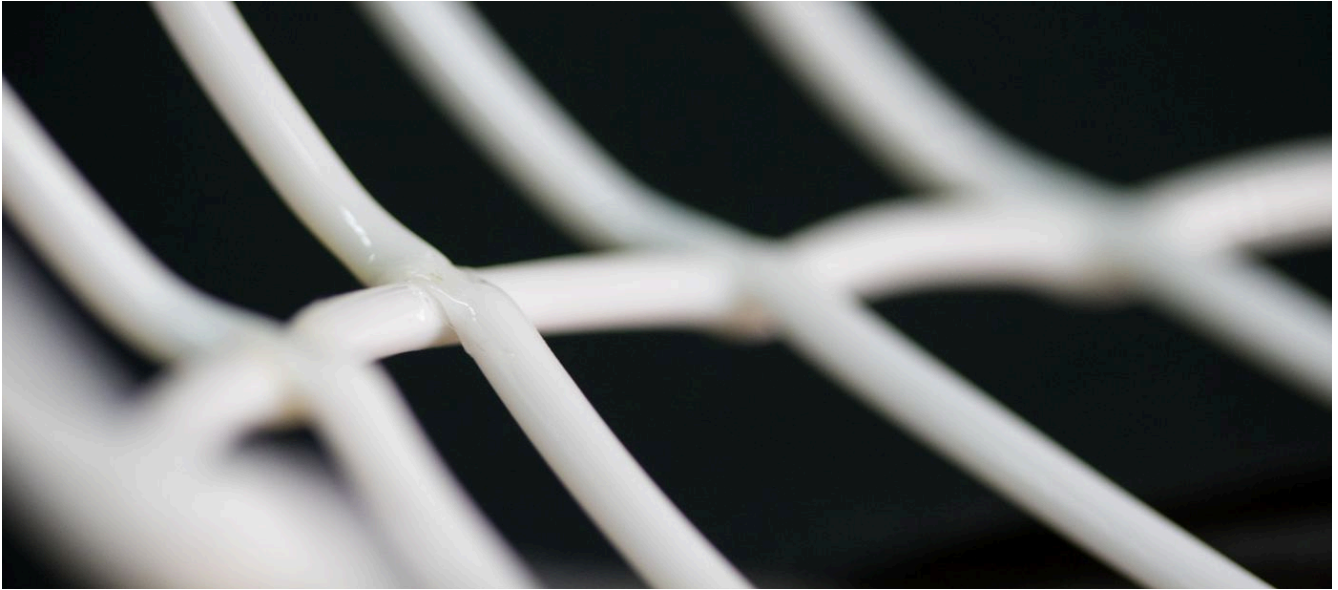


Spatial Printing Research

Plasma Technology in Spatial Additive Manufacturing



Abstract:

This research explores the integration of plasma technology in Spatial Printing and its application in tensile structures. This technique employs a filament uncoiling method, rather than heated extrusion as is traditional Freeform Printing. Numerous experiments have been carried out to refine and create the more effective and efficient bonding technique for creating connections with high tensile strength. Custom test rigs and plasma torch holders were made to work with the uncoiler made in the previous research study. These have been designed to work with the ABB IRB 1200 Robotic Arm. This robot allows for high degrees of accuracy allowing repetition, consist and and accurate testing. HAL Robotics plugins for grasshopper/Rhino were the basis for programming the Robotic Movements. Tensile testing was then carried out on the MARK-10 Motorised Tension and Compression Test Stand for analysis. Successful outcomes will enable dramatically reduced production time for tensile free-form structures.

Research by Hamish Visser

in collaboration with Victoria University of Wellington and GNS Science





2020 - 2021

Can high temperature plasma strategies be effectively integrated to create new techniques for spatial printing?

Does robotic uncoiling have a future in additive manufacturing, specifically creating tensile structures?



Acknowledgments

Many thanks to the team who gave me this opportunity to take part in advanced spatial printing research.

Supervisor: Tim Miller and Jerome Leveneur
Funding: National Science Challenge, Innovation Spearhead:
"Science for Technological Innovation"
GNS Science

Summer Scholarship project:
"Accelerating Large Scale Additive Manufacturing: Dealing with Stress During Plasma
Freeform Printing"
Victoria University of Wellington

Material and research providers: Scion, University of Waikato
With help and guidance: Hamish Morgan

Research Assignment carried out by Hamish Visser Date: 12/2020 - 02/2021



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Spatial Printing Background

Spatial Printing or Free-form Printing is an evolution in additive manufacturing that allows 3D printing without additional auxiliary structures. It is derived from traditional FDM printing which often requires support material. In traditional FDM a machine extrudes a bead of material along a linear path in small layers, each fusing together until an object is formed. Spatial printing moves away from layered building techniques and uses target by target building with the help from a 6-axis robot. This method involves the robot moving to targeted points in 3D space as opposed to layering. These techniques combined with software topology optimization have created comparable structures using significantly less material.

Because the surface area of adhesion is reduced the structural resilience can be hindered. VUW have previously investigated the potential for plasma technology to be integrated into Spatial Printing. The research investigated how quick and intense heat transfer could accelerate the building process, or the effects of plasma surface treatment on structural bonds.

This research aims to investigate opportunities integrating plasma treatment with the uncoiling technique may provide.

Section One

*Background Research and Research Direction
Latest Developments in Spatial Printing*



Institution/Company	University of Stuttgart	CurVoxels	University of Stuttgart	Tongi University	MIT
Name of Project/Study	Research Pavilion	Spatial Curves	Elytra Filament Pavilion	Incremental Forming	Silk Pavilion
Data/Year	2016-2017	2015	2016	2015	2013
Device/Machine	2 Robotic Arms, Drone	Robotic Arm	1 Robotic Arm, rotating base, unspooling device	Robotic Arm - Kuka	CNC Machine/Silkworms (Natural additive technique)
Software	Custom Adaptive control and communication system developed.	Custom-made computational application	Custom adaptive control and communication system was developed.	Rhino/Grasshopper	N.A
Extrusion Device	Uncoiling spool, drone with gripper/robotic arms with magnets.	Custom -made extruder	Uncoiling method utilising a DC motor and friction brake Rotating bed (winding frame).	Heated tip (comes in contact with plastic surface)	Digital and biological fibre based manufacturing. Silkworms
Material	Resin-impregnated glass and carbon fibre	PLA	Resin-impregnated glass and carbon fibre lengths	Plastics	Thread and silk
Temperature	N.A	N.A	N.A	N.A	N.A
Cooling System	N.A	N.A	N.A	N.A	N.A
Extrusion Speed	N.A	N.A	N.A	N.A	N.A
Extrusion Thickness	N.A	4-6mm	N.A	N.A	N.A
Context	Small Scale (Material weight prevents large scale)	Large scale architectural investigation	Architectural scale	Experimental application	Large scale architectural investigation
Notes	Lightweight, high tensile strength and affordance radically different approach to fabrication. Long-spanning fibrous construction. Lack of adequate fibre composite fabrication processes create limitations. No surface mould needed. "Multi-stage volumetric fibre unwinding." Spool carried between robotic arms via Drone, creating a tensile structure by wrapping the fibre around points. Spool used a DC Motor with encoder, friction brake, and timing belt.	Introduces different material densities into the structure. "Uses the algorithm that aggregates a single curvilinear element into a continuous long extrusion." "The size of the voxel changes depending on the amount of stress in the chair, distributing different material densities." Volumetric design rather than the surface-like original.	Similar to the research pavilion. Utilises a rotational base for the object/model. Impregnates fibre with resin upon uncoiling to allow the lengths to set. Soft, white glass fibres provide the formwork (e.g. Surfboards). Carbon fibre lengths provide stiffness and structural strengthening to the system. Exploration of how fibre composites could contribute to new structural forms beyond the traditional typologies and modern architecture.	Plastic deformation by pressing heated tip up against plastic sheet and melting it. Poor accuracy due to random plastic deformation.	26 silk-threaded polygonal panels laid down by CNC machine. Inspired by the silkworm's ability to generate a 3D cocoon out of a single multi-property silk filament. Single continuous thread, functional density modification based off environmental factors. E.g. heat, light, airflow.
Design Opportunity	Utilise friction uncoiling method. Combine uncoiling method with plasma connections.	Develop a system that simulates forces acting on model and introduce varying material densities accordingly.	Utilise rotating base to overcome memory problem and the filament angle of entry.	Use heat/plasma to modify the surface post extrusion/placement.	Use alternative methods to strengthen superimposed surfaces post extrusion/placement.
Reference	https://www.archdaily.com/869450/icd-itke-research-pavilion-2016-17-icd-itke-university-of-stuttgart	https://www.arch2o.com/spatial-curves-curvoxels	https://www.vam.ac.uk/articles/about-the-elytra-filament-pavilion	https://www.arosu.eu/215/incremental-forming	https://www.media.mit.edu/publications/silk-pavilion-a-case-study-in-fibre-based-digital-fabrication

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Graph created by Max Crosse, the 2019-2020 Summer Scholarship student. Summarising the latest developments in Spatial Additive Manufacturing / Free-form Printing.

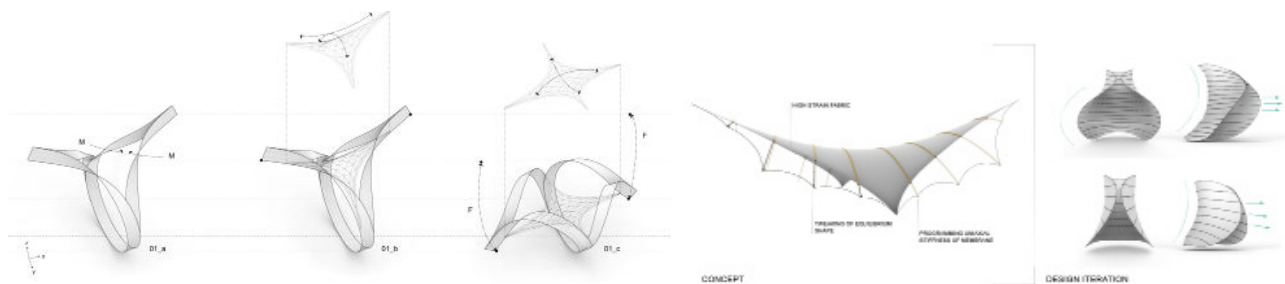
The following pages are a collection of projects and techniques not included in last years report. Although the research knowledge was not directly transferable, it is important to be well informed about the most recent discoveries and possibilities of 3D printing and the direction it is heading.

MULTIPLE STATES OF EQUILIBRIUM FOR BENDING-ACTIVE (TENSILE) STRUCTURES
2020

This research aims to develop an interface to help design and analyze bending-active tensile structures. The study explores the potential for its use in architecture, specifically lightweight architecture.

Tensile structures remain a challenge for designers but recent developments in CAM and CAE such as this one allow new concepts to be explored.

This has no direct use because it is custom software, but it showcases advancements in tensile structure design.



Institute for Advanced Architecture of California

PHRIENDS FOR SHELLS ADVANCED ROBOTICS FABRICATION
2016

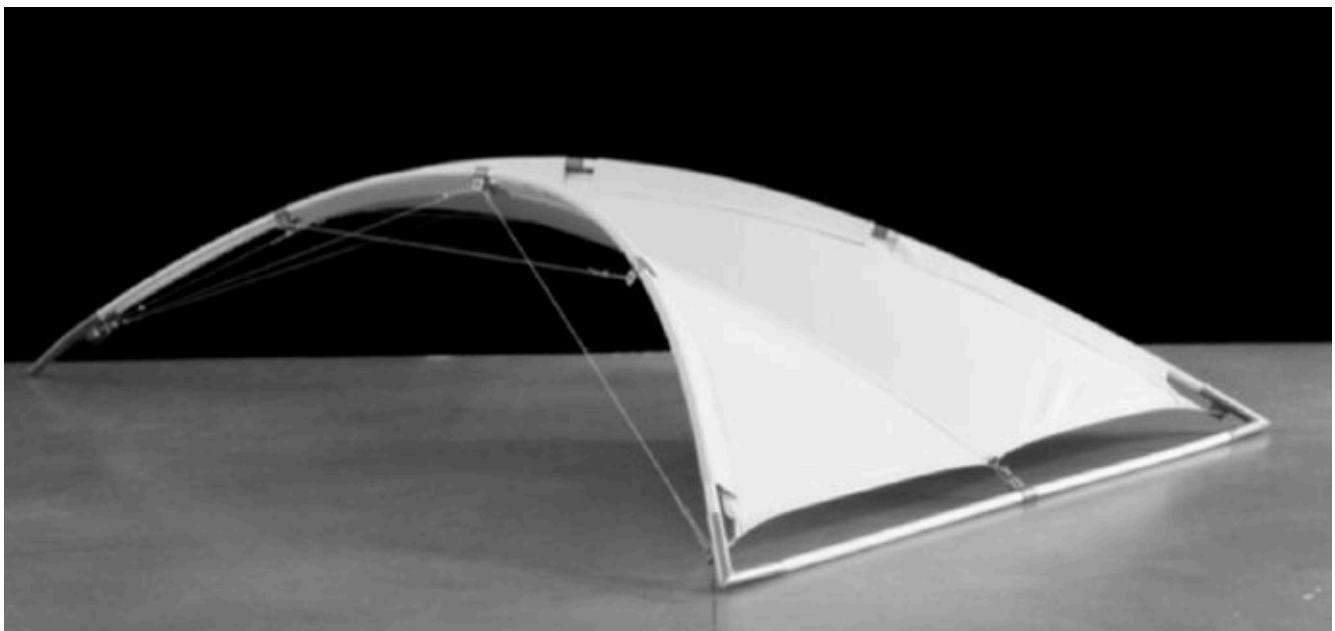
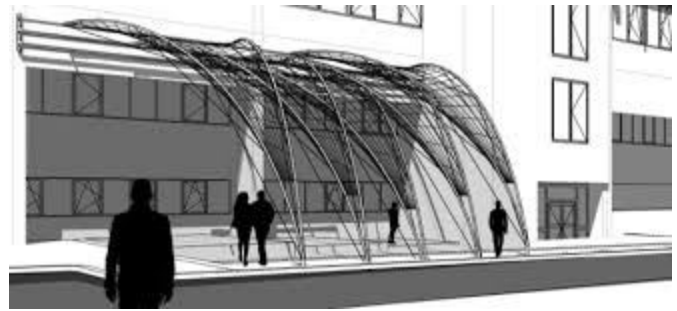
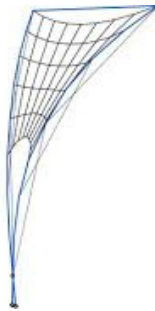
Phriends for shells is a project utilizing 6-axis robotic arms to help create buildings from tensile structures. A tensile structure is first created and left in its natural form. This is then digitally scanned to create a digital replication of the structure. A 6-axis robot then sprays several layers of clay over the top using the digital model as a reference. This clay hardens and forms a solid building. They believe this technique can be scaled up to create larger scaled structures.

This initial tensile structure may be replicated with our current system. Digital scanning after or throughout the building process would vastly increase accuracy of matching up digital and physical 3D points.



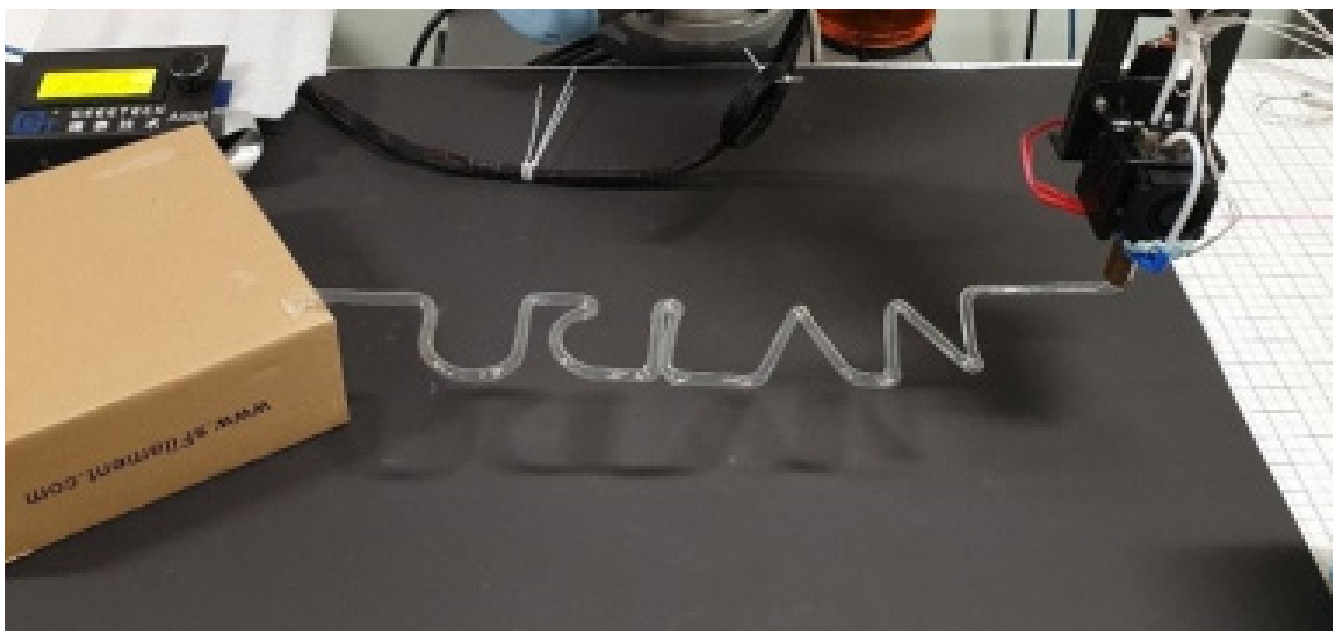
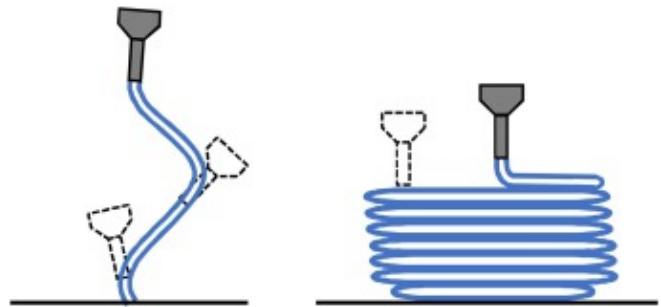
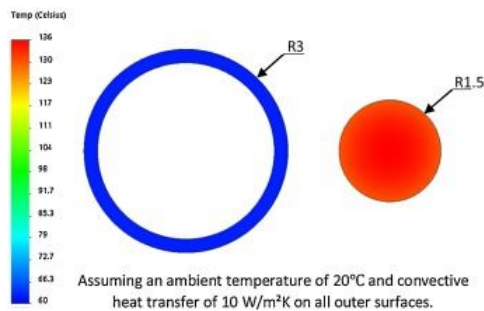
A canopy formed by several, modular, tensioned membrane structures was designed in this case study. Each membrane structure has a triangular shape and consists of elastically bent composite edges. The canopy is designed to be an entranceway for an existing building, it provides shelter, a shed for bikes and a smokers area. The impact of the structure on the existing building had to be kept to a minimum, hence designing a lightweight, self-supported structure.

This study provides an example of an experimental tensile structure and a possible application for the current technique.



Researches have created a custom 3D printing nozzle that extrudes hollow filament. Compared to solid extrusion, far less material is used and cooling properties are vastly improved due to the filaments increased surface area. Slight pressurization of the tube allows extrusion at an angle more than 90° and a distance of 400mm without sag. As well as free-form printing, traditional 3D printing slicing software can also be used to print layer by layer.

Advancing the cool-down rate of spatial printing is a vital step in advancing the field. The rate at which filament can harden restricts the rate at which a structure can be built. This is the major advantage of our current technique, and hollow filament could be used to reduce cool-down rate even more.



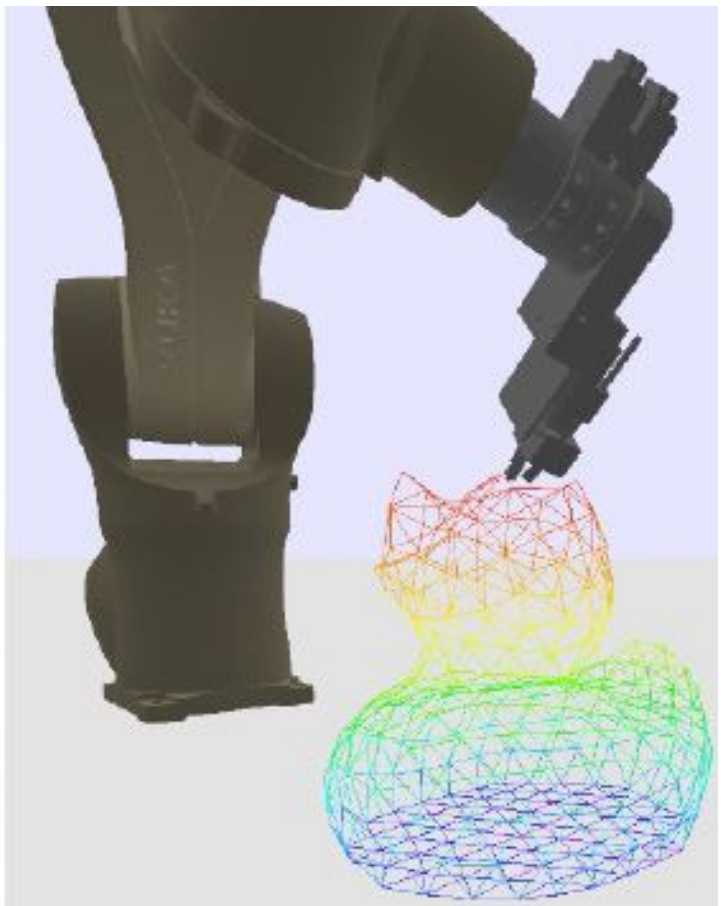
Massachusetts Institute of Technology

SCALABLE AND PROBABILISTICALLY COMPLETE PLANNING FOR ROBOTIC SPATIAL EXTRUSION
2020

Researchers have created a new concept for robotic spatial extrusion, accompanied by a complete planning algorithms.

Existing spatial printing algorithms require a substantial amount of human input and errors often occur when scaled. The two main challenges of spatial printing is satisfying stiffness constraints that limit deformation and geometric constraints that ensure the robot does not collide with the structure. This papers algorithm is able to successfully balance both constraints and produce a superior way of spatial printing.

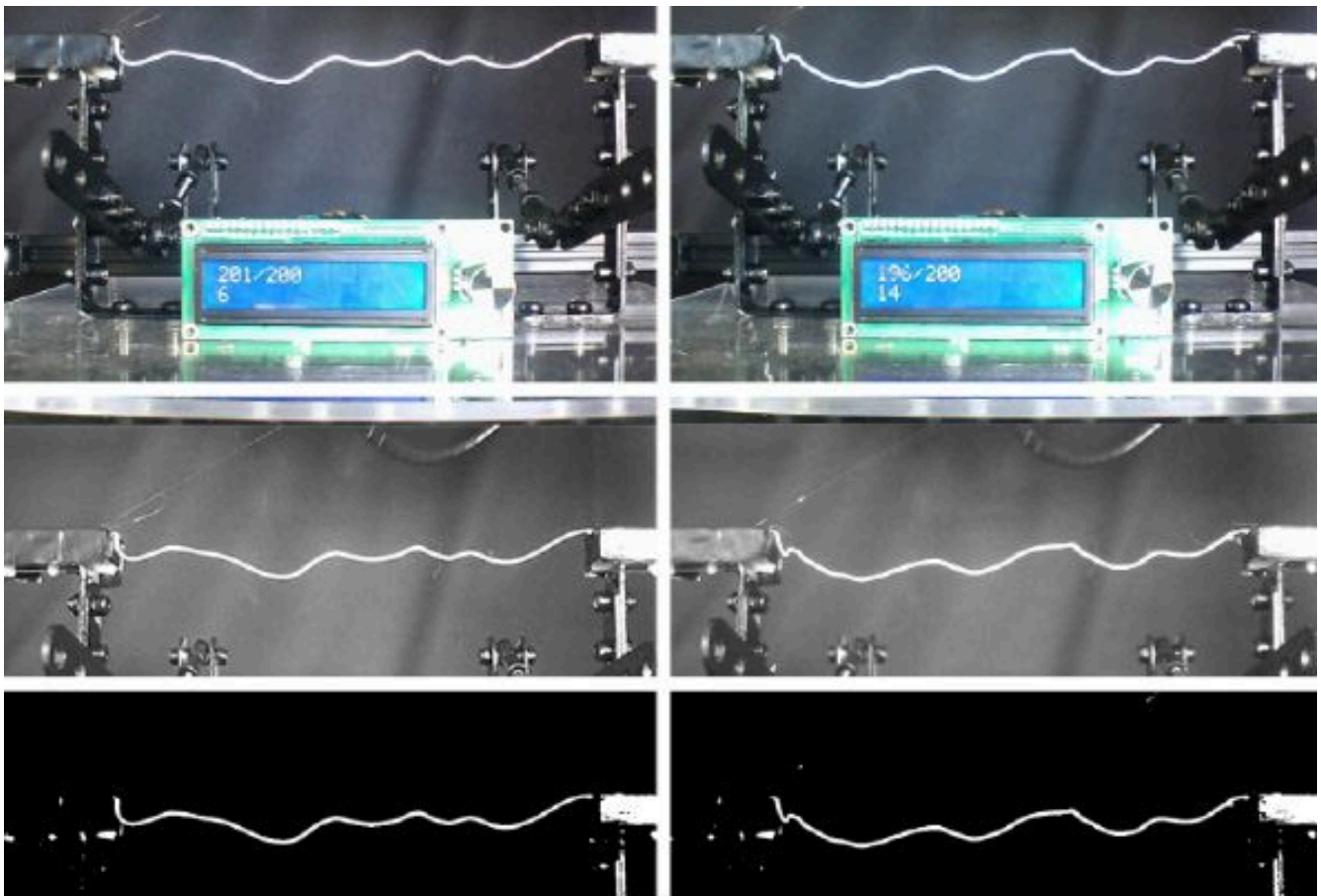
Geometric constraints regarding robotic collisions and singularities are a huge limitation on the possible geometric outputs. Any advancements in these type of algorithms will help accelerate spatial printing technology.



This paper presents a set of experiments researching a new 3D printing method. It investigates the dynamic control of thermoplastics utilizing mechanical automation, computer vision and artificial intelligence.

Researchers conducted experiments with PLA free-form printing and altered the nozzle temp and atmospheric conditions. Over time, AI then learned to produce a curve matching that of the extruded free-form print.

AI can not be utilized in our experiments, however, we may have issues with filament memory and it was an interesting experiment to see that AI may be able to predict the filaments path given the coil memory data.



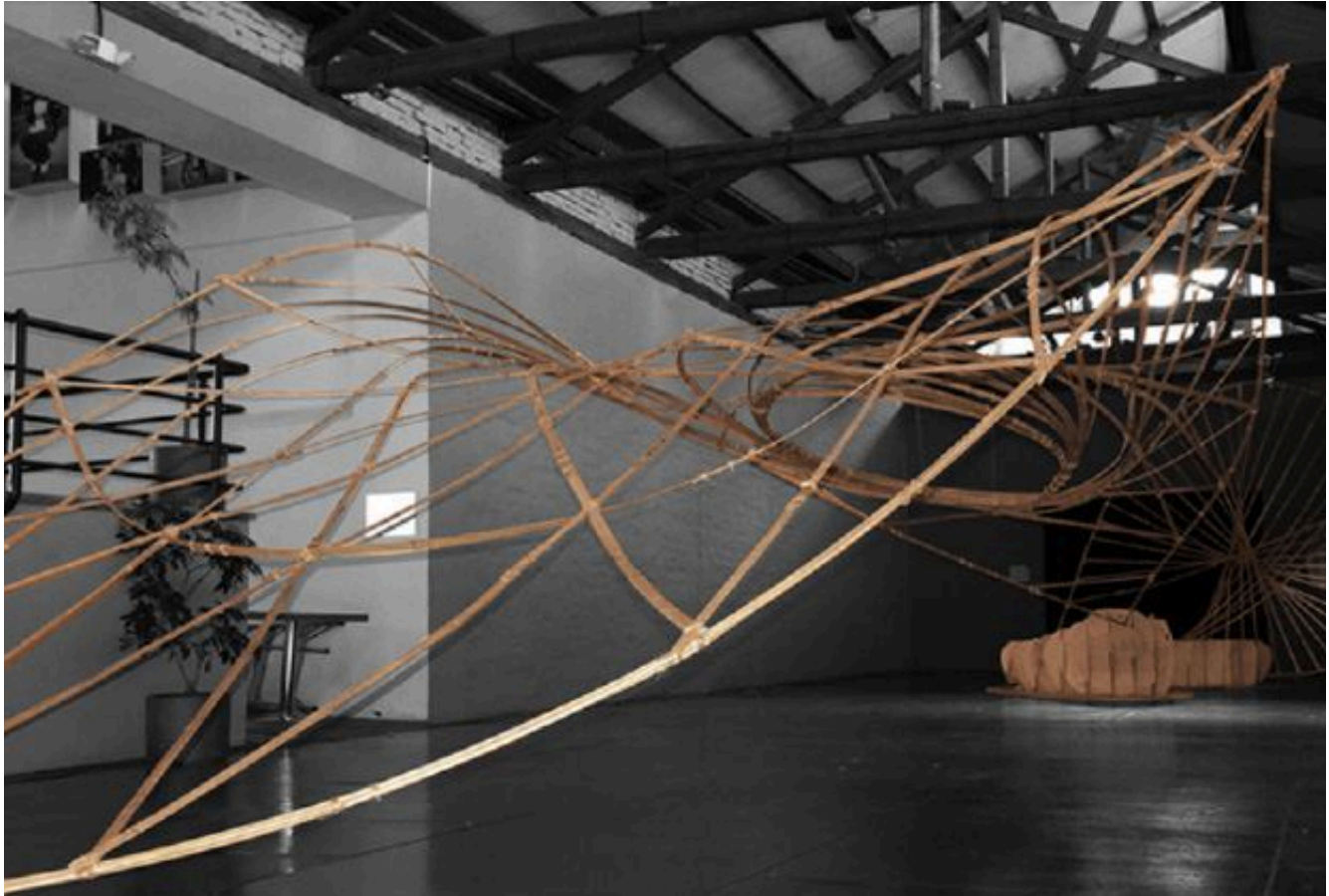
University of Stuttgart

COMPUTATIONAL BAMBOO
2018

Rapid advances in simulation technology and composite materials have allowed innovative advances in active bending structures. This computational bamboo installation was a result of in-house real-time physical-based modeling software called ElasticSpace that was combined with Grasshopper to gradually refine the geometry and topological arrangement of the structure.

ElasticSpace was developed as a specialized form-finding application for the design of bending-active and textile hybrid systems based on the continuous manipulation of topological spaces during numerical integration (Suzuki and Knippers 2017).

This study digitally considers material form and elasticity and creates a geometry centered around that. The form is then altered by adding extra support and then recalculated. This project is a reflection of advancements in tensile structures using natural composite materials.



University of Stuttgart

ICD / ITKE RESEARCH PAVILLION
2014-15

This pavilion was created using bio-mimicry strategies. Researchers investigated how the diving bell water spider created its underwater web. The structures fabrication process involved the robot placed in an inflated ETFE bubble, mimicking that of the spiders. Fiber layers were generated sequentially, allowing the generative model to incorporate production feedback. Each line in the program represented an approximate tool-path that was modified during the fabrication process based on sensor data. This was done to account for the pneumatic base surface.

This process shows how external surfaces can be utilized as guides or support of filament placement. With our uncoiling method movement in the perpendicular plane may be seen due to filament memory, a support quill would reduce this.



Section Two

Bonding Techniques with PLA Filament



Experimental Plan

Experiment One

Manual tests will be reproduced to verify previous findings. Variables such as plasma torch placement, distance and duration will be changed as well as testing various combinations of filament memory and manual pressing techniques. Using 2.75mm PLA filament.

A test jig was created to aid the experiment. Two sections of structural filament were clamped securely in place, laid filament was then placed on-top of the structural filament at a 90° angle. The plasma torch was aimed at the filament intersection at a constant 45° vertical and horizontal angle to the filament. The test involving multiple directions of heat was not reproduced as this would be extremely hard to replicate using the ABB IRB 1200 Robotic Arm. Refining the bond with one direction is a far more viable option.

The filaments memory was adjusted using a heat gun.

These tests are to certify previous results and ensure the correct technique is used moving forward.

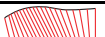
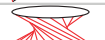
Experiment Two

These tests involved using the ABB IRB 1200 Robotic Arm. The end-effector was attached and a custom plasma torch holder was designed to secure onto the end of the end-effector. A new quadrant brass nozzle was used to aid the filaments uncoiling and guide it in the desired direction. A 'foot' was added onto the nozzle to test if the nozzle could be used to press and spread the filament for a stronger bond.

Filament memory was taken out of the structural filament.

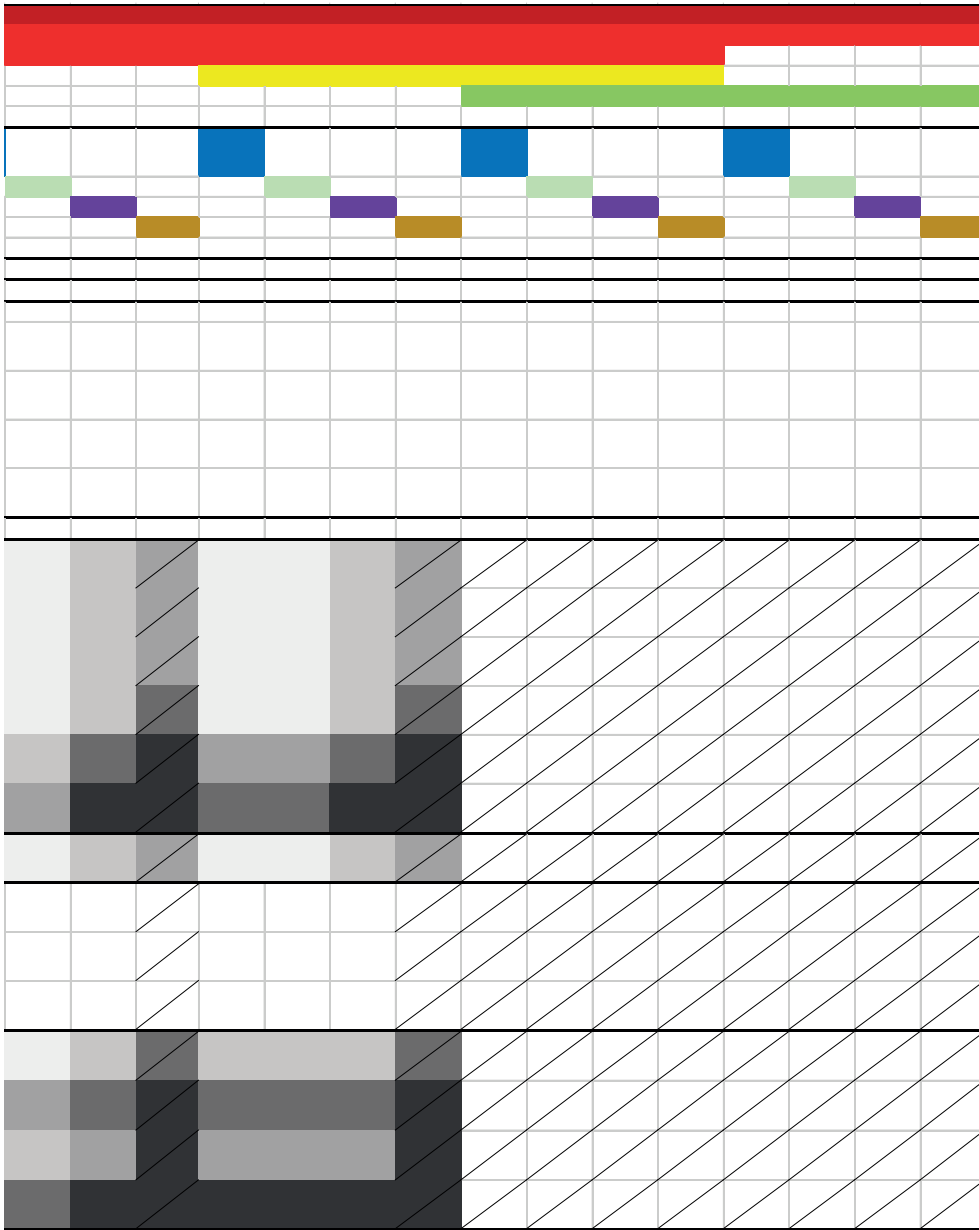
Filament memory was present in the laid filament.

The variables altered in these tests were pressing angles, TCP height, press height, angle of press and angle of attack. A new test jig was made to be able to effectively test the bond without object collisions. All plasma torch operation was manually controlled.

Joining Tech	Plasma	Bending	Powered extrusion	Powered extrusion + 3D movement around Fil	Plasma torch moving + 3D movement around Fil	Axial bending
Compression Tech	Pressing with end-effector (Forward/backward)					
	Pressing with end-effector (Sideways)					
	Pressing with end-effector (Rotation)					
	Pinching					
	Tipping					
Spreader/Foot design	Powered Uncoiling					
Coil Memory	No Change					
	Intermittent heated extruder					
	Heated extruder					
	Heated spool					
	Material choice - Flexible					
Plasma Heat	On/Off					
Basic Geometry On Rim						
						
						
						
						
						
						
						
	Parallel Join					
	Cutting					
	Wrapping					
Structural Examples						
						
						
						

Design Output	Design Notes
Chair (Pre-built Frame)	Previously Tested - Adding too much filament causes clumps and an unattractive bond Limited space around joint restricts arm This strategy requires 2 robot arms
Sunshade	
Hammock	
	This joining technique has limited structural applications due to lack of joins/bonds
	Requires modified end-effector. Increased difficulty in creating precise arm movements
	Requires more room around joint
	Requires a secondary mechanism to attach to the uncoiler - currently out of scope
	Requires modified end-effector. Increased difficulty in creating precise arm movements

1. Explore the pressing method with the simplest geometry and frame support.
2. Explore the pressing method without frame support.
3. Experiment in basic form/ruled surface forms. Test consistency and various angles.
4. With the new plasme torch attatchment, controlled air bending may be possible to explore.



Requires more room around join

Requires a secondary mechanism to attach to the uncroller - currently out of scope

Requires modified end-effector. Increased difficulty in creating precise arm movements. Requires more room around join at various angles

Requires a secondary mechanism to attach to the uncroller - currently out of scope

This strategy requires 2 robot arms

Possible design output - Chair (Pre-built Frame)
Sunshade
Hammok

Chart of Possibilities/Plan

Test Jig 1.0

This test jig was designed for early robotic tests and recreating previous manual tests.

It was built with three 3D printed parts and two nuts/bolts. The base section secures to the table with double sided tape, the two other sections clamp onto the base with M5 bolts to secure the filament in between. This provides an efficient and accurate way of testing.

A block of MDF was slid underneath the filament to stop the jig from melting/warping from the plasma torch heat (this did not touch the filament or alter any results).

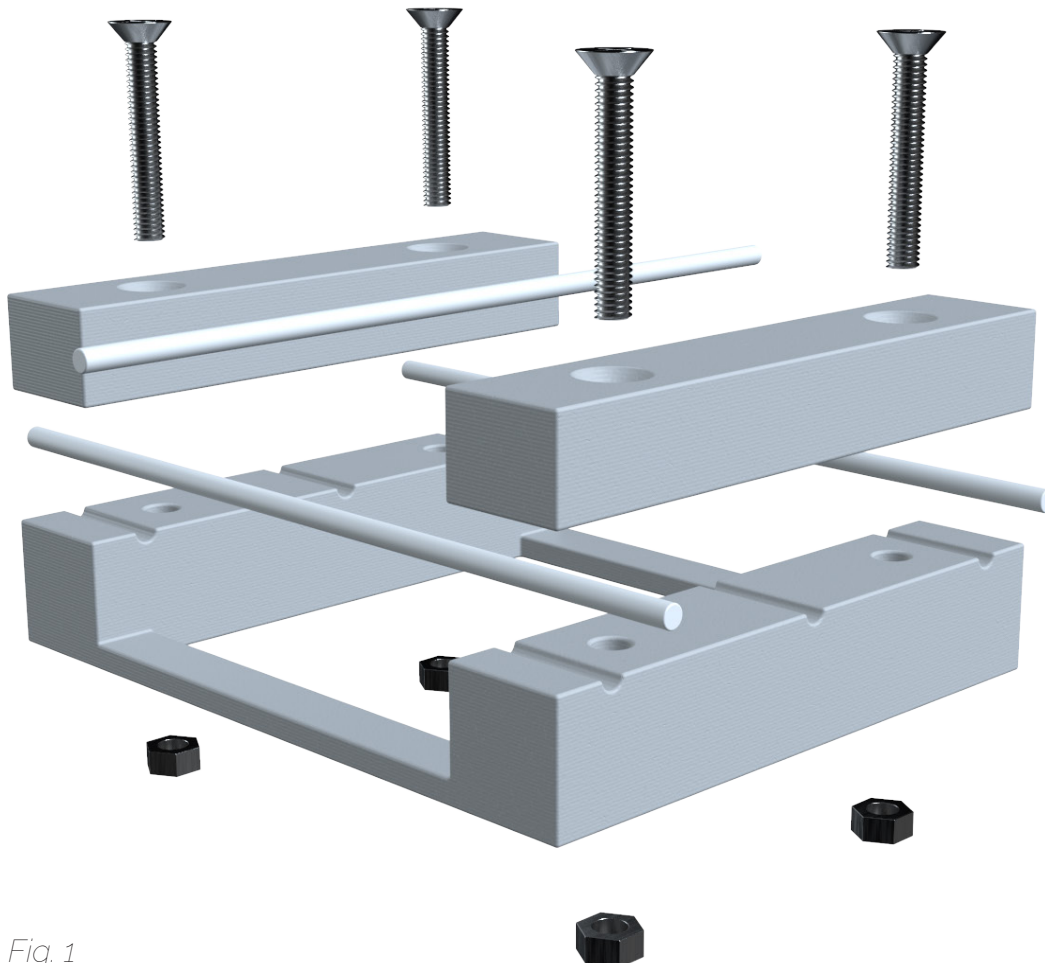
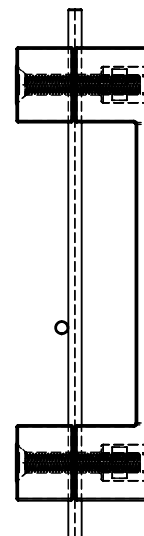
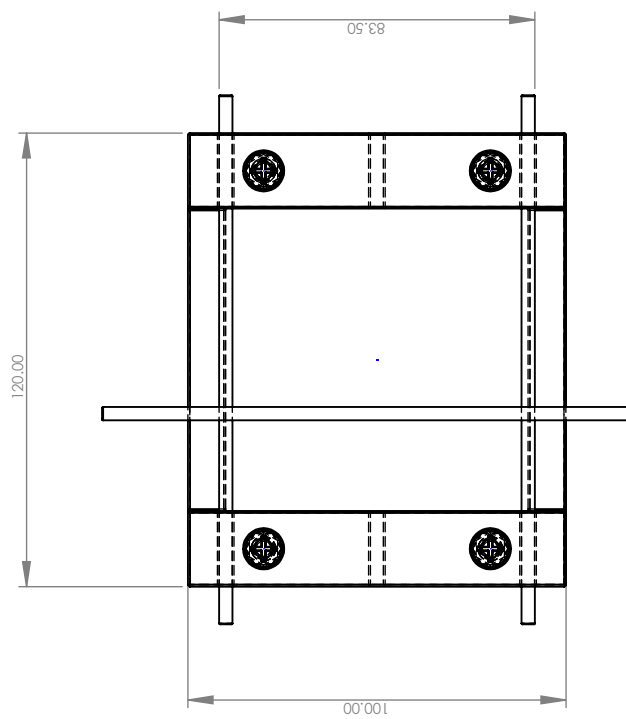
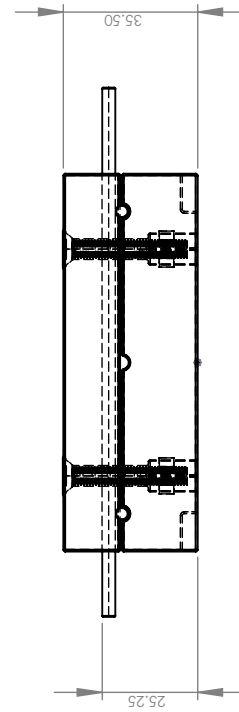
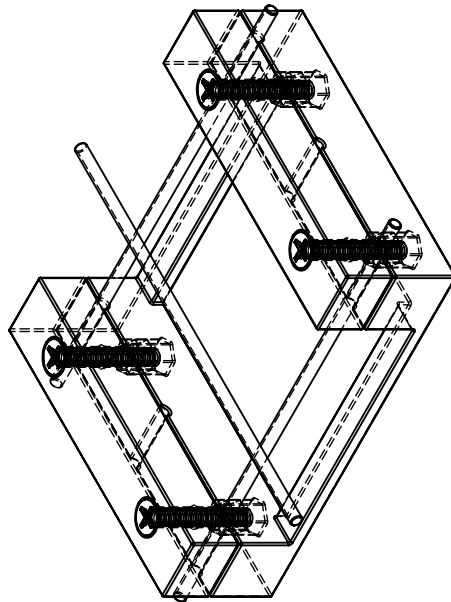


Fig. 1



Experiment One

Air flow from the plasma torch caused the laid filament to roll out of position. Wooden blocks were positioned either side of the filament to secure it.

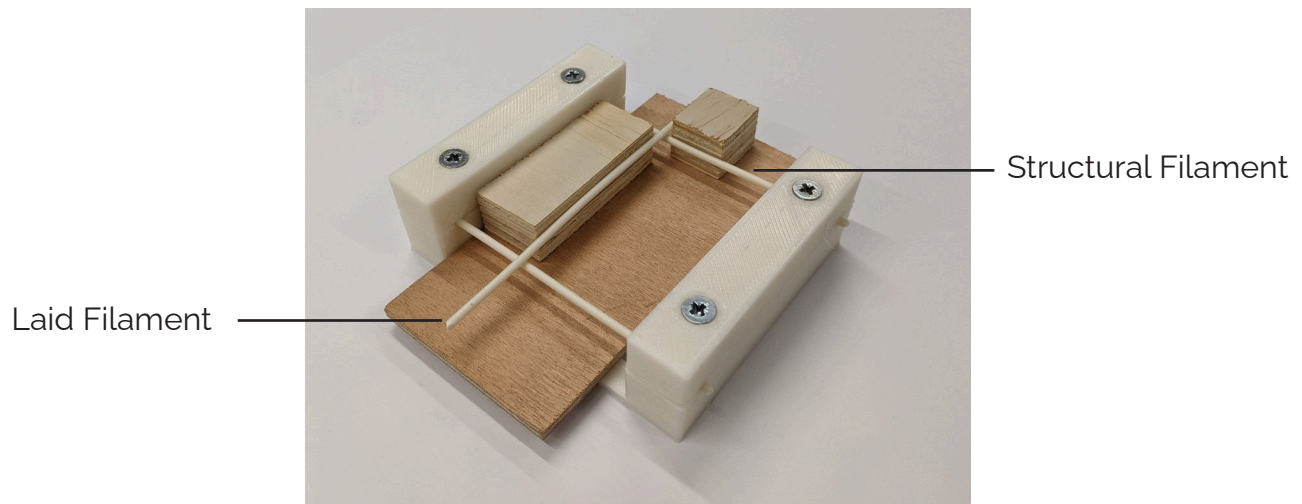


Fig. 2

(3) Structural strands with filament memory

Distance: 20mm - Duration: 10s - No Press

Bond 1: Because of filament memory in the structural strand, the filament would flex back into its original shape immediately after heat was applied. This resulted in the laid filament moving away from the bond location and the structural filament deforming before melting enough to bond.

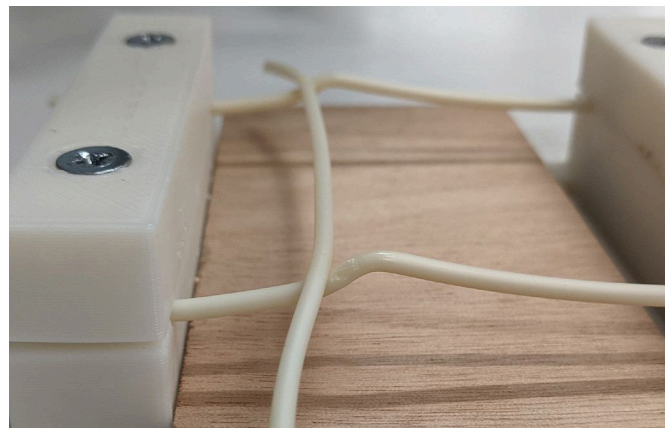


Fig. 3

(4) Structural strands without filament memory

Distance: 15mm - Duration: 10s - No Press

Bond 1: Filament was observed turning brown and becoming crispy. Either it was heated for too long or torch was too close to filament.

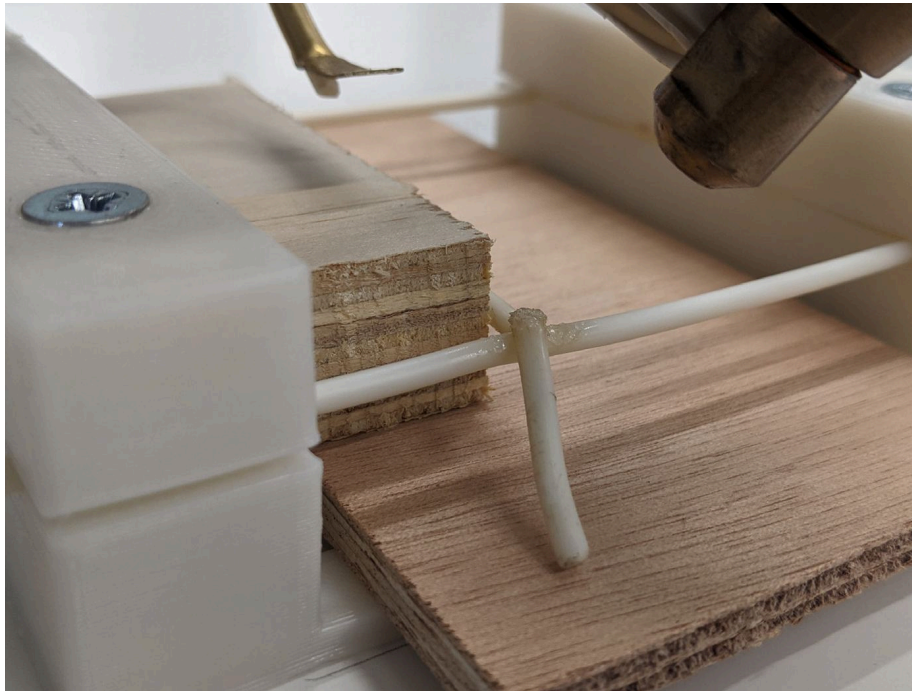


Fig. 4

(5) Structural strands without filament memory

Distance: 15mm - Duration :10s - Manual Press

Bond 1: Observed a bond with a far greater surface area. Slight bubbling present on filament.

(7) Structural strands without filament memory

Distance: 20mm - Duration 15s - Manual Press

Bond 1: Filament started to move away from bond location as it melted (may be due to air flow of plasma torch) and drooped on far side of bond. Manual press wasn't as effective because filament moved away from original position.

Bond 2: Because the filament was secured at bond 1, a more successful bond was produced.

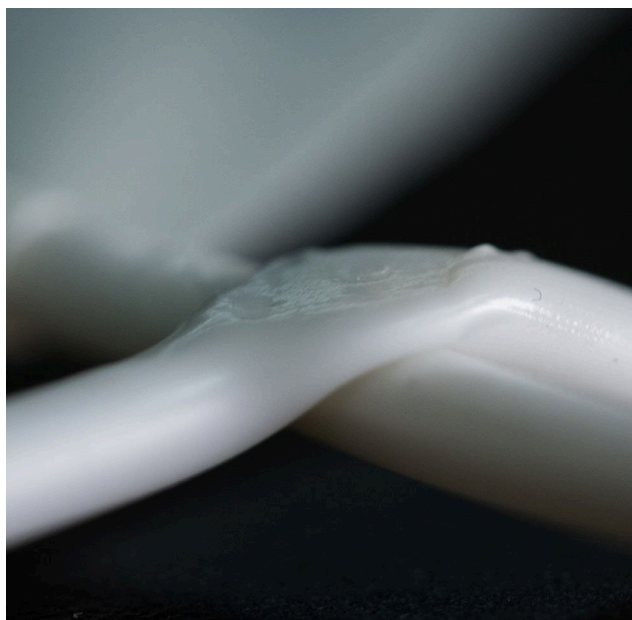


Fig. 5

5



Fig. 6

6



Fig. 7

7



Fig. 8

7

Findings

Manual test results confirmed that a plasma torch distance of 20mm for 10 seconds was around the optimum output for a reasonable bond to occur using 2.75mm PLA filament.

All structural filament used had to be straightened with a heat gun prior to testing. If it were left with its original memory the filament would move away from the bond location, move the laid filaments position and no bond would be created. The large deformation of the structural filament with memory reduces the likelihood of being able to successfully bond to a structure in tension using PLA (Fig. 3).

When the torch was positioned 15mm away from the filament it began to burn and no melting was observed (Fig. 4). This distance is too close for the torch and won't allow the filament enough time to melt for a successful bond.

Manual pressing successfully increased the bonds surface area and would likely result in a stronger bond (Fig. 5).

The second bond was often more successful because the filament was more secure due to the first bond. Reducing the filament movement is important to create strong bonds.

Accuracy of the plasma torch is very important as heat intensity varies greatly outside of the focal point, this variable is hard to control and often inconsistent.

Plasma Torch Holder 1.0

This torch holder was designed to attach onto the end-effector without any modifications. It has three areas for adjustment that allow accurate positioning of the torch. This plasma torch holder is vital in producing accurate, easily adjustable and consistent test results.

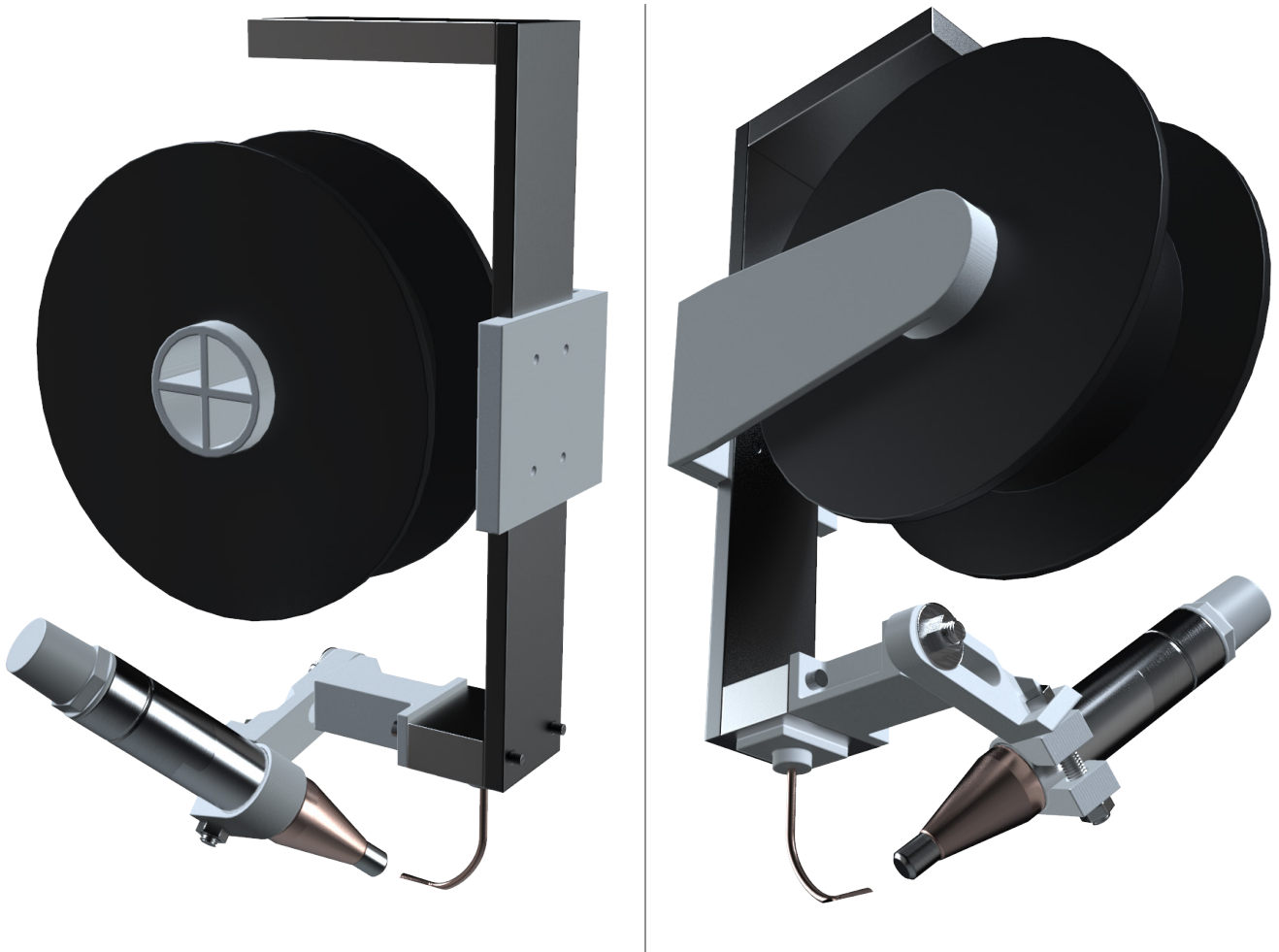
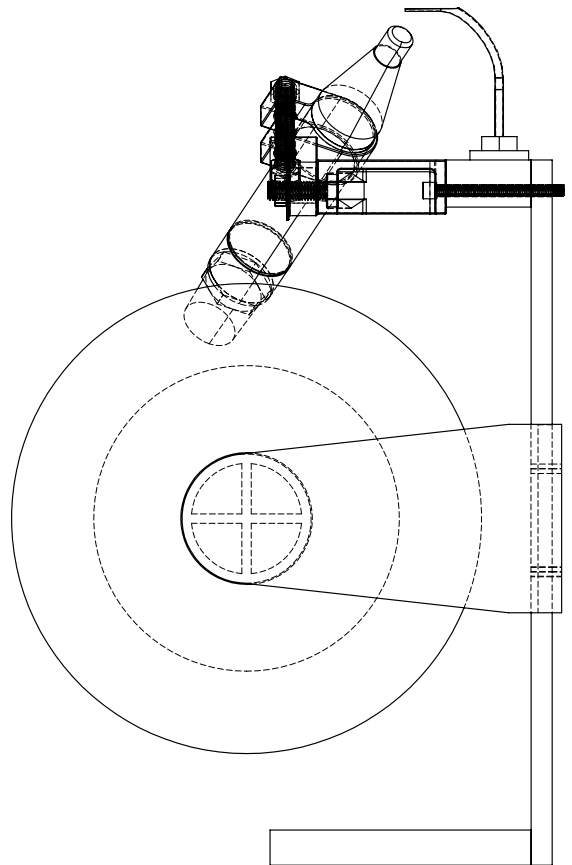
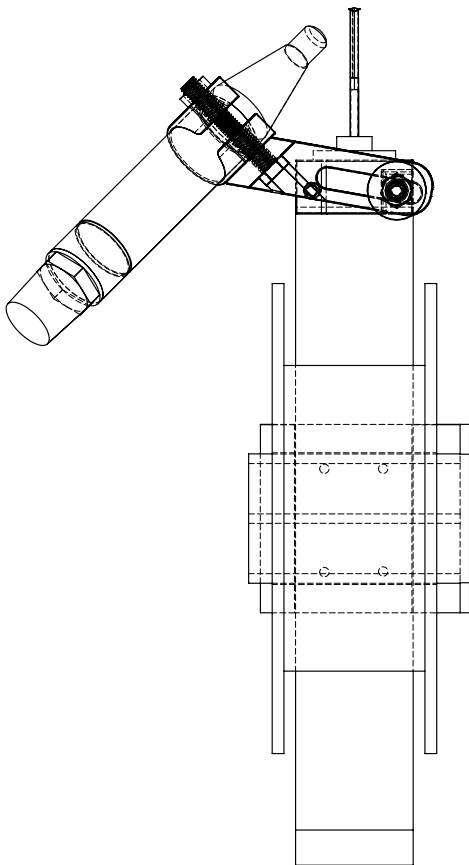
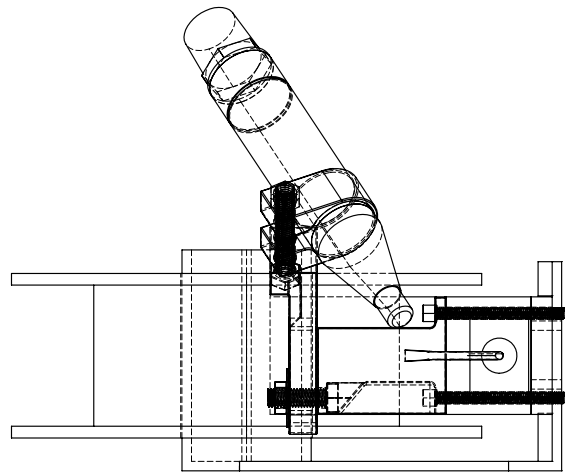
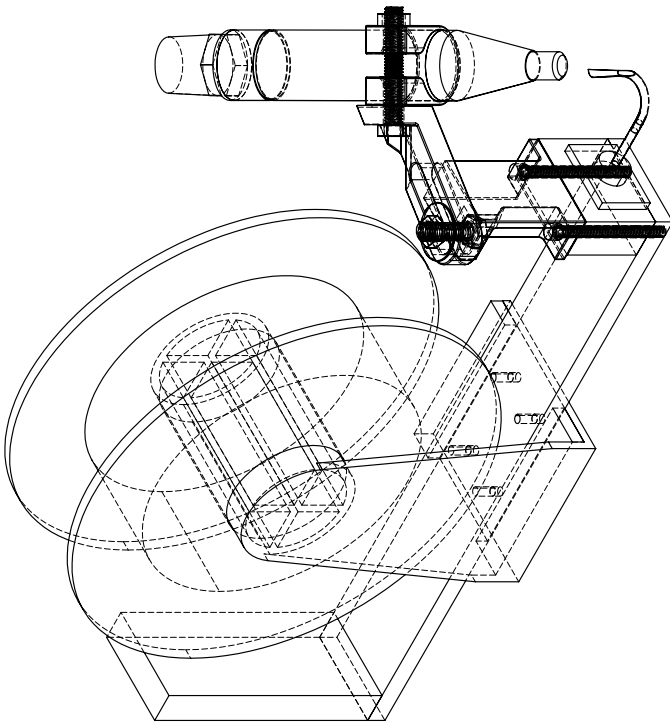
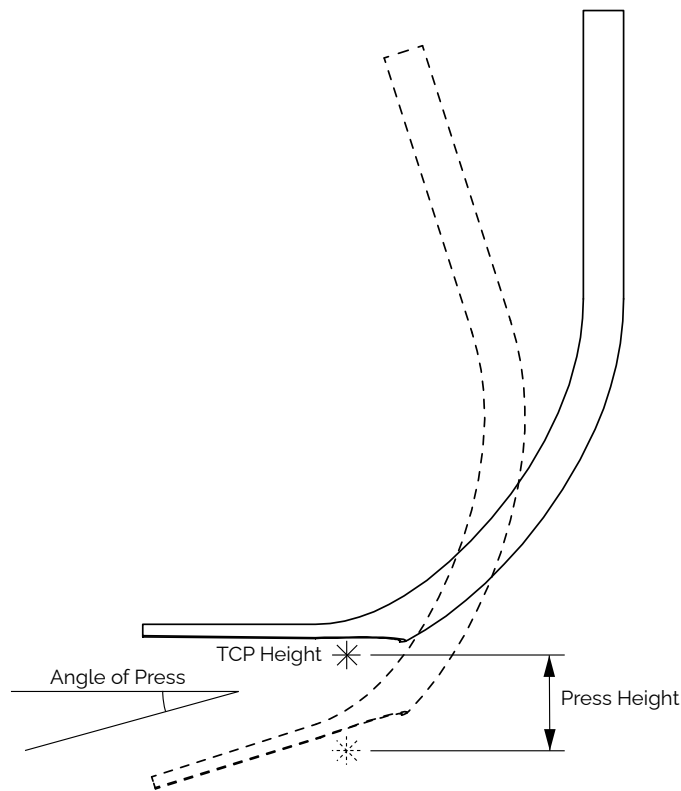


Fig. 9



Experiment Two (a)



Nozzle 1

TCP: 28.992, 25.699, 444.459

Fig. 10

A tipping/pressing technique was used to try and strengthen each bond. As shown in previous tests, increasing the surface area of the bond by pressing or squeezing greatly increases its tensile strength.

Tipping/pressing is the easiest method to produce without any additional equipment. An elongated nozzle is used as the pressing 'foot'.

Other techniques such as pinching require additional hardware such as clamps, this would also involve timing the pinch at every bond with an Arduino. Techniques such as these may produce better results but they may also restrict robotic movement and slow production. This simple tipping method will be tested first.

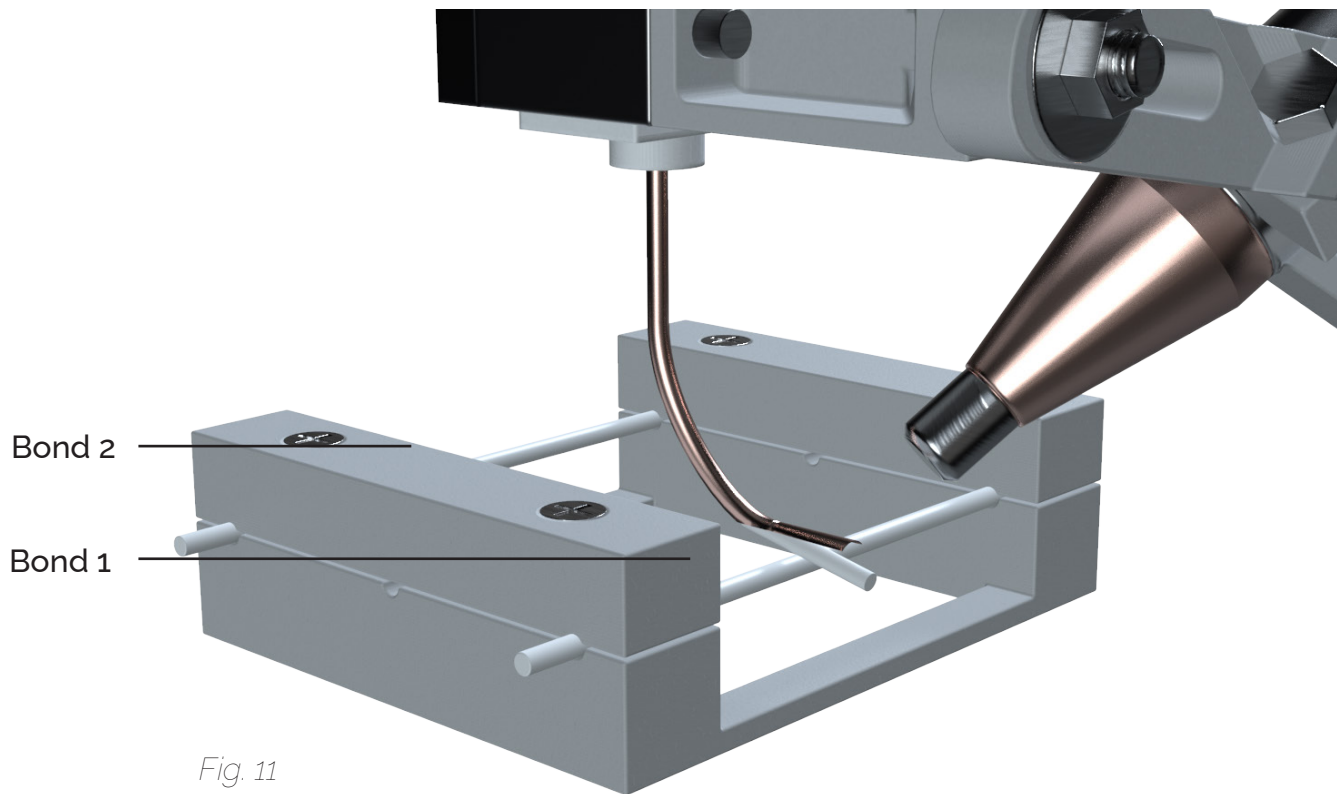


Fig. 11

(13) Distance: 20mm - Duration: 10s - TCP: 10 - Press Height: 8 - Press Angle: 0

Bond 1: Filament memory of laid strand curving up in Z axis. This did not greatly effect the results because of the downward press in the Z axis applied soon after heating. Need to aim torch lower because of curving.

(14) Distance: 20mm - Duration: 10s - TCP: 10 - Press Height: 13 - Press Angle: 0

Cooldown at press bottom: 10

Bond 1: Because of coil memory, when filament is allowed to cool at press max it creates a bend/kink in the bond.



Fig. 12

14

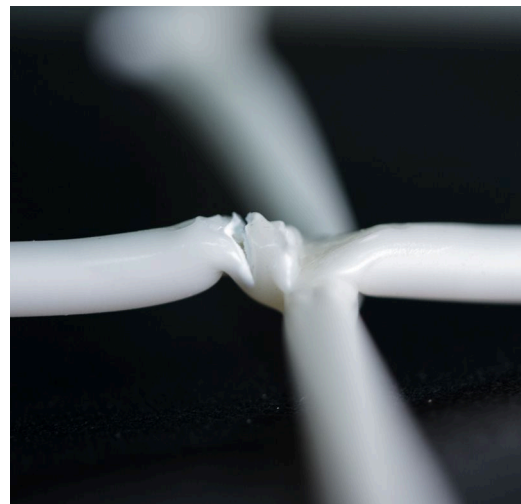


Fig. 13

15

(15) Distance: 20mm - Duration: 10s - TCP: 10 - Press Height: 8 - Press Angle: 0
Cooldown at press top: 10

Bond 1: No Bond. Filament started to move away because of torch air pressure.

Bond 2: Bond. Because of manual robot movement after join, the filament tore slightly. Slight kink after bond.

(18) Distance: 20mm - Duration: 10s - TCP: 8 - Press Height: 11 - Press Angle: -3
Cooldown at press bottom: 10

Bond 1: Bond. Bubbling of laid filament. Because of cool-down at max press, filament hardened with a kink. This will result in a weak point.

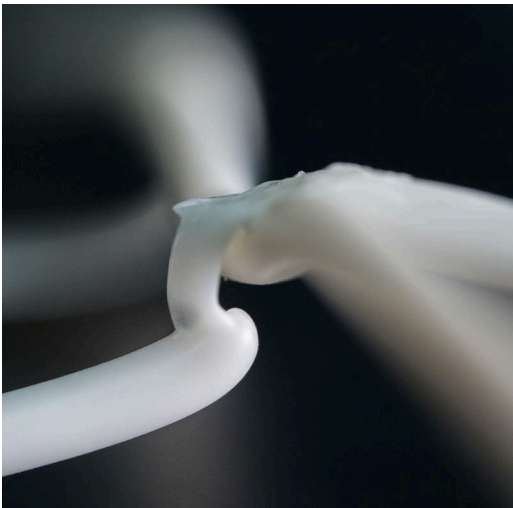


Fig. 14

18



Fig. 15

18

(20) Distance: 20mm - Duration: 10s - TCP: 8 - Press Height: 11 - Press Angle: -3
Cooldown at press bottom: 10

Bond 1: Bond. Slight droop at back on bond.

Bond 2: No Bond. Filament memory in Z axis is stopping torch from hitting laid filament. Filament bounces up after failed bond, this will be caused by pressure on both bonds.

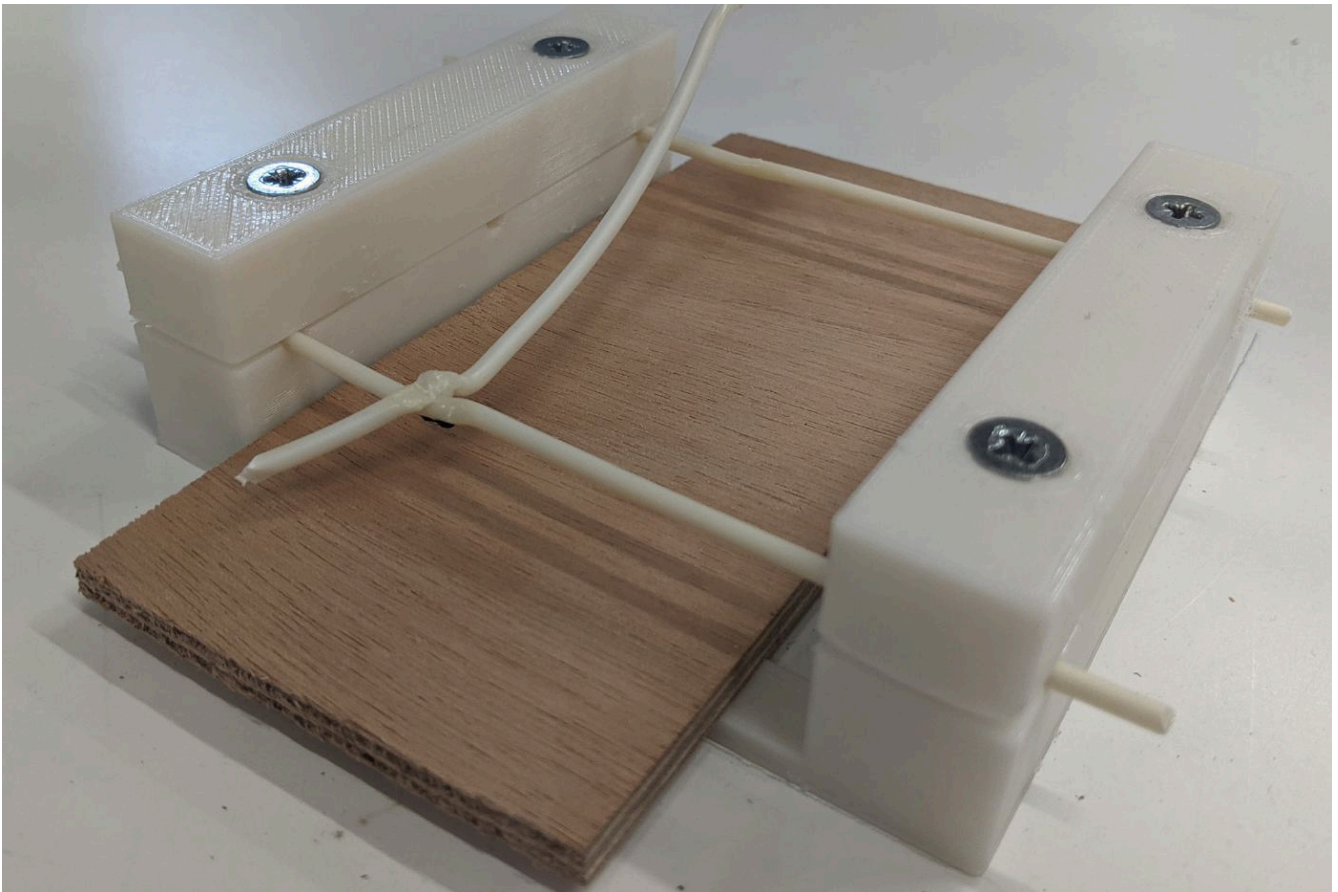


Fig. 16



Fig. 17 - Nozzle 2

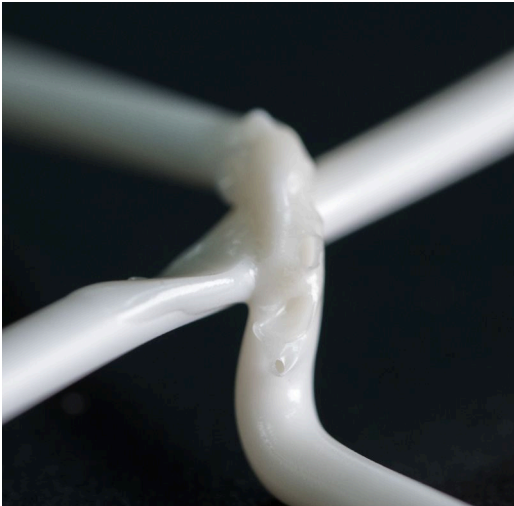


Fig. 18

9



Fig. 19

9

Findings

When heated with the plasma torch, laid filament will rise up in the Z axis (because of filament memory). This filament movement is an issue because it will move the filament out of the plasma torches focal point, resulting in inconsistent heating results (Fig. 16,17). This issue may be reduced/resolved because as the laid filament rises in the Z-axis it hits the nozzle foot, the foot could be used to restrict movement however further tests and refinement will need to be done to prove this.

After heat is applied and the bond is pressed, letting the filament cooldown in the pressed position creates a kink after the bond. This is due to the stiffness of material and angle the laid filament is uncoiled from. This kink creates a weak point in the bond. Cooldown at original TPU position will reduce this issue, however, because of the press distance the filament will always be stretched and thinned/weakened (Fig. 14,15).

If a previous bond was made that held the laid filament in place, because of the air pressure created by the torch and the perpendicular angle it is directed at the filament, unsecured filament will be pushed out of the way when heated to its glass temperature (Fig. 18,19).

Filament friction in the end-effector and fast robotic movement can cause stress in the structure and tear/break the bonds (Fig. 13). Friction in the uncoiler needs reducing to prevent this, or simultaneous powered extrusion synced to robotic movement.

In these tests, tipping seemed redundant due to filament stiffness. Because of the filaments stiffness and the foot location, the distance between the foot and the bond is too large.

Plasma torch precision continued to be an issue and even filament heating was hard to control.

Robotic pressing seems like a viable option.

Test Jig 2.0

This test jig was designed for robotic testing with minimal collision interference.

The main body of the jig is made with four removable/replaceable sections. These sections are designed to fasten multiple strands of filament across to give a large number of possible bonding options. Creating a multitude of options is important to reduce chances of robotic movement errors.

Four blocks of wood were secured to the table separate from the jig. This meant the jig could easily be removed and reset without recalibration.

To secure the filament in later tests two blocks were wedged underneath the filament. The filament was then hot glued to the wood.

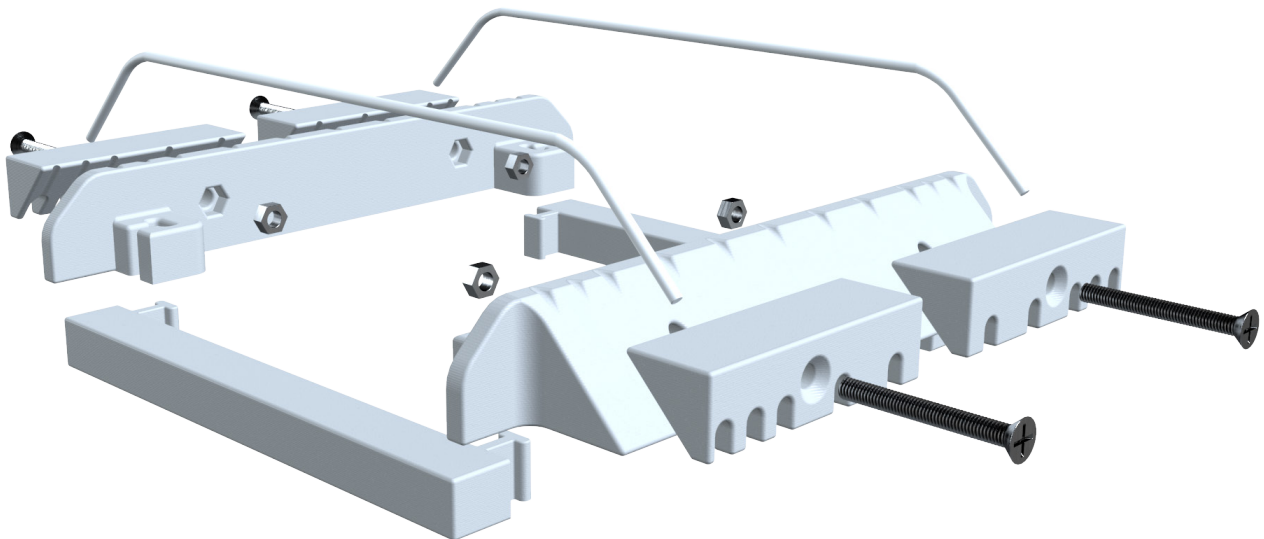
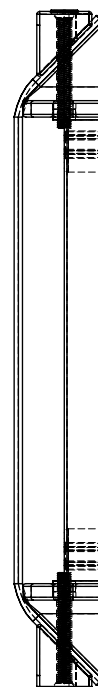
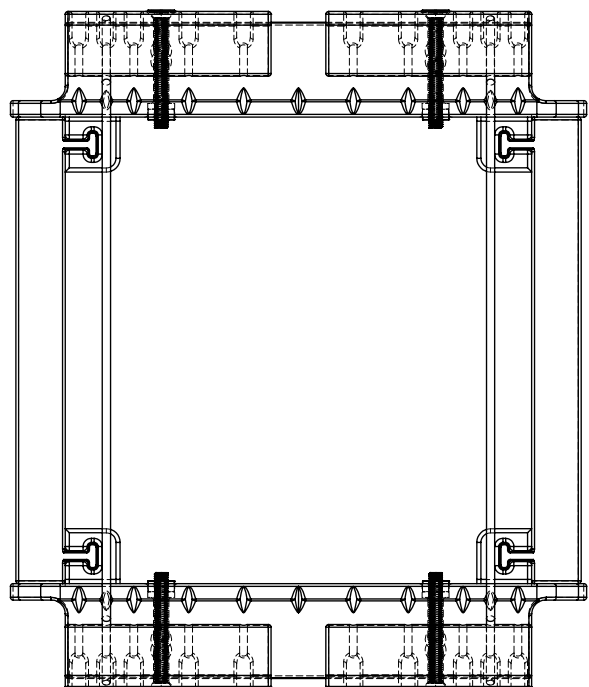
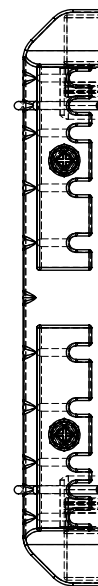
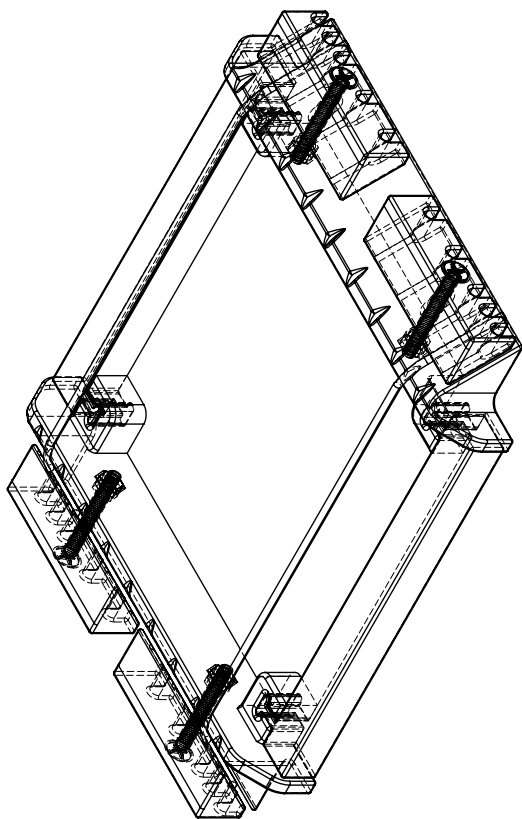


Fig. 20



Experiment Two (b)

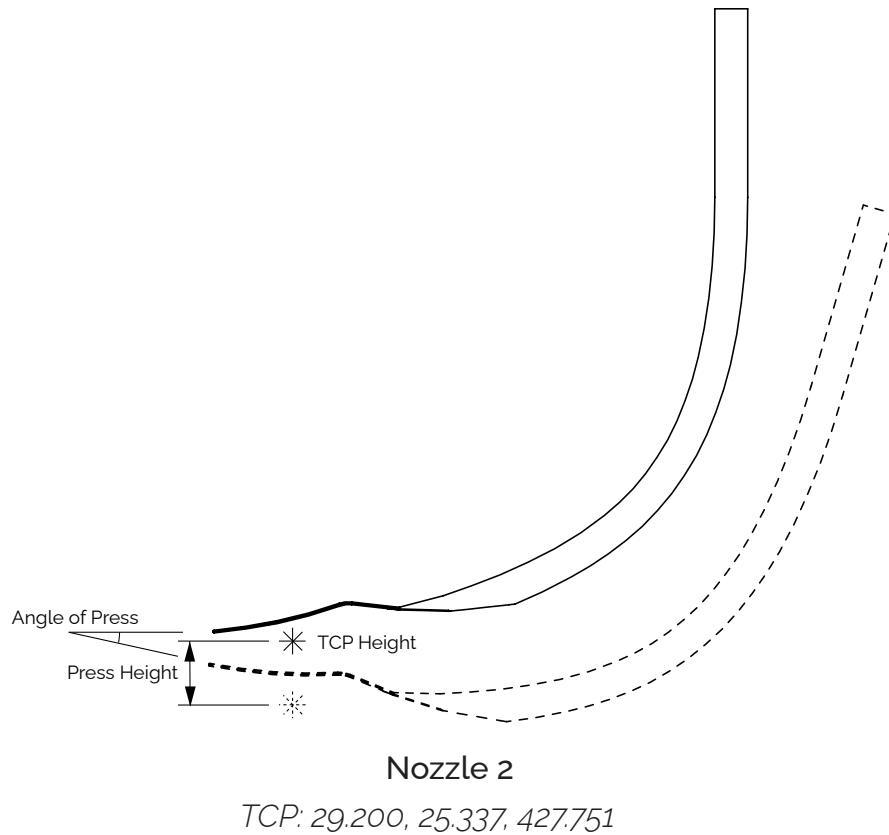


Fig. 21

This nozzle was created to allow a press with smaller robotic movements. The foot is angled downwards parallel to the laid filament. The distance from foot to filament will need to be adjusted to make sure they don't stick together when heated.

The nozzle is designed to be tipped the opposite way. This is to create less strain on the secondary bond as shown in Fig. 16 and reduce the amount it rises up in the Z-axis due to filament memory. Tipping this way will also reduce filament kinking after the bond like in Fig. 22.

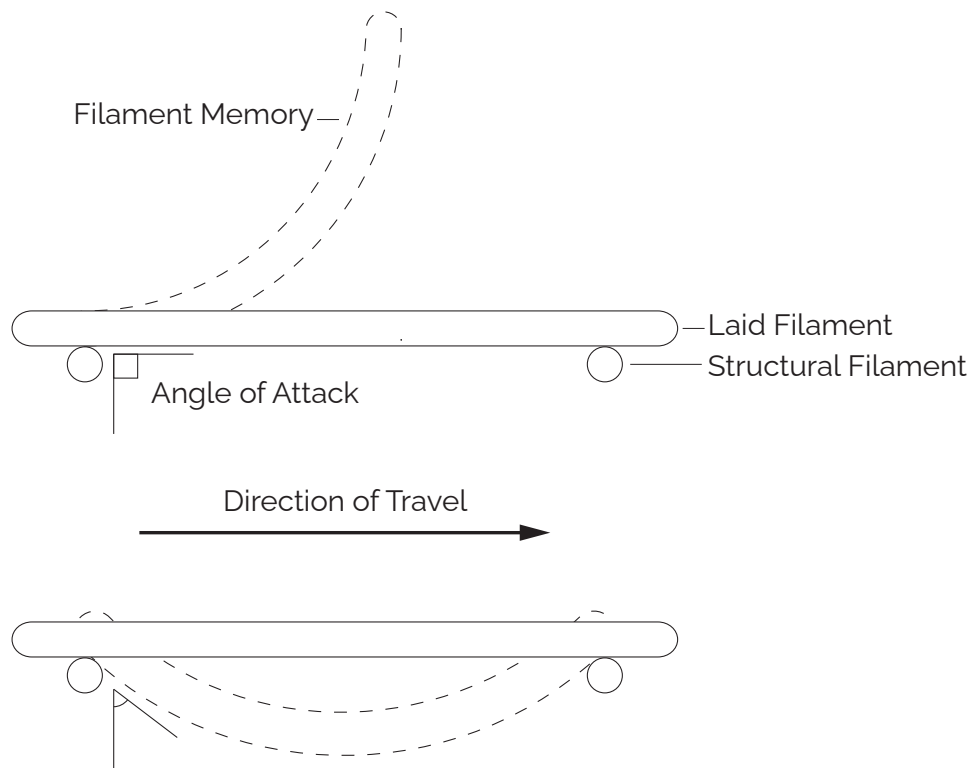


Fig. 22

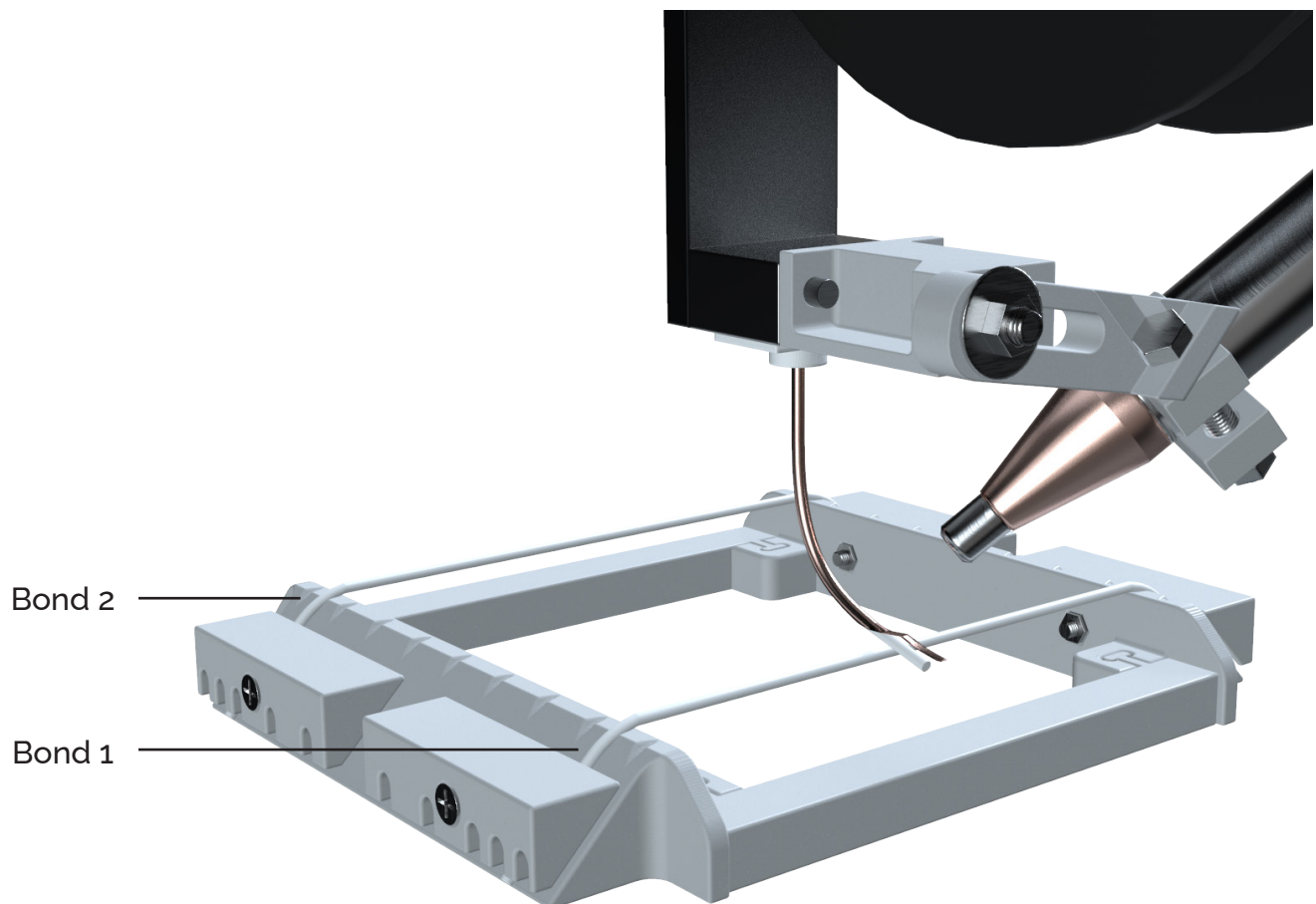


Fig. 23

(21) Distance: 20mm - Duration: 15s - TCP: -5 - Press Height: 4 - Press Angle: 12

Cooldown at press bottom: 10

Bond 1: No Bond. Melted filament was pushed up towards the foot and stuck to the foot. Foot may be too close to filament - tried to raise foot up slightly.

(23) Distance: 20mm - Duration: 15s - TCP: -2.5 - Press Height: 6 - Press Angle: 12

Cooldown at press top: 10

Bond 1: Bond. Laid filament moved away from structural filament slightly because of air pressure. Good result. Less of a kink/weak point at the far side of bond because of angle of press.



Fig. 24

23

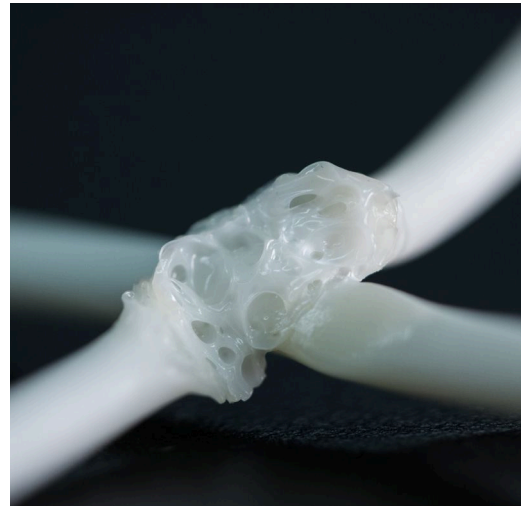


Fig. 25

24

(25) Distance: 20mm - Duration: 15s - TCP: -2.5 - Press Height: 6 - Press Angle: 12

Cooldown at press bottom: 10

Bond 1: Bond. Laid filament moved away from structural filament slightly because of air pressure, resulted in weak join. Torch is pointing at the correct point but filament is moving away.

Bond 2: Bond. Laid filament moved away from structural filament slightly because of laid filament memory, medium strength join. Torch begins pointing in the correct position but filament is moving away in the Z axis, results in filament melting too much on near side of bond. Was hard to differentiate between pause locations.

(28) Distance: 20mm - Duration: 15s - TCP: -2.5 - Press Height: 10 - Press Angle: 12

Cooldown at press bottom: 10

Bond 1: Initial Bond. Too much heat on laid filament. Bond broke because of filament memory and angle of movement away.

Bond 2: Slight kink after bond

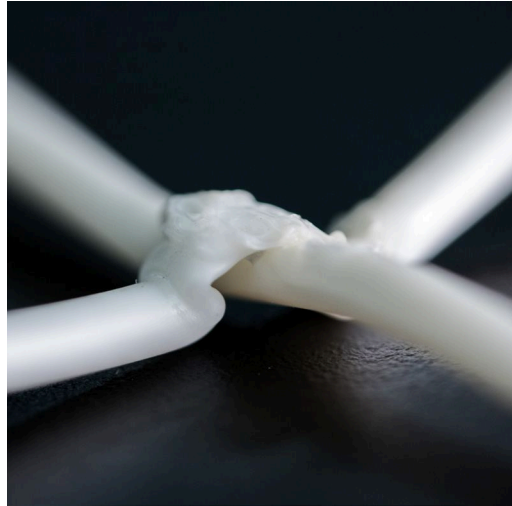


Fig. 26

28

(30) Distance: 20mm - Duration: 10s - TCP: -2.5 - Press Height: 10 - Press Angle: 12

Cooldown at press bottom: 10

Nozzle angle of attack: -12.5

Bond 1: Bond. Too much heat on laid filament. Best result straight after bond, no kink.

Bond 2: No Bond. Filament memory was less in laid filament but still forced it up in Z axis and moved away from torch/bond. Uneven melt of bond. Need to change torch position. Torch air pushing filament away from heat.



Fig. 27

30



Fig. 28

30

Findings

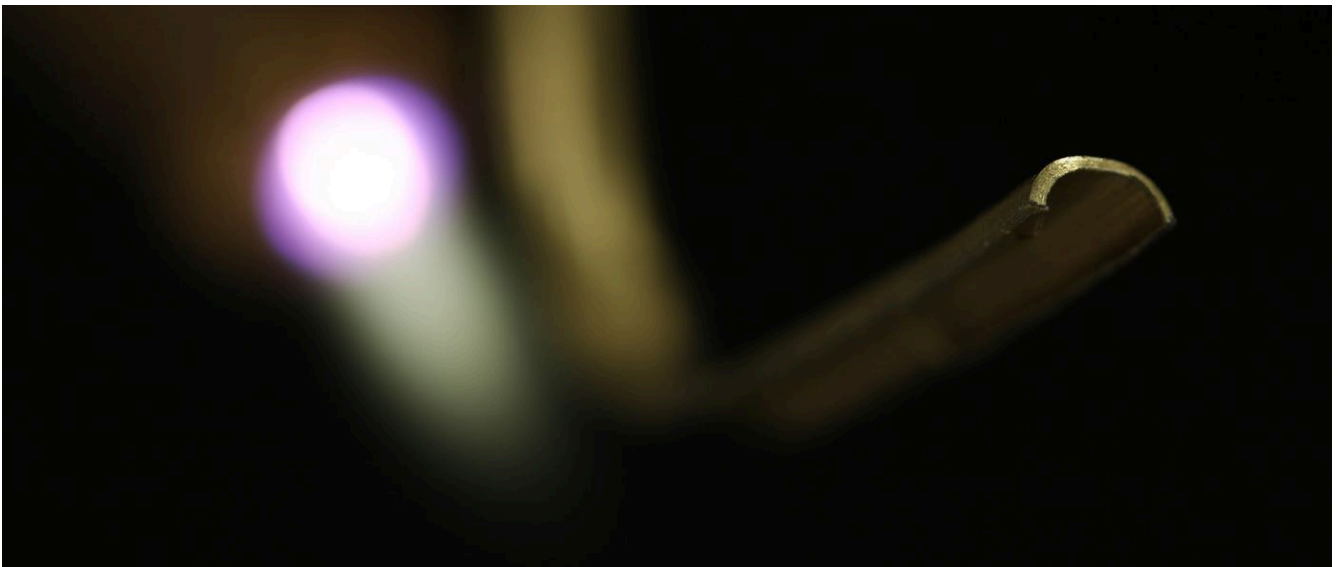
If the foot was positioned too close to the filament when heat was applied they would become stuck together. Foot placement needed some adjusting throughout to make sure it was in the correct position.

Because of the reversed press angle the kink created after the bond was dramatically reduced (Fig. 26). This technique has proven to be effective in creating cleaner bonds with PLA filament. With the current end-effector design this tipping movement is restricted. The movement cannot be too large or object collisions may occur.

Unnecessary tension created on the bond by robotic movement was still causing issues however this was reduced by manually pushing the filament out of the nozzle simulating powered extrusion.

Creating an even and precise melt on the filaments intersection is hard to produce and the main issue that needs resolving. With the current torch placement, melting the filament past its glass temperature and to the point of fusion is difficult. Often the laid filament on top melts far quicker than the structural filament underneath, due to the top filament being closer to the torch. The top filament is melted too much by the time the bottom filament get to a state of fusion.

The next stage is repositioning the plasma torch holder to be able to heat the two filaments evenly and with more precision at the filament intersection. Positioning the torch parallel to the laid filament and facing away from the direction of movement will also reduce the issue of filament moving away from the bond from the torches air pressure (Fig. 27,28).



Plasma Torch Holder 2.0

This torch holder was designed to reposition the torch parallel to the join location. It is repositioned to be aimed directly where the filament will intersect, at the top of the structural filament and bottom of laid filament.

This torch holder has two joints for easy parallel adjustment. This enables the torch focal point to be accurate and easily adjustable by altering only one position. The slide joint allows the torch to be moved closer to the end-effector if object collisions are becoming an issue.

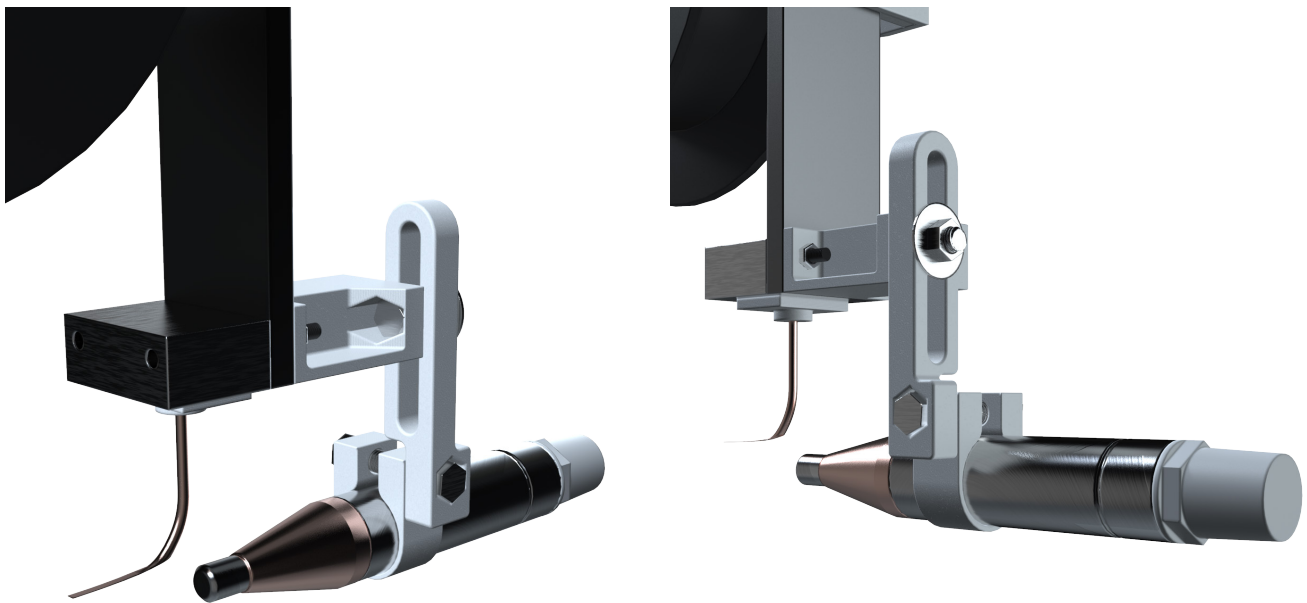
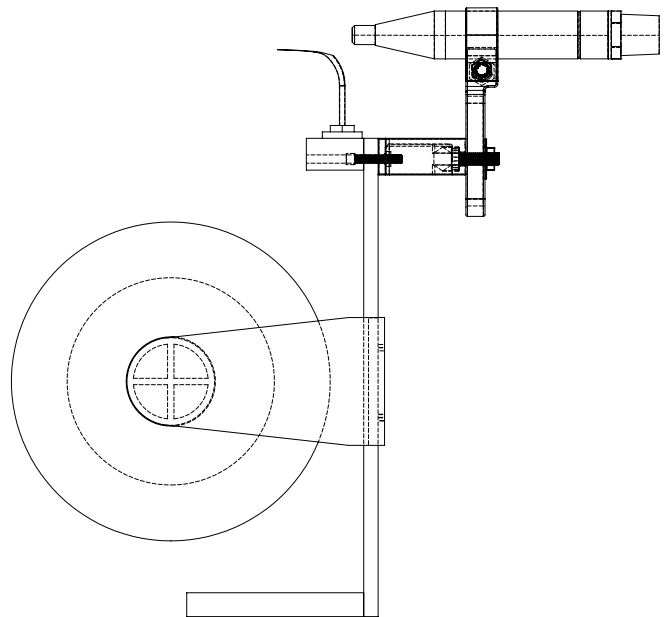
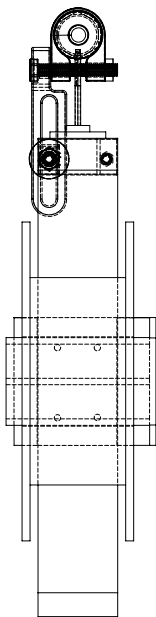
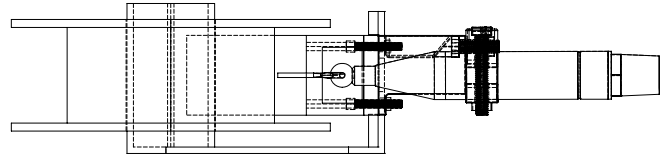
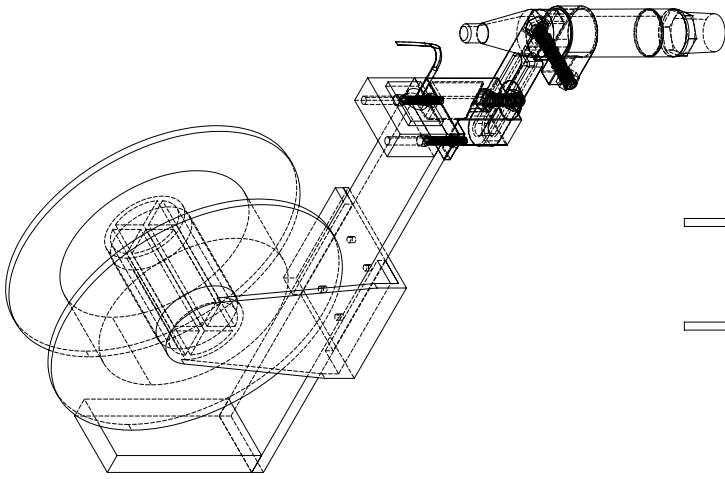


Fig. 29



Experiment Two (c)

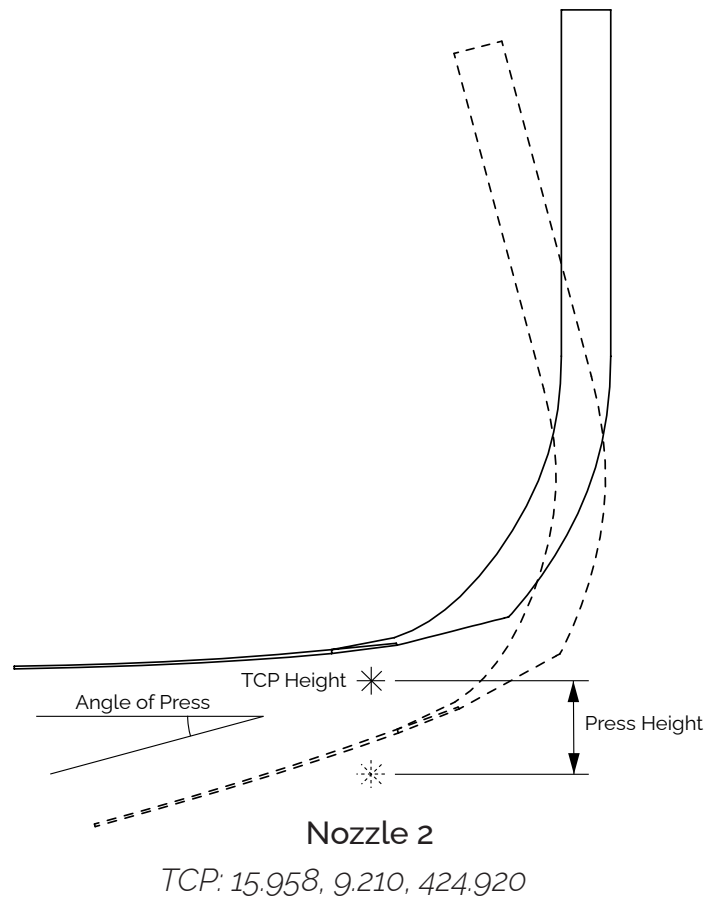


Fig. 30

(31) Distance: 20mm - Duration: 10s - TCP: 5 - Press Height: 6 - Press Angle: 5

Cooldown at press bottom: 10

Nozzle angle of attack: 15

Bond 1: Bond. Promising results. Bond broke when moving away because of angle of move in relation to nozzle curve (filament memory).

(32) Distance: 20mm - Duration: 10s - TCP: 5 - Press Height: 6 - Press Angle: 5

Cooldown at press bottom: 10

Nozzle angle of attack: 15

Bond 1: No bond. Filament memory is becoming too much of an issue. Will try a flexible TPU filament.

Findings

Applying an angle of attack reduced the filament memory issue on bond 2, however it created further problems with robotic movement. There were often object collision or joint singularities when trailing future movement tests on the Grasshopper/Rhino simulation.

PLA filament memory was becoming far too much of an issue. Solutions to issues would often incur further issues. I believe further technology or adaptations will need to be made to the end-effector to be able to effectively use PLA filament with the uncoiling method.

The filament memory will need to be controlled before uncoiling. For accurate filament placement filament memory will need to be reset (heated to its glass temperature) and readjusted to create the ideal curve from point to point.

As seen in Section One, point tracking could be used to accurately calculate the curved filaments position. A camera attached to the end-effector and/or multiple around the build area could be used to relay the filaments position in real time to the software/robot. Plasma position is vital to creating a strong join, this solution would rule out issues with any filament movement while building. AI could also be used to help predict filament curve and positioning.

A flexible TPU filament will be trailed that should nullify the previous issues with PLA filament.

Section Three

Bonding Techniques with TPU Filament



Experimental Plan

Experiment One

Initial manual tests were carried out to investigate material properties. TPU filament was held in front of the plasma torch at various distances and times then manually placed together. This is to get a rough estimate of the heat/distance needed for a strong bond.

Experiment Two

These test involved using the ABB IRB 1200 Robotic Arm and end-effector. Initial testing was carried out to perfect the robotic movement and positioning.

The variables of these tests were testing out various pressing angles and distances by changing the TCP height, press height, angle of press and angle of attack. Tests were carried out on test jig 2.

Experiment Three

Structural support was added to help pull/uncoil the filament from the end-effector. Uncoiling from cemented structures reduces the structural filament from warping and pulling away from it's original position. Manual/powered extrusion synced to robotic movement will have similar results however this was not tested.

Experiment Four

This test is to investigate the possibility of creating a mesh by leaving the plasma torch on as it passes over filament.

This will not be investigated thoroughly and will be documented as a proof of concept.

Experiment Five

This test is to try and create a continuous parallel bond between two lines of laid filament. An initial line of filament will be laid down then a secondary line will be laid ontop, while only slightly adjusting the TCP Height. The plasma torch will be left on for the duration of horizontal robotic movement.

This will not investigated thoroughly and will be documented as a proof of concept.

Experiment Six

Two structural filaments will be secured with hot glue and a continuous strand of laid filament will be bonded in a zig-zag between them. This will consist of six bonds, three on each side. This will be testing the ability to pivot at a join and uncoil at an angle dissimilar to the approach angle. The angle created between the first three bonds will be small and acute, this is done to accentuate the issues that may arise with this technique.

Experiment Seven

Thermo-chromatic filament created by Scion will be tested to see if similar results can be produced. The filament will be manually tested to get en estimate of the heat required to melt. Then the robotic movement from the most successful TPU test will be used to test its ability to spatial print using the uncoiling method.

Experiment One

(33) Distance: 20mm - Duration: 5s - No Press

Manual test holding filament under torch the placing them together, minimal force on the press. Small amount of melting was observed. Weak bond.



Fig. 31

33

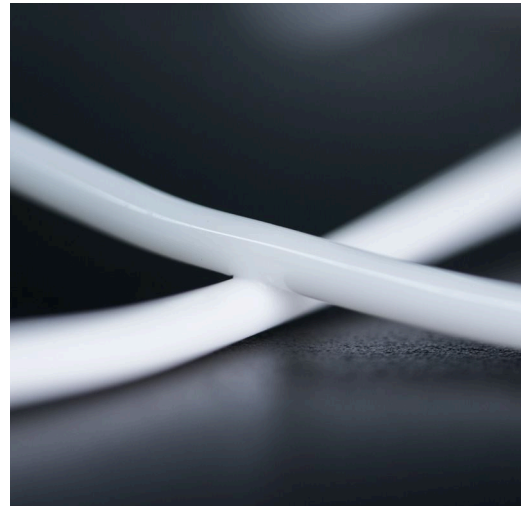


Fig. 32

33

(35) Distance: 20mm - Duration: 10s - No Press

Entire filament started to melt at around 7.5s. When pressed a good bond was created

(36) Distance: 20mm - Duration: 7.5s - No Press

Seemed like the ideal time for a join to occur. Filament bonded easily together without any added press.

(38) Distance: 20mm - Duration: 7.5s - Press

Manual press spread bond surface area and seemed to make bond stronger.

(39) Distance: 15mm - Duration: 5s - Press

Filament melted very fast. Created a slight burn on bond, may be too close to heat.

Findings

Initial observations TPU filament seemed far more forgiving as the time between melting to bond and melting/burning was far greater than PLA. Manual force tests shows the bond is far stronger than PLA. Because of it's flexibility it also looks more resilient to sheer forces, therefor far less fragile.

Around 8 sec at 20mm allows enough time for the filament to melt, not burn and create a strong bond.

Mark-10 Displacement Test

The 2.75mm TPU Filament was tested on the MARK-10 Motorised Tension and Compression Stand to gauge its unmodified tensile strength and displacement during and after tension.

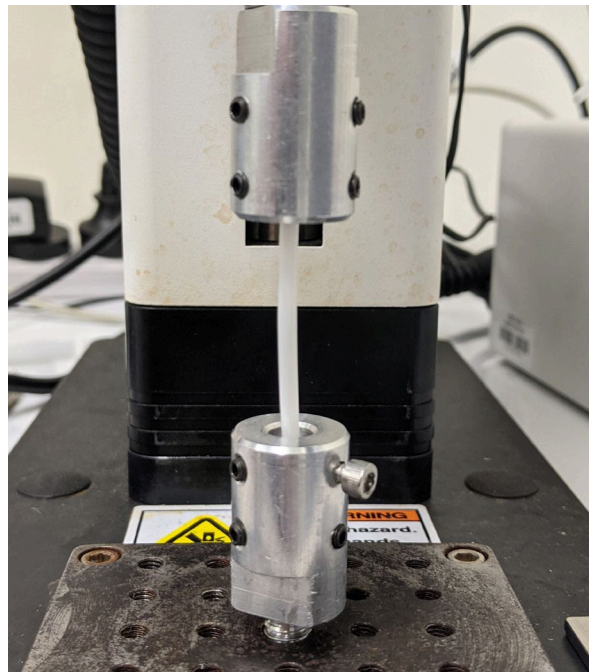


Fig. 33

Filament length before test:	34mm
Average displacement distance:	108.33mm
Average length after test:	43.33mm
Average force:	139.8N
Percentage increase during test:	218.62%
Percentage increase after test:	27.44%

This test was not accurate but worked well to get an approximation. The vice grip on the filament creates weak points and was the breaking point in all the tests.

Experiment Two

(44) Distance: 20mm - Duration: 8s - TCP: 0 - Press Height: 0

Bond 1: Solid bond was created with no movement

Bond2: Solid bond was created with no movement. Slight melting/deformity of structural filament.

(45) Distance: 20mm - Duration: 8s - TCP: 0 - Press Height: 0

Bond 1: Bond. Slight burn to filament.

Bond 2: Melting/deformity of structural filament

(46) Distance: 20mm - Duration: 8s - TCP: 0 - Press Height: 10

Cooldown at press bottom: 15

Bond 1: Solid bond was created with no movement. May have helped with holding cooldown at max press (spreading filament contact area). Torch never aimed at top of laid filament so potential for it to stick to nozzle is minimal

Bond 2: Solid bond was created with no movement. Slight melting/deformity of structural filament.

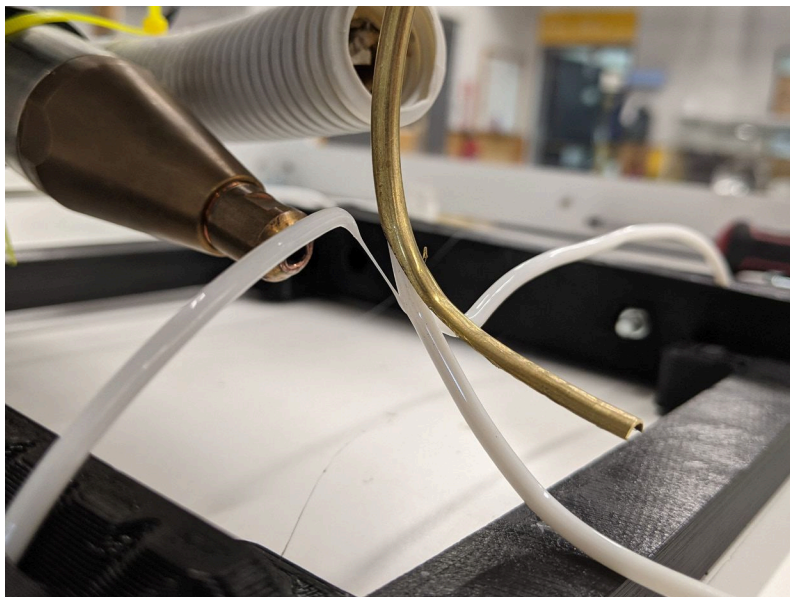


Fig. 34

Structural filament was overheated

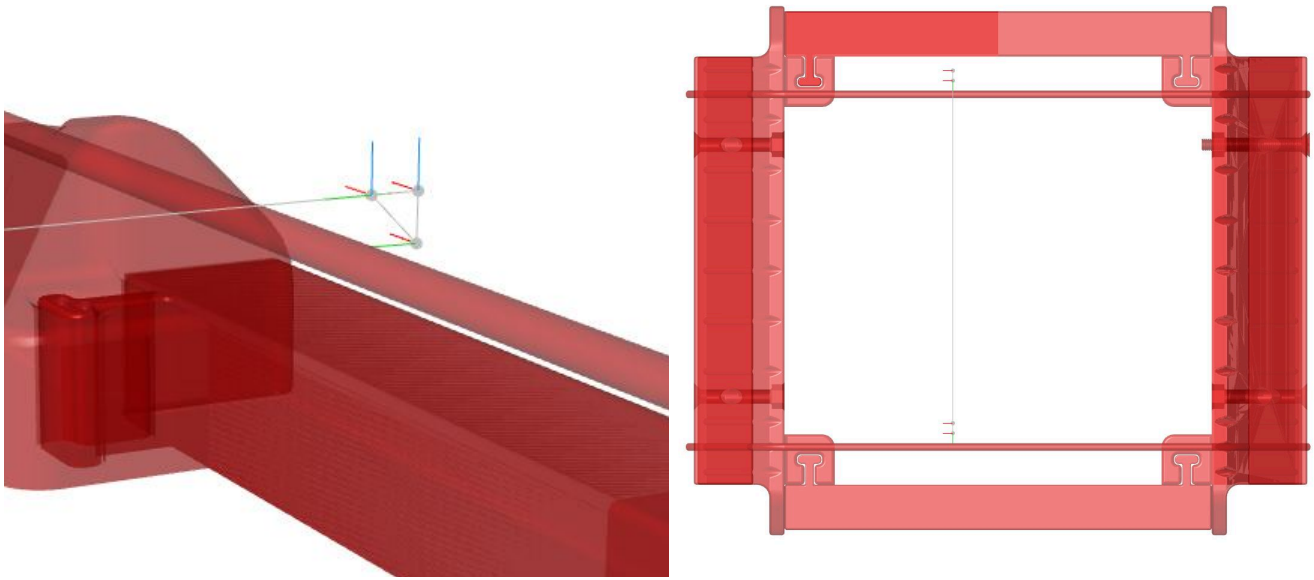


Fig. 35 Robotic movement visualized using Rhino/Grasshopper

Findings

Because of the friction created in the nozzle by pulling the filament away from bonds, there is too much strain on the structural firmament as it is getting pulled away with the end-effector. This is moving and stretching the position of the structural filament in the direction of robotic movement.

Friction needs to be reduced during uncoiling for future tests otherwise physical locations of filament won't match the perceived software location.

A solution to this may be timing powered extrusion with robotic movement. To simulate this structural filament could be secured in place and/or the filament could be assisted out of the nozzle with manual pushing .

Reasonably consistent results were produced even with filament movement. TPU is far more forgiving of slight inconsistencies with torch placement than PLA.

The angle of attack isn't as crucial because of reduced filament memory with a flexible filament, I will revert back to tipping in the opposite direction of movement (initial direction).

For the next tests the structural filament will be glued onto supports. This will assist the press/bond and allow multiple bonds to be created on the same strip of filament.

Experiment Three

(48) Distance: 20mm - Duration: 8s - TCP: 2 - Press Height: 5 - Press Angle: 5
Cooldown at press bottom: 15

Bond 1: Bond. Might be best join yet. Press was effective.

Bond 2: Bond, slightly worse than previous because of some subtle filament memory on the laid filament.

(49) Distance: 20mm - Duration: 8s - TCP: 4.5 - Press Height: 5 - Press Angle: 5
Cooldown at press bottom: 15

Bond 1: Bond. Tried to secure support filament only in the middle. Laid filament pulled and deformed structural filament.

(52) Distance: 20mm - Duration: 9s - TCP: 2 - Press Height: 5 - Press Angle: 1
Cooldown at press bottom: 12

Bond 1: Bond. Melted structural filament. Plasma was on for slightly too long

(56) Distance: 20mm - Duration: 7s - TCP: 2 - Press Height: 5 - Press Angle: 1
Cooldown at press bottom: 12

Bond 1: Bond, getting consistent results.

Findings

Implementing a support structure and cementing the structural filament produced far more consistent results and stopped the issues with the filament moving. After numerous tests refining the robotic movement, a consistent press was found that produced strong and even bonds.

Trying to keep tension in-between the laid filament was difficult. As the filament melted in preparation for the second bond it's tension released. To resolve this a clamping mechanism may need to be used to hold tension on the filament while the bond is being created.

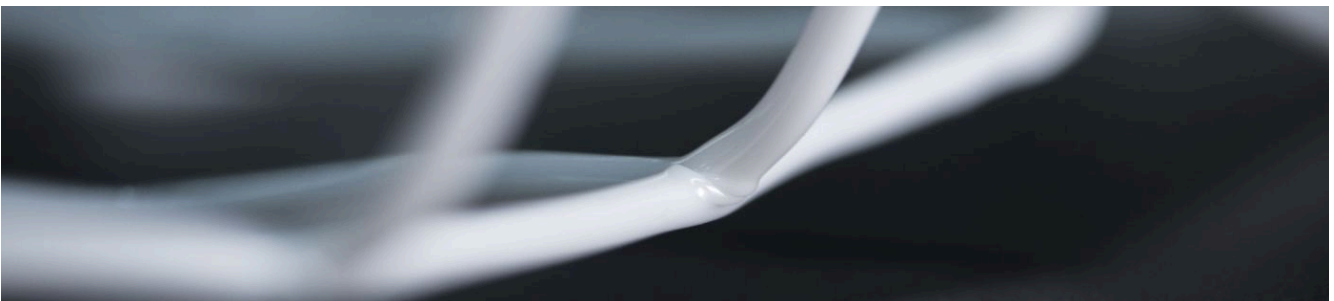




Fig. 36

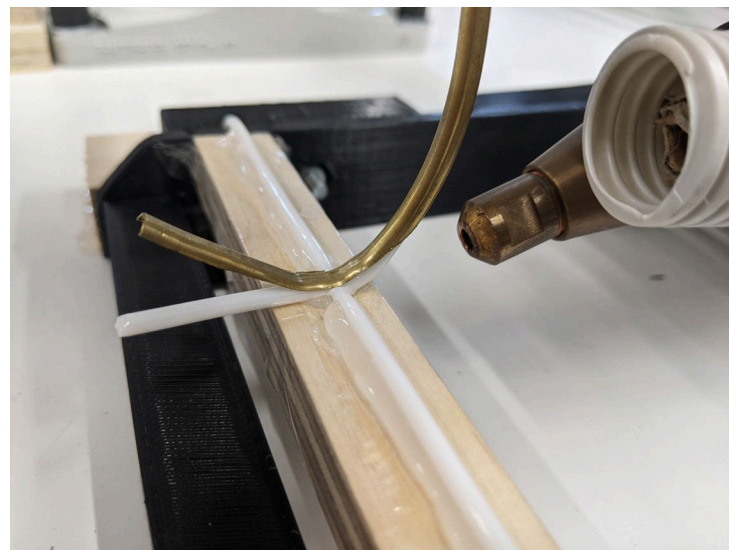


Fig. 37

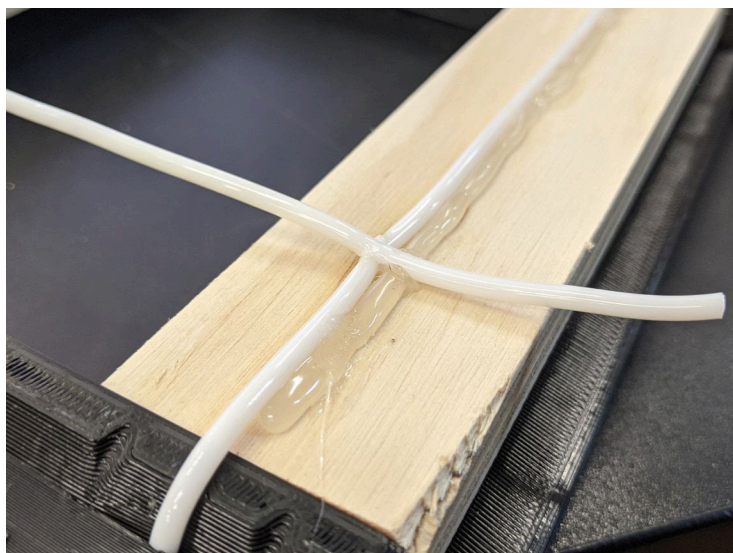


Fig. 38

Mark-10 Results

*(59-62) Distance: 20mm - TCP: 2 - Press Height: 5 - Press Angle: 1
Cooldown at press bottom: 15*

Once a robotic movement with consistent results was produced, tests were carried out to investigate the ideal plasma torch duration. Each bond was reproduced at least 5 times and tested on the Mark-10 motorized test stand.



Fig. 39



Fig. 40

PLA filament was tested to compare results to previous years studies.

Although it was a small and varied sample size, tests resulted in similar outcome to previous studies. The graph shows an immediate spike as pressure is applied, as expected with ridged materials. There is then either a sharp drop as the bond breaks (25) or a more gradual decline as the filament deforms and rips apart.

The average time taken for the bond to break/deform was 43.

Time is measured in Mark-10 units

PLA Bonds

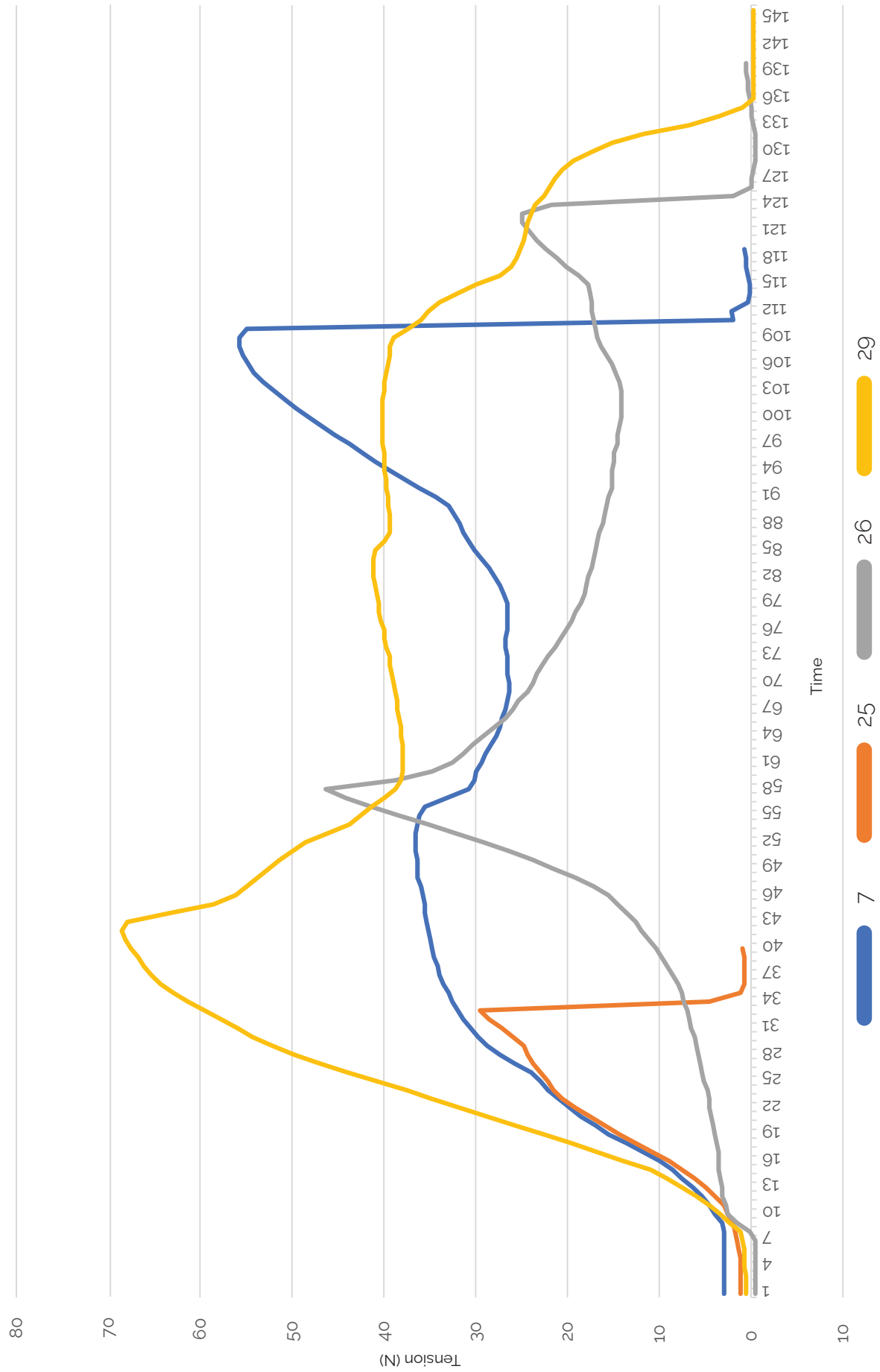




Fig. 41

Testing the TPU filament with the same conditions as the PLA filament resulted in the entire bond pulling through the hole because of its flexibility.



Fig. 42

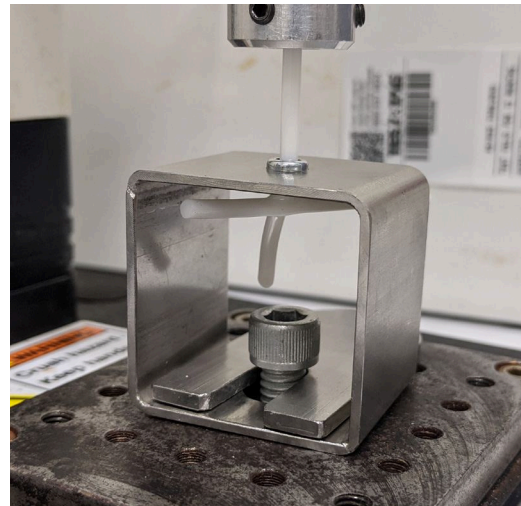


Fig. 43

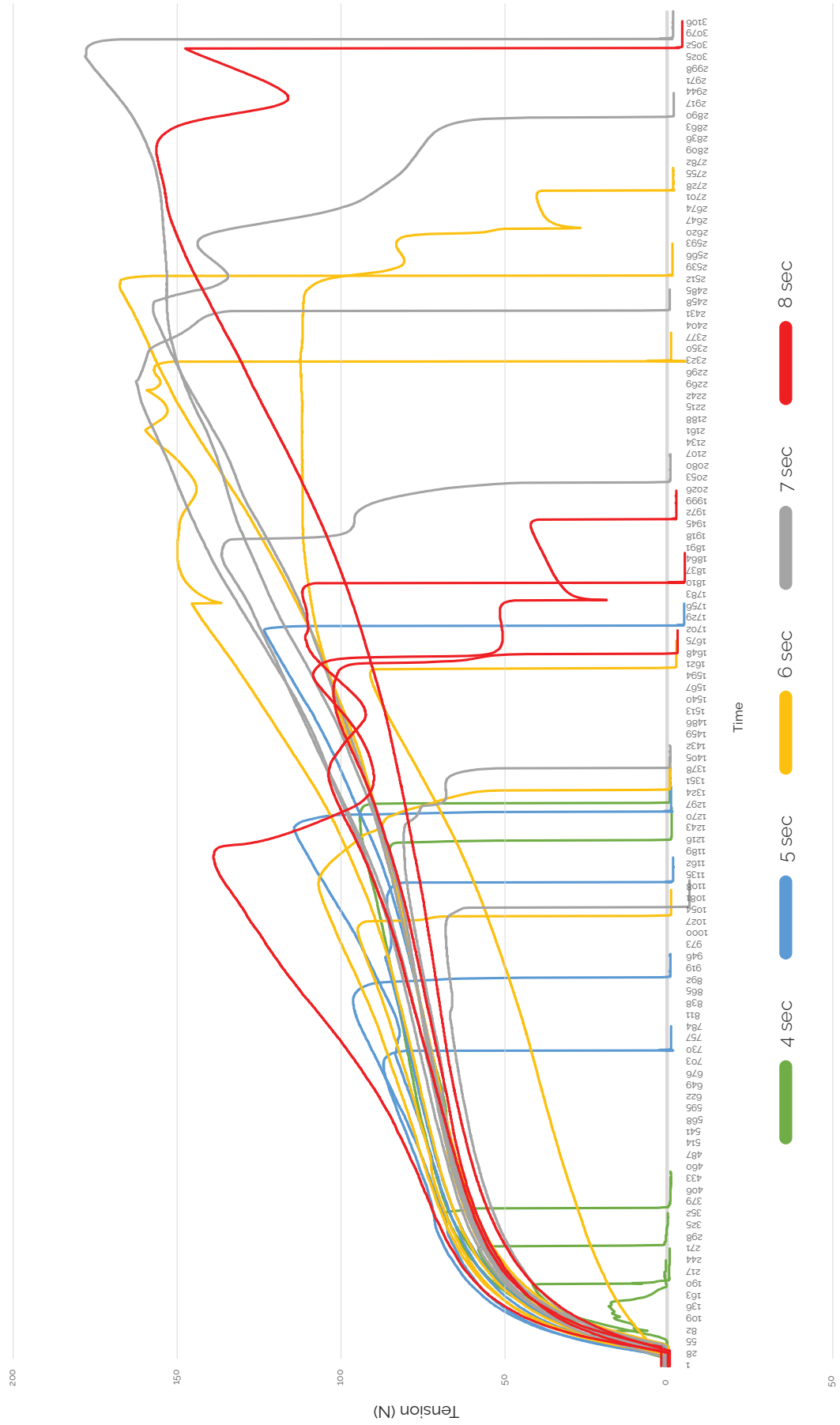
Mark-10 Test Setup

An M3 nut was used to narrow the hole to stop the 2.75mm filament from being pulled through.

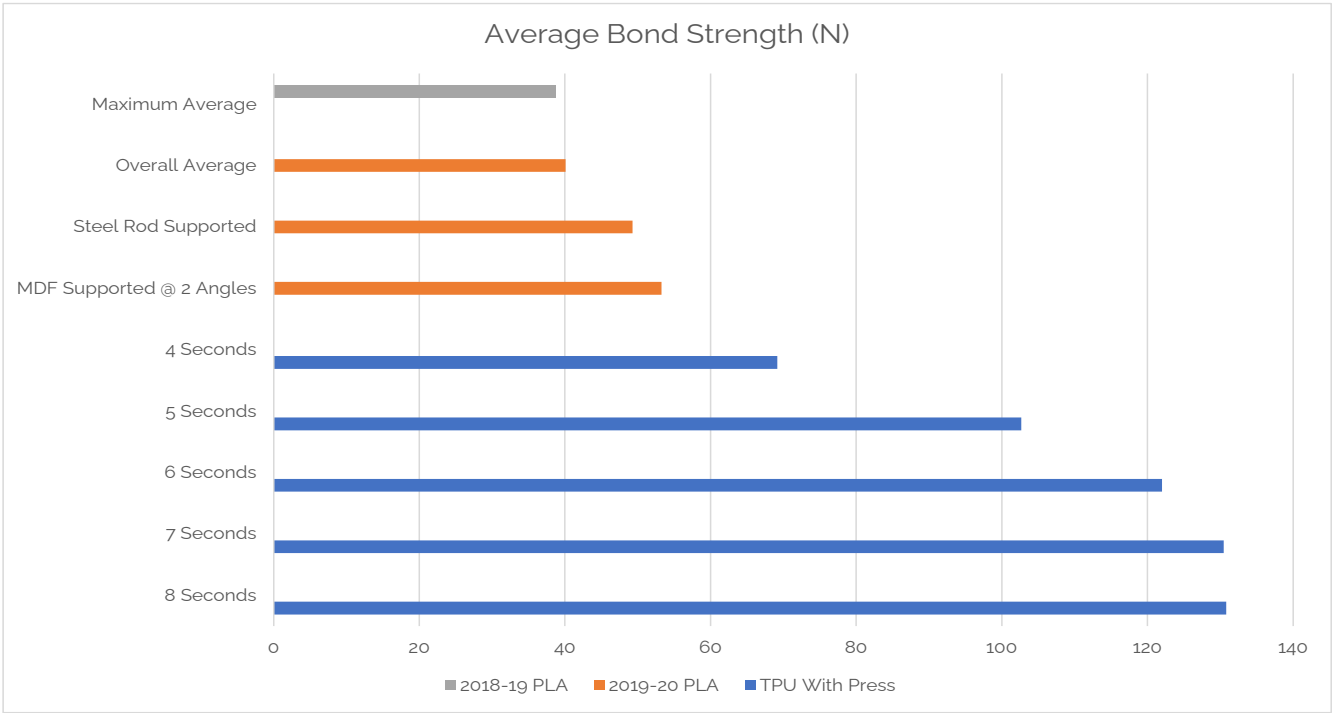
Because the hole is so similar in diameter to the filament it is possible some results may not be as precise. If a bond was created that spread the filament wider than 3mm then it may become blocked in the hole. However this may be irrelevant as when the filament is stretched it deforms to a smaller diameter.

Laid filament in the direction of robotic movement was clamped in the vice.

TPU Bonds



The previous graph reveals that at around 20N of pressure deformation starts occurring. The tension starts to flatten as the filament is stretched. Comparing the graphs of the 2 different materials, even the weakest TPU bond of 4 seconds outperforms PLA both in strength and time taken to break.



4 sec: 69.18N - 5 sec: 102.68N - 6 sec: 122.00N - 7 sec: 130.48N - 8 sec: 130.80N

This graph compares results from previous years. All of the TPU bonds outperform even the strongest PLA bond. This test was only measuring tension force. I also believe these TPU bonds will be very resilient to shear forces.

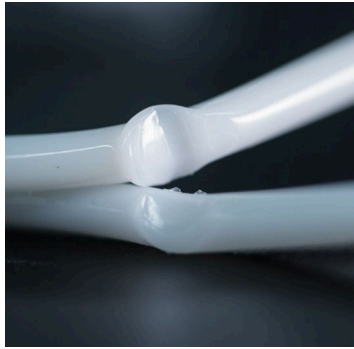


Fig. 44

4



Fig. 45

5



Fig. 46

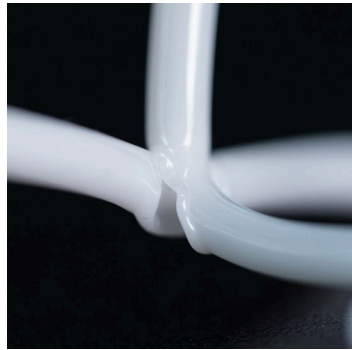


Fig. 47

6



Fig. 48

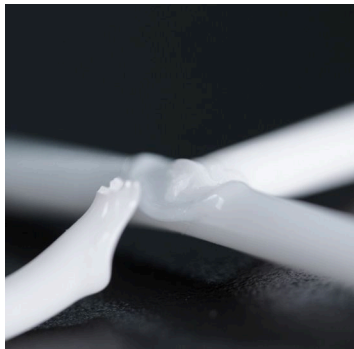


Fig. 49



7 Fig. 50



Fig. 51



Fig. 52

8

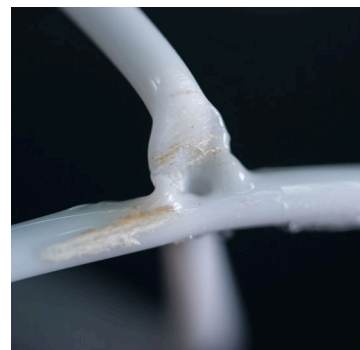


Fig. 53

Experiment Four

MESH STRUCTURE

*(57) Distance: 20mm - Duration: 9s - TCP: 2 - Press Height: 5 - Press Angle: 1
Cooldown at press bottom: 12*

In this experiment two more structural strands were clamped into place perpendicular to the laid filament direction, as shown in Fig. 54. The same script was then repeated from experiment three however the plasma torch was left on while traveling over the additional structural strands, no press was made on these added intersections.

Although weak, a bond was made on every intersection and a mat structure was created.

Speed of robotic movement, TCP height and any additional movement are variables that could be refined to produce a better result.

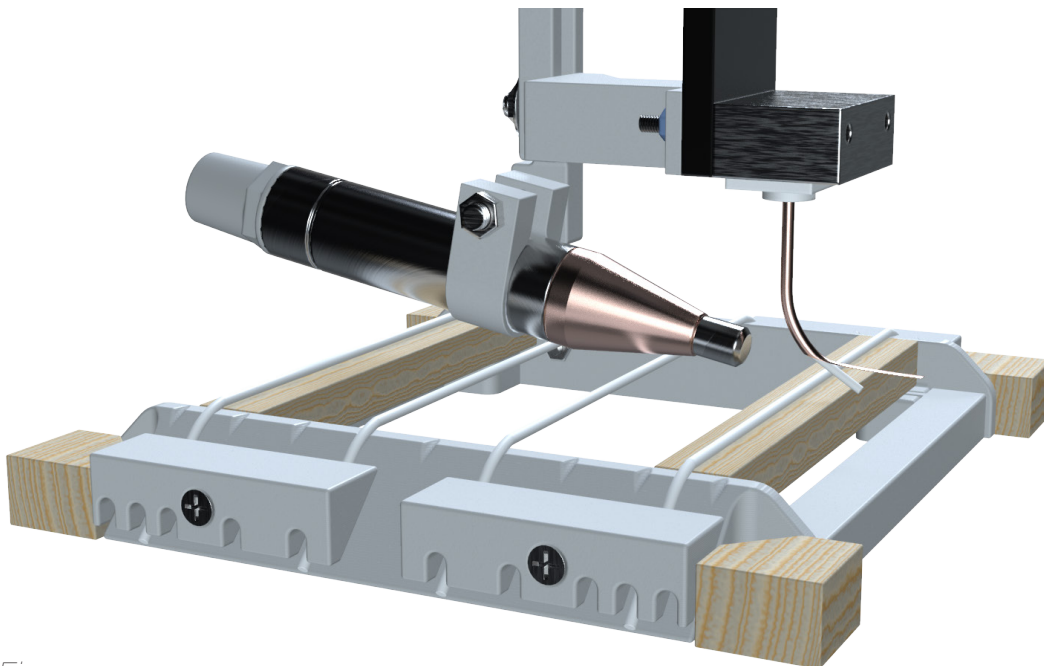


Fig. 54

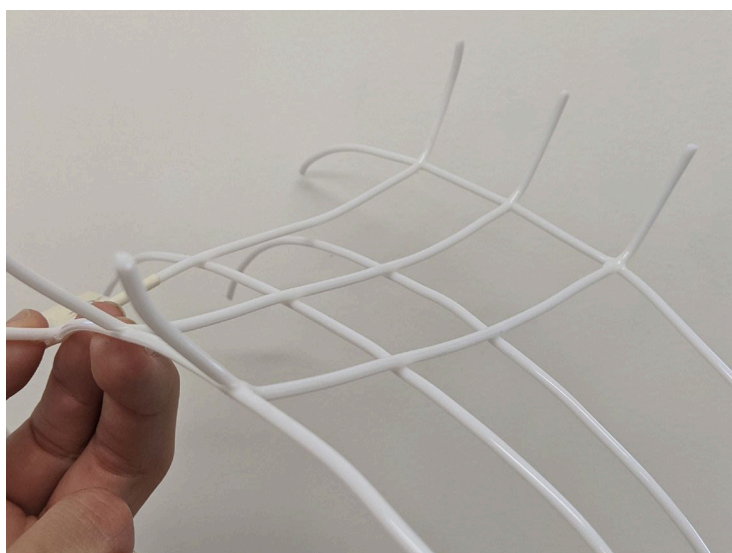
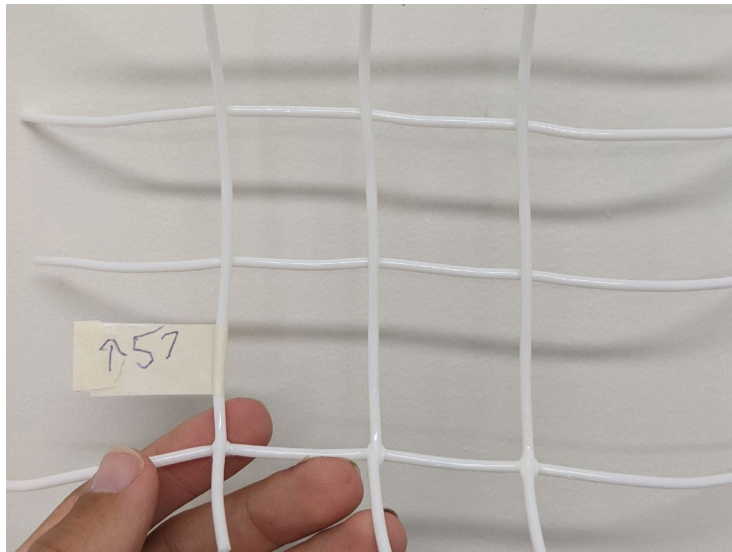


Fig. 55

Experiment Five

CONTINUOUS PARALLEL JOIN

(67) Distance: 20mm - Duration: 9s - TCP: 2 - Press Height: 5 - Press Angle: 1
Cooldown at press bottom: 12

The first test was setup as shown in Fig. 56. Because of the issues with maintaining tension on the laid strand after a second bond is made, the primary laid filament was far too slack for a continuous bond to be made. The secondary laid filament didn't come into contact with the primary after the initial press bond. The pull on the first bond location from robotic movement amplified the issue and caused the primary laid filament to become more slack.



Fig. 56

(69) Distance: 20mm - Duration: 9s - TCP: 2 - Press Height: 5 - Press Angle: 1
Cooldown at press bottom: 12

For the next test support was added underneath the primary laid filament and it was secured with hot glued. This produced far better results and the two filaments maintained continuous contact throughout. The main issue was the available surface area for the bond to occur. As these are two parallel cylinders the contact area is very small, the circular shape also caused the secondary filament to slide around the primary filament and not remain on a consistent path.

Speed of travel and TPU height could be adjusted to refine bond.

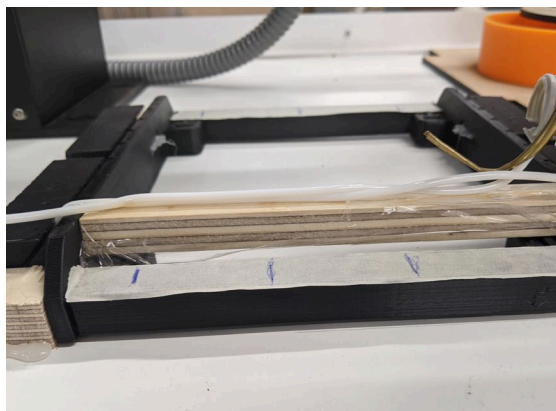


Fig. 57

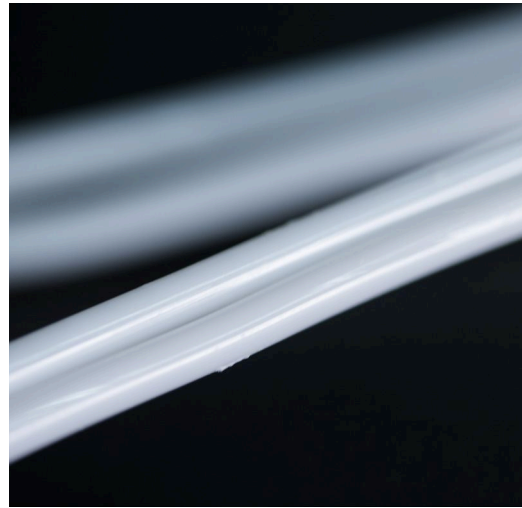
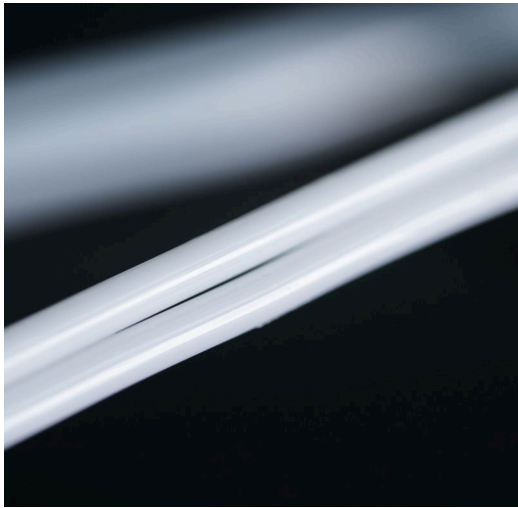


Fig. 58

69

This test proved that layering filament like this may be viable with the current technique, however the conditions need to be controlled and the movement refined.

Experiment Six (a)

(63) Distance: 20mm - Duration: 9s - TCP: 2 - Press Height: 5 - Press Angle: 1
Cooldown at press bottom: 12

A single press was made in the direction of the previous bond. This bond was then allowed to cool before the robot rotated around the bond location and moved towards the next bond.

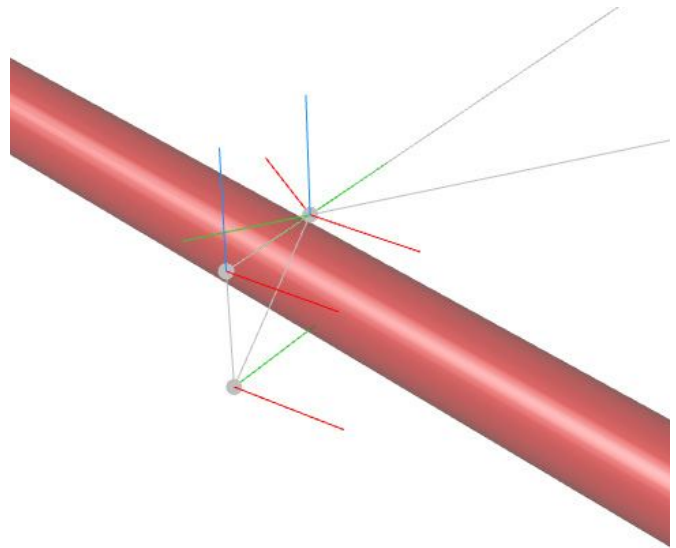
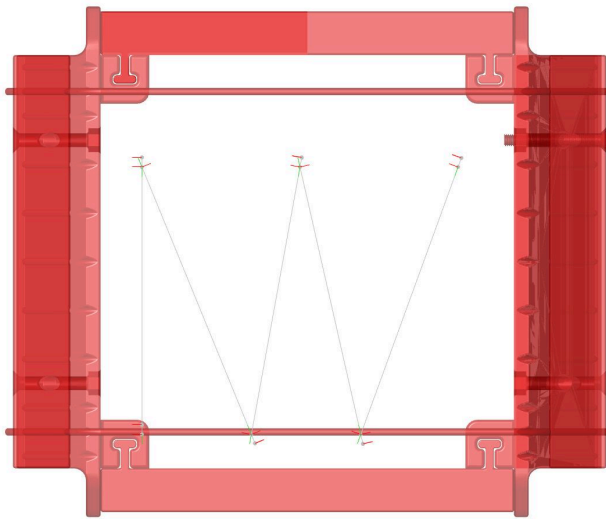


Fig. 59

Robotic movement

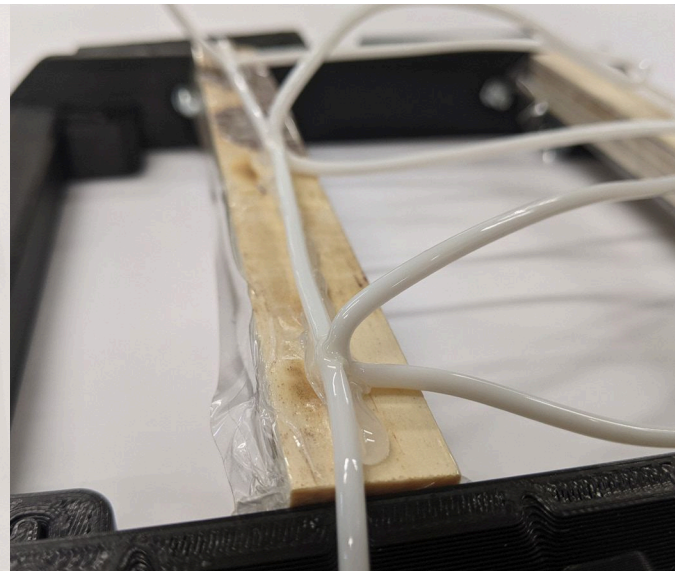
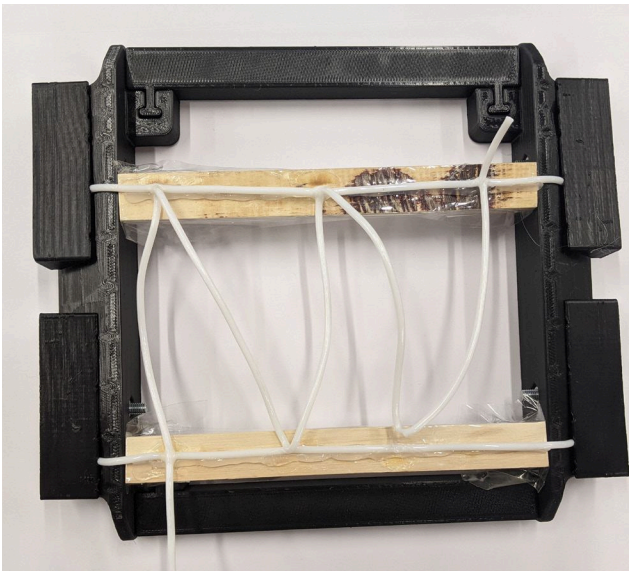


Fig. 60

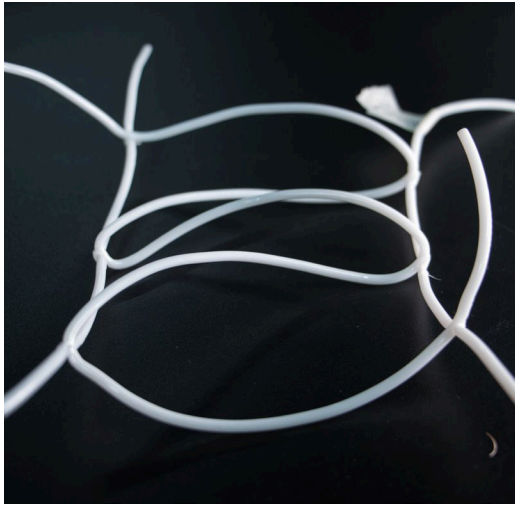


Fig. 61

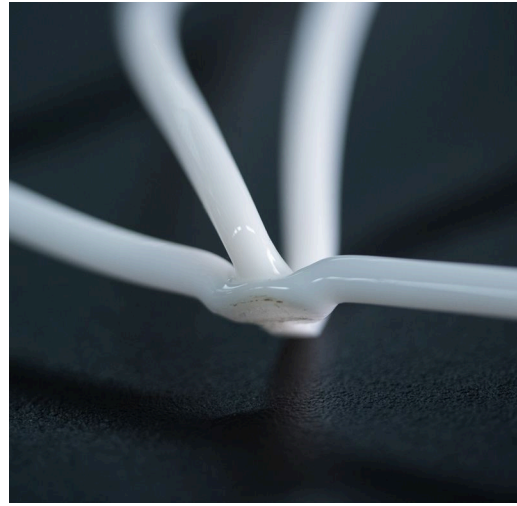


Fig. 62



Fig. 63



Fig. 64

Findings

This test produced successful first results. Because of the end-effector orientation while bonding, the filament stiffness created a large arch after every direction change. This created even more slack in-between the bonds. This also forced the filament to rise up in the Z-axis. If the two strands of structural filament are pulled apart and tension is applied to these joins, it will create a shear force as the bond orientation is not in line with the direction of tension. This may result in a weaker structure.

To reduce this, heat could be applied to the filament to point in the direction of the following bond.

Filament extrusion was manually simulated as friction in the nozzle was placing the bonds under too much tension.

Robotic movement was largely restricted because of the robots surroundings/closed environment. Increasing the scale of these test may fix this.

Experiment Six (b)

(63) Distance: 20mm - Duration: 9s - TCP: 2 - Press Height: 5 - Press Angle: 1
Cooldown at press bottom: 12

A single press was made in the direction of the previous bond. This bond was then allowed to cool before the robot rotated around the bond location and moved towards the next bond. During the rotation the plasma torch was turned on to assist in changing the filament direction.

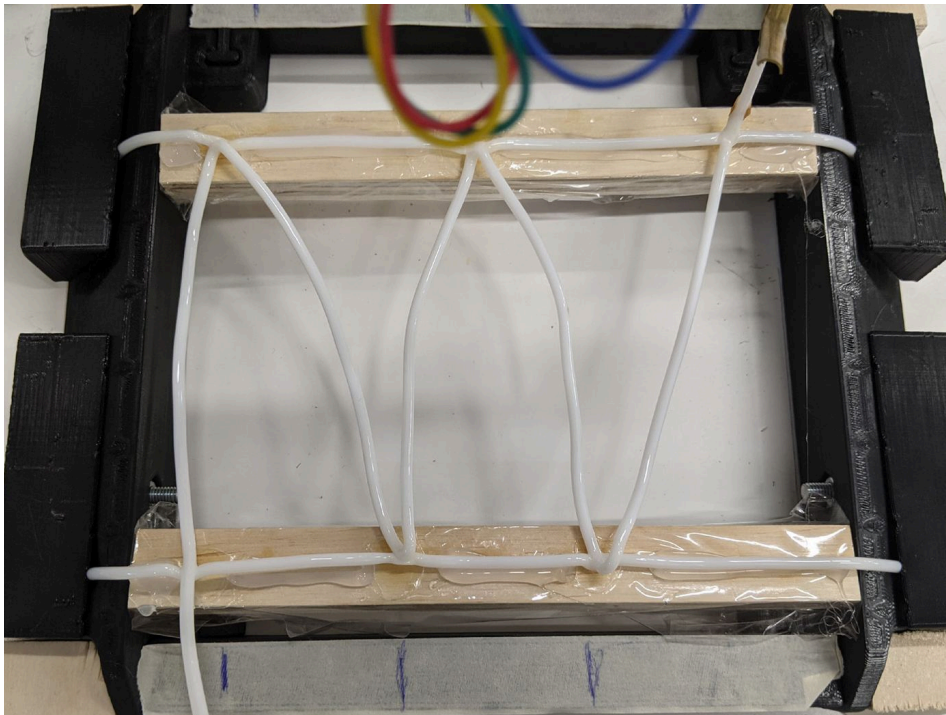


Fig. 65

Findings

This technique proved to be successful and helped reduce both the amount of slack in-between joints and filament rise in the Z-axis. As shown in Fig. 68, the bonds became far sharper and the direction the filament exited the bond was more in-line with the following bond location. The continuous plasma heating did not look to deform or weaken previously laid bonds.

This technique could be taken further with refining the timing of plasma and speed of rotation.

This technique also shows that re-orientating the filament midair may be possible.

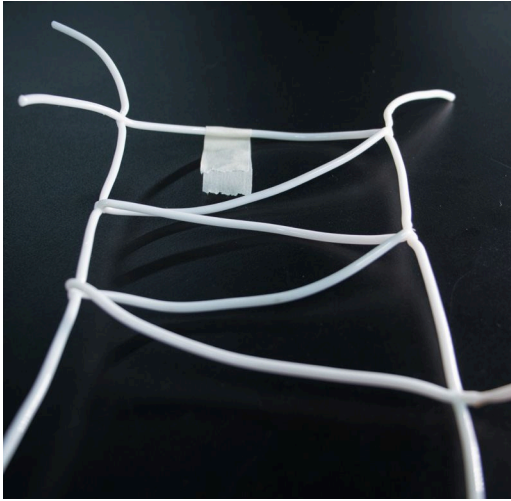


Fig. 66

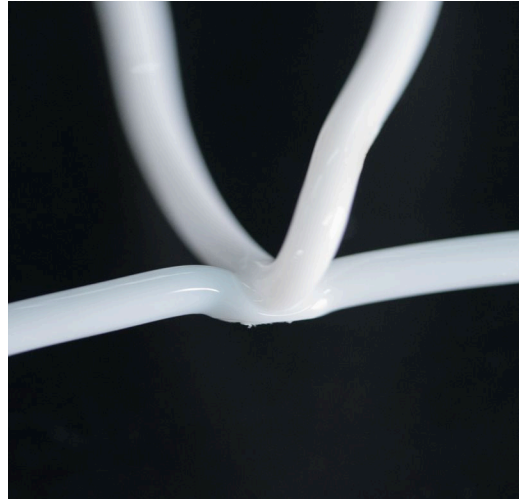


Fig. 67

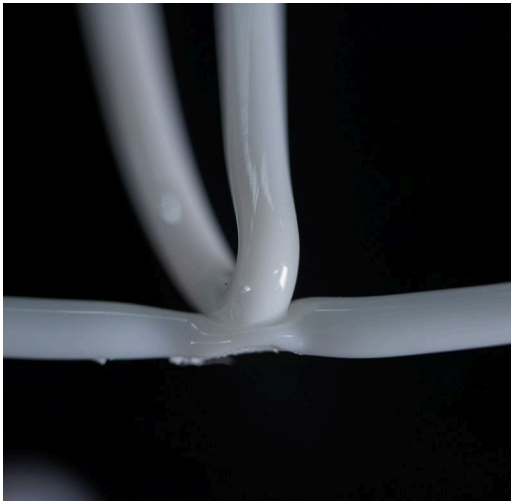


Fig. 68

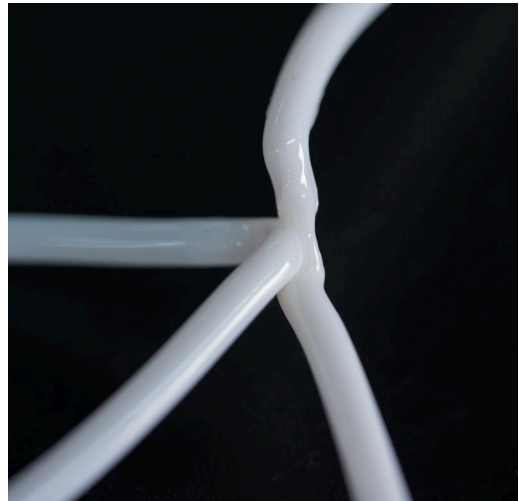


Fig. 69

Experiment Six (c)

(65) Distance: 20mm - Duration: 9s - TCP: 2 - Press Height: 5 - Press Angle: 1 - Secondary press 5mm

Cooldown at press bottom: 12

A 5mm sideways movement and a secondary press was added. This was done to help re-orientate the direction of the filament leaving after the bond and angle it towards the following bond.

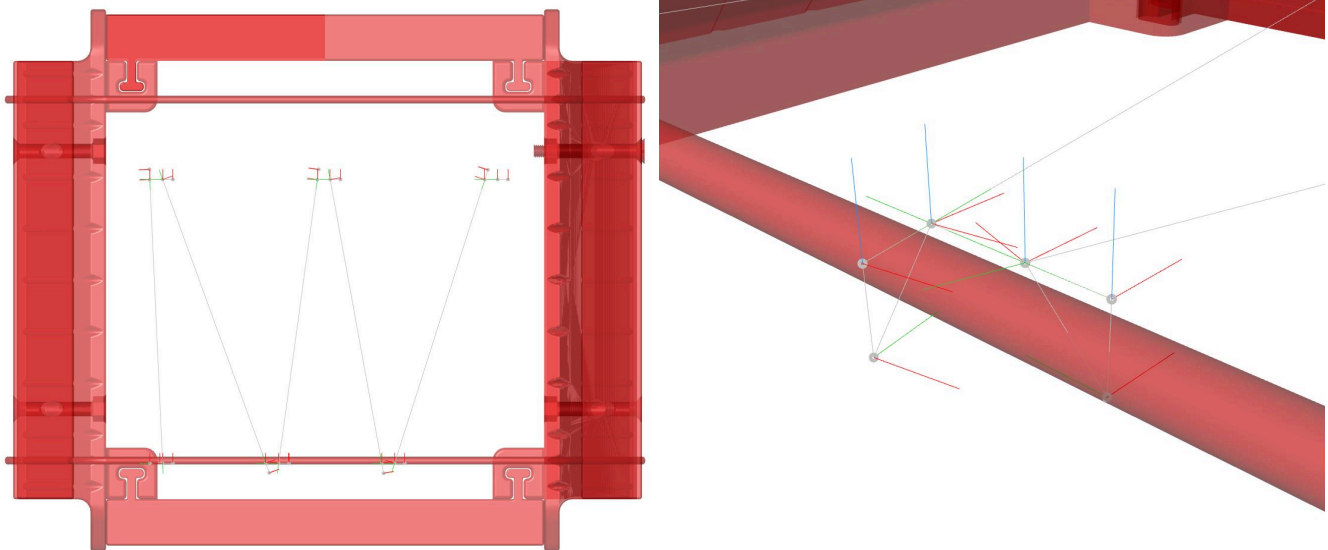


Fig. 70

Findings

Because of the filament stiffness a 5mm movement was too small and a kink was created in the laid filament before the secondary press. This meant the laid filament was no longer in line with the structural filament and nozzle, resulting in no contact between filament on the secondary press. Either the movement needs to be larger to reduce the stress due to stiffness, press position needs to be altered or plasma needs to remain on during turn like in the previous test.



Fig. 71



Fig. 72



Fig. 73

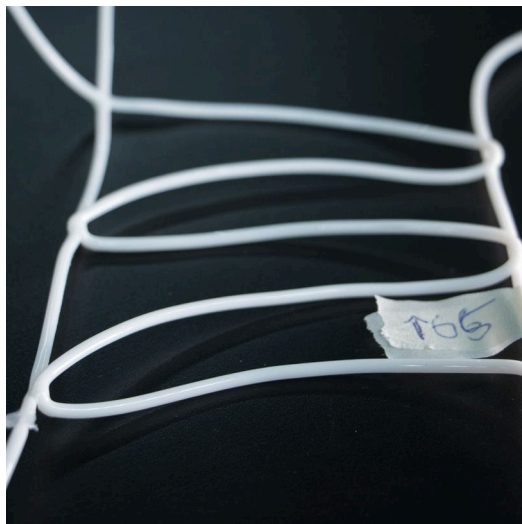


Fig. 74

Experiment Six (d)

(71) Distance: 20mm - Duration: 9s - TCP: 2 - Press Height: 5 - Press Angle: 1 - Secondary press 5+4mm

Cooldown at press bottom: 12

A 4mm interior movement was also added to try and compensate for filament kink.

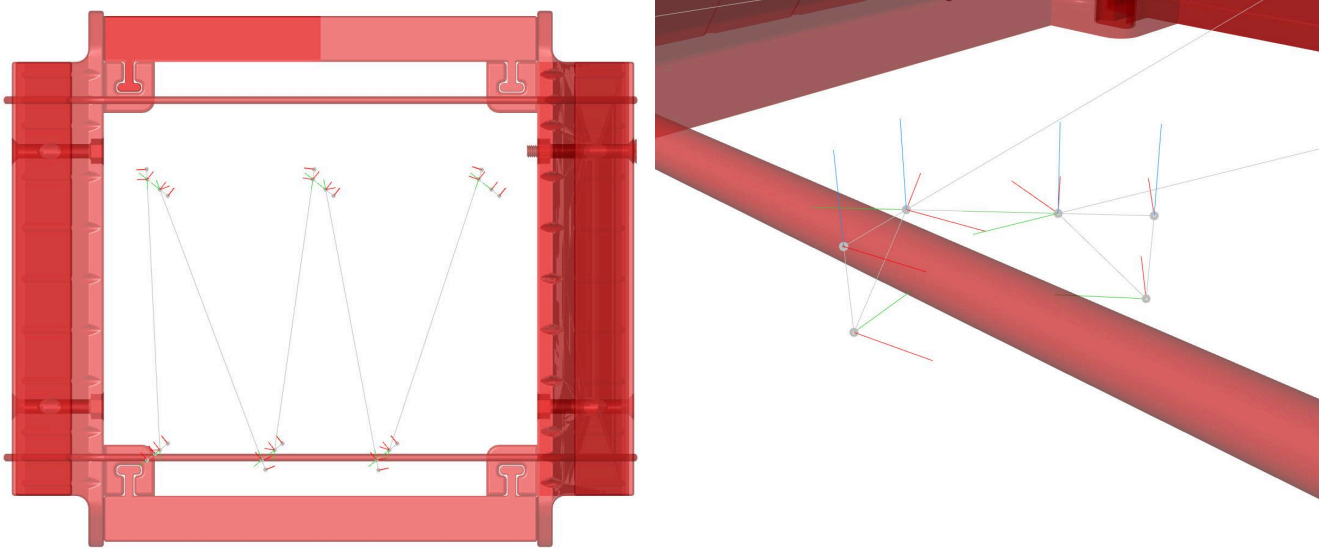


Fig. 75

Findings

Slightly altering the secondary press location fixed the previous issues and produced very clean bonds. Because of the secondary press, there was no movement in the Z-axis.

Filament direction approaching and exiting the bond is shown to be important in controlling tension between bonds, reducing extra filament movement (Z-axis) and creating an aesthetically pleasing bond. This is a successful technique to create a continuous zig-zig pattern using the uncoiling technique.

The next stage is to create a script that automatically creates a secondary press in line with the following bond location. The distance and angle of the secondary press may vary depending on the angle between bonds.

This structure can also act as a spring mechanism. Because of TPU filaments flexibility, squeezing the two structural filament strands together creates a spring force. This should be further investigated.

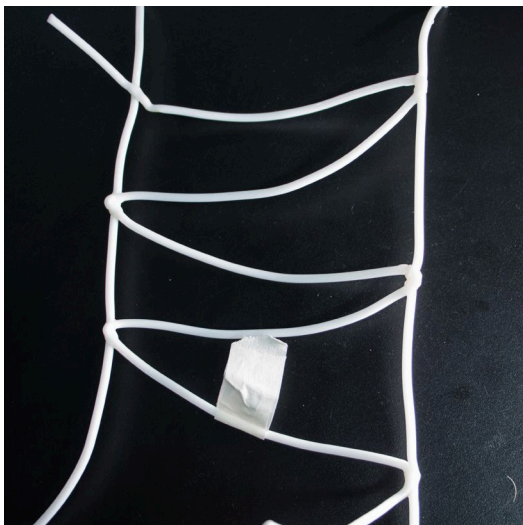


Fig. 76

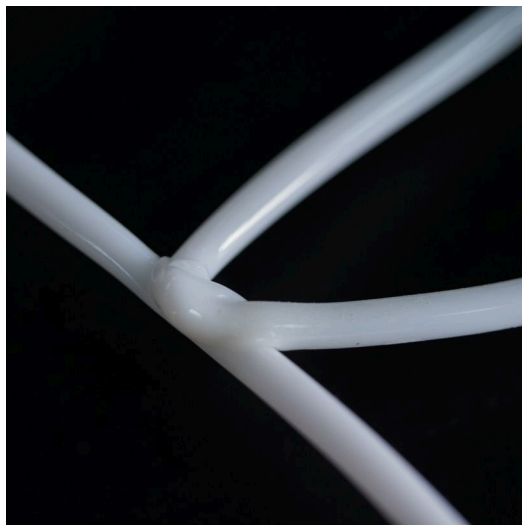


Fig. 77

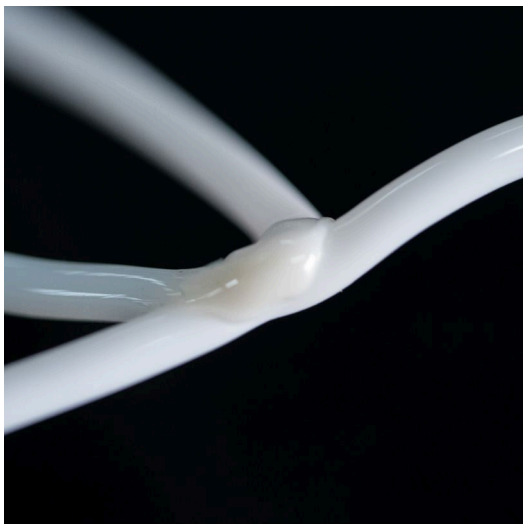


Fig. 78



Fig. 79

Experiment Seven

Manual tests indicated that Scions thermo-chromatic filament is less resilient to heat and has a lower melting threshold. A distance of 20mm with a plasma torch duration of 6 seconds was too much heat and melted through the filament enough to destroy the bond. The filament diameter was smaller at 2.5mm.



Fig. 80

*Distance: 20mm - Duration: 3-4s - TCP: 2 - Press Height: 5 - Press Angle: 1
Cooldown at press bottom: 12*

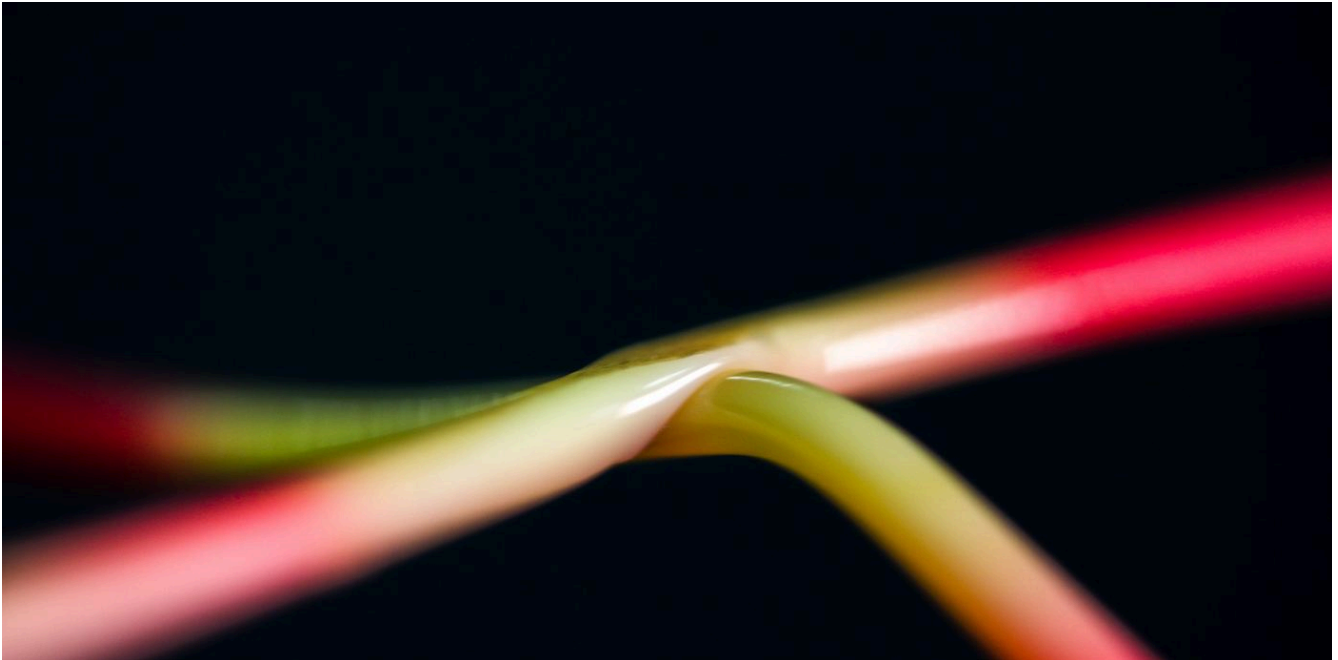


Fig. 81

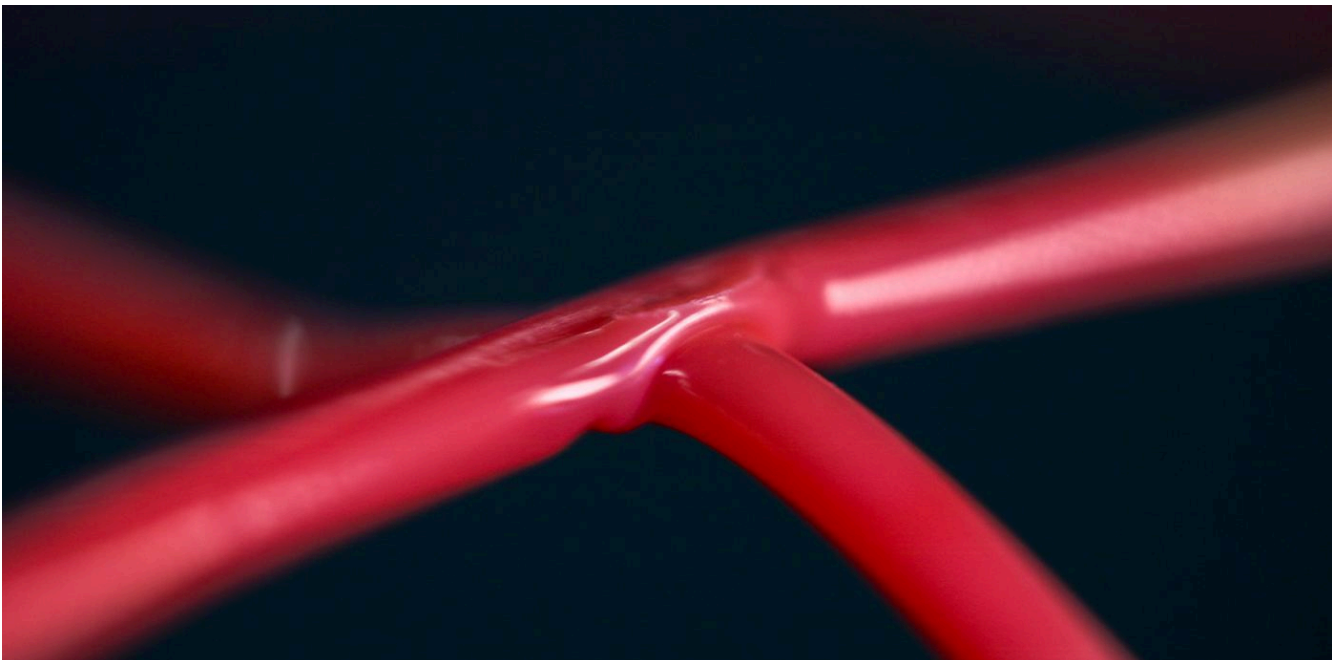


Fig. 82

Findings

This test proved that Scions thermo-chromatic filament could be used with the current uncoiling method. The reduced melting time could have been due to the smaller filament diameter, however, a smaller melting time may mean it is more effective than TPU by increasing the speed of printing.

Section Four

Exploring Forms

Because a consistent joining method has been found, the next stage of experiments is creating various forms and structures to test the possibilities of this spatial printing method. Because the ABB IRB 1200 Robotic Arm was in such a restricted work area, form creation was also restricted. The likelihood of object collisions in small forms is far greater than with larger forms because there is less space to work in. A limited number of geometries were able to be tested on the current system. More space around the robot will need to be created or a larger robot used if further form experiments are carried out.

Experimental Plan

Experiment One

Basic geometry will be explored and various forms made by altering extrusion distance.

Experiment Two

Parametric form creation using Rhino/Grasshopper will be explored. Because object collisions and joint singularities are a common issue with robotic movement, it is important to make designs parametric to be able to easily adjust a shape/movement if issues arise.



Experiment One

(71) Distance: 20mm - Duration: 9s - TCP: 2 - Press Height: 5 - Press Angle: 1
Cooldown at press bottom: 12

The varied lengths of laid filament were controlled via manual extrusion. The form was created to exhibit the ability for various shapes/nets to be created by altering the extrusion distance.



Fig. 83



Fig. 84



Fig. 85



Fig. 86

Experiment Two

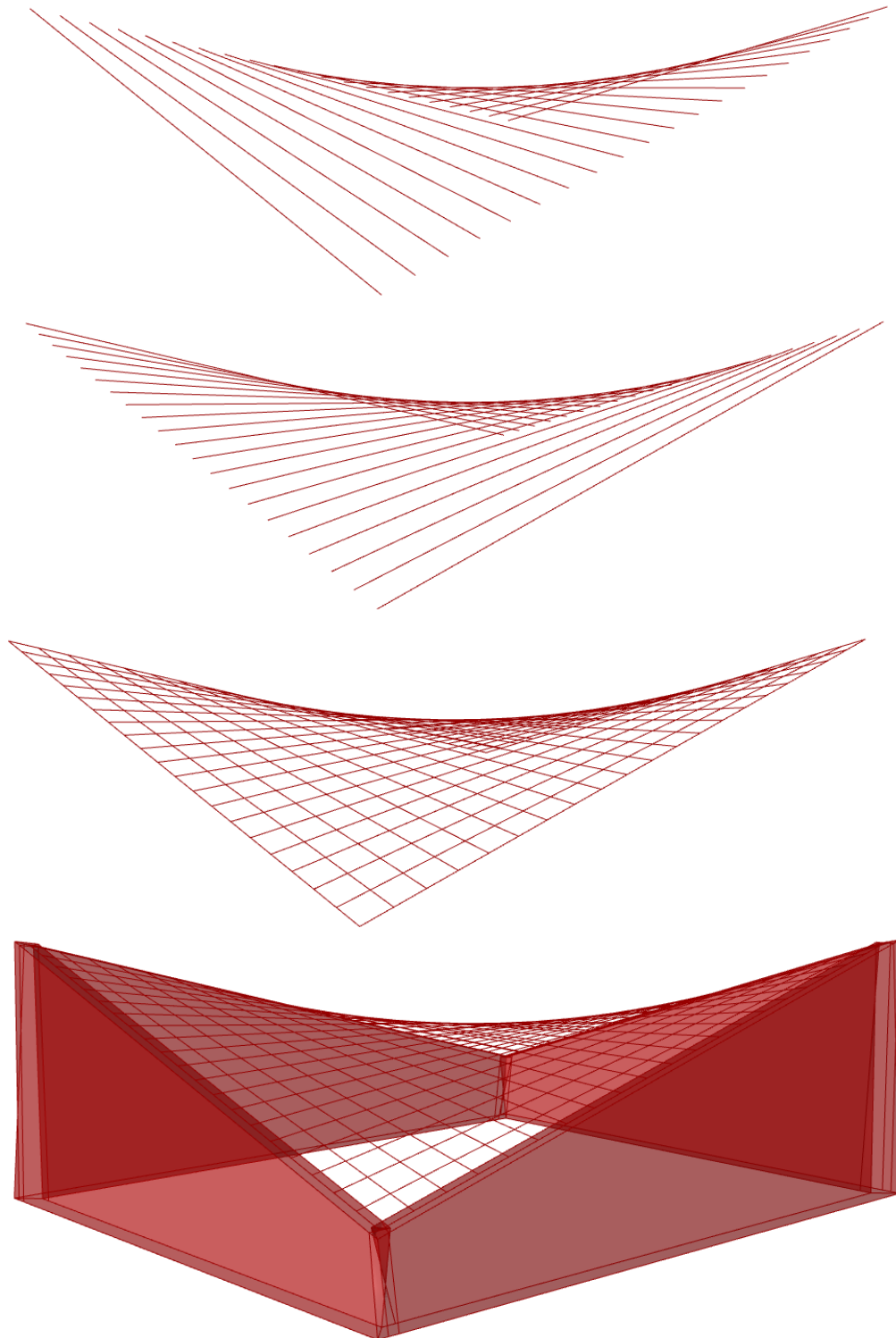


Fig. 87

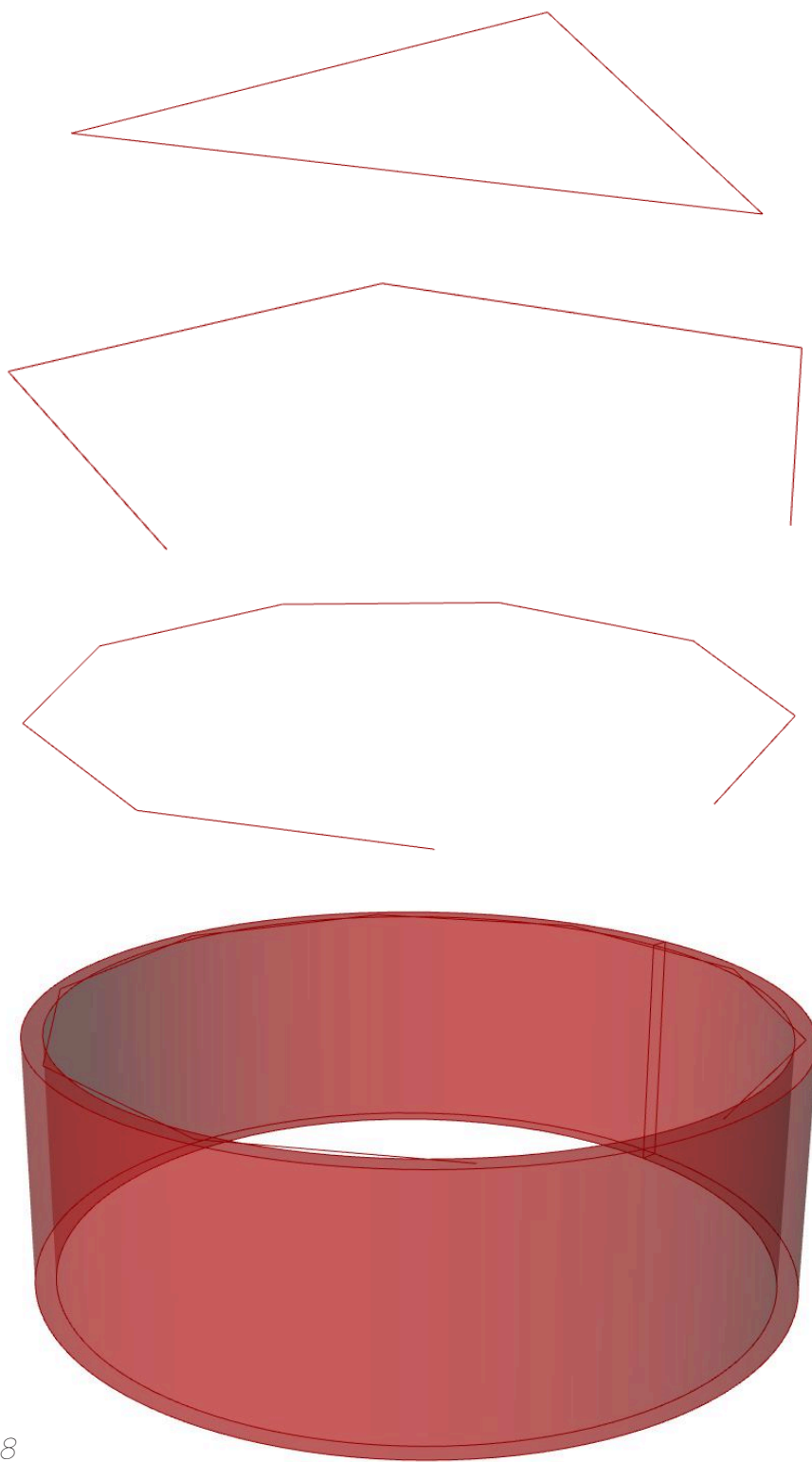


Fig. 88

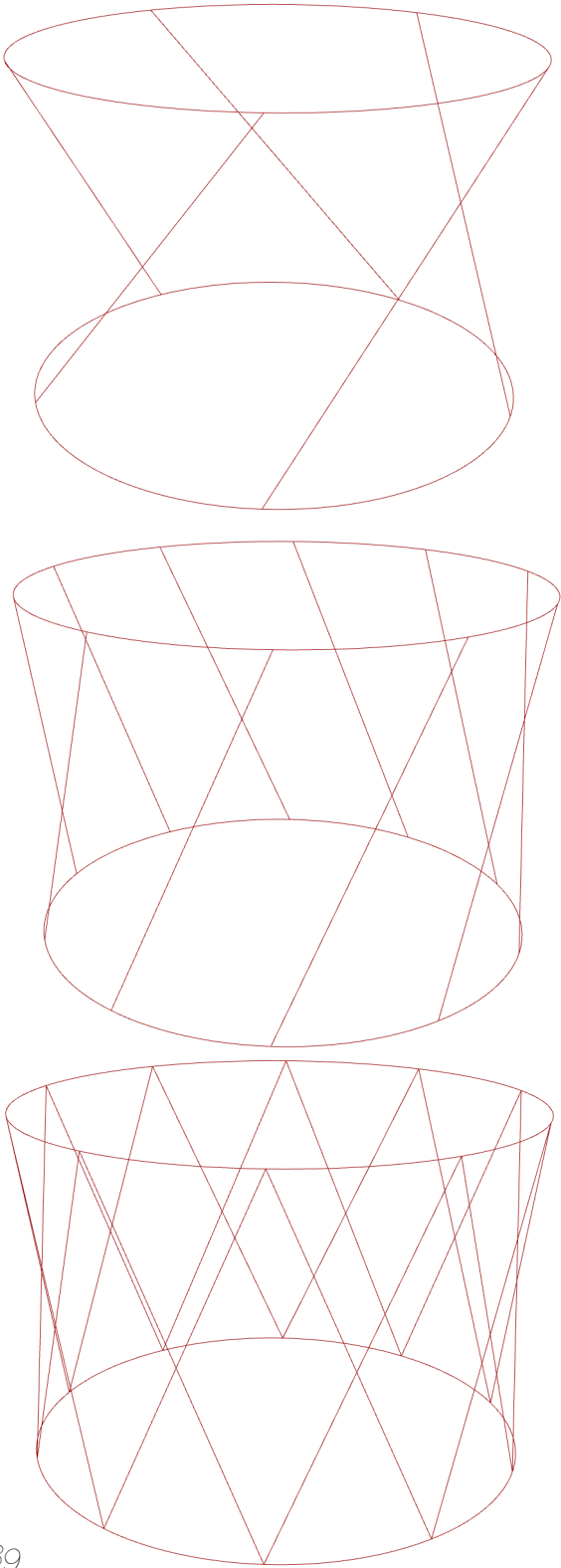


Fig. 89

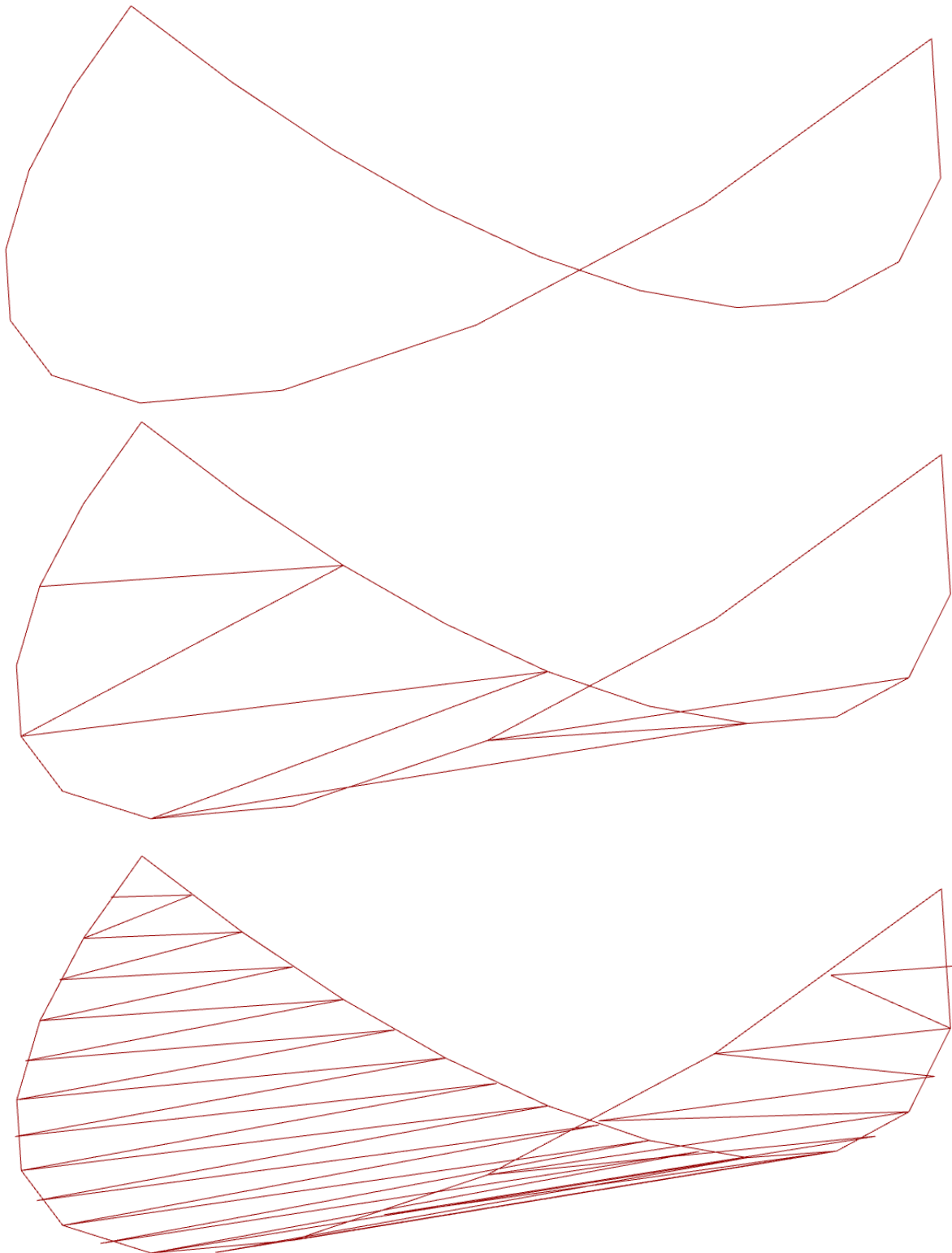


Fig. 90

Conclusion

Research Question A

Can high temperature plasma strategies be effectively integrated to create new techniques for spatial printing?

Integrating the plasma torch into spatial printing techniques has proven to be effective.

Bonds created between TPU filament have shown to have the same resilience, or become even more resilient to tension force than unmodified filament. Utilizing the intense heat produced by the torch, melting filament to its point of fusion is far more efficient than traditional techniques.

Research Question B

Does robotic uncoiling have a future in additive manufacturing, specifically creating tensile structures?

Structures built using the uncoiling technique can be created as fast as the speed of the robotic movement, or the speed at which the filament is assisted out of the nozzle. Comparing this speed to the slow heated extrusion of traditional Spatial Printing, I believe robotic uncoiling has a future in additive manufacturing.

A disadvantage of this method is correlating physical target points with their perceived location in software. Because the flexible filament is more likely to move around after being uncoiled, a way to track these locations may need to be implemented.

Because of the successful results with flexible TPU filament compared to ridged PLA filament, tensile structures made with TPU may be the best option until the uncoiling method becomes more refined using ridged filament.

Recommendations

- Automating plasma application will generate more consistent results and allow for conclusive evidence regarding the optimum plasma application time.
- Refer back to chart of possibilities and peruse any combinations that may produce superior results.
- Investigate the structural advantages of forms with multiple bonds at the same location.
- Continue testing and developing alternative forms and application for this uncoiling method. I believe the only way to develop this method is via trial and error.

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Appendices

Documentation

Test		1	2	3	4	5	6	7	8	9	10	11
Plasma Torch	Position Z 0=bottom 5=top	5	4	4	4	3	3	3	2	2	2	2
	Angle Hight (Degrees)	45	45	45	45	45	45	45	45	45	45	45
	Angle/orientation (Degrees) Back =0	135	135	135	135	135	135	135	135	135	135	135
	Distance	20	20	20	15	15	20	20	20	20	15	15
Plasma Timing	On Before Stop	n	n	n	n	n	n	n	n	n	n	n
	On At Stop	y	y	y	y	y	y	y	y	y	y	y
	Duration	10	10	10	10	15	15	15	15	20	15	10
	Intensity (V)	20	20	20	20	20	20	20	20	20	20	20
Pressing	Cooldown at press min. time	-	-	-	-	-	-	-	-	-	-	-
	Cooldown at press max. time	-	-	-	-	-	-	-	-	-	-	-
	Nozzle #	-	-	-	-	-	-	-	-	-	-	-
	Manual Press				y		y					
Fillament Properties	Laid Strand with memory	n	n	n	n	n	n	n	n	n	n	n
	Structual Strand with memory	n	n	y	n	n	n	n	n	n	n	n
	Structual Strand Support	n	n	n	n	n	n	n	n	n	n	n
	Structual Strand glued in place											
Digital Info	Point 1 Coordinate	-	-	-	-	-	-	-	-	-	-	-
	TCP Height	-	-	-	-	-	-	-	-	-	-	-
	Z Axis Press Height	-	-	-	-	-	-	-	-	-	-	-
	Press Angle	-	-	-	-	-	-	-	-	-	-	-
	Tilt	-	-	-	-	-	-	-	-	-	-	-
	Strand Distance											
	Factor Y axis											
Material	PLA	y	y	y	y	y	y	y	y	y	y	y
	TPU	-	-	-	-	-	-	-	-	-	-	-
	Strand 1 (fil. melt 1-5)	No Join, fil melt 1	No Join, fil melt 2	No Join, fil melt 0. Because of fil memory structural strand would move up in Z axis out of position of the plasma torch immediat rly after heat was	Join, fil melt 2. Observed slight crisping on top layer, torch may be too close therefore heat too intense	Join, slight bubbling of fil. Manual press spread laid strand surface area well	Join, fil melt 3. Fil started moving away from torch point as it melted	Join, fil melt 3. Fil started moving away from torch point as it melted and drooping on far side. Press wasn't as effective because structural	Join, fil melt 2.5. Fil started moving away from torch point as it melted. Slight melting of both fil	Join, fil melt 4. Fil started moving away from torch point as it melted. Melting of both side of laid fil started to droop	Join, fil melt 4. Fil started moving away from torch point as it melted. Melting of both side of laid fil started to	No join. Slight burn on laid fil. Slight melt of structural fil. Not close to bonding
Notes	Strand 2 (if Applicable)	No Join	No Join	No Join	No join, laid strand drooped before		Join, fil. Melt 3. More successfu l than	Join, fil. Melt 3. More successfu l than	Join, fil melt 3. Slight melting of both			

12	13	14	15	16	17	18	19	20
2	3	2	2	2	2	2	2	2
40	40	40	40	40	40	40	40	40
135	135	135	135	135	135	135	135	135
20	20	20	20	20	20	20	20	20
n	n	n	n	n	n	n	n	n
y	y	y	y	y	y	y	y	y
10	10	10	15	15	15	15	15	15
20	20	20	20	20	20	20	20	20
-	-	-	10	10	10	-	-	10
-	-	10	-	-	-	10	10	-
1	1	1	1	1	1	1	1	1
y	y	y	y	y	y	y	y	y
n	n	n	n	n	n	n	n	n
n	n	n	n	n	n	n	n	n
365.8, -67.32, 48.6								
12	10	10	10	8	8	8	8	8
-	8	13	13	13	11	11	11	11
-	-	-	-	-	-	-3	-3	-3
-	-	-	-	-	-	-	-	-
80	80	80	80	80	80	80	80	80
y	y	y	y	y	y	y	y	y
-	-	-	-	-	-	-	-	-
No join, Fil memory movement prevented fil to heat up. Have to aim torch lower because of coil memory	Noticed fil memory of laid strand curving up in Z axis. This is okay because of the downward press in the Z axis applied soon after heat.	Because of coil memory, when allowed to cool at press max it creates a bent joint	No Bond. Bond 1 fil started to move away because of torch air	No bond. Reduce Z axis press 1-2mm. Too much pressure on structural strand.	No bond, try pause at press max	Join, fil melt 4. Slight melt of both. Bubbling of laid fil. Because of cooldown at max press, fil hardend with a kink. This will result in a weak point.	Join, fil melt 4. Bubbling laid fil. Drooping back of bond. Join didn't move	Join, fil melt 3. Slight droop at back on bond.
			Bond, fil melt 4. Because of manual			Join, fil melt 3. Join moved slightly in		

Trv and cre

21	22	23	24	25	26	27	28	29	30
2	2	2	2	2	2	2	2	2	2
40	40	40	40	40	40	40	40	40	40
135	135	135	135	135	135	135	135	135	135
20	20	20	20	20	20	20	20	20	20
n	n	n	n	n	n	n	n	n	n
y	y	y	y	y	y	y	y	y	y
15	15	15	15	15	15	15	15	15	10
20	20	20	20	20	20	20	20	20	20
		10	10						
10	10			10	10	10	10	10	10
2	2	2	2	2	2	2	2	2	2
y	y	y	y	y	y	y	y	y	y
n	n	n	n	n	n	n	n	n	n
n	n	n	n	n	n	n	n	n	n
-5	-5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5
4	4	6	6	6	6	10	10	10	10
12	12	12	12	12	12	12	12	12	12
-	-	-	-	-	-	-	-	-12.5	-12.5
80	80	80	80	80	80	80	80	80	80
y	y	y	y	y	y	y	y	y	y
-	-	-	-	-	-	-	-	-	-
No join, melt 2. Melted fil was pushed up towards the foot and stuck to the foot. Foot may be too close to fil - tried to raise foot up slightly	No join, melt 2. Melted fil was pushed up towards the foot and stuck to the foot. Starting position may be too close to structural fil. Will	Join, melt 4. Laid fil moved away from structural fil slightly because of air pressure. Good result. Less of a kink/weak point at the far side of bond	No join, melt 4. Laid fil moved away from structural fil slightly because of air pressure. Slight bond with foot	Join, melt 4. Laid fil moved away from structural fil slightly because of air pressure, resulted in weak join. Torch is pointing at the correct point but	No join, melt 4. No melt on structural fil	No join, melt 4. Fil moving away.	Initial join. Fil melt 4. too much on laid fil. Bond broke because of fil memory and angle of movement away.	Join, melt 4. Good join, too much heat on laid fil. Best result straight after bond, no kink.	Join, melt 3. Very weak. Uneven melt of fil. Need to change torch position. Torch air pushing fil away from heat.
		Join, melt 4. (simulate d join on bond 1).	Join, melt 4. Laid fil moved away from	Join, melt 4. Moved torch to be more precise	No join, melt 4. Fil moving away.	Join, fil melt 4.5. Slight kink after bond	No join. Fil memory was less in laid fil	Join, slightly stronger. Melt 4. Laid fil	

31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
2	2										2	2				
90	90										90	90	90	90	90	90
0	0										0	0	0	0	0	0
25	20										20	20	20	20	20	20
n	n										n	n	n	n	n	n
y	y										y	y	y	y	y	y
15	15	5	5	10	7.5	7.5	7.5	5	8	8	10	8	8	8	8	8
20	20	20	20	20	20	20	20	15	20	20	20	20	20	20	20	20
15	10										15	15	15	15		
															15	15
3	3	-	-	-	-	-	-				3	3	3	3	3	3
								y		y						
y	y										n	n	n	n	n	n
n	n										n	n	n	n	n	n
n	n										n	n	n	n	n	n
5	5										5	5	-	-	-	-
6	6										6	6	-	-		10
5	5										5	5	-	-	-	-
15	15										15	15	-	-	-	-
											140	140		140	140	140
											5	5	5	5	5	5
y	y										-	-	-	-	-	-
-	-	y	y	y	y	y	y	y	y	y	y	y	y	y	y	y
Join, melt 3. Promising results. Bond broke when moving away because of angle of move in relation to nozzle bend (fil memory).	No join. Filament memory is becoming too much of an issue. Will try a flexible filament	Manual test holding fil under torch the pressing together, not a lot of force on the press. Small ammount of melting was observed but not a	Same observati on as previous test	Entire fil started to melt at around 7.5s. When pressed a good bond was created	Bond. Seemed like the idea time for a join to occur. Fil bonded easily together without any added press	Bond. Seemed like the idea time for a join to occur. Fil bonded easily together without any added press	Bond. Manual press seemed to spread bond and make it stronger	Fil melted very fast. Created a slight burn on fil, may be too close to heat	Join, Bond looks even and well joined	Join, Bond looks even and well joined, more surface area touching than non press	No join, structural fil melted through.	Join, very weak. Plasmecement is hard to get correct. Also movement needs some work	Join. Solid bond was created with no movement	Join. Was repeated on same rig, same fil but flipped. Previous fil became melted and loose/warped in the vice so structural fil wasn't in exact	Join. Solid bond was created with no movement	Join. Was repeated on same rig, same fil but flipped. Previous fil became melted and loose/warped in the vice so structural fil wasn't in exact
													Join. Solid bond was created with no	Join. Solid bond was created with no	Join. Solid bond was created with no	Join. Solid bond was created with no

48	49	50	51	52	52	53	54	55	56
90	90	90	90	90	90	90	90	90	90
0	0	0	15	17	17	17	17	18	18
20	20	20	20	20	20	20	20	20	20
n	n	n	n	n	n	n	n	n	n
y	y	y	y	y	y	y	y	y	y
8	8	8	8	8	9	7	8	8	7
20	20	20	20	20	20	20	20	20	20
15	15	12	12	12	12	15	15	15	15
3	3	3	3	3	3	3	3	3	3
n	n	n	n	n	n	n	n	n	n
n	n	n	n	n	n	n	n	n	n
y	y	y	y	y	y	y	y	y	y
y	y	y	y	y	y	y	y	y	y
2	4.5	4.5	2.5	5.3	2	2	2	2	2
5	5	9	6.5	5.5	5	5	5	5	5
1	1	-5	-2.5	-2.5	1	1	1	1	1
-	-	-	-	-	-	-	-	-	-
140	140	140	140	140	140	140	140	140	140
9	9	9	9	9	9	9	9	9	9
-	-	-	-	-	-	-	-	-	-
y	y	y	y	y	y	y	y	y	y
Join. Might be best join yet. Press was effective.	Join. Tried to hold support fil in only the middle. Laid fil pulled and deformed structural fil.	Join, Good join because laid fil is drooping and allowing good heat contact.	Join, Weak because of uneven heating. Torch was aimed at laid fil too much. Will move intersection point closer	Bond, Good melt on both. Not much spread on press operation	Melted struc fil. Plasma was on for slightly too long	bond. Great bond, press worked well. Slight over 8 seconds so struc fil melted	Great bond. Slight uneven bond. Need torch angled slightly lower	Bond, getting consistent. Created a mat	Good consistent bond
Join, slightly worse than previous				No bond, structural fil		bond. Great bond, press worked			

57	57		58
90	90	90	90
18	18	18	18
20	20	20	20
n	n	n	n
y	y	y	y
8	8	8	8
20	20	20	20
15	15	15	15
3	3	3	3
n	n	n	n
n	n	n	n
y	y	y	y
y	y	y	y
2	2	5	2
5	5	4	5
1	1	1	1
-	-	-	-
140	140	140	140
9	9	9	9
-	-	-	-
y	y	y	y
Test mesh with leaving torch on over already laid fil. Worked well as a proof of concept, bonds were made where fil overlapped.		Initial bond, because of previous fil stretch and the stretch on the fil after second join, Both laid fil were very far apart from each	First continuous test. Bond (except where hot glue contaminated). Direction of fil after melt/bond is an issue with the larger the rotation the more
If fil was laid tight across bonds, the melting			

59	59.5	60	61	62
90	90	90	90	90
18	18	18	18	18
20	20	20	20	20
n	n	n	n	n
y	y	y	y	y
8	7	6	5	4
20	20	20	20	20
15	15	15	15	15
3	3	3	3	3
n	n	n	n	n
n	n	n	n	n
y	y	y	y	y
y	y	y	y	y
2	2	2	2	2
5	5	5	5	5
1	1	1	1	1
-	-	-	-	-
140	140	140	140	140
9	9	9	9	9
-	-	-	-	-
y	y	y	y	y
Redo of percieved best result		Still a very good bond visually, not quite as deep as longer plasma	bond, look good, not as deep but less filament sag when heated on second bond	y

63	64	65	66	67	68
90	90	90	90	90	90
18	18	18	18	18	18
20	20	20	20	20	20
n	n	n	n	n	n
y	y	y	y	y	y
7	7	5	7	7	7
20	20	20	20	20	20
15	15	15	15	15	15
3	3	3	3	3	3
n	n	n	n	n	n
n	n	n	n	n	n
y	y	y	y	y	y
y	y	y	y	y	y
2	2	2	2	2	2
5	5	5	5	5	5
1	1	1	1	-2	1
-	-	-	-	-	-
140	140	140	140	140	140
9	9	9	9	9	9
-	-	-	-	-	-
y	y	y	y	y	y
Continuo us test. Betetr results with less hot glue at bond points. Simulate d fil extrusion , otherwis e friction was too much and pulled	Continuo us. Turned on for last 90D of turn. Fil inbetwee n bonds was far straighter , more of a significan t kink where bond was and laid	Tested with small sideways moveme nt along struc path. 5mm (1+4) Because of fil memory/ pull in outward dirsrctioin the 5mm was too	Circular structure test. Good bond. Proof of concept that circular loops can be produced with an extruder (although this was simulated).	Paralell Supporte d (no glue). Strted off bonding well, because the struc fil wasn't taught enough (or it loosened with heat from plasma), the end	Paralell unsupport ed across glue bonds

68	69	70	71	72
90	90	90	90	90
18	18	18	18	18
20	20	20	20	20
n	n	n	n	n
y	y	y	y	y
7	7	6	5	6
20	20	20	20	20
15	15	15	15	15
3	3	3	3	3
n	n	n	n	n
n	n	n	n	n
y	y	y	y	y
y	y	y	y	y
2	2	2	2	2
5	5	5	5	4
1	-2	-2	-2	1
-	-	-	-	-
140	140	140	140	140
9	9	9	9	9
-	-	-	-	-
y	y	y	y	y
Paralell unsupport ed across glue bonds	Paralell supporte d with glue bond. Far better result fil stuck together for majority of length. Speed of travel and TPU height could be adjusted	small sideways moveme nt along struc path. 9mm (5+4) Because of fil memory/ pull in outward dirsctioin the 9mm was still too small and a	small sideways and inward moveme nt along struc path. (5+4)x+4 y. This created a far sharper turning point and a cleaner/c onnected	Circular net. Consisant bonds all around.

