LA TROBE UNIVERSITY

Delta Printer Project Report

by

Keith Brown

Final Year Project Report

in the
Faculty of Science, Technology and Engineering
Department of Electronic Engineering

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LA TROBE UNIVERSITY

Abstract

Faculty of Science, Technology and Engineering
Department of Electronic Engineering

Bachelor of Electronic Engineering

by Keith Brown

This document describes the project plan for an inexpensive 3D printer. The project is developed for the final year engineering project at La Trobe University by Keith Brown.

The printer will be in the form of a delta machine. The intention is to reduce the number of components and utilise cheaper hardware while still achieving a fast accurate print. The electronics will not be a direct derivative of current implementations. Experimentation with alternative architecture will be trialled with the goal of delivering a more computational capable system.

An introduction into 3D Printing and its concepts, advantages and issues is outlined. The commercial viability for both commercial and consumer markets is described. This projects primary, secondary and tertiary objectives are listed. The strategies to achieve these goals is also described, followed by budget requirements and lastly a detailed schedule is included.

Acknowledgements

I would like to share my sincere gratitude to Professor Robert Ross, my primary supervisor whom has given me so much creative control. Robert has provided constant assistance. He also has bestowed me with his precious technical expertise. Adam Console my co-supervisor, has helped steer this project in the right direction on numerous occasions. It was Adam that suggested the delta machine design. His diverse knowledge is irreplaceable.

The RepRap community has paved the way for projects like this. There is a wealth of freely available information on their website and forums. I hope that I will be able to express my appreciation by giving something back to the open source community.

I would like to personally thank everyone who has supported me. I have discussed this project with many of my friends and family, who have contributed with valuable support and feedback.

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Introduction

3D Printers have received a lot of media attention recently. Additive manufacturing has been around for at least 30 years<cite>1, 2</cite>. However, in the last five years popularity has increased dramatically due to the availability of much cheaper entry level machines. It is now possible for the general public to purchase pre-assembled printers at a similar cost as a personal computer.

There will always be innovation and dangers associated with a new technology. We already have prime examples of both aspects; At a 2011 TED talk, Dr Anthony Atala presented a human kidney prototype that his team had printed<cite>3</cite>. Late 2012 Cody Wilson uploaded a video to Youtube that showed himself firing a gun mostly composed of 3D printed parts<cite>4</cite>.

The environment will benefit from this new way of producing products. Firstly, plastic items can be recycled and reused to create new, more useful items. This not only reduces costs but it also eliminates transportation of new items. They no longer need to be imported and transported all over the country, they can just be downloaded.

Whilst companies like Objet and Stratasys produce printers for the commercial sector, it is hobbyist style printers that have spread awareness of such technology. The Reprap foundation has produced numerous models under the GPL licence. Their main goal is to produce an affordable device that can self replicate. All of the designs are available to download and print. Makerbot Industries is a comercial operation that was born from an open source community.

Online services such as Shapeways provides 3D printing services. This allows their customers to receive a higher quality print without investing in expensive hardware. CAD design community sites have also been very popular such as 'thingiverse.com'.

There are over 30,000 free designs including a key-chain fob, mobile phone case, model radial engine and even 3D printer parts and upgrades.

1.1 3D printing methods

Additive manufacturing is the process of constructing a three-dimensional object by depositing material in discrete layers. Conversely, traditional machining methods are subtractive; material is removed to expose the desired object. This printer utilises an additive method as it produces fine plastic layers to build an object. There are many different approaches of additive manufacturing. The main four methods are outlined in the following paragraphs.

Fused deposition modelling or FDM is the method of extruding thermoplastics in layers. This project is considered to use an FDM method as it extrudes fine plastic layers to build an object. The printer deposits plastic material by melting it through a hot extruder. The extruder resembles a metal funnel that takes solid plastic and produces liquid plastic out of a small hole. The liquid plastic can be fused to previously deposited material. The machine must physically move the extruder around an area, while placing plastic where it is required. This process is repeated layer by layer to achieve a three-dimensional object. The technology was invented by S. Scott in 1980 <cite>2</cite>.

Selective laser sintering or SLS is a technique that allows either metal, plastic, ceramic and glass powder to be fused together with a powerful laser. The laser targets cross-sections, selectively fusing a fine layer of powder to the object. Once a layer has been complete, a fresh layer of powder is dusted over the object and the process repeats. The left over material acts as a support for the object being manufactured. After the procedure has finished, the excess powder can be removed and used for the next print. The process is slow, producing porous but strong results.

Stereolithography or SLA is the method of using an ultraviolet light to cure a photopolymer. The printing platform sits in a vat of liquid resin. The light targets a cross-section of the desired object and the exposed resin will solidify. Once the layer has completed, the platform will move down allowing for another layer to be added to the model. SLA produces accurate results but is a very slow process. SLA has received a lot of attention recently as the method has been adopted by a handful of young start ups. It offers a much greater result compared to the current generation of FDM printers. However the hardware and resin is very expensive.

Laminated object manufacturing or LOM is another rapid prototyping method. It uses a laser or a knife to cut out layers from an adhesive-coated material. The layer is then heated and pressed onto the previous layers. A new sheet of material is rolled in place and the process repeats. This method can be relatively cheap as readily available material such as paper can be used.

Each process is managed by a technique called '*computer numerical control*' or CNC. This method is essentially computer controlled automation. Three-dimensional models are developed using '*Computer aided design*' or CAD. These CAD models are processed to produce CNC commands known as G-code. The G-codes are instructions that tell the machine how to produce the CAD model.

1.2 FDM Articulation implementations

A Cartesian Gantry structure is the most common implementation. It consists of a linear actuator for each axis of freedom. The horizontal plane generally has a sturdy rail that a bridge is mounted on, this rail permits motion in the x direction. A carriage is mounted to a rail that connects the bridge together. The carriage can move along this rail and therefore permits motion in the y direction. Lastly the carriage has a tool that is capable of actuating in and out in the z direction.

The Gantry system is a well tested framework and is industry standard. It can be found in many applications from small desktop CNC machines to huge container cranes. While the frame is very strong, each linear actuator is dependent on another. The bridge actuator has to be the strongest as it must provide enough force to move the bridge, carriage and tool. This becomes an issue for fast moving applications as the momentum will be relatively large.

The Delta robot has three vertical rails placed in the formation of an equilateral triangle. Each linear actuator moves in the same direction and has kinetic linkages that connect each carriage to a central platform. This platform can be positioned by placing each carriage at a certain height. This is an improvement over the Gantry setup because each actuator shares the load equally. It is capable of faster speeds because there is less load on the tool end.

1.3 FDM accuracy and materials

Currently, leading consumer 3D printers can produce objects with layers heights of 0.1 millimetres. Such an accurate print will generally take around five hours for a medium sized print. Pricing for a mostly pre-assembled unit is around USD$2,200.

Currently there are two main types of plastics readily available for FDM printing. Firstly Acrylonitrile Butadiene Styrene or ABS is a strong material. It is a oil based plastic that can be melted and extruded at a temperature of approximately 105 ÂřC. It is fairly cheap at $40 a Kg. It does contract slightly as it cools.

Polylactic Acid or PLA is another alternative that can be used for FDM printing. It is marginally less expensive then ABS. While being more brittle then ABS it does not contract as much. PLA is a biodegradable polymer and actually is produced by corn starch. Because of it's lower melting point it is not ideal for applications related to heat.

1.4 Proposed Solution

The delta machine design has been adopted for this project. Recently the Rostock project has spawned many derivatives, most achieving cheaper construction over the last generation of reprap printers. Delta machines have been used for many applications including; pick and placers, packaging and production line sorters.

Its simplicity helps reduce hardware costs. But the biggest advantage is the machines speed and accuracy. If the central platform is kept light, fast acceleration can be maintained. This permits the machine to perform in a sporadic manner while maintaining an accurate position.

The electronics system will not be a derivative of current implementations. I will experiment with different architectures with the goal of producing a much cheaper but fully capable system. The components will be made modular to allow for a high level of customisation. This helps to keep the main-board costs low but still permits additional more expensive upgrades such as a Ethernet add on.

1.5 Commercial Viability

This old technology is becoming established in a new market. While it becomes more accessible, new opportunities begin to emerge and intern, increases demand. Prices are decreasing, materials are becoming more accessible and there is an increasing amount of printable designs being uploaded to the Internet. The later attributes the most positive influence to the 3D printing market. This makes an old product more valuable.

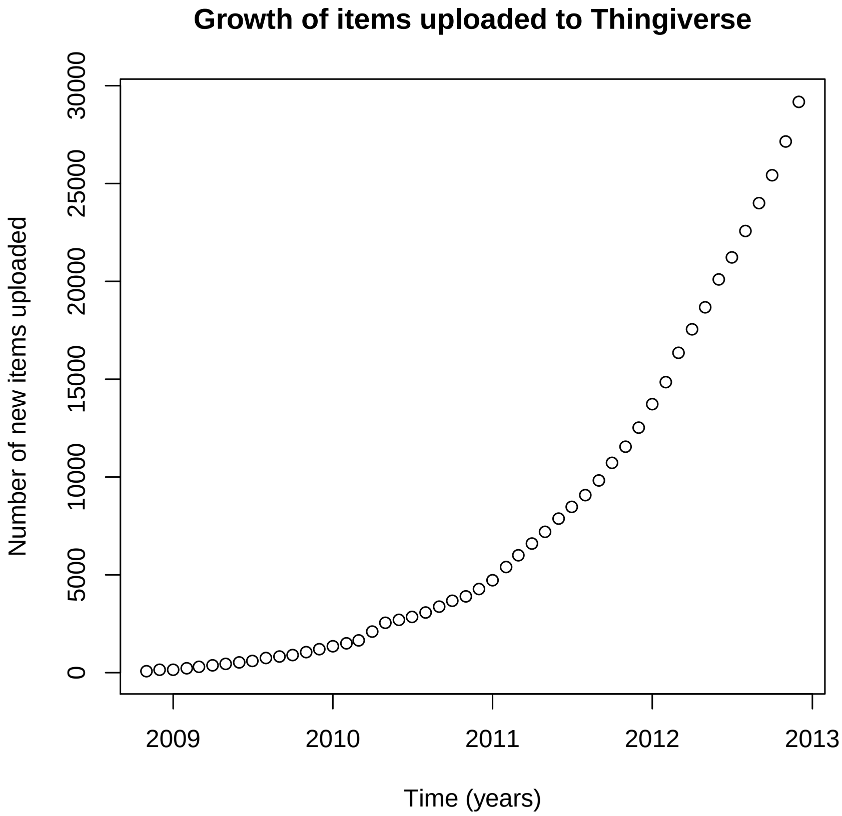

FIGURE 1.1: Growth of CAD designs on thingiverse.com

It is clear that this market is expanding at a promising rate. Furthermore because there is such a diverse range of neighbouring markets that will benefit from this technology, it is likely that it will be supported by commercial demand alone. Applications for 3D printing have yet to be completely discovered, the boundaries are always being pushed by innovators. It is apparent that a very successful industry has been created.

1.5.1 Commercial Market

3D printing can help many different businesses. For example; Product designers can produce prototypes within a few hours, prosthetics can be made for a person more frequently and engineers can produce custom parts easily. It is important to note that even if a 3D printer existed in every home, there are still many skills that can't be replaced by automation. Downloading a generalised product will never replace a professionally crafted custom version. 3D printing just streamlines the development cycle and promotes rapid growth.

Rapid prototyping reduces development costs and creates new opportunities. It is possible that we will see a rise in hardware start-ups similar to the influx of software start-ups we have seen recently. It may be more feasible for a young company to attempt entering into established markets with little overhead.

1.5.2 Consumer Market

There is a number of reasons why an individual might desire a 3D printer. It may help reduce our consumption rate by allowing us to easily repair broken household items. While it is unlikely for the average person to need a miniature factory, it is ideal for hackers, hobbyists, artists and craftsmen

Currently, the largest consumer market for 3D printing falls inside the open source community. Although intellectual property is freely shared, support and labour is very valuable. These customers are generally open to early adoption of new technology. The network of passionate, diversely skilled customers strive to improve the current designs and collaboratively innovate the CNC scene.

Chapter 2

Structure and motion analysis

2.1 Structure

A delta machine consists of a number of kinetic chains that meet at a central platform. This platform can be moved by actuating the pivots connected to the main structure. The platform is kept parallel to the floor during motion. [Figure 2] represents a simple two armed delta machine. The two-dimensional diagram helps to illustrate the important lengths and vectors. After we have analysed a two dimensional machine we will apply these concepts to three-dimensions.

fig/structure_positioning//img/structure_diagram.pdf

FIGURE 2.1: Structure Diagram

■İŚń	Horizontal length of the frame
■İŚş	Vertical length of the frame
■İŠĆ	Height of the actuator pivot point from the origin
■İŠĽ	Length of the kinetic linkage
■İŞĞ	Radius of the platform
■İŠŚ	Position of the extruder tip or centre of the platform
■İŚű	Origin of the system
■İŠŹ	Horizontal vector
■İŠŽ	Vertical vector
■İŠŻ	Depth vector

TABLE 2.1: List of vectors

The following assumptions are made to help define the system:

- Platform and linkages must stay within the frame's outer rails.

- Linkages are not restricted in any way, they may swivel on their joins in any direction.
- The platform can not move down into the base.
- Linkages are restricted to the rail's length.
- Linkages can not stretch or contract.

2.2 Simple one dimension motion

Lets consider one dimension to begin with, Figure 1 illustrates the movement of three key points; the platform and the left and right linear actuators. We can see that if the linkages are the same length as the vertical distance, the platform is capable of reaching any position along the x axis.

Simple ideal motion Also, it can be seen that a vertical actuator requires an equal amount of travel to permit full movement. It is important to note that the platform is considered a point source in this example. Practically this is not the case as we will require a place to mount tools.

For a desired position of ■İŠŚ(■İŠŹ), we need to derive where to place linear actuators. Take figure [3] below, lets derive the equations that will translate a desired ■İŠŹ into ■İŠĆâĆĄ and ■İŠĆâĆĆ.

Simple one dimension parameters Firstly, lets derive relationship between ■İŠŹ and ■İŠĆâĆĄ: (1)$h^2 = a_1^2+b_1^2 \Leftrightarrow a_1 = \sqrt{h^2 - b_1^2}$ (2)$x = b_1 - D/2 \Leftrightarrow b_1 = x + D/2$ substituting (1) into (2) gives $a_1(x) = \sqrt{h^2 - (x + D/2)^2}$ Now, lets find the relationship between ■İŠŹ and ■İŠĆâĆĆ: (3)$h^2 = a_2^2 + b_2^2 \Leftrightarrow a_2 = \sqrt{h^2 - b_2^2}$ (4)$b_2 = D - b_1$ substituting (2) into (4) gives $b_2 = D - (x + D/2) \Leftrightarrow b_2 = D/2 - x$ finally, substituting (4) into (3) $a_2(x) = \sqrt{h^2 - (D/2 - x)^2}$

2.3 Platform

We now need to consider what happens to the linkages when they are offset by the platforms width.

Simple platform By adding extra length to the horizontal component, we have decreased the horizontal outer bounds of the system. The smaller the platform the more room we are able to travel. It should also be noted that the larger the platform, the less vertical travel is required for the actuators.

The Platform reduces the b_1 and b_2 term in our position equation by r. We now have: $a_1(x) = \sqrt{h^2 - (x + D/2 - r)^2}$ $a_2(x) = \sqrt{h^2 - (D/2 - x - r)^2}$

2.4 Vertical travel constraints

We can also reduce the vertical travel required by reducing the linkages length. This intern reduces the available printing area. However, this can be used to our advantage. For example if we needed to restrict the horizontal bounds so that the platform can't physically interfere with the belt drive that runs alongside the vertical rails.

Variable linkage length

2.5 Two dimensional motion in the vertical plane

Now we are able to examine how we may add a vertical component to the system. From the last sections we discovered that the length required for the vertical actuators is the equal the linkages length. In this example, we have created a square printable area of (■İŠĽ-2■İŞĞ)Âš. This is possible as the rails are twice the length of the linkages length or ■İŚş = 2(■İŠĽ-2■İŞĞ).

Two dimensional motion Introducing the z component directly adds to the a_1 and a_2 terms. The position equations are amended as: $a_1(x, z) = \sqrt{h^2 - (x + D/2 - r)^2} + z$ $a_2(x, z) = \sqrt{h^2 - (D/2 - x - r)^2} + z$

2.6 Two dimensional motion in the horizontal plane

Now its time to examine how adding a third actuator allows for two dimensional movement in the horizontal plane. Figure [8] is a top-down view of our system. The actuators are placed in a equilateral triangle formation to distribute the load evenly. The position of the platform can be altered by changing the lengths of the linkages horizontal component, the b term. Remember, this is not stretching the linkages, it is merely displacing length between the horizontal and vertical component - the hypotenuse remains the same. By looking straight down into the system, only the b vectors are visible, the carriages on the rails or the a term is directed in/out of the page.

The coordinates system has been aligned with the actuators to help simplify the problem. The origin is placed at the centre of the print bed. Please note that the print bed is represented as a circle with its radius equal to the minimum distance from the origin to the frame. The printer is actually capable of printing in a slightly rounded three point triangle (see figure[9]), but to help visualise and simplify the system we have selected a circular print bed.

x and y motion To control the platforms position we must modify the carriages vertical position a. However, the horizontal plane position is completely dependent on b. We have already established the relationship between a and b, and that is $a = \sqrt{h^2 - b^2}$. We now need to develop the relationship between b and the position (x, y).

Each actuator will have its own equation for calculating its b term. This is because they are not placed uniformly around the coordinates system even though they are equally apart. Firstly, the general rule for calculating b as a function of the platforms position: $b_n(x, y) = |\overrightarrow{R_n P(x, y)}|$ Where R is the position vector of the target actuator and P is the position vector of the platform.

[Top view components] (/img/top-view$_{d}iagram.svg$)

Figure [8] illustrates that this problem can be solved by a simple application of Pythagoras' theorem again.

Top actuator: $d_1(x) = x \; e_1(y) = \frac{\sqrt{3}}{3}D - y \; b_1(x, y) = \sqrt{d_1^2 + e_1^2} \; b_1(x, y) = \sqrt{(x^2 + \frac{\sqrt{3}}{3}D - y)^2}$
Bottom left actuator: $d_2(x) = \frac{1}{2}D + x \; e_2(y) = \frac{\sqrt{3}}{6}D + y \; b_2(x, y) = \sqrt{(\frac{1}{2}D + x)^2 + (\frac{\sqrt{3}}{6}D + y)^2}$
Bottom right actuator: $d_3(x) = \frac{1}{2}D - x \; e_3(y) = \frac{\sqrt{3}}{6}D + y \; b_3(x, y) = \sqrt{(\frac{1}{2}D - x)^2 + (\frac{\sqrt{3}}{6}D + y)^2}$

2.7 Platform in the horizontal plane

fig/structure_positioning//img/top-view-platform_diagram.pdf

FIGURE 2.2: Top view components with platform

Adding a platform with a radius of r just offsets our x and y components as seen in figure [9]. The amended equations are:

$a_1(x,y) = \sqrt{(\frac{\sqrt{3}}{3}D - y + r)^2 + x^2}$ $a_2(x,y) = \sqrt{(\frac{1}{2}D + x - \frac{1}{2}r)^2 + (\frac{\sqrt{3}}{6}D + y - \frac{\sqrt{3}}{2}r)^2}$ $a_3(x,y) = \sqrt{(\frac{1}{2}D - x + \frac{1}{2}r)^2 + (\frac{\sqrt{3}}{6}D + y - \frac{\sqrt{3}}{2}r)^2}$

2.8 Three dimensional motion

Both horizontal and vertical components have been explained and now can be combined into one system. To implement a three dimensional system, we simply need to replace our b_n variable in the vertical plane equation with the horizontal plane equations. The result is: $a_1(x,y,z) = \sqrt{(\frac{\sqrt{3}}{3}D - y + r)^2 + x^2} + z$ $a_2(x,y,z) = \sqrt{(\frac{1}{2}D + x - \frac{1}{2}r)^2 + (\frac{\sqrt{3}}{6}D + y - \frac{\sqrt{3}}{2}r)^2} + z$ $a_3(x,y,z) = \sqrt{(\frac{1}{2}D - x + \frac{1}{2}r)^2 + (\frac{\sqrt{3}}{6}D + y - \frac{\sqrt{3}}{2}r)^2} + z$

2.9 Constraints

2.9.1 Printing Bed

A design assumption was made at the beginning of this section; The platform can not be positioned outside of the frame. To force this rule to apply, we must set the linkages length equal to the minimum distance from a rail to a side of the frame. The maximum length required is a line straight down the y axis from the rail to the frame which is equal to $\frac{\sqrt{3}}{2}D$. If we swing the platform around, pushing it to the maximum radius that this length permits, we see that the path is not actually a circle but a rounded triangle. The light blue path in figure [11] is the maximum positions. Such an unusual path is typically not needed, so we will simplify our problem by using a circular print bed (dark blue line in figure [11].

Printbed range To allow for a platform, we must subtract its radius from each of the linkages length. So, our rule for h is: $h = \frac{\sqrt{3}}{2}D - r$

2.9.2 Universal Joint Angle Range

Universal joint angle horizontal range The universal joints that will pivot to allow full movement will need to be capable of a certain range. This can be calculated exactly with:

$$\theta = 60 - 2\arctan\left(\frac{\frac{2-\sqrt{3}}{2}r}{\frac{1}{2}D}\right)$$

Practically, we can simplify the problem by aiming for 60° in the horizontal direction and 90° in the vertical direction.

Chapter 3

Motion

Chapter 4

Hardware

Now that we understand the physical constraints we can start to design the physical system. Firstly, lets reiterate over some of the main objectives that relate to this section:

- Kit like assembly
- Cheap hardware
- Solid and sturdy construction

4.1 Frame

We have selected two possible struts to build the framework. Both are made of aluminium so are reasonable light.

System30 Beam Positives

- Very strong in any direction
- Simple mounting and joining
- Reusable
- Easy to modify / tune

Negatives

- Expensive at $25 per meter
- Hard to source

H-Beam Positives

- Very strong in the vertical direction
- Cheap at $5 per meter
- Easy to obtain

Negatives

- Flexes in the horizontal direction
- Will have to drill to mount securely

Currently, the prototype material has not been decided. The H-Beam offers a significant reduction in price, and those savings can be passed on to other aspects of the project. However, System30s provide a better investment during the prototyping phase as they can be easily modified throughout the project. It should also be mentioned that System30 like beams are generally used for CNC machines, especially hobbyist versions.

Frame Design The frame will have a small enclosed area for the electronics and power supply. The printer bed is mounted on top of the case. There is a beam on the top level that intersects the face in half. This is primarily for a place to mount the plastic feeder but also serves as a structural support beam.

We will need to know how much material to order. There is 3 equilateral triangles with side lengths of D and there are 3 rails that need to be of $2D + 3 * .03$. The later 0.03 is to allocate room for an enclosure so that we can maintain a symmetrical print area. But for practiacle purposes, we will not consider the extra length so that it is possible to use a multiple of the original materials length. $M = 3(3D) + 3(2D) + \frac{\sqrt{3}}{2}D$ $M = (15 + \frac{\sqrt{3}}{2})D$ Now, we need rewrite this by substituting the relationship between D and the print bed radius b. $D = 2\sqrt{3}(b + r)$ $M(r, b) = (15 + \frac{\sqrt{3}}{2})(2\sqrt{3}(b + r))$ To minimise waste, D needs to be a multiple of the purchased material's length. The H-Beam comes in one and three meter lengths. To further reduce waste, the purchased length should be close to a whole number.

4.2 Frame Brackets

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