study, two potentials of the design are worth noting. The first is the potential of the hyperbolic paraboloid surface to act as acoustic diffuser where the twist of the individual surface can be parametrically adjusted.

The second potential emerges from the fabrication process. While the elastic ruling is replaced with aluminium tube system which minimised the bulging of the fabric under hydrostatic pressure of plaster, the fabric continued to bulge in between the aluminium tubes, this was seen as an interesting visual effect that the design team wanted to encourage. It allowed the design team to consider embedding pipes within the cast for evaporative cooling purposes. Pipe embedded building envelope has been developed recently to reduce heat transfer through facades which have the capacity to utilise passive cooling instead of mechanical cooling (Shen & Li 2016). Other researchers have been exploring the potential of porous ceramic pipes to absorb water and act as passive cooling devices; the potential of the research is in the capacity to combat urban heat island effect (Chen et al. 2015). HYPAR explores the potential of these evaporative cooling techniques through imbedding water pipes that could release water from within the cast allowing it to saturate the outer surface, creating a cooling effect in conjunction with air movement. Initial analysis of the cast panel suggests that the aperture in the panel has the capacity to create disturbance to increase air to surface contact, thereby assisting evaporative cooling through the process (figure 6).

5. Conclusion
HYPAR suggests a novel fabrication technique which integrates a robotic arm within its fabrication protocol to produce hyperbolic paraboloid cast panels. While the current design has limitations, the research identifies future area of research for fabric casting using robotic arms. The design procedure of the mould highlighted the need for interaction between the robotic arm and the mould in order to set up a continuous feedback procedure to improve the various iterations of the mould. It set up the digital workflow that has implications on the form generating process; integrating the logic and characteristic of hyperbolic paraboloid geometry and translates this into material articulation and behaviour of the robotic arm, resulting in the transformation of the geometry. This fabrication method proves to reduce material waste and manual labour in the construction of complex doubly curved panels. The mould design is a step towards a more sustainable means of construction in the wake of parametric and computational design application to construction. The responsibility, however still lies with us as designers and architects to construct new ways of reducing impact to our built environment, not just through design performance but also closely integrated into the construction process.
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