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Development of Multimaterial Additive Manufacturing Systems for Embedded Electronics

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Abstract

Hybrid additive manufacturing (AM) to integrate discrete material systems and structures in a monolithic part is a growing research interest. The layer-by-layer deposition system of the AM build process allows users to integrate multiple materials using custom made tools added to the gantry systems. State of the art machine development efforts are highly focused on thermoplastic based material extrusion systems. Compared to the significantly matured thermoplastic material extrusion AM system, thermoset systems are not well positioned in the market due to the lack of integrated tooling. This research develops a wire deposition tool that is designed to embed wire in a photocurable thermoset. Thermoset is relatively stable and does not require heat for implanting wire. The proposed design method has a more rapid production rate as the extrusion process can be conducted without any interruptions. The final design was manufactured in PLA with a traditional FDM machine allowing multiple design iterations to be made quickly. The final design will be printed on an SLA machine for more accurate, robust parts.

Introduction:

Multimaterial additive manufacturing systems are one of the most highly sought after technologies in the manufacturing community. Integration of the multiple materials in a monolithic structure within a single build is a unique characteristic of any AM system. Particularly, thermoplastic based material extrusion systems are ubiquitously developed from the desktop scale to large scale. Custom made tools are also developed and added to existing systems to incorporate multiple materials. Below we are providing brief yet to the points literature survey on the tool developments for the thermoplastic based material extrusion systems.

1. Thermoplastic Deformation Based Wire Embedding

The two main methods for wire deposition are ultrasonic and thermal embedding. Both methods increase the energy of the substrate to melt the surface. Ultrasonic has been the most tested form of wire deposition. Tests in multi-axis conformal deposition have been successfully performed. [4] The ultrasonic deposition process rapidly vibrates a horn to create friction. [1] The friction heats the surface and allows for various materials to be embedded. Ultrasonic horns can deposit copper wire, conductive ink, and wire meshes. However, there are some drawbacks. While conductive ink is easier to implement, its electrical resistance is much higher than traditional copper wire. Additionally, if deposition of the ink is not consistent the trace could be interrupted leading to a poor connection or broken circuit. Due to the high frequency vibrations while embedding solid wire, wear on the horn and wire breakage were common. Thermal deposition works in a similar way. However, rather than using friction to heat the substrate, it uses a heating block to heat the wire which melts the surface. Because it is only heating the embedding material, only copper wire can be embedded. [2] Due to the thermal conductivity of copper wire heat can travel down the wire and uproot previously embedded wire. That means this method has issues with sharp turns and retaining wire in the substrate. A difficulty that both methods face is the deformation of substrate surface. FDM relies on clean, smooth surfaces for printing. Rough or warped surfaces can lead to poor adhesion between layers causing cracks to form on the part. Rough surfaces can also cause clogging in the filament nozzle.

2. Channel Embedding

In channel embedding a trench is first created during printing or machined with end milling. [1] Wire is then placed in the trench and retained by friction. A printing head will then deposit new material over the placed wire to secure it in place. Although this method is the simplest it has several issues. Most concerning is its struggle to retain embedded material both before and after the substrate is layered over it. Leading to poor traces and damaged circuits. If the channels are decreased in size, tool wear will increase.

3. Coextrusion

In current coextrusion methods gallium liquid metals (LM) are fed through a nozzle and coated in SEBS elastomer. [3] The use of this method has not been tested in 3D printing and only the tool head was tested. Ensuring proper extrusion rate of each fluid was essential. If it was not perfect the liquid metal core would bead up and not become a continuous cylinder. Additionally, the syringe delivering the liquid metal had to stick out beyond the extruder or similar issues of beading would occur. At the end of the test flexible wires were created. However, the liquid metal used was a factor of 100 times more expensive than traditional copper wire making it economically difficult to implement in large scale manufacturing.

Proposed Method – Coextrusion of Solid Copper Wire with Photocurable Thermoset

The tool being created was based on the coextrusion method. Rather than using the LM a solid copper wire will be fed through the nozzle and in place of the SEBS a photocurable resin will be used. It is expected to overcome some existing challenges we surveyed in the thermoplastic systems. In our proposed design, there is no need for thermal energy to embed the wire. Therefore, it is expected there should be diminished warping of the print surface. Thermosets are known to be resistant to heat, which means if the wire is heated under electrical load, it will not shift. From the literature survey we learned that one of the largest issues faced by other methods is the accuracy of 90 degree turns [1,2]. While creating sharp corners using the proposed design the laying of wire will pause to wait for the curing of the thermoset. Once. It is cured the wire will have a new anchor point and will be able to be laid perpendicular to its old path.

Design of the Tool – Machine Interfacing and Considerations

The tool is designed to interface with the Hyrel Hydra 21. The Hydra has up to 5 head slots that are all attached to the XY carriage while printing. This means the tool's width must be constrained to 34 mm so that other tools can fit on either side. Additionally, the tips of the heads being used for a single print must be on the same plane. If one is longer than the others it will crash into the bed or the part during printing causing damage to the print, the head, or the bed.

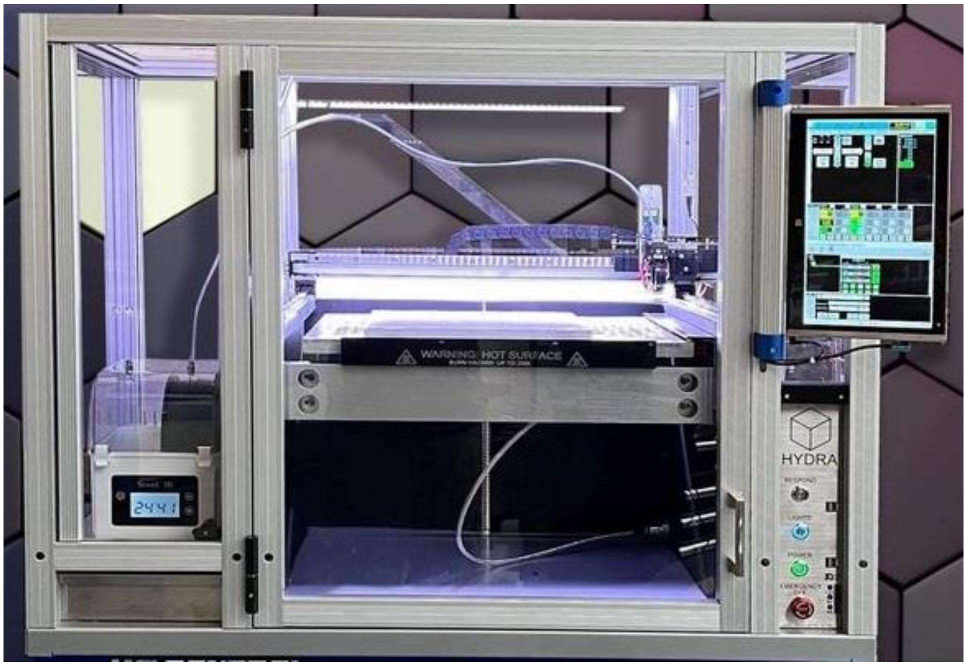

Figure 1: Hydra 21 [5]

Design of the Tool – Substrate Channels

With these constraints in mind a design was created. For coextrusion of the wire and gel there are two channels. The first channel, for the wire, is created by a syringe needle. The syringe for the original design is 23 gauge (0.337 mm) which was chosen to deposit 30 AWG wire (0.254 mm). This gives a loose enough fit while preventing the wire from buckling inside the needle. The syringe can be changed to deposit different gauges of wire. The second channel is set at a 20° angle from the wire channel. This channel will carry the gel. The syringe will ensure that they stay separate until exiting the tip of the tool.

Design of the Tool – Substrate Drive System

The wire will be driven much like a common FDM printer direct drive system. The gears for the direct drive were placed as close to the syringe entrance as possible to ensure the wire would not buckle. If it did buckle the wire would not pass into the syringe causing a clog to occur. The driving method for the gel is a syringe deposition tool already created by Hyrel. This tool head will connect to the wire deposition tool via a tube. Gcode will be created that will extrude the correct amount of gel for smooth deposition. The rate of deposition can be edited directly in the Hyrel software. This makes it easy to run experiments at different deposition rates to determine which is the best for printing.

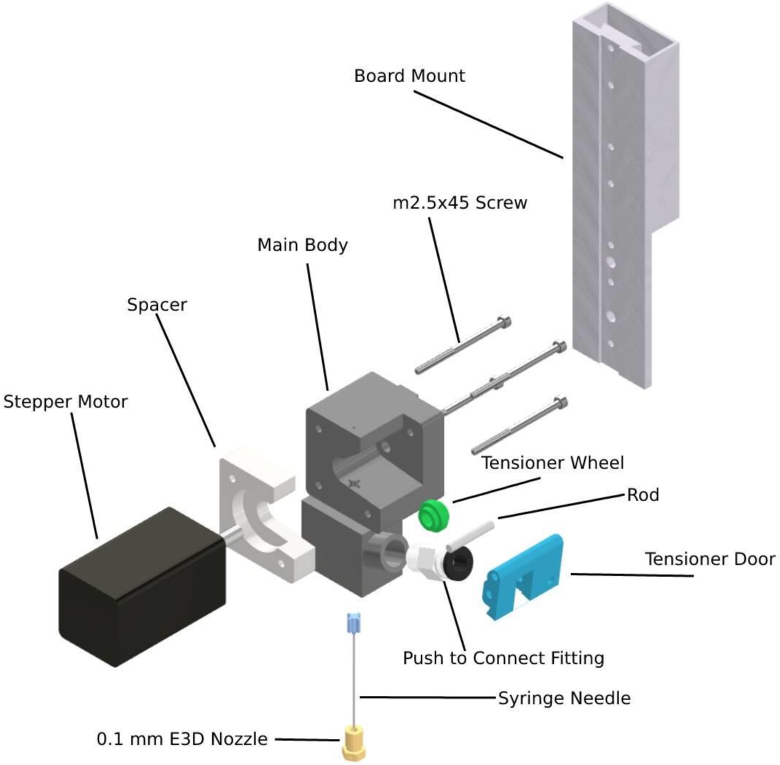

Figure 2: Full Tool Assembly

Parts List

1. Main Body – 1x
2. Spacer – 1x
3. 28 mm x 28 mm stepper motor – 1x
4. Spool of wire – 1x
5. M2.5x45 screw - 4x
6. .1 mm E3D nozzle – 1x
7. Syringe needle – 1x
8. 3 mm diameter 20 mm length metal rod – 1x
9. Extruder bearings – 2x
10. Tensioner wheel – 1x
11. Tensioner door – 1x
12. Push-to-connect fitting – 1x
13. Hyrel software development kit (SDK) board – 1x
14. Hyrel board mount – 1x

15. Hyrel syringe deposition head – 1x

Assembly Design

For easy cleaning, wire insertion, and printing the design was split into two parts; the main body and a spacer. The main half of the body holds the channels for the syringe and gel as seen in figure 4. Originally, the main body of the tool was split into two parts along the ZX plane of the syringe. This was so the syringe could be placed into one side of the body and then enclosed by the other half. However, concerns of gel leakage arose so it was determined that the syringe should be held by a single piece. There were also difficulties cleaning the internal structure, placing the syringe, and loading the wire with the single body design. Therefore, a part of the main body was cut away to allow easier access while maintaining proper dimensions for the bolts. These bolts are used to attach both main body parts to the stepper motor and act as a hinge for the tensioner door. The tensioner door houses an idler gear that adds pressure to the gear teeth driven by the stepper motor. The tension is created using a spring for a constant and easily adjustable force. Once all parts are attached to the stepper motor the tool is attached to a Hyrel board interface. This interface connects directly to the Hydra 21 and allows the board to seat into the connector. Since all tool heads must be at the same height the tool is able to be adjusted in the z direction. The gel will be delivered via the Hyrel syringe deposition device as seen in figure 3. A hose will connect the syringe depositor to the tool body via a push-to-connect fitting.

Figure 3: Hyrel Syringe Deposition Device [6]

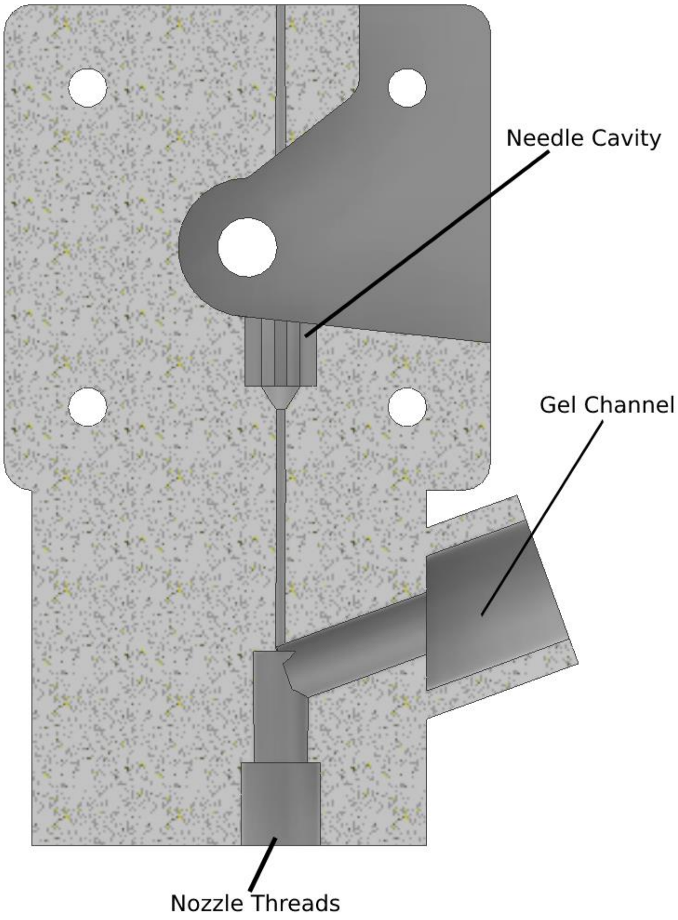

Figure 4: Tool Cross Section

Elecronic Control Systems

To interface the tool with the Hyrel system a Hyrel designed SDK board will be used. This board was designed to drive a typical FDM hot end but has the potential to drive a multitude of different systems. The SDK board has an A4988 micro stepping motor driver which is a common motor driver used in many different 3D printers. This will allow the board to control the 28 mm stepper motor chosen for this application. The board also offers other connections such as 12 volts, 5 volts, PWM (Pulse Width Modulation) signals, RTD connections, and switches that can be controlled by sensor inputs. This will be vital for the future of the tool. To make it completely autonomous, a wire cutter will be designed, and other connections will be utilized.

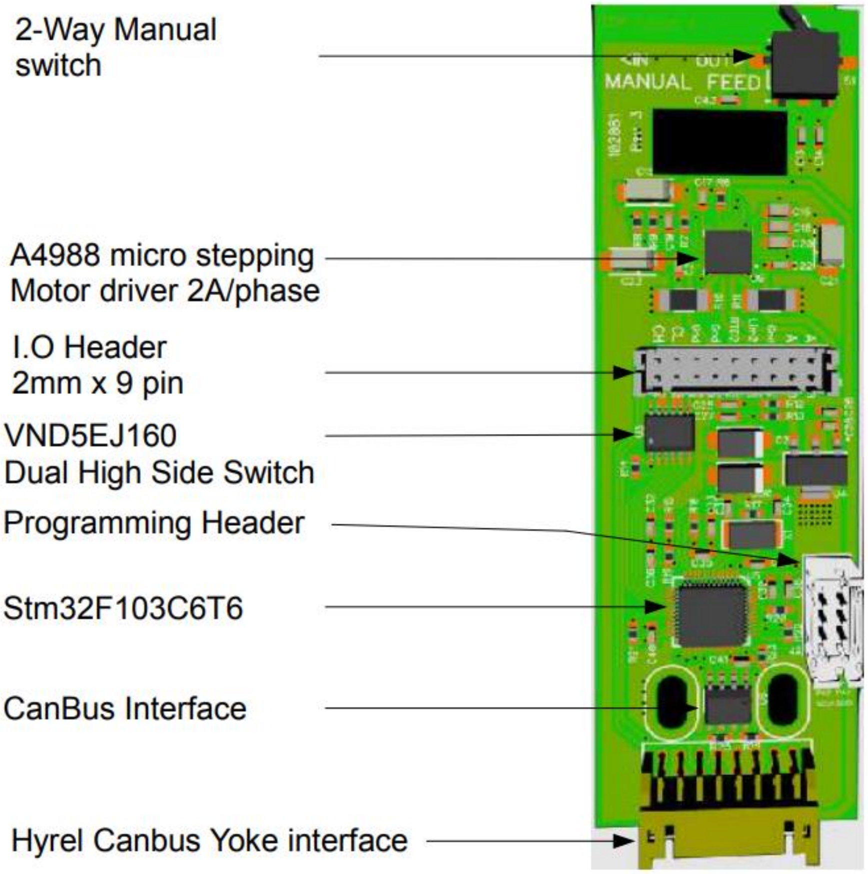

Figure 5: SDK Board [7]

Software and Control Method

For slicing parts Prusa Slicer will be used. Hyrel provides recipes for the software that allows Gcode to be generated for the Hydra 21 directly from Prusa Slicer. The slicer includes the ability to change heads during the print, which is vital for the tool's success. This will allow the printer to extrude PLA from a traditional head then swap to the wire extrusion head and change back once the wire has been deposited. The software on the Hydra known as Repetrel will also be used to control the tool. Built into the Repetrel system is a cloning function. This function was intended to print multiple parts at the same time from multiple heads by choosing a master head and mimicking the extrusion on other heads. In this application the cloning function will be used to drive the syringe deposition tool. This will be accomplished by choosing the main body of the tool as the master tool and cloning those moves to the syringe. That means that whenever the wire stepper is activated the syringe stepper will also be activated. To further control the gel, the extrusion rate can be overridden on the head software.

Results and Future Plans

The above assembly was built to test fit and function. A UV curable solder mask was used as the thermoset during testing. Both extruded at the same time as planned, however, the mask was too viscous and did not hold its shape after extrusion. A thermoset with a higher viscosity is desired, but if it is too thick the fluid will be difficult to pump through the system. Therefore, the thermoset chosen should be shear thinning to allow for easier flow while under pressure. Additionally, since the main body was printed in PLA the push-to-connect fitting was not sealed properly and there was leakage. Finally, the needle was not secured with epoxy so some of the mask traveled up the needle channel. Eventually, the syringe deposition will have to be replaced with a tool that has a larger reservoir as the current tool only holds 10 mL of liquid. A larger reservoir will prevent the need for refilling during longer prints. After testing, a larger gauge needle might be needed to allow for less friction as the wire passes through. Any defects in the wire increase frictional forces and prevent the wire going through smoothly.

Figure 6: Mask Spreading Post Coextrusion

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