Wire Embedding 3D Printer

Group 1013
Jacob Bayless, Mo Chen, Bing Dai

Engineering Physics
University of British Columbia

April 8, 2010

Preface

This project began when, seeking a self-sponsored project, we decided to pursue the concept of open-source hardware. While searching for a project to develop, we happened upon the RepRap 3D printer. The potential to close the gap between software and hardware that a 3D printer could offer was apparent, and we immediately set out in search of ways to improve the device. Thus began what would become the SpoolHead project, but we three may not claim all of the credit.

A large share of the credit goes to the inventors of the RepRap itself, primarily Adrian Bowyer and Ed Sells, but also many other contributors. We also should thank Sebastien Bailard for promoting our project and helping us manage documentation.

All of our work on the RepRap would never have been possible if we had not come across Wade Bortz, an inventive and unbelievably generous Vancouver RepRap developer who offered to print us a full set of Darwin parts. When we found that our extruder didn't have enough torque, Wade gave us one of his own geared extruders to "test out". He patiently bore our nagging questions and bicycled all the way to the University of British Columbia campus to attend our presentations. Wade represents the best example of how a community can build itself up around a project and bring people together.

It was already near to the end of February when we came into contact with Mr. Dany Lipsker, an inventor from Israel who had over a decade ago developed a technology quite similar to what we were aiming to achieve. Mr. Lipsker's technology was ahead of its time, but the market for 3D printing was in its infancy, so it did not catch on. He offered us a great deal of advice, not just for our project, but also about choosing a career as an inventor and the importance of keeping a flexible mind. For that we are very grateful.

From the advice and help that Bernhard Zender, Dr. Jon Nakane, and Prof. Chris Waltham offered us, to our lab space and an endless supply of sorted nuts and bolts, the support we have received from the UBC community has also been exceptional. We could never have succeeded without the tireless efforts of our Engineering Physics Project Lab directors.

Executive Summary

The RepRap 3D printer is an open-source rapid prototyping machine capable of producing most of its own structural components. This printer can be built and run at a much lower price than a commercial 3D printer, and used to create copies of itself. Its first model, Darwin, was released online in 2008. It can print durable and accurate parts from thermoplastic materials, but it cannot currently print with electrically conductive materials. The Gada Prize, established in 2010 to advance the RepRap project, is a $80,000 grand prize and $20,000 interim prize that will be awarded to a machine like the RepRap which meets several additional specifications, including the ability to print conductors.

The wire-embedding 3D printer project adds a wire-printing tool head, "SpoolHead", to the RepRap Darwin model. The SpoolHead is a promising new approach to manufacturing hybrid wire-and-plastic parts, and an attempt to meet the conductive materials requirement of the Gada prize.

This report documents the development and testing of the first SpoolHead prototype, a wire-printing mechanism that uses a servo-actuated mechanical pencil to insert metal wires into the heated surface of a printed thermoplastic part. The wires are then to be cut by a solenoid-actuated mechanism that shears the wire inside the main tube of the print head.

Benchtop tests performed to validate the design philosophy of the SpoolHead gave positive results. The print head was then manufactured and tested on two designs proposed at the outset of the project, a rectangle and a spiral. The SpoolHead was able to print the spiral design to within the specified ±0.5 mm tolerances outlined at the beginning of the project. The printed rectangle was out of specification, with straightness errors of up to 0.8 mm and dimensions short by 1 mm of the design length. However, the errors responsible for this have been identified and can be easily resolved in future versions.

It was found that the cutter design failed, requiring manual intervention in the cutting process. While alternative methods have been proposed to improve the cutter, a fully satisfactory solution remains to be found.

Numerous recommendations are presented that outline how the future development of the SpoolHead should proceed, beginning with investigating replacing the cutter. Methods for future miniaturization of the device are presented, as well as plans for improved electronics and software.

Contents

List of Figures

1 Background and Motivation

1.1 3D Printing

Current manufacturing techniques can be divided into three categories: Additive, subtractive, and deformation. Deformation manufacturing is the process of bending, stretching, or molding a solid block of material to form a desired part. Subtractive manufacturing , such as milling, lathing, or laser-cutting, begins with a bar, rod, or sheet of material and cuts it into the desired (smaller) shape. Additive manufacturing, however, builds a part by successively adding and fusing raw material to a workpiece; examples include laser sintering of metal powder, electron beam melting, and 3D printing.

3D printing comprises many techniques, but they all share the common feature of a print head that selectively deposits material in the required geometry, layer by layer, to build up a 3D shape. In one technique, developed by Stratasys Inc. and known as fused deposition modeling (FDM), a thin filament of thermoplastic is heated above its glass transition temperature and extruded through a fine nozzle, which is moved over a substrate to produce a two-dimensional pattern. The substrate material is selected such that the plastic adheres, but can be easily removed when the part is completed. Subsequent layers of plastic fuse with the ones below and are printed in a similar manner, building up a three-dimensional part. Most systems also extrude a support material which can be dissolved in a basic solution, allowing parts to be printed with large overhang features and hollow spaces.

Due to prohibitively high fixed and operating costs, commercially manufactured 3D printers are used almost exclusively by businesses and industry, having minimal market penetration into the personal market. A desktop 3D printing machine from Stratasys costs $16,000 CAD ($14,900 USD). [1]

1.2 RepRap

The RepRap project [2], short for "Replicating rapid prototyper", is an open-source, low-cost 3D printer that is capable of printing as many of its constituent parts as possible. A sufficiently developed RepRap should be flexible enough to be able to manufacture a copy of itself. This ambitious project has to date produced two printer models, the "Darwin" and its successor, "Mendel". Like Stratasys, RepRap uses the FDM method of 3D printing, but aims at the personal rather than commercial market. The cost of a RepRap ranges between $700 (€395) for a machine assembled from parts to $1340 (€750) for an off-the-shelf model. [3] [4]

As an open-source project, RepRap has extensive documentation online through its website, which can be studied to obtain a complete understanding of how the machine works. Furthermore, RepRap has an active community of developers and users, who can provide

technical assistance. The authors have found this to be an invaluable resource. In particular, RepRap builder Wade Bortz supplied the authors with printed parts to build a Darwin, as well as a geared extruder of his own design (referred to as "Wade's extruder").

1.2.1   RepRap Specifications

Following are specifications for the Darwin-model RepRap, the model that was used in this project.
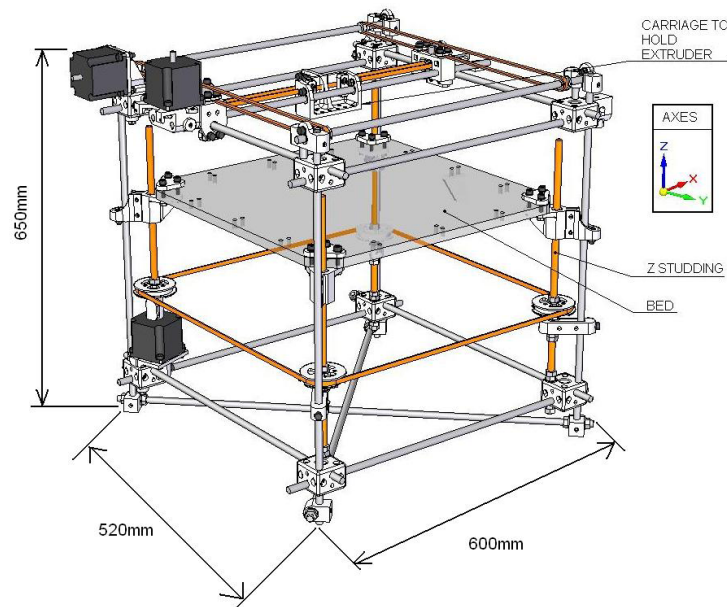
Figure 1: Darwin cartesian robot overview

The Darwin consists of an FDM extruder mounted on a Cartesian 3-D robot. The robot's Z stage forms the printing bed to support the substrate, while the XY stage carries the extruder above. During a typical print procedure, the XY stage will translate the extruder print head to trace the required 2D cross-section on the printing bed, and then the Z stage lowers to allow the process to be repeated for the subsequent layer.

Actuation is performed by stepper motors driving timing pulleys; reported precision is ± 0.1 mm for the Z-axis and ± 0.5 mm for the XY axes. This construction gives the Darwin a total build volume of 5.5 litres.

Presently the RepRap lacks a soluble support material.

Figure 2: Wade's extruder

Wade's plastic extruder drives a 3mm filament of polylactic acid (PLA) thermoplastic. The filament is pressed between a stepper-driven toothed wheel and a ball bearing,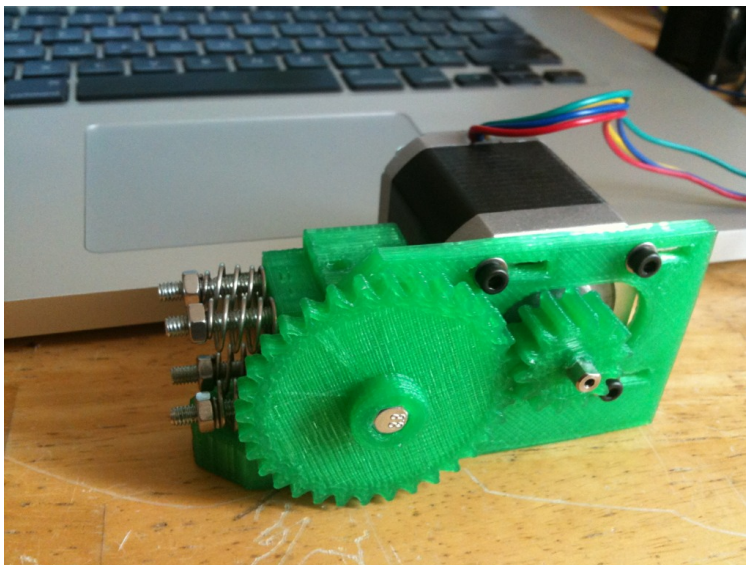 and thereby forced into the nozzle. The nozzle is an insulated tube containing a Nichrome wire heating element and a temperature sensor, terminating in a fine (under 1 mm) hole through which the plastic is extruded. The RepRap is already a fully operational 3D printer system, complete with electronics and several software packages. The electronics have been designed in a modular fashion, to allow expansion with multiple extruders running simultaneously and indeed, there are successful examples of RepRaps printing a part with two extruders [5]. RepRap-specific software tools automatically process 3D parts and communicate with the machine firmware to create a printed part.

1.3 Motivation for Further Improvements

While RepRap can replicate all of its plastic parts, it is unable to print with other materials. This is a major obstacle to the project's goal of eventual self-replication. Many efforts are underway to expand its printing capability to additional materials; for example, recently a group announced that they had developed a process for printing ceramics with the RepRap [6]. Others are developing heated beds to improve print quality [7], and milling heads for hybrid additive/subtractive manufacturing [8], to name a few.

In his Ph.D thesis, Ed Sells (one of the lead developers of the RepRap) discusses in detail the mechanical design of the Darwin model. In the section "Remaining challenges for pure self-manufacture", he writes that, of the RepRap's own parts, the most difficult to self-manufacture would be "electronic components, motors, conductive cable, solenoids, and the

heating element". He adds that "it is unlikely the machine will be able to self-manufacture these parts for at least a couple of years"[9]. The challenging element that all of these parts have in common is the printing of electrically conductive materials, in particular copper wire.

On 27 January 2010, the Foresight Institute announced its Kartik M. Gada Humanitarian Innovation Prize (also known as the Gada Prize). This consists of an $80,000 grand prize and $20,000 interim prize to motivate the development of a printer similar to the RepRap, but with many additional capabilities. Notably, to achieve the interim prize the machine must be able to "print at least three different materials, including one that is usefully electrically conductive", and have "the ability to print electronic circuit boards". [10]

Attempts are already underway to achieve these goals. In April 2009, Rhys Jones demonstrated a RepRap toolhead that printed paths from melted solder, using a method similar to the thermoplastic print head [11]. Additionally, proposals have been made to utilize low-melting point alloys such as Wood's metal or Field's metal[9], or conductive inks and polymers [12].

These approaches have severe drawbacks. High surface tension limits the print quality of extruded metals such as solder, and the low melting points that make the metals suitable for extrusion also limit the performance of electronic components made by those methods. Conductive inks, made from silver, have good conductivity and temperature stability but are expensive and prone to corrosion [13].

Copper is the conductor of choice for electronics applications, but has not been pursued due in part to its high melting point and the difficulty of chemical etching. A novel approach is to print copper wire directly into the fabricated part, as a continuous strand. This method would allow for the construction of higher-performance conductive parts, potentially including circuit boards, than current methods. And if the only consumable material is the wire itself, then the cost of fabrication would be exceptionally low.

This method has additional advantages, as the same tool head could be used to print a wide variety of wires (such as steel piano wire, or Nitinol) for mechanical reinforcement purposes. One application envisioned by the authors is printing durable flexure hinges using steel wire embedded in a part, as in figure 3. Some machines are already being printed with embedded flexure hinges [14], but plastic is not ideal for this application because it suffers from crazing and fatigue.
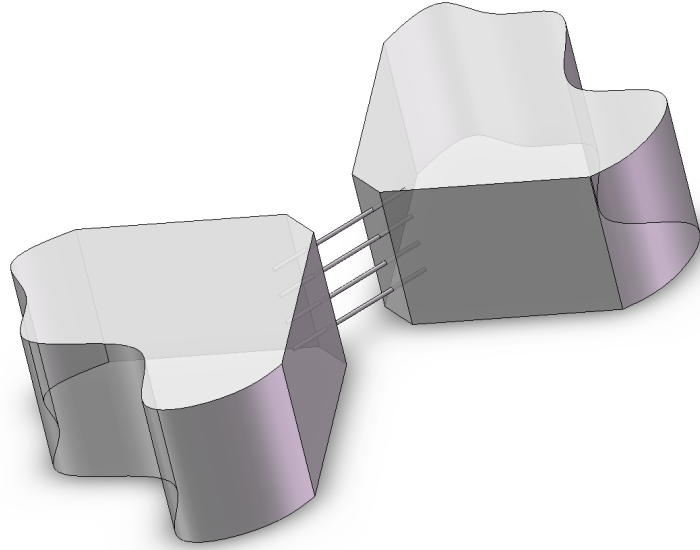
Figure 3: Embedded wires can serve as a "living hinge" flexure bearing for a printed part.

1.4 Current Approaches to Wire Printing

Wires are ubiquitous in manufacturing, from CNC bending devices for making springs and coathangers, to precision ultrasonic wirebonding machines used in the semiconductor industry. However, they are rarely incorporated into rapid prototyping systems. One notable exception is the patented design developed by Mr. Dany Lipsker of Micromod Technologies. His approach uses wires coated in a UV-sensitive polymer, which cures as the wire is printed, simultaneously hardening it and bonding it to the layer below. This allows for parts to be printed cheaply from wires with high precision and no support material. Mr. Lipsker generously offered to donate his design to the RepRap foundation [15], and acted as a consultant for this project.
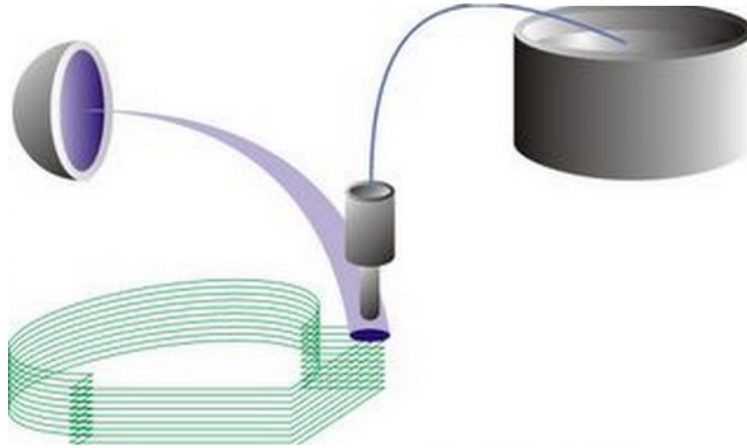
Figure 4: The Micromod system: Wire impregnated with UV-curing resin is exposed to a photodiode as it is guided about in 3D. (Image courtesy of Dany Lipsker, Micromod Technologies).

Figure 5: A part printed entirely from wire. (Image courtesy of Dany Lipsker, Micromod Technologies).

While the Micromod technique allows for precise construction of strong, thin-walled surfaces, it has so far not been combined with the RepRap's FDM method for creation of wire-and-plastic hybrid parts.

1.5   The SpoolHead Project

The spool-printing tool head (or "SpoolHead") project has therefore been proposed by the authors. Its goal is to implement a new tool head for the RepRap that can manufacture hybrid wire-and-plastic parts. This project is funded in part by the Engineering Physics Project Laboratory, and the remainder by the authors who are self-sponsoring the project.

2 Discussion

2.1 Project Objectives

The objective of the project is to add to the RepRap the ability to embed copper wire in a printed part. The following criteria should be met:

- The wire may be laid in arbitrary planar (XY) configurations, including multiple wires on multiple paths.

- The printed wire pattern should accurately reflect the specifications of the part. Wire placement should not stray from the design intent by more than one millimeter.

- The machine should automatically handle tasks related to printing the wire with a minimum of manual user involvement. For example: The printer should automatically cut the wire and affix it to the part.

- The prototype that prints the wire may or may not be printable by the RepRap itself. Future developments can improve the self-replication of the SpoolHead after the concept has been proven.

Furthermore, upon the completion of the project, design documentation must be released to the wider RepRap community by no later than 1 May, 2010.

2.2 Technical Background

In order to properly fabricate a part with embedded wires, the SpoolHead must be able to accomplish several tasks:

- Advancing a wire without tension;
- Anchoring the end of the wire to the printed part;
- Controlling the wire as it is printed;
- Automatic cutting of the wire at its termination.

The process used by Micromod Technologies begins by fixing the wire to a point on a surface to begin the print, and then using tension to draw wire off the spool as the print head moves. This means that the wire is always anchored, so it can be easily dispensed simply by pulling the print head. However, this method needs to be modified for hybrid printing, because the wire is attached in the middle of the print process, not at the beginning. Thus, a method

of "pushing" the wire forward is needed. The wire can then be anchored to any point in the printed part, from which point control becomes very easy.

Rather than using UV-curing polymers, the printed thermoplastic is an ideal substance to use to bond the wire. Controllable heating and cooling of the thermoplastic can be used to bond the wire and hold its shape, just like the resin used in the Micromod process. Mr. Lipsker had successfully tested thermoplastics in this role before selecting UV-curing polymers for this purpose [16].

2.3   Modifications on Existing Darwin

2.3.1   Mechanical

As the SpoolHead project consists only of an additional tool head, no modifications had to be made to the existing Darwin system to print wires. However, over the term of this project, the authors developed some modifications to Darwin that improved its reliability and ease of assembly; those are documented here.

The Cartesian platform design relied on press-fits for its corner bracket connectors. However, pre-drilling the parts created holes that were too large for these brackets. Acting on a suggestion by Professor Chris Waltham, slots were cut in the connectors to create an adjustable, tightening clamp. This modification has since been documented on the RepRap website [17].

While Wade's extruder design is a significant improvement over the RepRap's previous direct-drive extruder, both designs were prone to failure. The PTFE insulator, subjected to high temperatures and stresses, has been known to creep [18]. PEEK insulators tended to suffer from high friction and could bond with the melted filament [19]. The authors observed an additional type of failure, wherein molten filament would flow back and coat the inner surfaces of the extruder, and subsequently cool, creating a jam [19]. The authors therefore improved upon Wade's extruder by substituting the standard cylindrical insulator and screw-in heater barrel for a larger bolted-on PTFE block with a tight-fitting hole for the filament, preventing any backflow of molten plastic. To avoid creep, the PTFE block was made non-load-bearing; instead, the loads were supported by an aluminum plate below the block, which the heater barrel screwed into. The aluminum also acts as a heat sink in this design, cooling the PTFE.
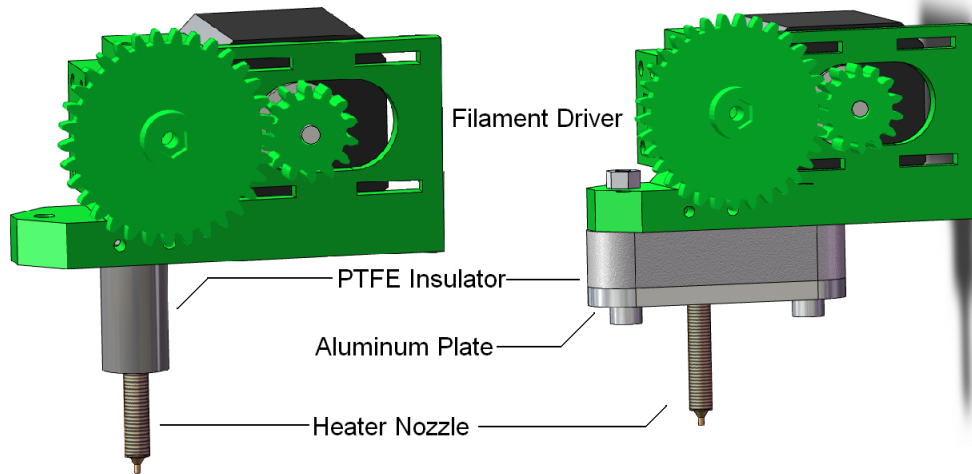
Figure 6: Comparison of standard configuration extruder (left) with the new design (right).

2.3.2 Electrical

The electrical system consists of a computer communicating directly with a Sanguino board, which communicates with the stepper motor driver (to control XYZ motion) and the Arduino board (to control the plastic print head). The default communication protocol between the Sanguino board and the Arduino board is via Ethernet cable. Standard commands for controlling the stepper motor driver and the Arduino board can be sent through the Ethernet cables. However, it is still unclear how to add new commands to be sent through the same protocol; therefore, unused digital outputs on the Sanguino have been chosen to be used for sending new commands which controls a stepper motor on the plastic extruder.

2.3.3 Software

Heater

The heater consisted of regular wire soldered to Nichrome wire that is wrapped around the print head tip. The default firmware controlling the heater uses a simple on/off control: below the target temperature, the heater will turn fully on, and on or above the target temperature, the heater will turn off. This caused the Nichrome wire to glow when the heater is on, and regularly melt the solder that connected Nichrome wire and braided wire together, as well as destroying its insulation. This meant that the heater would only work for at most two weeks before burning out.

To address this issue, the firmware was modified so that the heater uses pulse-width mod-

ulation (PWM). With the new modification, the heater now turns on with a PWM of 59% (150/255) when the temperature is below target, and off when the temperature is on or above target. This modification proved to be reliable as the heater has not malfunctioned since the modification's implementation, a duration of over a month.

Extruder Stepper Motor

The particular plastic extruder design in this project uses a stepper motor to drive the plastic filament. Frequently a brushed DC motor is used on the Darwin, so the default firmware for the plastic extruder was not suitable for the stepper driven print head. To address this issue, the authors found a software module that was able to drive the stepper motor and implemented it in the firmware. Communication between the Sanguino and Arduino boards are modified as outlined in section 2.3.2 Electrical Modifications.

2.4 Final Design: Wire Printing System

2.4.1 Mechanical

The final design consisted of three stages: The mechanical pencil and servo, the cutter, and the heater. The mechanical pencil was a standard Pilot H-165 mechanical pencil, which uses 0.5 mm graphite. Similar pencils are available inexpensively worldwide. It is actuated ("clicked") by the servo motor, advancing the wire in closely-spaced increments (approximately 0.5 mm per click). This device is able to advance the wire to prepare it for anchoring to the plastic surface. The servo simply connects to the pencil by a string tied about its shaft, this allows for various models of pencils to be used and maintains a cheap and simple construction (figure 7).

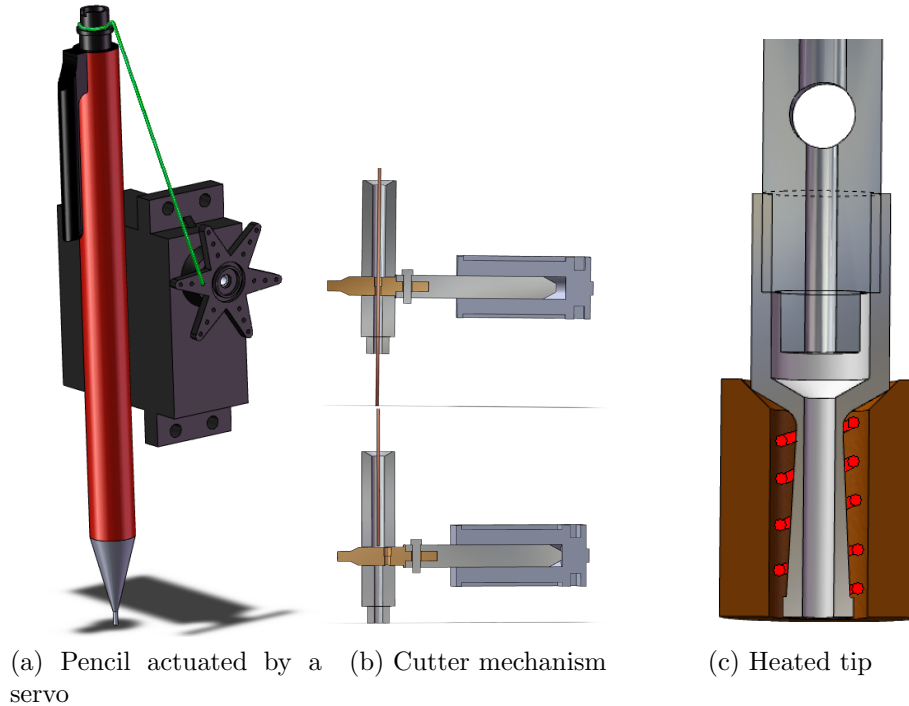(a) Pencil actuated by a servo   (b) Cutter mechanism   (c) Heated tip

Figure 7: Wire-printing implementation summary

For the cutter mechanism, the wire is passed through two concentric holes. A solenoid pulls one of the holes out of alignment with the other, shearing the wire. Ideally the wire will shear in only one place; to ensure this, the hole is drilled to a larger diameter at its entrance than exit.

The heater design differs slightly from that used by the RepRap plastic extruder. Whereas the plastic extruder is designed to heat plastic inside the melt chamber, the SpoolHead heater is meant to heat plastic external to the tip, as well as the wire inside it. Heat is injected into the Nichrome heating element, and as much heat as possible is directed downward to the plastic. A detailed thermal resistance model is shown in figure 8, illustrating the paths that heat can take through the extruder. A desire to maximize the resistance upward into the steel, and minimize the resistance downward. The thermal resistance of a bar is inversely proportional to its cross-sectional area, so the tapered design helps the heat flow in the desired direction. To further reduce undesired heat flow, a large internal hollow space is left between the aluminum and the steel.
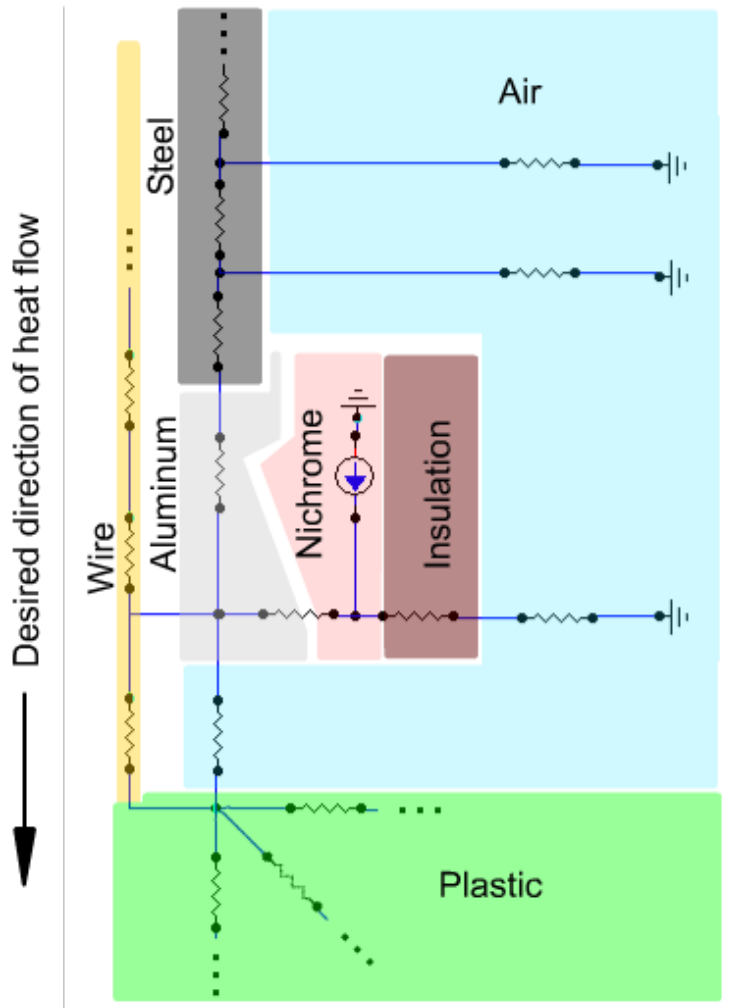
Figure 8: Thermal resistance model of the SpoolHead heater

When all of these elements were combined, the result is the assembly in figure 9:
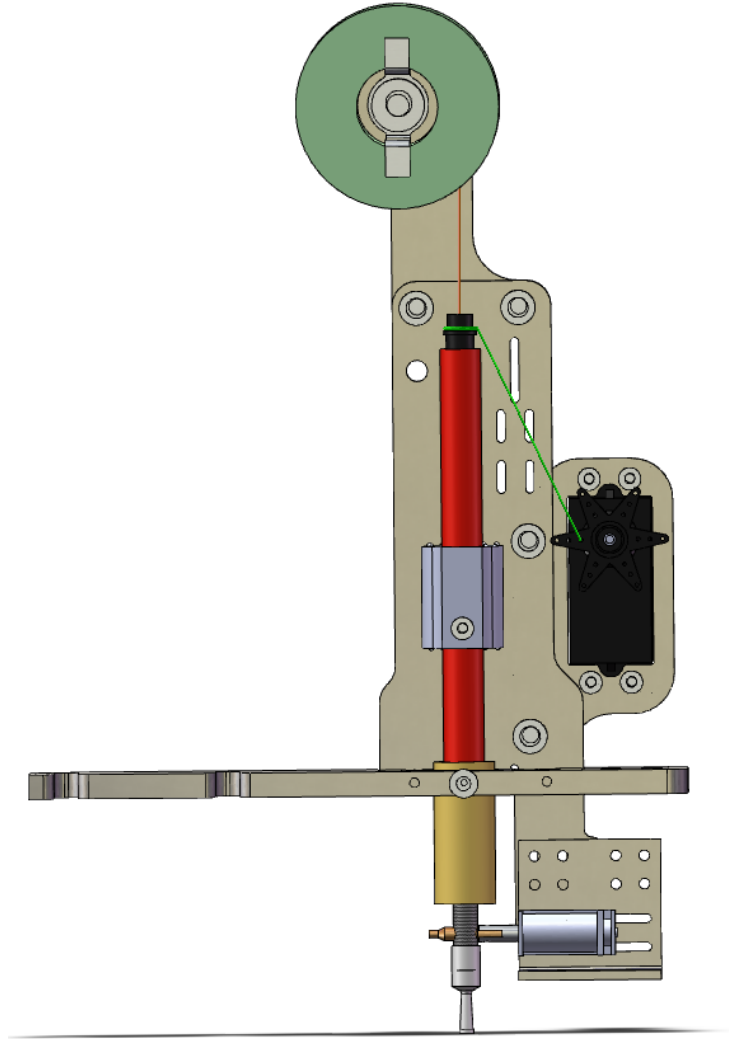
Figure 9: The SpoolHead prototype

Because the extruder bracket could safely support only one extruder, the plastic extruder was taken off so that the wire extruder could be mounted.
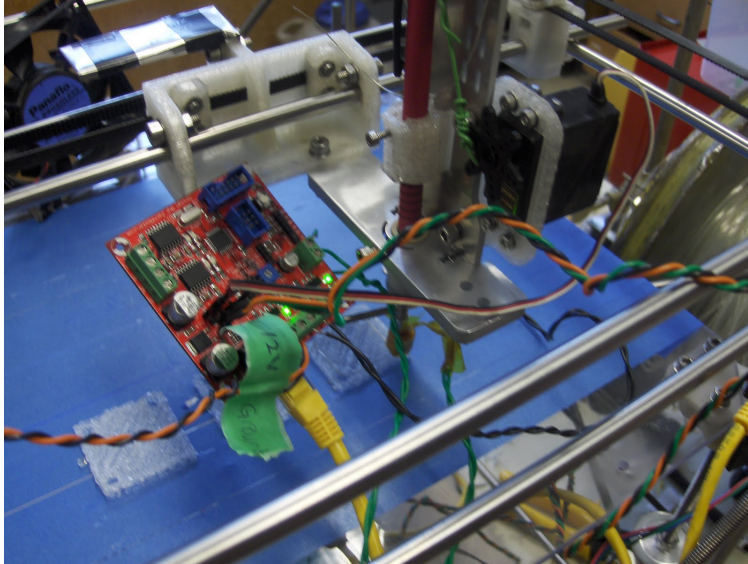
Figure 10: Wire-Printing Setup. SpoolHead is mounted on the right, extruder control electronics are on the left.

2.4.2 Electrical

The electronics system for wire printing consists of an extra Arduino extruder controller board, identical to the plastic extruder board, which interprets commands from the Sanguino motherboard to control the wire printing actuators. The extruder controller has a servo output which switches between two preset angles, one corresponding to "press pencil" and the other corresponding to "release pencil".

The heater and fan implementation in the wire printing system is the same way as that of the plastic printing system: a digital output turns the fan on and off, and a PWM output controls the heater. The cutter is controlled by a separate but identical digital output as the fan.

An alternate wire-feeding mechanism is using a stepper motor to squeeze feed the wire in a similar way as how the plastic is pushed through a nozzle. However, this was not implemented in the first wire printing prototype. As mentioned in section 2.3.2 (Electrical Modifications), unused digital pins are used to send new commands required to control the print head. for the wire print head, this new communication protocol is used to control the servo, but can also control a stepper motor.

2.4.3 Software

Servo Motor Control

The wire printing head used an Arduino loaded with a modified version of the Reprap firmware. Besides having the modifications to receive and interpret stepper motor driving instructions described in section 2.3.3 Software Modifications to Darwin, this firmware is also modified to be able receive and interpret servo driving instructions. In order to drive a servo motor, the Arduino library for driving servo motors was incorporated into the wire printing head's software.

Cooler, Cutter, and Heater

The cooler and cutter are driven by Arduino digital outputs. No software modifications were needed to control these outputs. The heater output in the wire printing head has the same modifications as the heater output of the plastic printing head described in section 2.3.3. To reach a target temperature, the heater is sent 59% of the maximum power that can be supplied when the temperature is below target, and the heater is turned off when the temperature is on or above target.

Wire Printing G-code Generator

As with in the plastic printing head, G-code is used to coordinate all the outputs of the wire printing head as well as the stepper motors that moves the head in the X, Y, and Z directions. The RepRap Java Host software programmed by the RepRap community sends G-code to the Sanguino board, which then converts software instructions into mechanical movement.

The wire printing G-code generator is written in MatLab. The G-code generator takes the desired path of the wire printing head as input, and outputs the G-code necessary to move the print head. More specifically, a curve in the XY plane expressed in parametric form is converted by the MatLab code into G-code, instructions that the Sanguino can understand. MatLab provides a convenient environment for generating many common curves such as the line segments, arcs of a circle, spirals, and piecewise continuous curves in the XY plane.

Algorithm for Printing Rectilinear Patterns

Wire printing of any rectilinear shape can be broken down into a combination of the actions below by the wire printing head, each broken down here into a sequence of more basic actions. The initial position of the wire printing head must be at the beginning of a wire segment, and about 2 mm above the plastic on which wire is to be laid.

- Fix the beginning of a wire segment to the plastic. This step always occurs at the beginning of a wire printing task.

  1. The Z-bed lowers by 2 mm and the Servo motor presses the pencil so that the wire is pushed out to touch the plastic.
  2. Heat the print head to 170°C(empirically determined).
  3. Move the Z-bed up 2 mm so that the wire penetrates the plastic.

    4. Cool the print head to 70°C.

    5. Move to a new location.

- Move to a desired location.

- fix the middle of the wire segment to the plastic

    1. Heat the print head to 170°C.

    2. Raise the Z-bed so that the hot wire melts into the plastic.

    3. Cool the print head to 70°C.

    4. Move to the next location or cut the wire.

- Cut the wire at the end of the wire segment. This action is done at the end of a wire segment. It simply requires turning the actuation solenoid on to cut the wire, and then off to return the cutter to its resting location.

Algorithm for Printing Curvilinear Patterns

This algorithm is the same as the algorithm described above, except that, after the starting point is fixed to the plastic, the extruder drags the wire along wire guides, and then the end point is fixed. The wire guides are pre-designed in the plastic model and printed by the plastic extruder.

2.5 Alternative Designs

2.5.1 Stepper-Actuated Pinchwheel Extruder

Many mechanical designs were proposed. One alternative was a stepper-actuated pinchwheel extruder (Figure 11), similar to the thermoplastic extruder but adapted to the wire's fine diameter, and with a set of straightening wheels. This design could accomodate a wide-range of wire diameters and materials. Another advantage was its compatibility with existing electronics and software. However, this design was not chosen due to its numerous disadvantages: First, it suffered from high cost, weight, and complexity. Second, it was suspected that the wire would not be fed straight through the pinchwheel, but instead would bend. Commercial wire feeders use two active wheels, connected by gears or a belt, to ensure that the wire feeding is absolutely symmetric [20]. This was deemed too difficult to achieve.
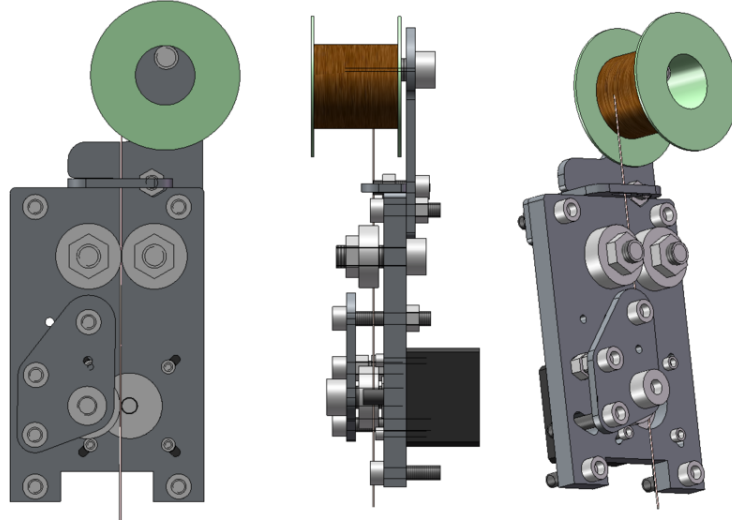
Figure 11: Alternative design: pinchwheel wire extruder

2.5.2 Superglue and Nail Clipper Setup

In this design, common nail clippers were incorporated into the print head, illustrated in Figure 12. They were actuated by a solenoid, cam, or similar system. The illustrated mechanism used a DC motor and pulley system; the motor pulled on the cable, which closed the clippers with a slight mechanical advantage. The clippers then returned to the original position by their spring effect. The authors did not implement this design for two reasons: superglue is expensive and prone to fouling, and the glue bottle/clipper assembly would consume ten times the space of the final design.
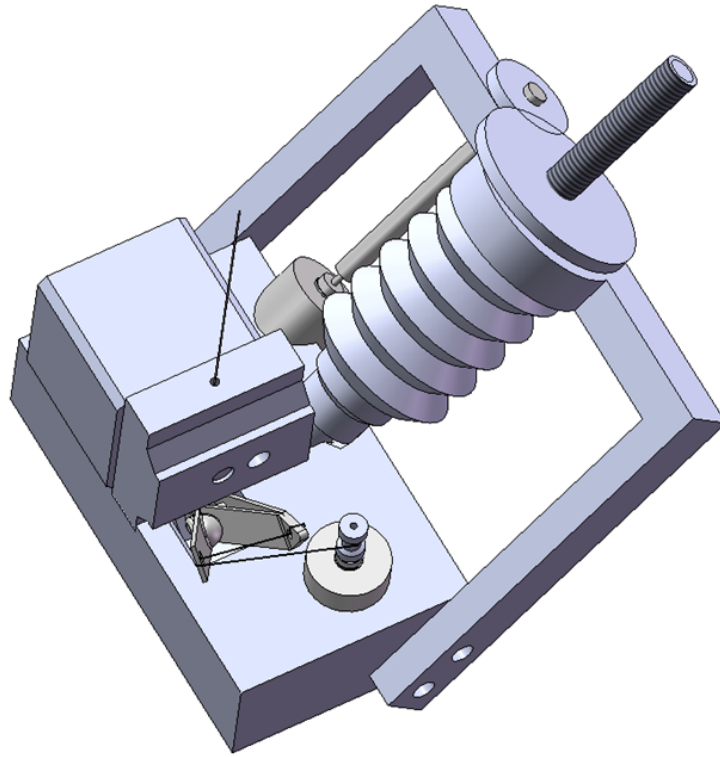
Figure 12: An alternative wire-cutting and gluing setup

2.5.3 Rotating cutter mechanism

Two cutting methods were proposed, but only one was fully implemented. The alternative rotating cutter was similar in approach to the translating cutter, but rather than sliding the concentric holes out of alignment, it rotated them (figure 13). This design was abandoned for the translating cutter because the aluminum linkage acted as a strong heat sink. However, it does offer a much greater mechanical advantage than the translating cutter.
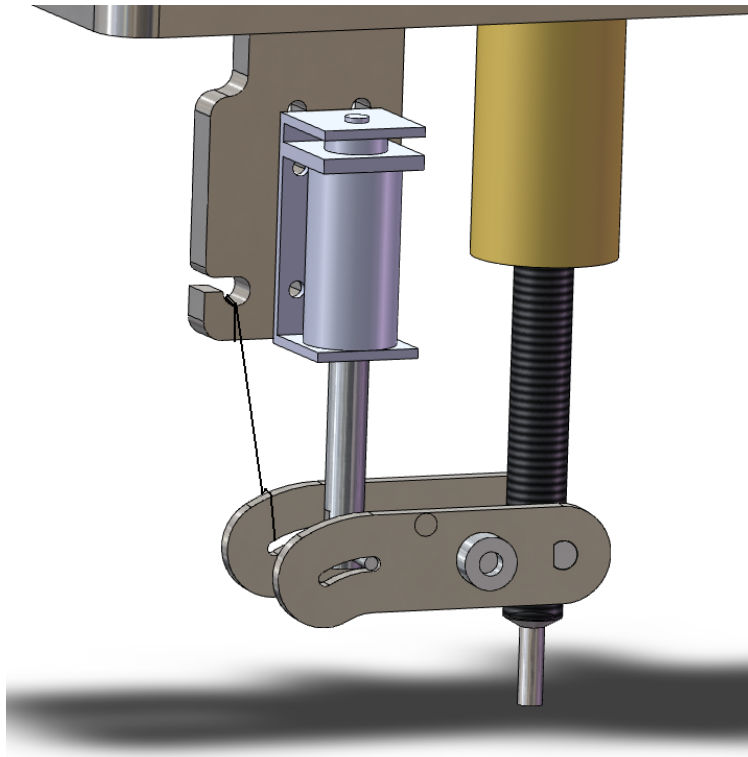
Figure 13: Rotating cutter design

Figure 14: Rotating cutter principle

2.6 Experimentals

To assist in the design process, experiments were performed to verify many of the funda-
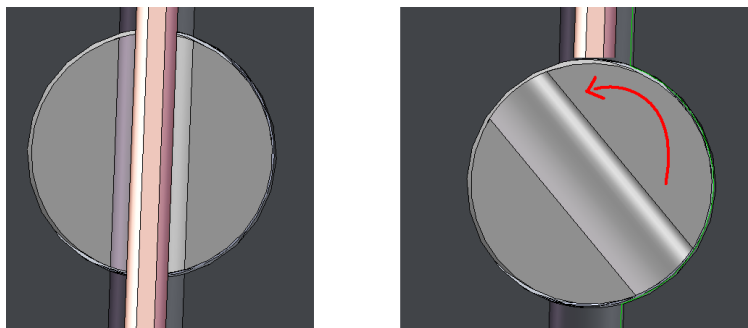mental concepts upon which the design relied. For example, there were significant doubts
about whether or not the printed plastic could be re-heated and softened enough to accept
a wire, and there was no way to predict how strong the wire-plastic bond would be after

it had formed. Before the design could proceed, therefore, the authors carried out a set of experiments to verify these ideas.

2.6.1   Bond Strength Test

A strong bond between the wire and plastic is required for anchoring the wire, because it must resist pulling out under the bending forces during printing. The wire-plastic bonding strength was first tested by inserting wire into a plastic part that had been melted by a lighter (Figure 15) and hanging weights from the wire in various orientations (Figure 16). The experiment shows that the bond could support stresses greater than 2 MPa. The breaking strength is unknown, because failure always occurred in the wire before it occurred at the bond. As wire should never be subjected to stresses close to its breaking strength during printing, this bond strength was deemed more than adequate.
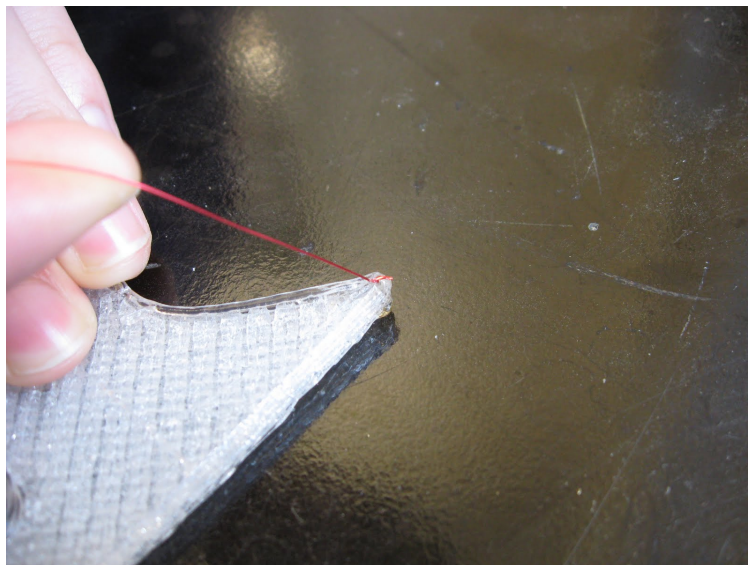
Figure 15: Wire-plastic bond

Figure 16: Test of wire-plastic bond strength

2.6.2 Benchtop Wire-Printing

The wire-printing process was tested using the setup shown in figure 17: a clamp held the mechanical pencil above the heater nozzle, and the plastic piece sat on a stand with adjustable height. The following operating variables were determined through the experiment:

- Extruder temperature should reach 170 degrees Celsius to insert wires into the plastic

- Extruder temperature should drop below 70 degrees Celsius for the bond to set

- Each pencil clicking advanced the wire by 0.5mm

- The extruder tip should be approximately 2mm above the surface of the plastic as it drags the wire. This creates a gentle bend radius as the wire transitions from vertical to horizontal, reducing the forces needed to print the wire.

Figure 17: Benchtop wire printing

2.7 Results

Two test prints were defined in the project proposal: a rectangle, and a spiral pattern, to test printing of straight lines and curves respectively (Figure 18).

The design length of the rectangle's narrow side was 15 mm, however, the authors' early printing algorithms struggled to print short line segments due to heat conduction along the wire re-melting the bonded areas, causing pull-out. The design was therefore changed to a 30 mm square (Figure 19). Subsequent algorithm developments avoided subjecting the wire bonds to any pull stresses while the wire was hot, potentially avoiding this error; however, the 15 mm rectangle print has not been tested. The wire deviated from a straight line by at most 0.8 mm along the sides, and the length of each side was always approximately 1 mm shorter than specified. The rectangle print thus did not meet the ± 0.5 mm tolerance requirements in the project proposal.

For the spiral pattern, the indicated dimensions agree to within under 0.2 mm of the design specifications, with measured deviations from the designed path smaller than 0.4 mm. The tolerances achieved on the spiral thus satisfy the ±0.5 mm tolerance proposed in the project proposal.

In both cases, the cutter failed to cut the wire, so manual cutting was performed.
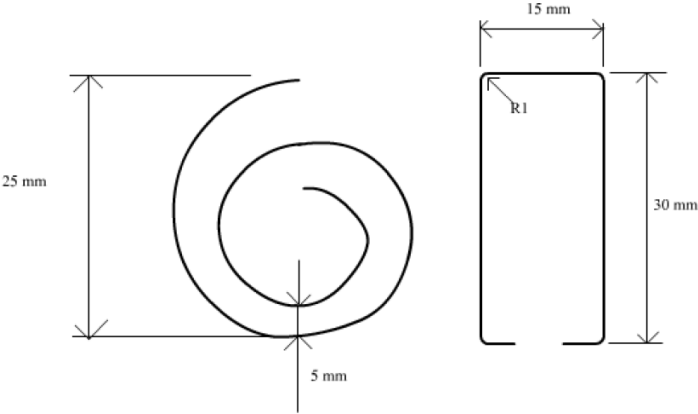
Figure 18: Test wire patterns

Figure 19: Printed square pattern

Figure 20: Printed spiral pattern

2.8   Sources of Error

Deflection of Extruder Tip

The wire extruder mount is not stiff, so the extruder undergoes a deflection of approximately 2 degrees when it drags the wire horizontally, which resulted in the wires in the printed wire pattern always falling 1 mm short of the targeted length. The authors were able to compensate for this error in straight line segments by adding that1 mm distance to the targeted travel, and then moving backward by that amount at the end to return the tip to its vertical position.

Figure 21: Schematic Demonstration: Wire is not laid at the target location as extruder tip deflects

A superior solution is to increase the stiffness of the extruder. The cantilevered Darwin extruder carriage is the main cause of the low stiffness; however, Mendel's design is not cantilevered, so the deflection problem can be avoided in the future by mounting the extruder on a Mendel.
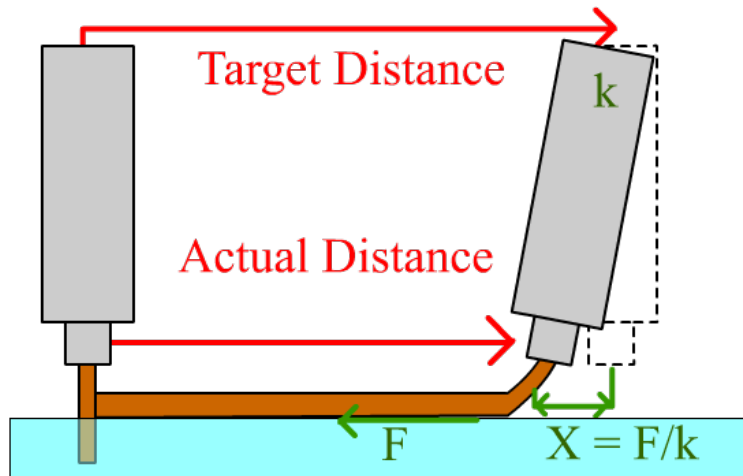
Manual Homing

Because mounting both extruders simultaneously could stress the Darwin's X-axis carriage, the extruder had to be manually swapped to begin a wire printing operation. The extruders can never be positioned exactly the same way each time, so manual homing of the axes was necessary to ensure that swapping the extruder did not introduce an error in the print. This consisted of aligning the axes by eye, which of course introduced some small random errors.

Tolerances of Wire Guides

The rectangular wire pattern was fixed to the plastic at each corner. But the spiral pattern only has its beginning and end points fixed: the middle section is supported by plastic guides. Therefore, the wires can only be as accurate as the plastic guides upon which they are printed.

Straightness of Wire

The straightness errors in the rectangle part's printed wires likely represent straightness errors in the wires inside the pencil, created as the wire was being fed into the pencil for the first time. These errors are expected to diminish after a sufficient length of wire has been printed, so that the wire in the pencil is entirely "fresh" from the spool.

Tip Deflection in Cutting

The translational cutter suffered from a significant design flaw, also due to the low extruder stiffness. When the cutting solenoid was activated, the entire tip deflected under the solenoid's pull. This caused the wire cutter to fail to cut the wire, because the deflection allowed the solenoid to close while keeping the two holes in alignment. The rotating cutter design outlined in section 2.5.3 (Rotating Cutter Mechanism) would not suffer from this stiffness issue.

3   Conclusion

The wire-embedding 3D printer project adds a wire-printing tool head, "SpoolHead", to the RepRap 3D printer. The RepRap machine is able to print plastic parts, including all of the plastic components of the machine itself, so RepRap has the potential to self-replicate. However, it is not able to print electronic components. The Gada Prize, established in 2010 to advance the RepRap project, requires a printer that can print conductors and circuit boards. The SpoolHead, a promising new approach to manufacturing hybrid wire-and-plastic parts, is an attempt to achieve this formidable goal.

In this design, the wire-printing mechanism uses a servo-actuated mechanical pencil to insert metal wires into the heated surface of a printed thermoplastic part. The wires are then to be cut by a solenoid-actuated mechanism that shears the wire inside the main tube of the print head.

Benchtop tests performed to validate the design philosophy of the SpoolHead gave positive results. The print head was then manufactured and tested on two designs proposed at the outset of the project, a rectangle and a spiral. The SpoolHead was able to print the spiral design to within the specified ±0.5 mm tolerances. The rectangle part was out of specification, with straightness errors of up to 0.8 mm and dimensions short by 1 mm. The errors responsible for this have been identified and can be easily resolved.

The cutter failed to perform its role, requiring manual intervention in the cutting process. While alternative methods have been proposed to replace the cutter, a fully satisfactory solution remains to be found.

4 Recommendations

4.1 Mechanical

Replacement of the cutter mechanism

The cutter design proved incapable of shearing the wire. An alternative design, using a rotating cutter as proposed in the body of the report, is more likely to succeed, but introduces problems as a heat sink. Thus, a new method must be identified to replace the cutter. Initially, using scissors at the tip (as Micromod Technologies does) was ruled out due to its predicted interference with the heater. This technique should be re-examined in light of the failure of alternative methods.

Miniaturization

The key components of a mechanical pencil are the spring, the friction bushing in the nose and the clutch ring, all locating within 5 cm from the tip of the pencil. Only this 5 cm of mechanical pencil is actually necessary for wire extruding. However the existing wire extruder design uses the whole mechanical pencil (length 14 cm). The excess can be easily removed, resulting in a more compact design that has many advantages:

- A smaller pencil mount that frees space in the extruder and reduces weight;

- Greatly reduced difficulty in feeding the wire through the pencil from the spool.

Stiffness and Mendel mounting

The low stiffness of Darwin's cantilevered mount had a detrimental effect on print quality. A redesign should place a higher priority on the stiffness of the extruder tip. Adapting the design to Mendel's frame would likely achieve this.

Printability

Many of the parts are currently designed to be cut from sheet metal, without consideration given to the ease of printing such parts on a RepRap machine. Actions should be taken to improve the printed part count of the SpoolHead.

4.2 Electrical

Switch from screw terminals to bullet terminals

In total, 24 screw terminals are current used to connect circuit boards to motors, thermistors, heating elements and fans. The disadvantages of screw terminals are as follows:

- It is time-consuming, as securing or undoing one terminal takes approximately 15 seconds. Considering users secure or undo each terminal around five times, the total time spent on it is more than 30 minutes.

- It is inconvenient as a screw driver is required.

- It is hard to control the connection tightness: loose clamping leads to weak electrical connection; but over-tightening may break wires.

Bullet terminals (figure 22) are easy to plug/unplug and have a strong connection. Replacing all the screw terminals with bullet terminals is estimated to reduce 90% of wire connecting time and 95% of loose or over-tight connections. Therefore, bullet terminals are recommended as the new connectors.

Figure 22: Bullet Terminals (adapted from `http://shop1.actinicexpress.co.uk/shops/partsforaircraft/index.php?cat=Terminals`)/

4.3 Software

Communication between Sanguino and Arduino via ethernet

Although using digital outputs on the Sanguino to communicate with the Arduino is sufficient for our project goals, the extra wires adds to the already messy wiring of the RepRap. Also, all digital outputs on the Sanguino are now being used, and extra functionalities cannot be added in the future. Thus, it is advisable to figure out a way to add new extra commands to be sent over the ethernet connections.

Replacement of the STL File Standard

Currently, the standard file used by the RepRap and 3D printing community is the stereo-olithography (STL) file format. This is the format used by the RepRap Host software, and other toolchains such as Skeinforge, to generate G-code for printing. However, it is a severely limiting file format, supporting only triangulated surfaces. Not only is this file

format is not appropriate for defining 3D models with embedded wire structures, it is insufficient for any structure with multiple materials. The RepRap community is therefore strongly recommended to seek a replacement for the .STL file format.

CAM Software for G-code Generation

The current MatLab G-code generator requires manual entry of the set of coordinates describing the wire segment to be printed. Also, the current software implementation requires coordinates of the outline of the plastic part on which wire is printed to also be manually specified. This process is simple for a test piece, but would be tedious for a complicated wire pattern.

Use of new computer-aided manufacturing (CAM) and software is therefore recommended. The CAM software should process the model boundaries and embedded wires in the 3D model, and output G-code instructions for printing the part. This should include printing plastic guides for wires when necessary.

3D Wire-Printing Algorithm

A wide range of electronic devices, such as solenoids and motors, are based on 3D wire patterns. Although the SpoolHead is currently only able to print 2D patterns, it has demonstrated potential for 3D-printin ug. As shown in Figure 23, hot wires can pierce through several layers of plastic to a depth of up to 5mm. The injected wire pieces can serve as the Z-direction connectors (or "vias") to link 2D wire patters in different XY planes. Therefore, 3D wire printing is feasible. It is recommended to pursue this avenue further.
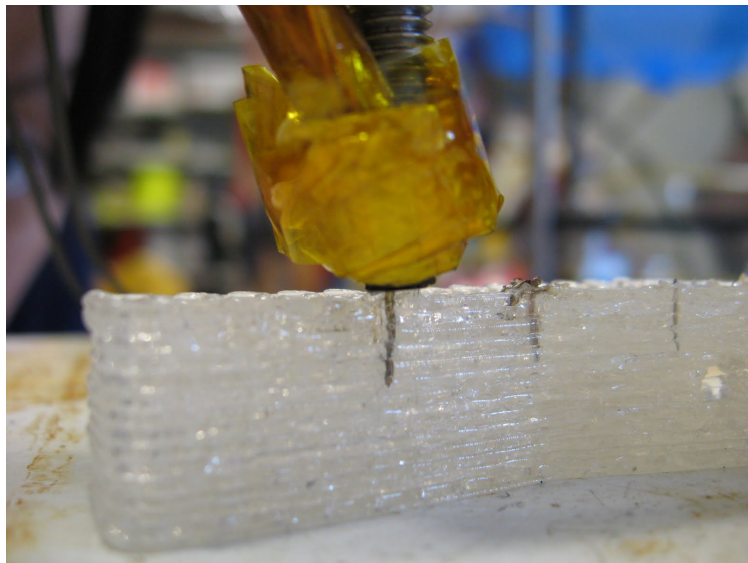

Figure 23: Wire in Z direction

A Appendix

A.1 MatLab Script

```
%%%% Spiral G-code generator %%%%
%%% Change parameters and run code to generate G-code
%%% Units are millimetres and radians

%%%%%%%%%% PATH OF PRINT HEAD %%%%%%%%%%
%%% Parameters %%%
iniphi=315*pi/180;        % Initial angle
rev=2.875;                % Number of revolutions
N=25;                     % Number of points
rmin=0;                   % Starting radius
rmax=18;                  % Ending radius
%%%%%%%%%%%%%%%%%%%

theta=linspace(iniphi,iniphi-2*pi*rev,N);
r=linspace(rmin,rmax,N);
x=r.*cos(theta);
y=r.*sin(theta);

%%%%%%%%%% LOCATION OF PLASTIC WIRE GUIDE %%%%%%%%
%%% Parameters %%%
iniphi2=90*pi/180;        % Initial angle
rev2=2;                   % Number of revolutions
rmin2 = 2.5;              % Starting radius
rmax2 = 12.5;             % Ending radius
%%%%%%%%%%%%%%%%%%%%
theta2=linspace(iniphi2,iniphi2-2*pi*rev2,100);
r2=linspace(rmin2,rmax2,100);
x2=r2.*cos(theta2);
y2=r2.*sin(theta2);

%%%%%%%%%%% PLOT PATH AND PLASTIC GUIDE LOCATION %%%%%%%%
plot(x,y,'b-',x2,y2,'r--')
xlim([-22 22])
ylim([-22 22])
axis square

%%%%%%%%%%% OUTPUT G-code %%%%%%%%%%%%
for i=1:length(x)
    xpos=round(100*x(i))/100;
```

```
    ypos=round(100*y(i))/100;
    disp(['G1 X' num2str(xpos) ' Y' num2str(ypos) ' F200'])
end
```

A.2   G-code: Rectangular Wire Pattern

```
;# Printing wire

;# Initialization
G21                 ; Metric
G90                 ; Absolute positioning
G92    X0 Y0 Z0     ; set starting point
T1                  ; Select wire head
M107            ; Cooler off
G1 Z3 F30.0         ; Lower Z bed a bit so head can move

;# Attach wire to plastic
G1 X-5.0 Y5.0 F800.0    ; Move to the correct XY position
M95 S10             ; Press pencil N times (pick N)
M109 S170       ; Set temperature to 170 degrees
G4 P10000       ; Wait 10000 ms
G1 Z0 F30.0       ; Raise Z bed
M94                 ; Toggle pencil state to hold it
M106            ; Cooler on
M109 S70        ; Set temperature to 70 degrees
G4 P10000       ; Wait 1000 ms
M107            ; Cooler off
G1 Z3 F30.0         ; Lower Z bed

;# Fix wire to corner
G1 X-35.0 Y5.0 F800.0    ; Move to next XY position
M109 S170       ; Set tempearture to 170 degrees
G4 P10000       ; Wait 1000 ms
G1 Z-2 F30.0        ; Raise Z bed to fix wire to plastic
M106            ; Cooler on
M109 S70        ; Set temperature to 70 degrees
G4 P10000       ; Wait 1000 ms
M107            ; Cooler off
G1 Z3 F30.0        ; Lower Z bed

;# Fix wire to corner
G1 X-35.0 Y35.0 F800.0; Move to next XY position
M109 S170         ; Set tempearture to 170 degrees
```

```
G4 P10000          ; Wait 1000 ms
G1 Z-2 F30.0          ; Raise Z bed to fix wire to plastic
M106               ; Cooler on
M109 S70           ; Set temperature to 70 degrees
G4 P10000          ; Wait 1000 ms
M107               ; Cooler off
G1 Z3 F30.0           ; Lower Z bed

;# Fix wire to corner
G1 X-5.0 Y35.0 F800.0    ; Move to next XY position
M109 S170          ; Set tempearture to 170 degrees
G4 P10000          ; Wait 1000 ms
G1 Z-2 F30.0          ; Raise Z bed to fix wire to plastic
M106               ; Cooler on
M109 S70           ; Set temperature to 70 degrees
G4 P10000          ; Wait 1000 ms
M107               ; Cooler off
G1 Z3 F30.0           ; Lower Z bed

;# Fix wire to corner
G1 X-5.0 Y5.0 F800.0    ; Move to next XY position
M109 S170          ; Set tempearture to 170 degrees
G4 P10000          ; Wait 1000 ms
G1 Z-2 F30.0          ; Raise Z bed to fix wire to plastic
M106               ; Cooler on
M109 S70           ; Set temperature to 70 degrees
G4 P10000          ; Wait 1000 ms
M107               ; Cooler off
G1 Z3 F30.0           ; Lower Z bed

;# Coda
M94                   ; Release pencil
T0             ; Select plastic head;# Printing wire
```

A.3   G-code: Spiral Wire Pattern

```
; position the extruder bottom at the same height of the guide!
;# Printing wire

;# Initialization
G21                ; Metric
G90                ; Absolute positioning
G92    X0 Y0 Z0    ; set starting point
```

```
T1                 ; Select wire head
M107               ; Cooler off


G1 X-0.452933329 Y4.10370196 F200


;# Attach wire to plastic
G1 Z3 F30.0        ; Lower Z bed a bit so the wire can stick out more
M95 S10            ; Press pencil N times (pick N)
M109 S170          ; Set temperature to 170 degrees
G4 P10000          ; Wait 10000 ms
G1 Z0 F15.0        ; Raise Z bed
M94                ; Toggle pencil state to hold it
M106               ; Cooler on
M109 S70           ; Set temperature to 70 degrees
G4 P10000          ; Wait 1000 ms
M107               ; Cooler off



;G1 X0 Y0 F200
;G1 X-4.194184173 Y1.03266625 F200
;G1 X-3.5 Y 4.0 F200
;G1 X-2.3 Y 4.5 F200
G1 X2.33 Y4.8 F200
G1 X3.29 Y4.47 F200
G1 X4.21 Y3.95 F200
G1 X5.05 Y3.24 F200
G1 X5.76 Y2.36 F200
G1 X6.31 Y1.32 F200
G1 X6.66 Y0.16 F200
G1 X6.8 Y-1.09 F200
G1 X6.7 Y-2.38 F200
G1 X6.35 Y-3.67 F200
G1 X5.75 Y-4.9 F200
G1 X4.9 Y-6.04 F200
G1 X3.83 Y-7.02 F200
G1 X2.57 Y-7.81 F200
G1 X1.14 Y-8.37 F200
G1 X-0.41 Y-8.66 F200
G1 X-2.03 Y-8.65 F200
G1 X-3.65 Y-8.35 F200
G1 X-5.23 Y-7.73 F200
G1 X-6.7 Y-6.81 F200
G1 X-8.01 Y-5.61 F200
G1 X-9.1 Y-4.15 F200
G1 X-9.91 Y-2.49 F200
```

```
G1 X-10.42 Y-0.66 F200
G1 X-10.59 Y1.27 F200
G1 X-10.4 Y3.23 F200
G1 X-9.84 Y5.17 F200
G1 X-8.91 Y7.01 F200
G1 X-7.64 Y8.67 F200
G1 X-6.05 Y10.11 F200
G1 X-4.19 Y11.24 F200
G1 X-2.12 Y12.04 F200
G1 X0.1 Y12.44 F200
G1 X2.4 Y12.44 F200
G1 X4.7 Y12 F200
G1 X6.91 Y11.14 F200
G1 X8.97 Y9.87 F200
G1 X10.79 Y8.21 F200
G1 X12.3 Y6.22 F200
G1 X13.43 Y3.94 F200
G1 X14.15 Y1.46 F200
G1 X14.4 Y-1.14 F200
G1 X14.17 Y-3.8 F200
G1 X13.44 Y-6.4 F200
G1 X12.24 Y-8.86 F200
G1 X10.58 Y-11.1 F200
G1 X8.51 Y-13.02 F200
G1 X6.1 Y-14.55 F200
G1 X3.4 Y-15.63 F200
G1 X0.51 Y-16.21 F200
G1 X-2.47 Y-16.26 F200
G1 X-5.45 Y-15.75 F200
G1 X-8.33 Y-14.69 F200
G1 X-11 Y-13.11 F200
G1 X-13.37 Y-11.04 F200
G1 X-15.34 Y-8.54 F200
G1 X-16.85 Y-5.68 F200
G1 X-17.82 Y-2.56 F200
G1 X-18.21 Y0.72 F200
G1 X-17.99 Y4.06 F200
G1 X-17.16 Y7.35 F200
G1 X-15.73 Y10.46 F200
G1 X-13.73 Y13.3 F200
G1 X-11.21 Y15.75 F200
G1 X-8.26 Y17.72 F200
G1 X-4.97 Y19.14 F200
G1 X-1.43 Y19.95 F200
G1 X2.24 Y20.1 F200
```

```
G1 X5.92 Y19.57 F200
G1 X7.47 Y18.37 F200
G1 X9.78 Y13.52 F200

;# Fix wire to the end
M109 S170        ; Set temperature to 170 degrees
G4 P10000        ; Wait 10000 ms
G1 Z-2.0 F15.0       ; Raise Z bed
M94               ; Toggle pencil state to hold it
M106            ; Cooler on
M109 S70        ; Set temperature to 70 degrees
G4 P10000        ; Wait 1000 ms
M107            ; Cooler off
G1 Z3 F30.0       ; Lower Z bed
```

References

[1] http://www.dimensionprinting.com/3d-printers/3d-printing-uprint.aspx

[2] Reprap Project http://reprap.org/bin/view/Main/WebHome

[3] "Costing Mendel": http://blog.reprap.org/2009/10/costing-mendel.html

[4] "Bits from Bytes Complete Kit":
http://bitsfrombytes.com/index.php?page=shop.product_details&product_id=
168&category_id=5&flypage=flypage-ask.tpl&option=com_virtuemart&Itemid=1

[5] "Colour Printing":http://builders.reprap.org/2009/10/colour-printing.html

[6] Unfold Fab, "The Future's Here". 14 Februrary 2010. http://unfoldfab.blogspot.
com/2010/02/futures-here-baby-first-successfully.html

[7] Heated bed: http://reprap.org/wiki/Heated_Bed

[8] Milling tool: http://reprap.org/wiki/MillingDrillingHead

[9] Ed Sells, Towards a Self-Manufacturing Rapid Prototyping Machine, Ph.D Thesis,
Bath: University of Bath, 2009. [Accessed online]
http://dev.www.reprap.org/pub/Main/DocumentationMain/
Thesis-EdSells-TowardsaSelf-ManufacturingRapidPrototypingMachine.pdf

[10] The Foresight Institute, http://www.foresight.org/gadaprize.php.

[11] Jones, R. "First RepRapped Circuit". 19 April 2010.
http://blog.reprap.org/2009/04/first-reprapped-circuit.html

[12] Citation - RepRap Forums, multiple occasions. For example:
http://forums.reprap.org/read.php?70,21723 and
http://dev.forums.reprap.org/read.php?70,27044,27860

[13] Meoli, D. and May-Plumlee, T. 2002. "Interactive Electronic Textile Development: A
Review of Technologies". Journal of Textile and Apparel, Technology and
Management. Vol 2:2

[14] Davies, F. "Sarrus Z Linkage"
http://objects.reprap.org/wiki/Sarrus_Z_Linkage

[15] Bailard, S., Personal communication

[16] Lipsker, D., Personal communication

[17] Bayless, J., Chen, M., Dai, B. "Diagonal Brace Patch"
http://objects.reprap.org/wiki/Darwin/Patch.

[18] Palmer, C. "Extruder Postmortem", 2 Friday 2010.
`http://hydraraptor.blogspot.com/2008/01/extruder-postmortem_27.html`

[19] for the next two. Bayless, J., Chen, M., Dai, B. "Backflow and Bench Experiments".
23 Feburary 2010. `http:`
`//spoolhead.blogspot.com/2010/02/extruders-pt-1-backflow-and-bench.html`

[20] Witels-Albert GmbH Wire Drivers. For example, NAD 60 S,
`http://www.witels-albert.com/produkte_alles/PDF/NAD_S.pdf`