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Towards a Self-Manufacturing Rapid Prototyping Machine

Volume 1 of 1

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ACKNOWLEDGEMENTS

First and foremost I would like to thank my supervisor and mentor, Dr Adrian Bowyer. His guidance throughout my PhD was outstanding, maintaining a perfect balance between direction and liberty. Our meetings were something I always looked forward to: rough ideas were always met with an open mind and often bounced into profound and highly evolved solutions. Adrian always put my PhD first and I have left the term with a wealth of knowledge thanks to his education. It was great fun, and I consider myself to have been a very lucky research student indeed.

Working with the core RepRap team was also a privilege. The majority of the team was made up of volunteers, all highly skilled, dedicated to the cause, and invaluable to the project's success. For those I met in the real world (Vik Olliver, Zach Smith and Ian Adkins) it was a joy tinkering on those mechanical concepts together into the small hours of the morning.

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Finally, thanks to the two people who started it all: my parents. Their complete understanding throughout the course of my PhD was a pillar of strength and confidence, and I don't think I could have done it without all those undisturbed hours in the attic. This is for you.

DECLARATION OF A PREVIOUSLY SUBMITTED THESIS AND WORK DONE IN CONJUNCTION WITH OTHERS

The author has previously submitted a dissertation entitled 'Towards A Self Replicating Rapid Prototyping Machine' for his Master of Engineering degree. It documented the development of a new 'circuit inclusion' process to create electrical circuits in mechanical components: molten alloy was injected into casting channels in a physical component which, on solidification, formed robust electrical circuits within the structure of the component.

This previous work is associated with the subject of this thesis and it has been referenced. Beyond referencing, however, the dissertation has not been incorporated.

The work presented in this thesis has been part of a team effort, with co-workers from the open-source RepRap project. Whilst the author's area of work has been fairly distinct, he has distinguished his own work from that of others throughout this thesis. Chapter 5 (page 56) outlines these contributions more specifically.

ABSTRACT

Fused Filament Fabrication (FFF) is a layer manufacturing process which can manufacture highly complex components from CAD files using a polymer extruder. RepRap is an open-source project to produce a rapid prototyping machine which can manufacture its own parts using the FFF process. This thesis focuses on the mechanical design of the 'RepRap printer' and documents how it was conceived, developed, tested, and finally used to make a set of its own parts. Self-manufacture was demonstrated by assembling this set of parts into a working copy of the original machine. The child machine went on to demonstrate replication without degeneracy by successfully manufacturing one of its own parts.

A part count analysis of the child machine, not including the fasteners it needed in its early development phase, identified a self-manufacturing ratio of 48%. This proportion is relatively low because the design adopts modularity and redundancy principles to encourage development. Should the machine's design be adapted to fully demonstrate self-manufacture, this ratio could rise to 67% in the near future. To increase the ratio further, the machine needs three new tool heads to print resin, conductive alloy, and flexible polymer. These developments are achievable in the mid-future and could increase the self-manufactured parts ratio to 94%. As this machine is the first version of the RepRap printer, these results are encouraging.

Parts which the RepRap printer is unlikely to make until the far-future include some of the electronic components, motors, conductive cable, solenoids and a heating element. However, a 94% self-manufacturing ratio will qualify it as an assisted self-replicating machine. As with natural self-reproducing organisms, the printer will benefit from geometric growth and evolution. The author discusses how, by trading power, computing, feedstock and assembly for manufacturing capability with human beings, the RepRap printer may become a household item, offering a radical alternative to the way our society manufactures and consumes.

LIST OF ABBREVIATIONS

A glossary of terms has also been included on page 182.

3DP	Three dimensional printing
ABS	Acrylonitrile Butadiene Styrene
CAD	Computer Aided Design
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
J-P	Jetted Photopolymer
KCA	Kinematic Cellular Automata
LOM	Laminated Object Manufacturing
M/C	Machine
MM	Single Jet Inkjet
PCB	Printed Circuit Board
PCL	Polycaprolactone
PLA	Polylactic Acid
RepRap	*Rep*licating *Rap*id-prototyping
RP	Rapid Prototyping
RTV	Room Temperature Vulcanisation
SFF	Solid Freeform Fabrication
SLA	Stereolithography
SLS	Selective Laser Sintering
SMP	Self-Manufactured Part
SRM	Self-Replicating Machine
STL	Three dimensional objects digital file format

1   INTRODUCTION PART I: SELF REPLICATING MACHINES

Scientists generally agree that there are seven phenomena which an organism must exhibit to be considered alive [1]. One phenomenon is self-reproduction[1]: the ability to balance the death toll and maintain the population of the species. Specifically, self-reproduction gives the species two key survival characteristics:

- A geometric growth rate. This is the fastest mathematically possible and enables 'safety in numbers'.

- The opportunity to adapt. Self-reproduction enables a non-random selection of genes from a gene pool to occur which gives organisms a competitive advantage in what Darwin would call their 'struggle' for survival[2].

Self-reproduction is responsible for generating the fabric of the natural world we see around us. We have, of course, developed technologies to take advantage of this powerful ability (for example selective breeding, agriculture, and harvesting bi-products from bacteria), but until recently this ability has resided firmly in the biological domain.

What if we could enable self-reproduction in the mechanical domain? Imagine a machine capable of making a copy of itself. Such a machine would benefit from those same survival characteristics found in a natural organism. Perhaps such characteristics could re-generate the fabric of the mechanical world?

Freitas and Merkle [2] suggest that a crude model for an autotrophic[3] self-replicating[4] machine (SRM) might need up to 137 design properties. These properties can be categorised into twelve design dimensions, listed below in Table 1.

---

[1] The remaining phenomena of living organisms are homeostasis, organisation, metabolism, growth, adaptation and response to stimuli.

[2] This is the basis for Darwinian evolution.

[3] *i.e.* fully automatic. Defined in Section 1.1.12, page 8.

[4] In the mechanical context the author prefers the use of the word 'replicating' rather than 'reproducing' because it implies a functional, like-for-like copy. This is discussed further in Section 1.1.9, page 6.

Table 1: Freitas and Merkle's primary design dimensions for their 'Kinematic Replicator Design Space' [2]

Dimension	Brief Description
Replication control	The control under which the replicator is instructed to replicate.
Replication information	The information structure which the replicator may or may not need to replicate.
Replication substrate	Considerations for material inputs into the system.
Replication structure	Structural considerations for the design of the replicator.
Passive parts	'Passive parts' refers to the primitive parts handled by the replicator which are manipulated for the purpose of manufacture or assembly (*e.g.* mechanical struts and gears).
Active subunits	'Active sub units' refers to the components which possess power, control or autonomous mechanical action (*e.g.* a complete manipulator arm or an onboard computer).
Replicator energetics	How the replicator is powered and how it distributes that power.
Replicator kinematics	Processes to effect internal movement.
Replication process	Considerations for the processes used during the replicator's operations.
Replicator performance	Attributes of the replicator's processes.
Product structure	Assessment of products manufactured by the replicator.
Evolvability	Considerations given to the replicator's ability to evolve.

The scope of these requirements means that we are unlikely to see a fully integrated autotrophic SRM in our lifetime, at least on a macroscopic scale[5]. However, by determining its requirements we start to bring the autotrophic SRM out of the realms of fantasy, pushing it towards the real world.

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[5] The same cannot be said, however, for the scientific advances at the atomic scale, specifically nanotechnology. This rapidly advancing field may, if Drexler's book '*Engines of Creation*' is to be believed, achieve autotrophic self-replication within our lifetime. Also, the J. Craig Venter Institute (MD, USA) is building a bacterium from the ground up.

This thesis focuses on achieving one of the required design properties: the SRM's ability to make its own parts (referred to in this thesis as self-manufacture). Until recently we have not had a technology sufficiently versatile to achieve a significant proportion of self-manufactured parts. Rapid Prototyping, however, is a new and flexible technology which may be able to do just that. This thesis documents the development of a machine which was designed to demonstrate self-manufacture through rapid prototyping technology.

The consequences of a successful self-manufacturing machine may prove interesting, considering the remaining requirements for an SRM. If this self-manufacturing machine was circulated in society it may, with the help of humans, fulfil the remaining requirements. People may wish to donate power, resource, computing and assembly skills, in return for what they don't have: the ability to manufacture. Through symbiosis with human beings this self-manufacturing machine would become an *assisted* SRM, enabling the aforementioned survival characteristics found in a biological organism: a geometric growth rate and the ability to adapt. In turn, geometric growth could lower the cost of the machine to parts and labour, making it affordable for the domestic market, and its ability to adapt may improve its performance to the point where the machine becomes an indispensable household item.

It will be interesting to observe the machine's progress. With such powerful characteristics one *can* imagine it regenerating a part of our mechanical world. Perhaps we will feel this when we ask ourselves: "Do I need to go to the shop to buy this thing? Or shall I just make it in my living room?"

This chapter will show how self-manufacture is a crucial requirement for a practical autotrophic self-replicating machine (SRM). To fully understand the context of SRMs this chapter will define terms, explore initial theories and critically analyse prior art. It is one of three introductory chapters, all of which are necessary precursors to understanding the aims and objectives of the author's work.

1.1   Definition of Terms

In this section the author makes distinctions between almost-synonymous terms like 'replicate' and 'reproduce'. These definitions and distinctions are maintained for the rest of the thesis, but the rest of the thesis can be read without constant reference back to this section. In other words, these distinctions are needed for precision and completeness, but the reader is not required to learn them before proceeding.

Terms in this sphere of research have been confused at all levels. Even von Neumann's original book that started the field, "Theory of self-reproducing automata" [3] is considered by Nehaniv and Dautenhahn to be poorly titled [4]: confusingly, the book is actually only defining self-*replicating* automata not self-*reproducing* automata. A recent loose definition from Zykov *et al.* [5] shows that matters have not improved by stating that "a physical system is self-reproducing if it can construct a detached, functional copy of itself"; this is confusing because the same could be said for a self-*replicating* system, indeed the use of the word 'copy' has close connotations with replication. To make matters worse, both terms are ambiguous with respect to whether they are autotrophic (entirely self-sufficient) or assisted in some way.

The author will attempt to eliminate confusion by defining a set of terms which are unambiguous and universal in the context of a macroscopic, kinematic, self-replicating machine (also defined below).

1.1.1   Macroscopic machinery

This is machinery which can be seen with the naked eye and easily manipulated by hand (*e.g.* an adjustable spanner).

1.1.2   Microscopic machinery

This is machinery which needs to be viewed and manipulated under a microscope (*e.g.* microtechnological or nanotechnological machinery).

1.1.3   Part

In this thesis a 'part' refers to a physical entity of specific geometry which performs a specific function in an assembly.

1.1.4   Self-manufactured part

This refers to a machine's own part which the machine can make for itself.

1.1.5   Manufacture

This is the process by which a macroscopic machine makes a part. Other texts use the term "fabricate" to describe this process, but this term is ambiguous because it can be confused with assembly and therefore will not be used in this thesis.

1.1.6   Assembly

This is the process of fitting of parts, or subassemblies, together to make a complete product such as a machine or electronic circuit.

1.1.7   Kinematic machinery

This implies machinery which is made up of mobile mechanical parts. The use of the word 'kinematic' simply stresses that the assembly is not a software model and exists in the physical sense.

1.1.8   Self-replication

In the context of this thesis, self-replication refers to the process by which a machine makes a copy of itself.

Freitas and Merkle [2] define a [self-]replicator as "an entity that can give rise to a copy of itself, though apparently not an exact copy at the quantum level of fidelity". The reader should be aware that the use of the word "replication" is made in the practical sense. The second law of thermodynamics and Shannon's theorem [6] state that information cannot be copied with perfect fidelity forever[6]. Therefore the concept of a perfect replicator is an impossible ideal, but one which the physical replicators covered in this thesis strive towards.

For a machine to achieve autotrophic self-replication *i.e.* unassisted self-replication, it must contain a number of critical subsystems geared to the task. Two relevant studies which attempt to identify these subsystems are Miller's "Critical Subsystems of Living Systems"

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[6] It is this fact upon which evolution by natural selection depends.

[7] and, as mentioned at the start of this chapter, Freitas and Merkle's "Map of the Kinematic Replicator Design Space" [2].

Miller's framework seeks to identify critical subsystems found in all scales of living systems, from cells to societies. Whilst he usefully identifies nineteen critical subsystems necessary to support life, his analysis over such a broad range of systems yields generic definitions which are not specifically tailored towards the identification of the critical elements of a self-replicating machine.

Freitas and Merkle's "Map of the Kinematic Replicator Design Space" [2] is, however, a taxonomy specific to a self-replicating machine "subsuming all known prior work and providing a wealth of new design dimensions that may inform and inspire future engineering design efforts. [Their] design space at minimum identifies $>10^{70}$ theoretical distinct kinematic replicator subclasses…" This most comprehensive work defines 137 design properties which may be interdependent or mutually exclusive. Table 1 on page 2 categorises these properties. The authors acknowledge that this design space is truly vast, and has only been lightly explored via systematic engineering efforts to date.

Self-replicating systems can either be fully automatic (autotrophic) or assisted, as noted in Taylor's PhD thesis on artificial life [8]. Examples and definitions of both cases are detailed later in this section (page 8).

1.1.9   Replication versus Reproduction

The simplest distinction between replication and reproduction is made by Adams and Lipson [9]: "Replication seeks to copy an entire system without error, while reproduction includes a developmental process that allows for variations". The following section attempts to define these variations in a mechanical context.

1.1.10   Self-manufacture

Self-manufacture refers to the ability of a system to manufacture a set of the system's own parts. These parts are referred to in this thesis as self-manufactured parts (SMPs). However, after considering the issue of fidelity in the definition of self-replication (above), it is important to define the difference between a replicated part and a reproduced part.

This author attempts to make the distinction in terms of specifications and tolerances. Here, the term 'specification' will refer to the information (or geometric description) which

defines the parts using engineering tolerances. The use of specifications and tolerances to define self-manufacture has three major benefits:

1. It is a proven approach for *macroscopic* manufacturing technologies,

2. Specifications and tolerances ensure that the part or system functions, and

3. Information in the specification is discrete (information can be copied between self-replicating systems rather than using measurement processes of parent parts, which may lead to stack-up errors).

The author argues that a replicated part is one which is equal to its own specification *i.e.* its geometries lie within the stated tolerances. A self-replicating system would depend on such parts to avoid degeneracy. A self-manufacturing machine for *replication* would therefore be considered as:

"A machine that can manufacture all of its own parts, equal to its own specification."

In contrast to a replicated part, a reproduced part would be one which may or may not equal the specification. Should a manufactured part fall outside the specification it would be considered here to be a mutation. A self-manufacturing machine for *reproduction* would therefore be considered as:

"A machine that can manufacture its own parts subject to mutations or other variations which may or may not lie within the original specification."

It is worth noting that in the context of mechanical structures the notion of mutation is considered to be a bad thing – at the molecular level it is considered unsafe [10] (because molecular evolution may result in an escape from the mechanisms of control) and at the macroscopic level it induces vast non-functionality *i.e.* waste [9]. However, because of the Shannon/Second-Law argument introduced previously, when striving to manufacture parts equal to the specification, mutation is always inevitable; it can be reduced but never entirely eliminated.

1.1.11   Self-assembly

This refers to a machine which can manipulate supplied parts into an assembled copy of itself.

The concept of assembly is much more discrete than that of manufacture. A part is constrained in an assembly by an integer number of other parts. If the number of

constraints for that part does not match the assembly specification then the assembly is incorrect, and the machine is unlikely to function.

A definition from Sipper [11], made in the molecular assembly context, defines assembly for self-replication as the assembly of an *exact duplicate* of the parent (ontogenetic). Luisi [12] concurs by defining assembly for self-replication as the process of assembling identical copies. Bringing this idea into the macroscopic scale, a self-assembling machine for *replication* would be:

"A machine that can assemble a set of its own parts into a configuration identical to its own."

As with self-manufacture, assembly for self-reproduction implies assembly which may or may not match the parent configuration. Again, at the molecular level Sipper [11] distinguishes assembly for self-reproduction as a phylogenetic process which uses genetic operators such as crossover and mutation. The author posits that a self-assembling machine for *reproduction* would be:

"A machine that can assemble a set of its own parts into a configuration which may or may not be identical to its own."

1.1.12   Autotrophic self-replication

This is a system's ability to make a copy of itself, fulfilling all of the requirements discussed in Section 1.1.8 (page 5) *without* assistance.

As yet, there are no mechanical autotrophic SRMs. Biology, however is full of them. As mentioned in the at the start of this chapter, living organisms must have the ability self-reproduce, else their species would not survive. An example of an 'autotrophic self-reproducing' organism would be a bacterium. It has the ability to absorb all the nutrients (resources) it needs from its environment, which are then converted into the energy it needs to function. Its DNA (information) dictates which proteins to manufacture and these are assembled for growth and, as with all asexual organisms, this results in the reproduction of a clone.

1.1.13   Assisted self-replication

This is a system's ability to achieve at least one, *but not all* of the closures required for self-replication (detailed in Section 1.1.8, page 5).

There are few practical examples of mechanical *assisted* SRMs.[7] Those that do exist are mostly the subject of research experiments which are focussed on achieving automated self-assembly. These research examples are covered in prior art in Section 1.1.11, page 7.

Biology, again, has many examples. A good example of an 'assisted self-reproducing' organism would be yourself. You have to ability to gather all the food sources you require. Your digestive system enables these foods to be used in metabolism which releases the energy you need to function. DNA provides the information your cells need to manufacture and assemble the materials for your growth and repair, and the production of your gametes. It is at this point that self-reproduction must be assisted because, as with all sexual reproduction, a gamete from the opposite sex is needed to conceive a new organism: the reproduction of yourself.

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[7] with respect to individual, self-contained, assisted, self-replicating machines. This thesis is not concerned with the factory model (a collection of specialised machines) discussed in Section 1.3.3.1 (page 23).

Also, until closure of one or more of the requirements mentioned in Section 1.1.8 (page 5) has been fulfilled the author does not consider the machine to be eligible for classification as an 'assisted self-replicator'.

1.2   Self-replication theory

The first person to start formalising thoughts on self-replicating machines was John von Neumann [3]. Sadly, in 1957, von Neumann contracted a cancer and died before being able to completely write up his ideas. Notes on his cellular machine (a theoretical, mathematical model) were compiled into his book "Theory of Self-Reproducing Automata" [3] but his ideas on the kinematic machine (a physical entity) were only detailed in an informal description. Much of the theory presented here is based on Freitas and Merkle's summary [2].

von Neumann stipulated three characteristics for replication without degeneracy:

- Logical universality: the ability to carry out complex instructions.

- Construction capability: manipulation of information, energy and materials of the same sort of which the machine itself is composed.

- Constructional universality: the ability to manufacture any of the finitely-sized machines which can be formed from specific kinds of parts (given a finite number of different parts, but an indefinitely large supply of parts of each kind).

The assumption, *'given a finite number of different parts'*, indicates that, in the context of this thesis, this machine was a self-assembling machine. von Neumann's work on the cellular machine was done to mathematically prove the idea that a machine can self-replicate, albeit assisted with the provision of a finite number of parts. He did this with a theoretical 29-state cellular automaton. It occupies tens of thousands of cells and is so large that it has never been completely simulated [13, 14]. A detailed technical study in 1980 [15] concluded that "there appear to be no fundamental inconsistencies or insoluble paradoxes associated with the concept of self-replicating machines". This leaves the kinematic self-replicating machine variety to be completed.

von Neumann first published his kinematic theory in 1951 [16] and described it in Scientific American in 1955 [17]. Cairns-Smith [18] attempts to illustrate it using the schematic shown in Figure 1.
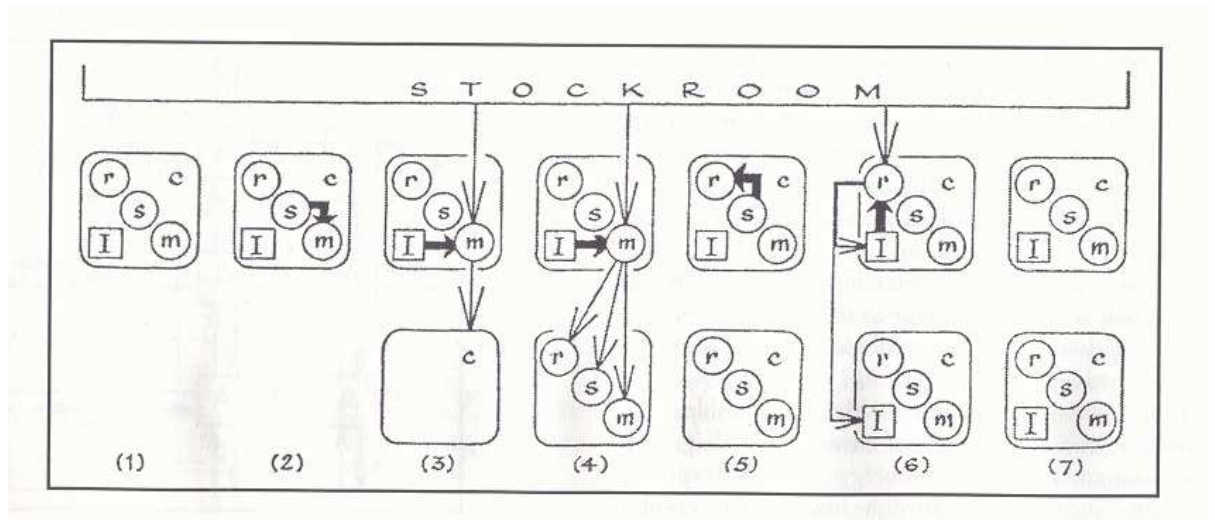
Figure 1: Schematic of von Neumann's kinematic replicator [18].

The replicating phases are described below:

The kinematic replicator machine consists of a chassis, *c*, which holds a box of instructions *I*, machinery "*m*" and "*r*" for acting on and replicating the instructions, respectively, and a timer switch or sequencer "*s*". Replication proceeds as follows:

1. Resting phase.

2. Sequencer turns on *m*.

3. *m* makes another chassis from materials in the stockroom, following instructions drawn from *I*.

4. *m* makes and installs another manufacturing unit *m*, another instruction replicator *r*, and another sequencer *s*. (The latter is possible because this machinery is being instructed from outside itself).

5. Sequencer turns off *m* and turns on *r*.

6. *r* takes recording material (*e.g.* blank punch cards or magnetic tape) from the stockroom and duplicates *I*, then installs the copied instructions in the offspring machine, producing a second machine identical to the first.

7. Resting phase… (von Neumann also mentions the ability to manufacture any other product at this stage before repeating the cycle – thus enabling an exponential rate of manufacture for that product).

Cairns-Smith's model is a fairly close representation of von Neumann's idea, other than that it refers to a stock room rather than a "sea" of parts, *i.e.* in the latter the parts come to

the machine at random, in the former these parts are collected after deliberate selection from a single ordered point. Cairns-Smith does not mention von Neumann's "manipulative appendage" needed to move parts around (represented by the thin arrows), nor the ability for the cell to move to gather its parts (implied by the movement of sequences past the static stockroom). Also Cairns-Smith does not include an inspection process for the materials taken in stage three; however it is conceivable that they are inspected before being put on the stock-room shelf. It does usefully illustrate however, that three out of the five elements (*I, r* and *s*) could be effected with a single modern electronics module, for example a computer.

von Neumann disregarded the fuel and energy problem, planning to tackle that later, and with a part count estimated to be 32,000 parts for the chassis and 150,000 binary bits for the information [17], the machine's feasibility was, and since has been, poor. It does, however, demonstrate the working principle of an assisted self-replicator, achieving closure in both self-assembly and information management.

1.3   Prior Art

The author has identified three distinct, relevant categories of work towards macroscopic kinematic self-replicating machines:

- Concepts for autotrophic self-replicating systems (systems which can synthesise their surrounding inorganic substances to produce copies of themselves in an entirely self-sufficient manner)

- Self-assembling processes[8] (machines which can assemble their own parts)

- Self-manufacturing processes (machines which can make their own parts)

This section will attempt to summarise efforts made in these areas.

Summaries on cellular automata (computer simulations for non-kinematic, theoretical structures) micro-scale and molecular kinematic machine replicators will not be included as these are not within the scope of a macroscopic kinematic self-replicating machine.

Also, this section has been written to provide a context for the author's work, and therefore focuses on ideas relevant to a self-manufacturing machine. For a comprehensive review of the field of kinematic self-replicating machines, the author recommends Robert A. Freitas Jr. and Ralph C. Merkle's book: "Kinematic Self-Replicating Machines" [2]. This recent text serves as an excellent, thorough reference to relevant contributions made over the past 60 years.

This section will attempt to summarise research towards macroscopic kinematic self-replicating machines. Therefore, studies on cellular automata (computer simulations for non-kinematic, theoretical structures),

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[8] Whilst this thesis is primarily concerned with self-manufacture the author has also included self-assembly in the review to strengthen the context: to understand the immediate requirements of self-manufacture it is necessary to know how the parts will be assembled.

1.3.1   Concepts for autotrophic self-replicating systems

As indicated in the first part of the introduction, the category of autotrophic self-replicating machines resides in science fiction. The ideas included in this section provide only concept-level detail, but give a useful indication of the technologies needed, specifically in the area of self-manufacturing processes.

In 1956, shortly after von Neumann's theories, Moore proposed the idea of an artificial living plant [19]. It would be jet propelled, solar powered and have the appearance of a large mechanical squid (Figure 2). Moore proposed that his machine would "draw on a large variety of materials. The air would provide nitrogen, oxygen and argon; the sea water would provide hydrogen, chlorine, sodium, magnesium, sulphur…; the beach would provide silicon and possibly aluminium and iron….From these elements the machine would make wires, solenoids, gears, screws, relays, pipes, tanks and other parts, and then assemble them into a machine like itself, which in turn could make more copies…". Moore then went on to suggest these machines could be developed to be seafaring and could be harvested for the materials they collected.
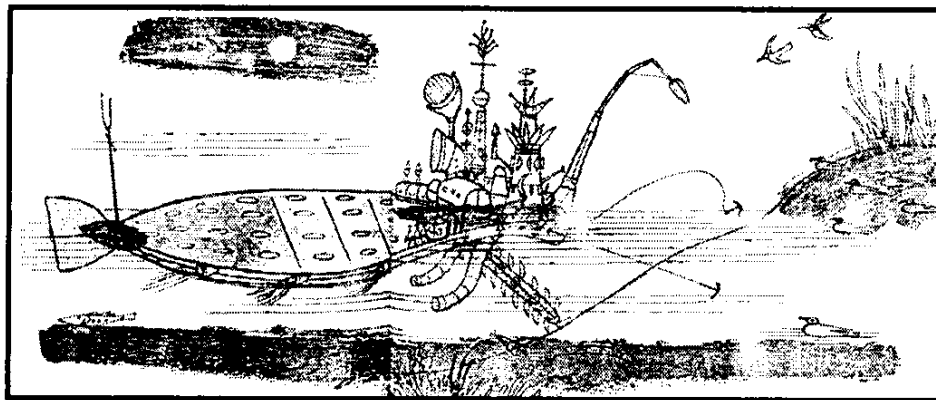
Figure 2: Artists conception of Moore's artificial living plant floating on the seashore [19].

In 1970 and 1972 Freeman Dyson suggested taking self-replicating machines into space [20]. Since then most visions for autotrophic self-replicating machines have been set in space, with NASA providing a significant impetus.

Talyor's idea for the "Santa Claus machine" was initially published in 1978 [21]. His fully autotrophic self-replicating spaceship concept uses solar and nuclear energy to mine materials. It takes advantage of the vacuum in space to separate elements using mass spectrometry and then to revapourise selected materials into moulds to create parts. Whilst this is an interesting idea, there is no detail given on the tools required to manufacture the

moulds. References have been made, however, to the field of rapid prototyping [22-24] a technology which will be detailed in the next chapter.

Freitas' factory replication system (1979-1980) [25] defines the processes needed for a self-replicating interstellar probe to be casting, laser machining and electronics fabrication. In 1981 Freitas also sketched out an idea as a scaling study, not a full systems design, to use an atomic separator to make the parts [2]. As an alternate proposal the Chirikjian Group's Self-Replicating Lunar Factory concept (2002) [26] uses casting in their proposed self-replicating lunar factory whilst the Self-Replicating Robotic Lunar Factory Concept [27], from two private groups, uses moulding, welding, selective deposition, curing and cutting.

Dyson recently popularised the idea of an autotrophic self-replicating machine with the 'Astrochicken'. In 1979, Dyson described the Astrochicken as a thought experiment [28]: it would be a blend of organic and electronic components forming a 1 kg spacecraft to be fired out into space. Using a solar energy collector, ion drive and nutrients from other planets, the Astrochicken would populate itself around space and periodically transmit radio signals back to earth.

To summarise, all of the autotrophic visions are vague about precisely how they would be implemented. As Dyson put it, "We don't have the science yet; we don't have the technology". But these visions do serve to illustrate the general requirements for an autotrophic self-replicating system mentioned in Section 1.1.8 (page 5).

1.3.2   Self-assembling processes

As defined in Section 1.1.11 (page 7) the author defines a self-assembling machine as a machine which can manipulate supplied parts into an assembled copy of itself. It cannot manufacture its own parts. This has been an area of fascination since von Neumann's ideas because of the hope that one day a bucket (or "sea", to use von Neumann's terminology) of mass-produced parts might be dumped and left to assemble themselves into a working, self-assembling machine.

Some of the earliest studies into self replicating machines focus on this area. Perhaps the most famous are the Penroses' Block Replicators (1957-1962) [29, 30]. Lionel and Roger Penrose designed some simple wooden blocks which, when placed on a horizontally agitating surface, would assemble to make copies of a "seed" assembly. This was done for

one and two dimensions and the workings are illustrated below in Figure 3 and Figure 4 respectively.
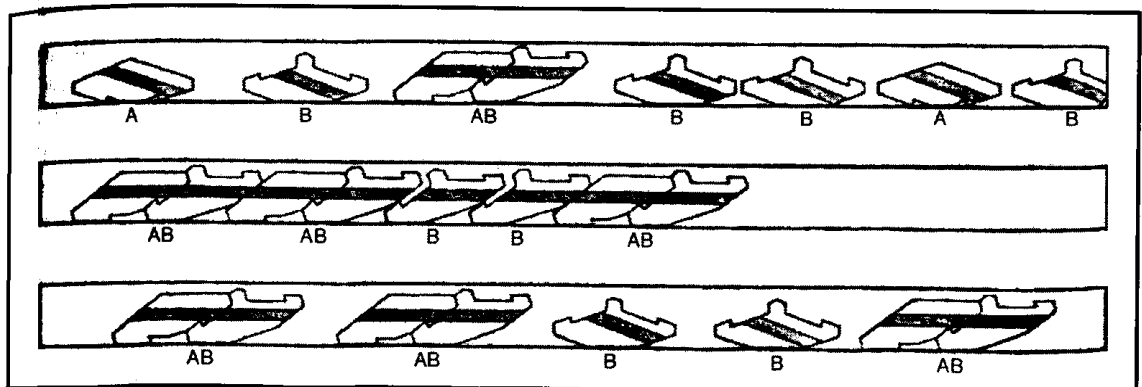
Figure 3: A 1-D self replicating "machine" made from parts of two kinds [29].
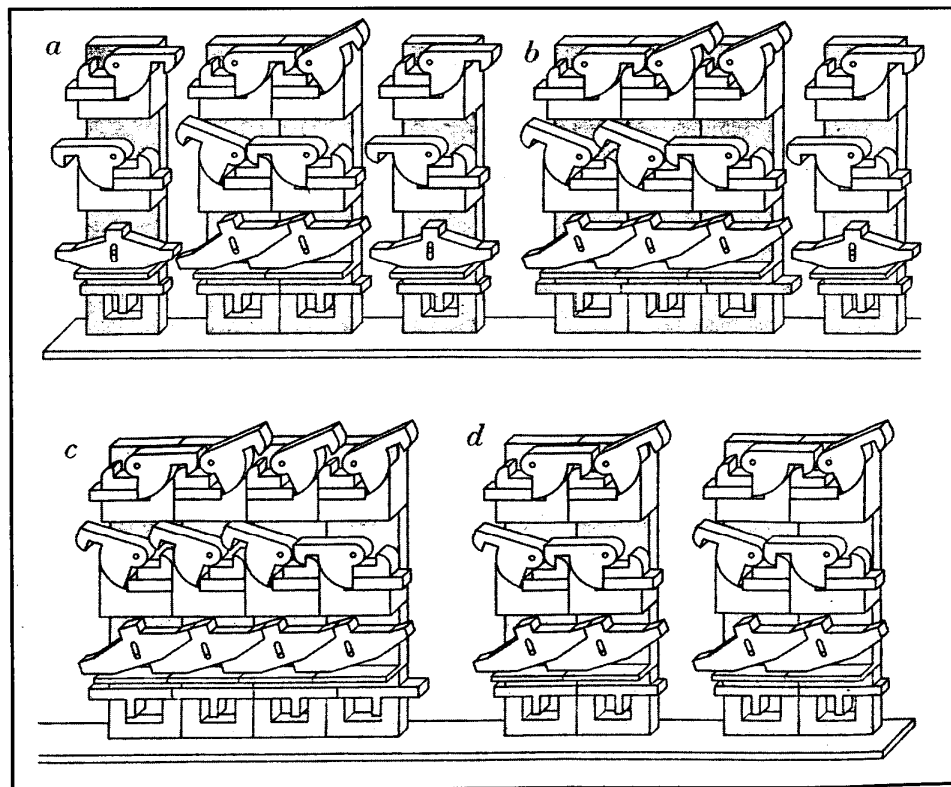
Figure 4: One replication cycle of the Penrose 3D block replicator [30].

Penrose's example relies on a sea of parts for the units to assemble in a Brownian-motion fashion.

Further cases of simple self-assembling "machines" followed. In 1958 Jacobson used a model railway to create copies of carriage combinations [31]. In 1959, Harold Morowitz designed a simple self-replicator using two parts: an electromagnetic housing and an

electret – these would combine and create copies when suspended in water & surrounded by a sea of identical parts [32] (Morowitz's idea was later refined in 1998 by Lohn [33]).

Work continues into the study of self-assembling processes. The author has identified three categories of contemporary self-assembly study, sorted by the variety of parts (or modules) used in the assembly design:

- Kinematic cellular automata (assemblies made up of identical modules)

- Limited part assembly (assemblies made from a finite set of two or more parts or modules)

- Custom part assembly (assemblies from parts shaped according to their specific function)

These three categories of self-assembly will be introduced below.

1.3.2.1 Kinematic cellular automata

Kinematic cellular automata (KCA): Toth-Fejel defined KCA in 1996 as automata which are made up of identical mechatronic module. The modules are based on the concept of cellular automata, but with the idea that the cells can move around autonomously in the physical world. One example (of many) is the work completed by Zykov *et al.* [5]: identical cubes latch onto each other using electromagnets and then, under external control, twist into each other by means of split planes. Thus the cubes manipulate each other into copies of parent assemblies, as shown in Figure 5.
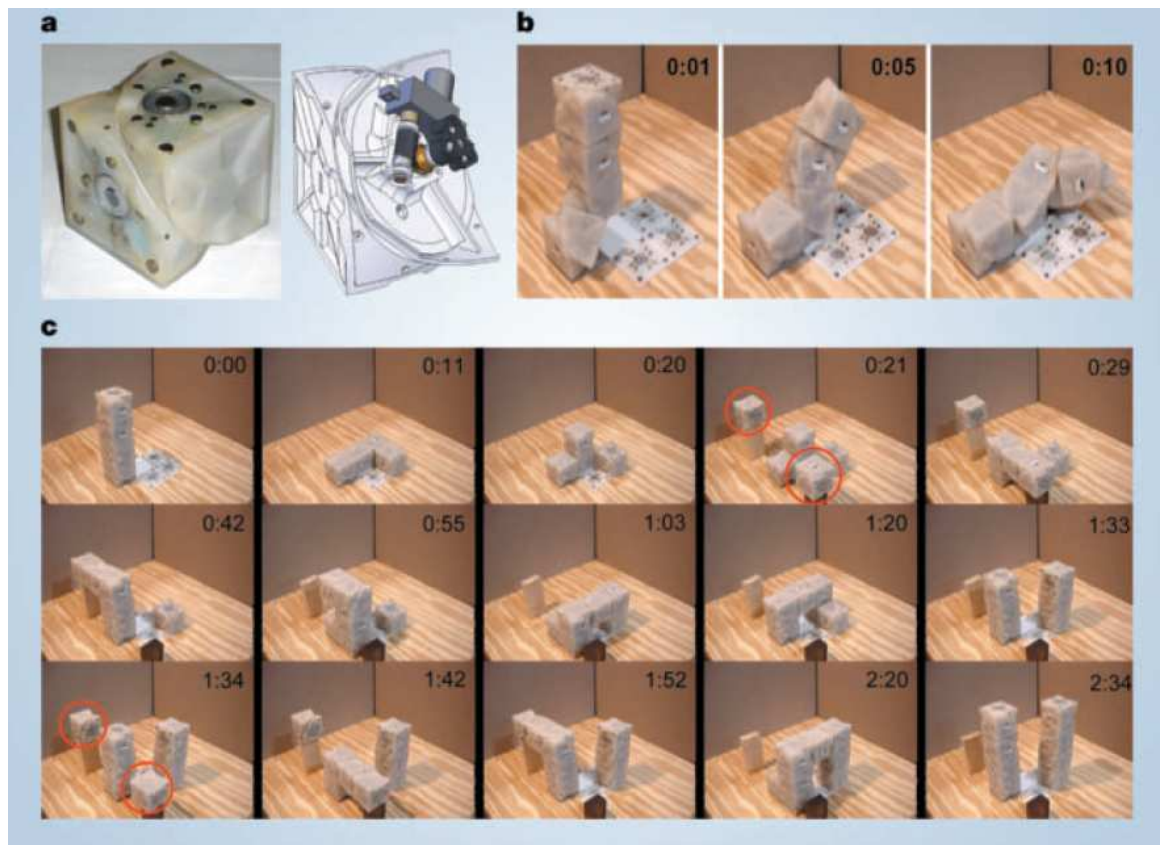
Figure 5: Zykov el al's example of KCA [5]: (a) Basic module, with an illustration of its internal actuation mechanism. (b) Snapshots from the first 10 seconds showing how a four-module robot transforms when its modules swivel simultaneously. (c) Sequence of frames showing the self-reproduction process, which spans about 2.5 minutes and runs continuously without human intervention, apart from the replenishing of building blocks at the two 'feeding' locations (circled).

1.3.2.2   Limited part self-assembling automata

The author defines the group of limited part automata as machines which are made up from a limited set of multifunctional parts or modules [34]. The earliest example in this area was done by Moses [35]. Figure 6, below, shows how he used sixteen types of snap-fit parts to create a Cartesian manipulator. It was designed in such a manner that, if supplied with enough blocks, it would be able to build a copy of itself.
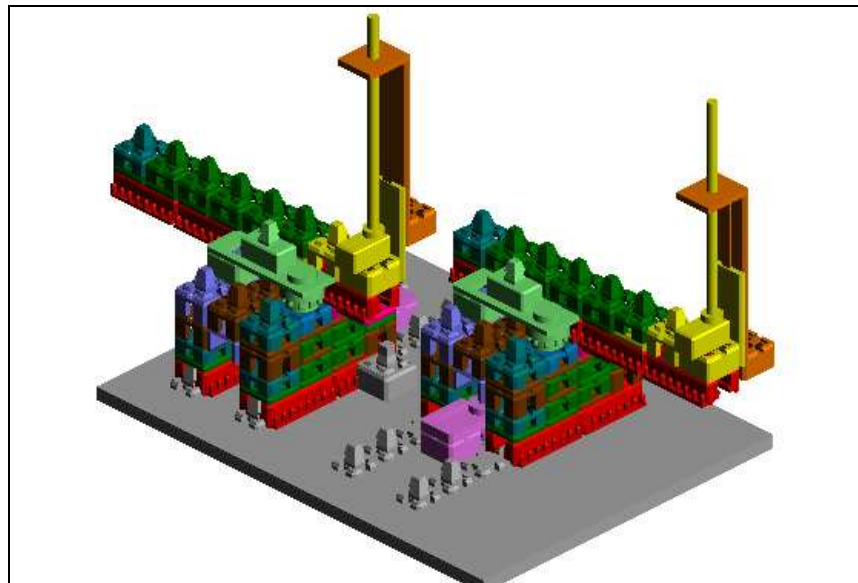
Figure 6: Moses' self assembling machine [35].

This was a prototype which suffered from a lack of stiffness in the original design and required some degree of help during the replication cycle (namely gluing and the provision of extra force), but demonstrated an excellent concept. This work was furthered in 2003 by Suthakorn *et al.* [36] to produce the world's first semi-autonomous limited part self-assembling machine using LEGO bricks, shown below in Figure 7 (it was only *semi*-autonomous because it required supervision). The system is an example of a robotic factory, as defined in the previous section. It consists of an original robot, subsystems of three assembly stations and a set of subsystems from which replicas of the original robot are assembled. The cycle takes 135 seconds.
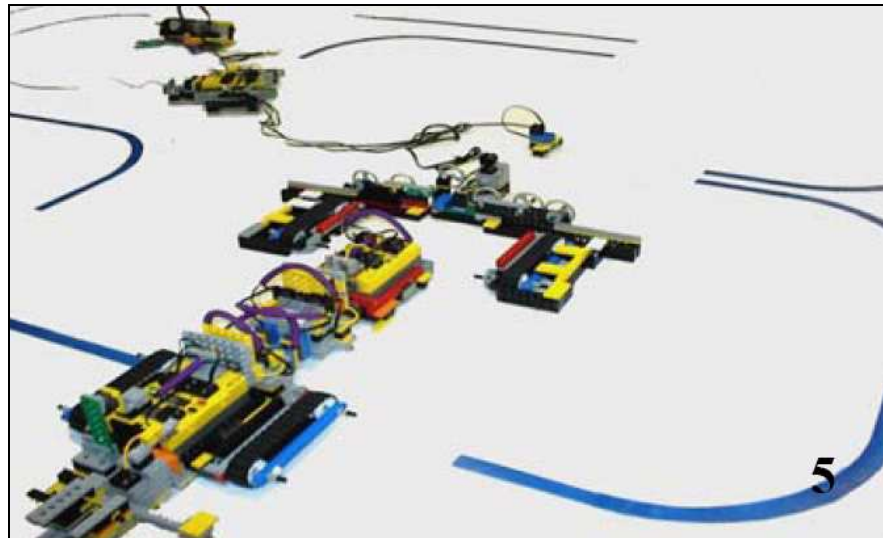
Figure 7: Suthakorn *et al.*'s self-assembling machine [36]

1.3.2.3   *Custom part self-assembly*

The author defines the group of custom part self-assembled automata as machines made up of as many different types of parts as it takes to create a working assembly *i.e.* using parts specific to their function.

NASA's robot replication feasibility study in 1982 illustrates this idea starting with a stockroom of parts used to build second and third generation robots [37] (Figure 8, below). Also, in 1998 Fujitsu Funac opened a fully automatic robot factory which assembled its own robots from supplied parts [38]. Aside from this, research into custom part self-assembly is rare.
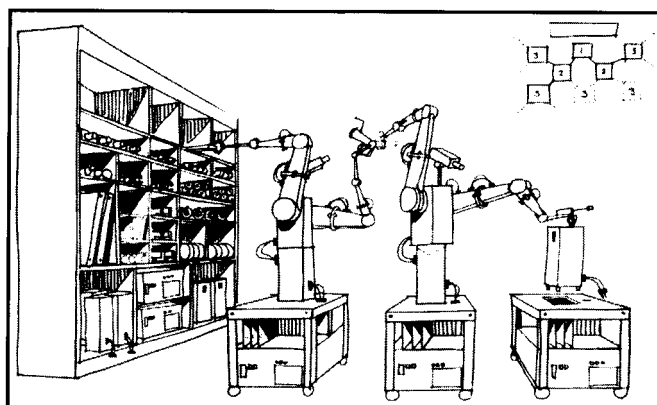
Figure 8: An illustration of self-assembly from stock parts in NASA's robot replication feasibility study

Table 2 identifies the characteristics of each of these three self-assembly categories with a view to the assembly of a useful machine.

Table 2: Benefits of the three different self-assembler types with respect to creating a self-replicating machine.

Type	Pros	Cons
KCA	Only one part is required to develop & manufacture. Improvement of the module instantly improves the whole assembly. It assumes a "sea" of parts environment which, according to von Neumann, is an environment which can theoretically yield a self-replicating machine.	Minimum functionality for the finished assembly. High module complexity & cost. Significant redundancy – bulky inefficient final assemblies. Over-use of critical interfaces between multiple modules leads to stack up errors & weakness.
Limited Part Automata	Improved assembly efficiency (parts have distinct, immediate functionalities) Each part can be less complex & therefore cheaper. It assumes a "sea" of parts environment which is a theoretically valid environment for a self-replicating machine.	Development cost increases with increasing number of part types. Multiple parts are often still needed to achieve a single mechanical function. Over-use of critical interfaces between multiple parts leads to stack up errors & weakness.
Custom Part Automata	Zero part redundancy – efficient final design. Fewer parts to assemble. Minimal complexity. Higher performance – parts are custom designed for each application within the assembly and there are fewer unnecessary interfaces.	A versatile technology is required to supply the wide range of custom parts. Parts must be retrieved from an ordered facility. Wide range of parts increases development time and cost.

The author is of the opinion that whilst KCA is an interesting field in its own right, it will serve more as a useful analogy for nanotechnology (discussed further in Section 9.5 on page 175) rather than to produce a fully functional machine. Whilst Toth-Fejel maps out a sensible strategy for KCA towards an autotrophic design, he neglects to detail how the

complex modules would be manufactured on such a necessarily vast scale for the KCA to perform useful functions.

'Limited part automata', however, go some way to improving the situation by reducing part complexity, and reducing the total number of parts, but it is still a relatively bulky approach, illustrated by the following analogy: a kinematic self-assembling replicating machine, using modular building blocks, might be compared to a cell. A cell is a fully functional biological autotrophic self-reproducer made out of simple building blocks, namely amino acids and other materials, but vastly more advanced than any of the artificial cases here. It is interesting to determine the size of an artificial machine which could cater for the same functionality using the limited module automata approach.

To make a crude approximation: if a cell weighs 1×10^{-9} kg, and the average amino acid weight is 1.66×10^{-25} kg and we assume that the amino acids occupy 10% of the cell, then we can roughly estimate the order of the number amino acids in a cell to be 6×10^{14}.

If this was translated using Moses' blocks [35] as cubes of 40 mm sides (again occupying 10% of the whole structure), the "cell" would occupy a cube with 7.3 km sides. This is a conservative estimation:

- It assumes that amino acids are the major building blocks (parts) in a cell. This already large variety is incomplete. It would be expected that the larger the variety of building blocks the lower the part count and the smaller the cell.

- Assuming only 10% of the total cell volume is occupied by amino acids.

- Cells are more economical with their assemblies – they use polar positioning of their amino acids, rather than bulky Cartesian positioning.

Obviously this is a crude analogy, but it does illustrate how self-assembling systems using modular parts can only really be practical when these modules are extremely small, entering the domain of the micro-scale. Again, this research might serve as a useful analogy for nanotechnology rather than to produce a fully functional machine.

The 'custom part' approach seems to be the most likely to succeed in creating a workable machine because its internal operations can be effected through function-specific, volume-efficient parts. It does steer away from von Neumann's idea of bumping into materials from a sea of standard parts, instead forcing the parts to be assembled from an ordered facility, or 'stockroom', but this is an improvement in practicalities. The requirement,

however, is a highly flexible manufacturing process which can produce such a wide variety of custom parts.

To summarise, self-assembly has been proven for KCA and limited module assemblies. However, the author has made attempts to justify why these fields are impractical for a functional macroscopic self-replicating machine. The only self-assembly field likely to achieve this in a practical manner would use custom, function-specific, volume-efficient parts, for which a highly flexible manufacturing process is needed.

This concludes the review of self-assembling processes.

1.3.3   Self-manufacturing machines

This is the third and final section of prior art. After briefly reviewing 'concepts for autotrophic self-replicating systems' and 'self-assembling processes' this section refers to self-manufacturing machines: machines which can actually *make* the parts needed to create a copy of themselves.

The only completed research in this area comes from The Replicating Systems Concepts team. From the 1980-1982 NASA conducted a summer study on self-replicating systems and identified two approaches to self-manufacture [2]:

- "*Unit growth* or factory model: a population of specialist devices, each one individually incapable of self-replication, can collectively [manufacture] and assemble all necessary parts comprising all specialist devices within the system. Hence the factory is capable of expanding its size up to the limits of available resources in an appropriate environment."

- "*Unit replication* or 'organismic' model: the replicator is an independent unit which employs the surrounding substrate to directly produce an identical copy of itself. Both the original and the copy remain fertile and may replicate again, thus exponentiating their numbers."

This section will briefly summarise the idea of the factory model and highlight the idea behind the organismic model.

1.3.3.1   Unit growth, or factory model

von Neumann noted [3] that a machine shop with enough facilities can make all of the tools needed to make itself and can be considered to be a self-manufacturing unit. Bradley

[37] makes the point that this is more achievable by simplifying the machine shop using standardisation and limitation of scope where feasible. He admits that computer chips would fall out of the scope of the shop, and so categorises these parts as feedstock. He lists other exogenous items to be power, transmission elements (motors/belts), abrasives, furnace heating arrangements for tool heat treatment, and raw material such as basic feedstock including steel rods, strips, and plates are among the most obvious. He points out that the functionality of the shop is not only limited to self-replication, and program memory should also be extended for the manufacture of other non-vital machinery. Such a system would also have the capacity to carry out maintenance on itself and notes that "high fecundity can to some degree make up for a lack of reliability".

Today, Yamazaki Mazak has several Flexible Manufacturing Systems (FMSs), which make the parts needed for the CNC machines, which make up the FMSs [39]. This is one of many examples.

The diversity of output for unit growth is of course very large and the quality industrially robust. This is a model that has already been achieved. But any unit growth systems are large, as its name 'factory model' illustrates quite well, and as such they carry fairly heavy-weight dynamics. For example, you could never fit one in your home. In fact you'd almost certainly need planning permission. These systems are therefore of little interest to the author.

1.3.3.2   The unit replication, or organismic, model

Conversely, a unit self-replicator *does* have the potential to fit in your home. It is a fascinating idea because it is free of the heavy-weight dynamics that come with the factory model, and has the potential to behave, as its name suggests, much like an organism. At the time of writing the organismic model has not been realised – the challenge of achieving unit replication remains, and so becomes the subject of this thesis.

Perhaps the conception of the organismic model has been restricted by the lack of a manufacturing technology sufficiently versatile to make all of its own parts. Traditional manufacturing technologies are only able to process single feature types as a contribution to the unit growth model *e.g.* a lathe is used for cutting about an axis, a milling machine is used for cutting along a plane *etc*. These traditional technologies are insufficiently versatile to achieve unit replication.

1.4   Chapter conclusions

Concepts for fully autotrophic self-replicators remain in the science fiction domain because they rely on many different technologies which have not yet been realised.

Some individual aspects of self-replication have already been demonstrated, specifically self-assembly. The author considers most of the approaches towards self-assembly to unsuitable for a practical macroscopic self-replicator (unless the system uses custom parts) and that modularity and redundancy are key design elements to facilitate replication at this level.

On examining the aspect of self-manufacture the author has noted that little work has been done in this area. Further examination has defined the challenge for self-manufacture to be to create a unit replicator, but our traditional manufacturing processes seem unsuitable. Fortunately, the next chapter details a recent, extremely versatile technology which may be sufficiently versatile to achieve unit replication. This technology is called 'Rapid Prototyping' (RP).

2   INTRODUCTION PART II: RAPID PROTOTYPING TECHNOLOGY FOR SELF MANUFACTURE

As stated in the previous chapter, a self-manufacturing machine requires a process which is sufficiently versatile to manufacture all of its own parts. Until recently this versatility has been unavailable. Rapid Prototyping (RP) is a relatively new technology which can manufacture a large range of parts using a single process, condensing the functionality of many workshop machines into one single machine. RP is, therefore, an excellent contender for achieving unit replication. This chapter will explore the different RP variants and note previous research attempts towards the self-manufacturing element of unit replication using this technology.

2.1   Historical perspective of RP technology and current terminology

There are many terms which refer to RP technology, many of which are confused in today's media. This is unsurprising since RP has only recently been commercialised (The introduction of the first commercial RP system was by 3D systems, CA, in 1988).

Prior to this the early roots of rapid mechanical prototyping technology can be traced back to the fields of 'photosculpture' [40] in 1860 (attempts to create exact three-dimensional replicas of objects, including human forms) and later topography in 1890 [41]. These techniques relied on stages of intensive manual crafting and stacking of layers of material to achieve three dimensional models, and it was not until 1981 that Kodama demonstrated a fully automated rapid prototyping machine [42]. To learn more about the history of RP technologies the author recommends further reading of Beaman's chapter in the 'Japanese/World Technology Evaluation Center Panel Report on Rapid Prototyping in Europe and Japan' [43].

To clarify the contemporary context of RP this section will outline three of the most important terms. Definitions have been derived from Chua and Leong [44].

2.1.1   Rapid Prototyping (RP)

RP systems take information from a CAD solid model file via an STL file and convert it into a sliced model. They then use this information to drive an SFF process (defined

below) to physically build the layers. These layers are deposited on top of each other to form the final part.

2.1.2   Solid Freeform Fabrication (SFF)

SFF refers to a collection of techniques for manufacturing solid objects by the sequential delivery of energy and/or material to specified points in space to produce that solid.

2.1.3   3D Printing (3DP)

3DP refers to the category of RP processes which implement the simplest of the SFF technologies to achieve fast and affordable 3D printers.

Whilst 3DP is currently a term favoured by the media, its scope is limited to the simplest of SFF techniques. For consistency and clarity this thesis will use the term Rapid Prototyping (which refers to all SFF techniques) throughout, despite the fact it would be equally accurate to refer to 3D printing in some instances.

2.2   RP characteristics

RP is extremely versatile. Unlike traditional subtractive approaches, part design complexity carries no overhead (though surface quality may differ depending on the type of features built). Indeed it is possible to manufacture designs on an RP machine of such complexity that they would be near-impossible to make in a traditional machine shop (for example, the corner bracket design in Figure 42 on page 87). It is also possible to make full working assemblies as the parts are manufactured. The important advantage of RP technology with a view to building a self-manufacturing machine is that the SFF process is capable of making the entire part from start to finish[9].

As versatile as RP systems are, they can suffer from some generic limitations. Madellin *et al.* [45] offer the following list:

- It is sometimes difficult, occasionally impossible, to remove support material from cavities.

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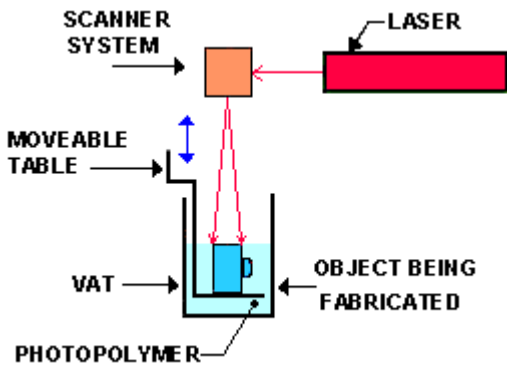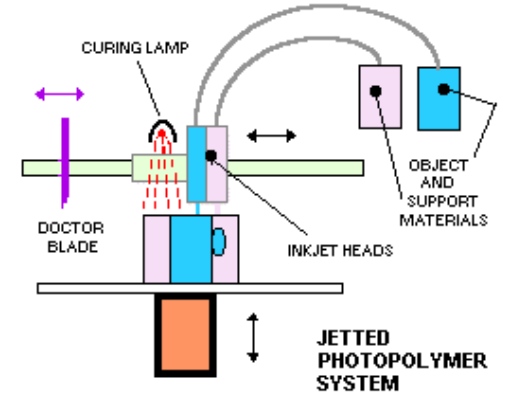
[9] These capabilities depend on the type of SFF process used. Some SFF do not have the capability to manufacture working assemblies due to issues of support material removal, and some RP processes do require post-processing when the part is complete.
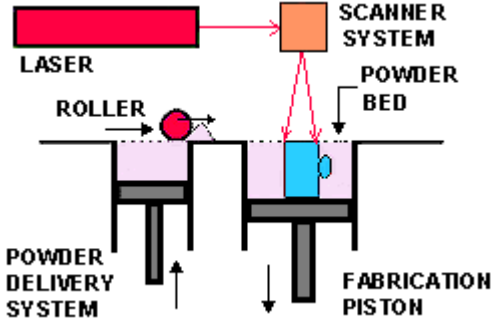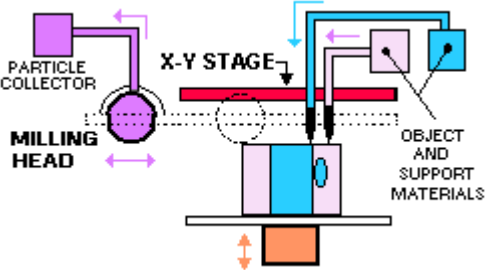
- Distortion, shrinkage and warping can occur due to residual stresses in print material solidification.

- Feature damage can occur during support material removal.

- Build features must not be too small, too closely spaced, or require accuracy beyond the technology's capabilities.

- Overhanging features may affect the surface flatness.

- Surface finish is dependent on material, build orientation, layer thickness, sloped surfaces, intricate features, and curves surfaces. [Surface finish is generally rougher than that from a part made using traditional subtractive techniques such as turning, milling and grinding.]

- The maximum size of the part is defined by the build volume of the RP system.
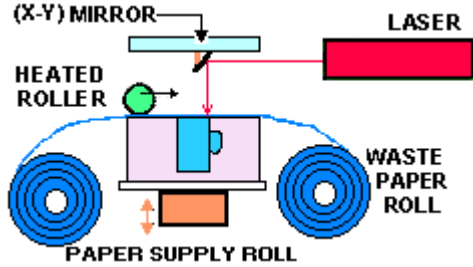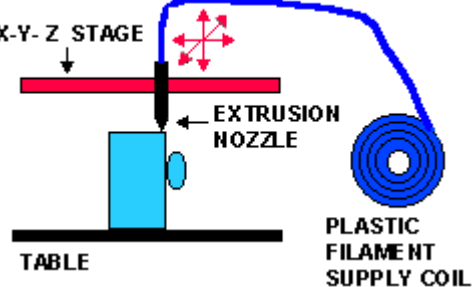
Different RP systems suffer from these limitations with varying degrees. Also different SFF processes deliver different results, measured in cost, part strength and resolution.
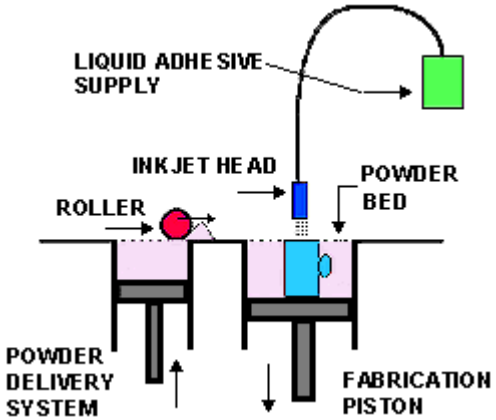
Table 3 describes seven established SFF processes [44]. Illustrations are courtesy of the Worldwide Guide to Rapid Prototyping [46].

Table 3: Descriptions of established SFF technologies, illustrations are courtesy of the Worldwide Guide to Rapid Prototyping [46]

SFF Technology	Description	Illustration
Stereolithography (SLA)	The process begins with a vat of photo-curable liquid resin and an elevator table set just below the surface of the liquid. The computer controlled optical scanning system then directs and focuses the laser beam so that it solidifies a 2D cross section. The elevator then drops enough to cover the solid polymer with another layer of liquid resin. The process is repeated. Active patent: Hull, *Apparatus for making three-dimensional objects by stereolithography,* August 1984, U.S.	
Jetted Photopolymer (J-P)	A similar system to 'Single Jet Inkjet' (below) is available using photopolymers and a curing lamp. It subsequently completely cures each layer after it is deposited with a UV flood lamp mounted on the print head. The support material, which is also a photopolymer, is removed by washing it away with pressurized water in a secondary operation. Active patent: Fudim, *Method and apparatus for producing three-dimensional objects by photosolidification; radiating an uncured photopolymer,* February 1987, U.S.	

SFF Technology	Description	Illustration
Selective Laser Sintering (SLS)	Parts are built by sintering when a CO_2 laser beam hits a thin layer of powdered material. The interaction of the laser beam with the powder raises the temperature to the point of melting, resulting in particle bonding, fusing the particles to themselves and the previous layer to form a solid. The next layer is then built directly on top of the sintered layer after an additional layer of powder is deposited via a roller mechanism on top of the previously formed layer. Active patent: Deckard, Method and apparatus for producing parts by selective sintering, October 1986, U.S.	
Single Jet Inkjet (MM)	The illustration uses a single jet each for a plastic build material and a wax-like support material, which are held in a melted liquid state in reservoirs. The liquids are fed to individual jetting heads which squirt tiny droplets of the materials as they are moved in X/Y fashion in the required pattern to form a layer of the object. The materials harden by rapidly dropping in temperature as they are deposited. After an entire layer of jetting, a milling head is passed over the layer to make it a uniform thickness. Particles are vacuumed away as the milling head cuts and are captured in a filter. The process is repeated to form the entire object.	

SFF Technology	Description	Illustration
Laminated Object Manufacturing (LOM)	Parts are built, layer by layer, by laminating each layer of paper or other sheet-form materials and the contour of the part on that layer is cut by a CO_2 laser. The Z control is activated by an elevation platform which lowers when each layer is completed, and the next [paper] layer is [rolled over the build] then laminated [to the top of the build] ready for cutting. No additional support structures are necessary as the "excess" material, which is cross-hatched for later removal, acts as a support. Active patent: Feygin, *Apparatus and method for forming an integral object from laminations,* June 1986, Israel.	
Fused Filament Fabrication (FFF)	Filament is fed into an extrusion head and heated to a semi liquid state. The semi liquid material is extruded through the head and then deposited in ultra thin layers from the head, one layer at a time. Since the air surrounding the head is maintained at a temperature below the material's melting point the material quickly solidifies. The technology was developed by S. Scott Crump in the late 1980s and was commercialized in 1990. The technology is marketed commercially by Stratasys Inc as FDM™. Active patent: Crump, *Apparatus and method for creating three-dimensional objects,* October 1989, U.S.	

SFF Technology	Description	Illustration
Solvent jet printing (also sometimes referred to as Three-Dimensional Printing)	The machine spreads a layer of powder from the feed box to cover the surface of the build piston. The printer then prints binder solution onto the loose powder forming the first cross section. The powder is glued together where the binder is printed. The remaining powder remains loose and supports the layers that will be printed above. When the section is completed, the build piston is lowered, a new layer of powder is spread over its surface and the process is repeated. Active patent: Sachs et al. *Three-dimensional printing*, December 1989, U.S.	

A survey of the available RP systems has been made by the Worldwide Guide to Rapid Prototyping [46] and adapted by the author to include reference to specific printers and data relevant to the context of this thesis (Table 4).

Table 4: Rapid Prototyping Technology comparison chart based on information from the Worldwide Guide to Rapid Prototyping [46] and the author's own research.

	Stereo-lithography	Jetted Photopolymer	Selective Laser Sintering	Single Jet Inkjet	Laminated Object Manufacturing	Fused Filament Fabrication	Solvent jet/ 3D printing
Acronym	SLA	J-P	SLS	MM	LOM	FFF/FDM	Solvent jet/3DP
Representative Vendor	3D Systems	Objet	EOS	Solidscape	Solidscape	Stratasys	Z Corp.
Example product	iPro8000	Connex 500	EOSINT P390	T612 Benchtop	SD300	Dimension 1200es	Zprinter 310 plus
Maximum Part Size (mm)	508 x 508 x 610	298 x 185 x 203	699 x 381 x 584	305 x 152 x 229	160 x 210 x 135	610 x 508 x 610	508 x 610 x 406
Speed	Average	Good	Average to fair	Poor	Good	Poor	Excellent
Minimum layer thickness (mm)	0.05	0.016	0.1	0.013	0.168	0.254	0.089

XY accuracy	Very good	Good to very good	Good	Excellent	Fair	Fair	Fair
Surface finish	Very good	Good to very good	Fair	Excellent	Fair	Fair	Fair
Strengths	Large part size, accuracy	Accuracy and finish, office OK	Accuracy, materials,	Accuracy, finish, office OK	Office OK, price, size	Office OK price, materials	Speed, office OK, price, colour
Weaknesses	Post processing, messy liquids	Size and weight, post processing	Size and weight, system price, surface finish	Speed, limited materials, part size	Limited materials, finish and accuracy	Speed	Limited materials, fragile parts, finish
System price	$75K-800K	$60K-85K	$300K	$70K-80K	$15K	$19K-300K	$20K-70K

Build material properties & characteristics	Acrylics (fair selection). Clear and rigid. ABS-like. Polypropylene -like (PP). Flexible or elastomeric. Water-resistant.	Acrylics (limited selection). Elastomeric.	Nylon, including flame-retardant, glass-, aluminum-, carbon-filled and others providing increased strength and other properties. Polystyrene (PS). Elastomeric. Steel and stainless steel alloys. Bonze alloy. Cobalt-chrome alloy. Titanium.	Polyester-based plastic. Investment casting wax.	Bonded PVC-based plastic film. Bonded paper.	ABS. Polycarbonate (PC). Polyphenyl-sulfone. Elastomer.	Bonded plaster / plaster composite. Elastomeric. Investment & direct casting.

Typical applications	Very detailed parts and models for fit & form testing. Trade show and marketing parts & models. Rapid manufacturing of small detailed parts. Fabrication of specialized manufacturing tools. Patterns for investment casting. Patterns for urethane & RTV molding.	Very detailed parts and models for fit & form testing. Trade show and marketing parts & models. Patterns for investment casting, especially jewelry and fine items. Patterns for urethane & RTV molding.	Slightly less detailed parts and models for fit & form testing compared to photopolymer-based methods using engineering plastics. Rapid manufacturing of parts, including larger items such as air ducts. Parts with snap-fits & living hinges. Parts which are durable and provide the patterns for investment casting.	Most detailed parts and models available using additive technologies for fit & form testing. Patterns for investment casting, especially jewelry and fine items, especially medical devices. Patterns for urethane & RTV molding.	Somewhat less detailed parts and models for fit & form testing compared to other methods. Patterns for urethane & RTV molding. Larger patterns for sand-casting	Detailed parts and models for fit & form testing using engineering plastics. Detailed parts for patient- and food-contacting applications. Plastic parts for higher-temperature applications. Trade show and marketing parts & models. Rapid manufacturing of small detailed parts. Patterns for investment casting. Fabrication of specialized manufacturing tools. Patterns for urethane & RTV	Concept models. Parts for limited functional testing. Color models for FEA and other engineering related applications. Architectural & landscape models. Color industrial design models, especially consumer goods & packaging. Castings.

2.3   Choosing a suitable SFF technology for a domestic unit-replicator

From NASA's definition of the 'organismic' model in the previous chapter, it is easy to imagine a unit-replicator becoming a household item if it is capable of making useful things as well. The RepRap project, detailed in the following chapter, attempts to achieve this. Therefore, primary considerations for the selection of a SFF technology to meet the needs of the domestic market must be:

- low cost (within a household budget)

- acceptable performance (suitable for the manufacture of consumer items)

- spatial efficiency (to fit into a home)

- zero emissions (to eliminate any extra installation infrastructure)

- simple material handling (for ease of use)

- zero post-processing would be ideal (so that produce is immediately ready with minimum effort on the part of the owner).

Also with respect to the self-replicating aspects:

- it would be beneficial, from the evolutionary aspects of a self-replicating machine, for the technology to be highly versatile, or have the capacity for its versatility to be improved.

- the process should be as simple as possible, reducing the probability of process failure and maintenance involved.

- the performance of the printer must be suitable to manufacture components to within an engineering specification, i.e. to an accuracy which will enable self-manufacture.

2.3.1   Analysis of with respect to cost and performance

Figure 9, below, compares the minimum cost of these RP technologies with the resulting minimum layer thicknesses (a parameter used to evaluate product resolution). Data for this graph has been taken from Table 4.
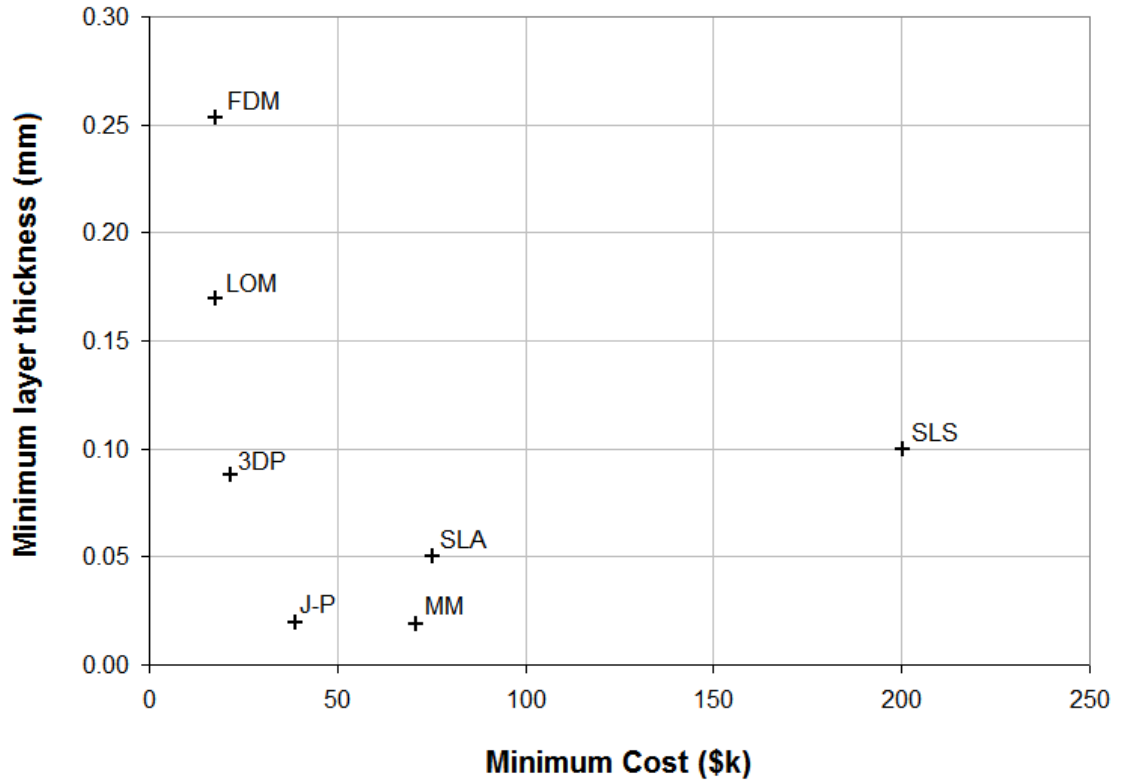
Figure 9: Data from Table 4 illustrated to compare the different RP technologies with respect to the cost of a system and the resulting resolution.

Figure 9 illustrates that the cheapest RP technologies are 3DP, LOM and FDM (or FFF). All fall within a similar price range. Of the three, 3DP is the most accurate, LOM represents the average and FFF is the worst: a layer resolution of 0.254 mm is likely to suffice for the manufacture of most consumer items, however, the question as to whether or not it will be suitable for self-manufacture will become an element of the hypothesis for the author's work (Chapter 4, page 54).

2.3.2   Analysis with respect to system volume

To measure the volume efficiency for the available technologies the author has examined the example products in Table 4 and used two metrics to evaluate each product. The first is the volume index where:

$$\text{Volume index} = \text{Build volume}/\text{Machine volume}$$

Similarly the author uses a footprint index:

$$\text{Footprint index} = \text{Build area}/\text{Machine footprint}$$

These simple metrics dictate that the higher the index the greater the spatial efficiency of the RP system.
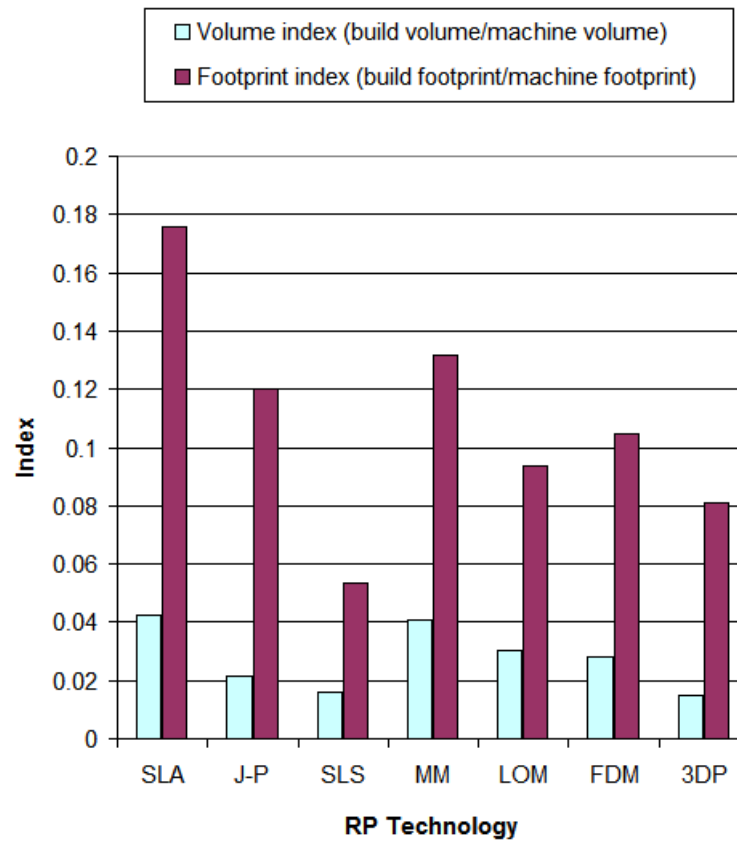
Figure 10: Bar chart to illustrate the different spatial efficiencies for the different RP systems currently available.

Figure 10 illustrates that of the cheapest technologies established in the previous section FDM (or FFF) proves the most volume efficient, LOM represents the average and 3DP is the worst. However, the distribution of efficiencies is close, therefore neither of three technologies should be ruled out on this basis.

2.3.3   Suitability in the home

Table 5 compares the three cheapest RP technologies in terms of emissions, material handling and post-processing.

Table 5: Comparison of the cheapest RP technologies for emissions, material handling and post-processing.

RP technology	Emissions	Material handling	Post-processing
FDM/FFF	Suitable: zero emissions.	Suitable: filament is contained in reels.	Suitable: no post processing is required.
LOM	Suitable: minor solvent emissions.	Suitable: plastic sheet is contained in reels.	Suitable: no post processing is required.
3DP	Suitable: zero emissions.	Unsuitable: starch or plaster powder is hard to completely contain, especially if the powder requires recycling between builds.	Unsuitable: post processing is required – infiltration is necessary to make a structural component.

Table 1 demonstrates that whilst FFF and LOM technologies are suitable for the home in all three areas, 3DP fails in two of them. The author considers the powder substrate to be messy to handle, and the requirement of post-processing a significant handicap for domestic users who require the minimum amount of technical involvement with the process.

2.3.4   Simplicity

Of the two remaining RP technologies, LOM is slightly more complex. This is because it requires two key sub-process: cutting and gluing. FFF simply relies on one process: fusing a molten filament. It is so simple in fact that Saul Griffith [47] managed to make an FFF prototype using a LEGO® toolkit to print in chocolate or beeswax, all within a budget of $100.

2.3.5   Versatility

As mentioned earlier, it would be beneficial for the technology to be highly versatile, or have the capacity for its versatility to be improved.

For example, if it were possible to a printed a mechanical part with its associated electronics inside its structure [48] this would certainly facilitate self-replication [49]. This idea is developing quickly in the filament deposition field. At the macro scale, work has been done by the author to inject molten bend alloy through a heated syringe to successfully create electronic circuits of 1.2 mm track width [50]. Similar techniques have

been used to print a zinc-air battery [48]. Whilst both of these initial techniques yielded rather bulky electronics by today's circuit board standards, their affinity with the FFF process is encouraging for future development. Work on the fused deposition of ceramics has created sensors and actuators with feature sizes as small as 200 microns [51].

It is also worth noting FFF's parallels with inkjet technology. This also promises work towards printing electronic parts [52-54]. Transistors with feature sizes of ~ 100 microns were printed in 2002 [55] – a significant achievement bringing the manufacture of processors out of the clean room, and another step closer towards the desktop. Proposals have already been made for a gadget printer [56], detailed below in Figure 11. This figure also serves to demonstrate the similarity between the inkjet and FFF processes.

THE 3D GADGET PRINTER

How to print a remote control all in one go

Ink-jet cartridges containing different types of electroactive polymer print moving parts as well as electronics

Electronics are embedded within the polymer casing itself, rather than being soldered separately on a printed circuit board

Remote control is "printed" layer by layer
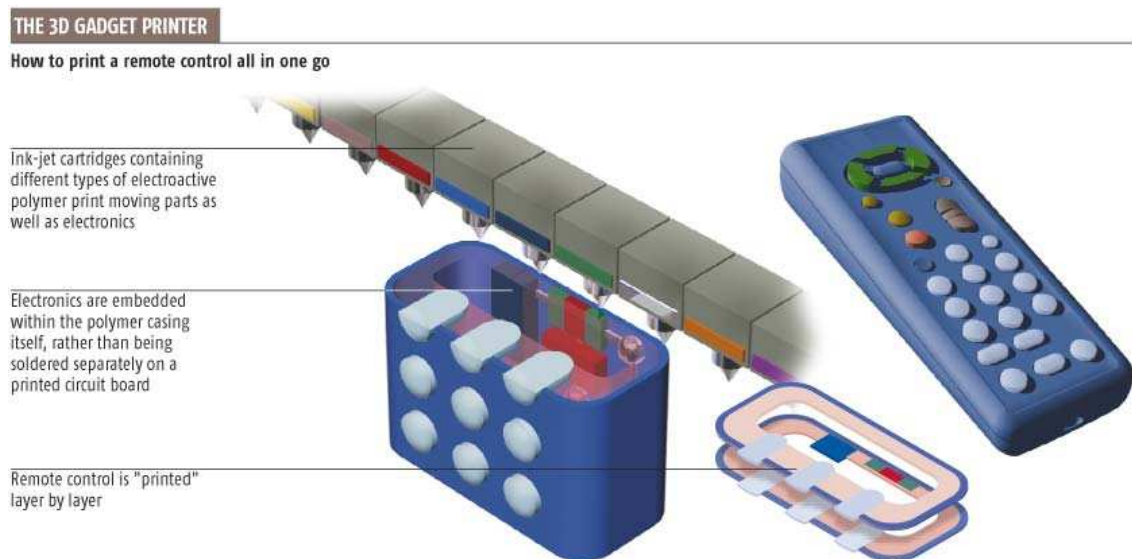
Figure 11: The 3D Gadget printer using ink-jet technology

For LOM, however, there are fewer parallels. It is hard to imagine the cutting process being re-used in any other process, and if it were, the requirement for the build material to be dispensed in thin film is limiting.

2.3.6 Summary

Of the seven RP technologies considered for a domestic, self-manufacturing unit replicator, three compete to be the cheapest on the market: 3DP, LOM and FFF. All three systems have similar spatial efficiencies. 3DP, however, fails on two of the criteria for domestic use: its build material (a starch or plaster powder) is difficult to handle and post-processing is a requirement to make the components strong enough for mechanical use. The LOM and FFF processes are both suitable with respect to material handle, emissions

and post-processing. Between LOM and FFF the author considers FFF to be a simpler process and more versatile. Whilst its layer resolution (0.254 mm) is questionably thick, on average the author considers FFF to be the most suitable process for a domestic self-manufacturing unit replicator.

2.4   Previous attempts at using RP technology for unit replication

Whilst this promising technology has not yet produced a RP machine which can print another RP machine, the author is aware of two attempts to realise self-manufacture using RP technology.

For the first, Freitas and Merkle [2] describe a sketched-out design by C. Phoenix in 1998 for "a macro-scale kinematic replicator a few cubic feet in volume that would use two hydraulic-powered manipulator arms to machine, then assemble its own parts out of a soft plastic feedstock which would then be ultraviolet-cured to yield hard plastic parts, analogous to the stereolithography system offered by Vicale Corp. The acoustically-powered plastic replicator, composed of perhaps ~2000 parts, would be controlled by an onboard 8086-class computer built from cured-plastic fluidic logic elements including 1 KB of RAM, receiving instructions from a 1400-foot long strip of hole-punched control tape. Most details such as specific materials and assembly procedures, basic closure issues, process error rates, and accessibility of required machining tolerances were not explicitly addressed". This work is, to date, unpublished.

Secondly a masters thesis is underway by Mike Collins, University of Florida, "to build a piece of hardware that can take amorphous raw material and draw on an unconstrained amount of energy to build a copy of itself and any tools that it used to make that copy. [He is] using Rapid Prototyping Machinery to build part parts and specialized equipment for mass manufacturing. [His] aim is to focus on the mechanics and logistics of such a system. This project will be aided by the following simplifying factors: 0% energy closure, limited materials to be refined, and large initial material store allowed (yolk subassemblies); the project will be hindered by the following complicating factors: limited materials from which to design parts and subassemblies, and high information closure (90% target)" (personal communication to Robert A. Freitas Jr., 15 October 2003). Specific details of the yolk assemblies, the extent to which RP is used and progress to date are unknown. Neither the author, nor Freitas (confirmed by personal communication) have been able to determine the outcome, if any, of this thesis.

3   INTRODUCTION PART III: THE REPRAP PROJECT

The author's work is driven by the RepRap project – a project which is attempts to make a self-manufacturing RP machine using the FFF process. This chapter introduces the RepRap project, outlines the project's ideal final result and explores how a distributed manufacturing unit like the RepRap printer offers an alternative to our current, centralised mass-manufacturing infrastructure.

3.1   The idea behind the RepRap project

Initiated by Adrian Bowyer in 2005, the RepRap project aims to put RP technology into the home. It attempts to do this by designing an assisted self-*Rep*licating *Rap*id Prototyping machine. Section 3.6 (page 46) details how the ability to self-replicate will make RP technology more accessible to the public through geometric growth and accelerated evolution.

The RP machine uses the FFF process to manufacture a set of most of its own parts. These are then assembled with standard, readily available components, by hand, into a working copy of the original machine. The child machine is then capable of making the parts for future copies, and so on. In other words, through its own ability to self-manufacture and the assistance from humans, it becomes an assisted self-replicating machine.

This machine will be referred to for the rest of this thesis as 'the RepRap printer'. It is important to note that the idea behind the RepRap project is to demonstrate self-manufacture, not self-assembly (as mention above, the RepRap printer will be put together by hand).

3.2   The vision of the RepRap printer's assisted self-replication cycle

Once the owner has a copy of the machine he or she may then connect it to a computer and manufacture anything within the bounds of the FFF process. Figure 12, below, illustrates the concept for use in the home.
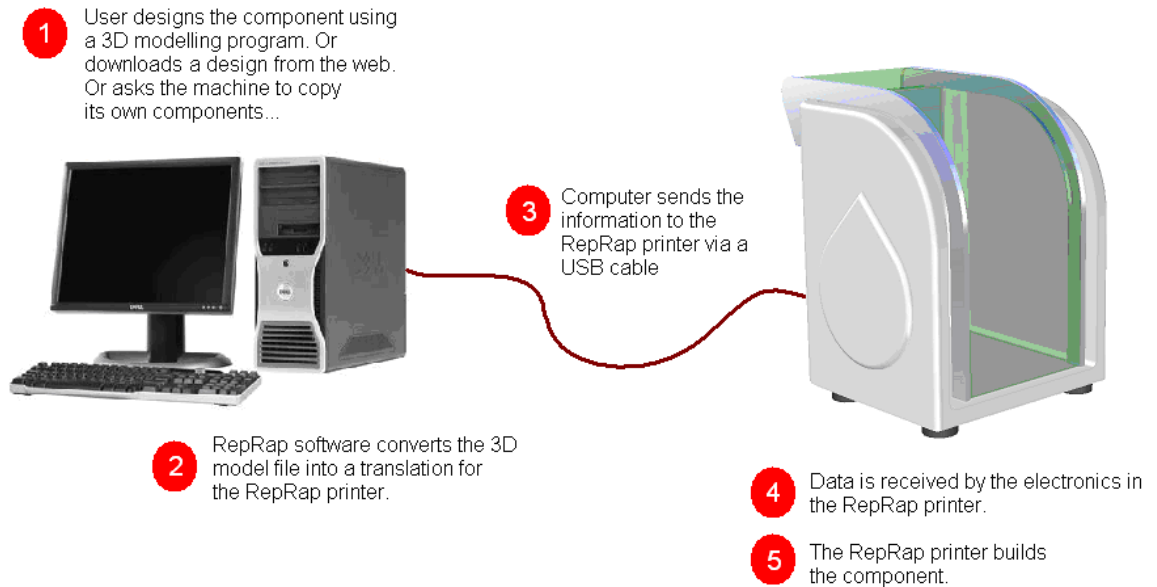
Figure 12: An illustration of how the RepRap printer could work in the home.

As well as printing whatever design the user wants, the user can also choose to make another copy of the printer[10]. On receiving this instruction the printer will make a set of most of its own parts. The design information (part files) for these parts will be freely available on the internet through the GNU General Public Licence (Section 13.11, page 277).

To complete self-replication, the child printer will also need some parts which the parent printer is unable to make. At the time of writing, the RepRap project is in the early stages of self-replication, and therefore accepts a set of readily-available, standard 'imported' resources which the printer will not have to make:

- grease

- standard electronic chips (such as microcontrollers and optical sensors, standard electrical wiring, USB connectors *etc*.)

- stepper motors

- a 12V power brick

- nuts

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[10] Freitas and Merkle [1] would therefore refer to this machine as a 'productive replicator', *i.e.* a self-replicator which can also make non-vital products.

- bolts

- ø 8 mm steel rods

All of these imported resources are deliberately available through local hardware shops or online. It is hoped that this list will reduce with further development - indeed the interest in the percentage of self-manufactured parts forms the basis of the hypothesis for this thesis, detailed in the next chapter.

After manual assembly the copy of the RepRap printer can then be given away or sold for as much or as little as the owner likes (though this is expected to reduce to material costs and assembly as the machine proliferates, also discussed further in Section 3.6.3, page 50).

3.3   The RepRap team and communications

Consisting of twelve members from around the globe (Section 13.7, page 220), the design team communicate almost solely via the internet. VOIP technology and email are used for synchronous and asynchronous communication, a blog is used to record progress, a wiki is used for documentation and a regulated repository is used to build software code and CAD designs. The team releases the latest versions of the RepRap printer through these channels under the GNU General Public License, free of charge. These channels are all accessed through a central website: www.reprap.org.

3.4   Initial goals and validation

To validate the idea behind the printer (*i.e.* demonstrate replication without degeneracy) it must span three generations, as illustrated below in Figure 13. A commercial FDM RP machine will be used to manufacture the printed parts of the first RepRap printer, known as the parent. To prove self-replication the parent must manufacture a child. To demonstrate self-replication without degeneracy the child must manufacture a grand-child and this grand-child must achieve the same performance as the parent.
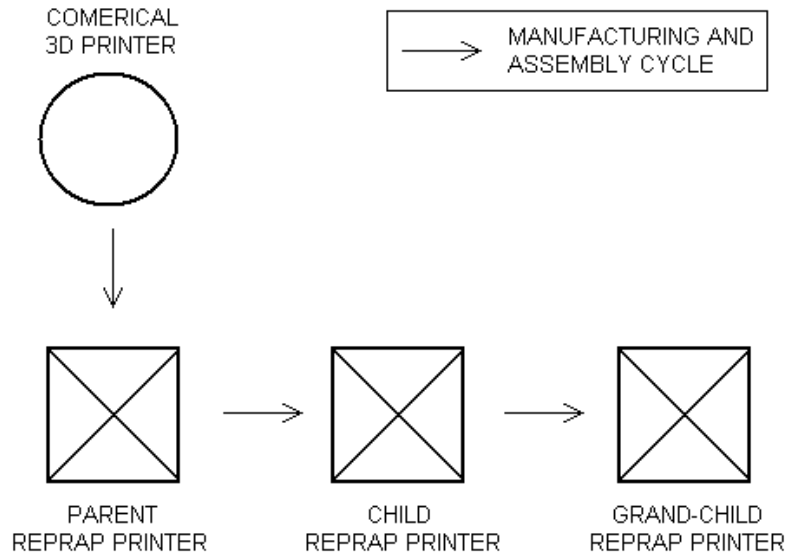
Figure 13: The generations required to validate idea behind the RepRap self-replication

3.5   The ideal final result for the design of the RepRap printer

The 'Ideal Final Result' (IFR) is a useful tool from the 'Theory of inventive problem solving' used to further understand printer requirements [57]. As the name of the tool suggests, it simply asks "what would a perfect result for the printer be, in an ideal world?"

The IFR for the RepRap printer would be a machine capable of printing 100% of its own parts, qualifying it as an assisted self-replicating machine. It is expected that with development the imported parts list will diminish, and perhaps be eliminated from the cycle altogether. This expectation is discussed further in Section 9.2.8, page 159.

In an ideal world, the replication cycle would happen instantly and incur no cost to either the owner or the recipient. The child machine's design would be to the most recent release.

3.6   How an assisted, self-replicating, distributed manufacturing unit like the RepRap printer would compare with our current non-self-replicating, centralised mass manufacturing systems for consumer items.

The RepRep printer offers a radical alternative to the way our society manufactures and consumes. In response to the idea, the front page of *The Guardian* for November 25, 2006, reads:

"[RepRap] has been called the invention that will bring down global capitalism, start a second industrial revolution and save the environment..."

This section attempts to justify, in part, this newspaper's (perhaps over-grand) claim by looking at the characteristics of distributed, assisted, self-replicating manufacturing systems (like the RepRap printer) and comparing them with our current, centralised mass-manufacturing systems. Because a fully functional distributed, self-manufacturing system does not yet exist in industry, biological analogies will be used where appropriate (as mentioned in the first chapter, all biological organisms need to self-reproduce).

Note: The RepRap printer is not yet 100% self-manufacturing, though projections made later in this thesis (Section 9.2.8, page 159) estimate that the printer will be able to achieve 94% self-manufacture in the mid-future. To improve readability this section will assume that the RepRap printer is in its advanced state, capable of achieving near-total self-manufacture, thus (from the definitions in Chapter 1) qualifying it as an assisted self-replicating machine.

3.6.1   Introduction

For this section it is necessary to understand the difference between centralised and distributed manufacture.

- Centralised manufacture is the mass production of many goods at one site, before transporting the goods to many different markets.

- Distributed manufacture is the production of one or a few goods at the site of the market. No transportation is needed, except for raw materials, but for all markets to be satisfied a manufacturing machine must exist at each market location.

3.6.1.1 *Examples of centralised manufacture*

The Industrial Revolution (late 18th and early 19th centuries) enabled centralised manufacture with the birth of mechanisation and improved transport networks. Since then centralised manufacture has made everyday household items available to the general population at affordable prices. To illustrate this example, let us examine a simple household item: a plastic cup.

One company which makes plastic cups is Tisa Injection Moulding Ltd. Their factory is based in Wolverhampton and they use their injection moulding machines to mass produce thousands of plastic cups from one or a few specific designs.

Once made on this central site the cups are driven in lorries all over the country, and indeed the world, to central holding stores. They are then distributed from these stores to shops, in vans. If we want a plastic cup we probably leave our house by car to buy one from a shop. Once satisfied that we've made the right choice we drive back and the plastic cup finally arrives at our home.

This delivery system is also prevalent in biology. For example, adrenaline is made in the adrenal gland and insulin is made in the pancreas. Both are delivered via the blood in our circulation system to many other parts of our bodies.

3.6.1.2   *Examples of distributed manufacture*

Conversely, distributed manufacture delivers the product through an on-site manufacturing process. Industrial examples of distributed mechanical manufacture exist to meet extremely personal demands. One example is 2D printing. With a word processor and a printer you can print your own documents and photographs. With a suitable kitchen you can also cook your meals, resources and skills permitting. Generally though, mass manufacture operates on the centralised model (even the latter two examples have centralised solutions: internet print shops and microwave dinners).

In micro-biology, distributed manufacture is a mechanism used frequently for growth and repair: if we cut ourselves blot clots are not made centrally within the body and sent to the wound, they are made on site from local proteins. Hairs are made in follicles and salty fluid is made in the eyes' lacrimal glands.

3.6.1.3   *The role of self-replication for centralised and distributed manufacturing systems*

Biological organisms are well equipped for self-reproduction, representing distributed manufacturing systems themselves by reproducing on location. We are not born in a central factory and then shipped around the world: we were born from our parents, wherever they might have been at the time. Biology uses distributed, self-replicating manufacture for species to grow. If we were to translate the idea of distributed, self-replicating manufacture into engineering, the analogy would be very close to the RepRap printer: a machine for small communities capable of manufacturing goods locally.

Conversely, industrial, centralised manufacturing systems are only concerned with manufacturing a high volume of products of limited range, and therefore are not equipped for self-replication.

3.6.2   Growth in self-replicating and non-self-replicating manufacturing systems

The organism's ability to self-reproduce means that the growth rate of the species is a geometric progression (resources permitting). Assuming a perfect reproduction environment and an infinite lifespan, the total number of organisms (T) can be expressed as:

$$T = ab^n$$

where a is a scalar factor, b is the common ratio and n is the number of replication cycles since the first replication of the original self-reproducing organism. For example, the binary fission process for single celled organisms (in ideal conditions) exhibits a growth with a common ratio of 2 and a scalar factor of 1:

$$T = 2^n$$

Despite low initial totals, the nature of geometric progression is far more powerful than the arithmetic progressions found in industrial production.

To illustrate this consider the mass manufacture of a simple comb. The traditional industrial approach would use an injection moulding machine capable of manufacturing approximately 10,000 combs per hour, working 24 hours per day, seven days per week. Consider a biological approach: a biological machine which could only make one comb per day, but also make a copy of itself. Figure 14, below, compares production for both approaches, and demonstrates the power of geometric progression assuming ideal conditions.
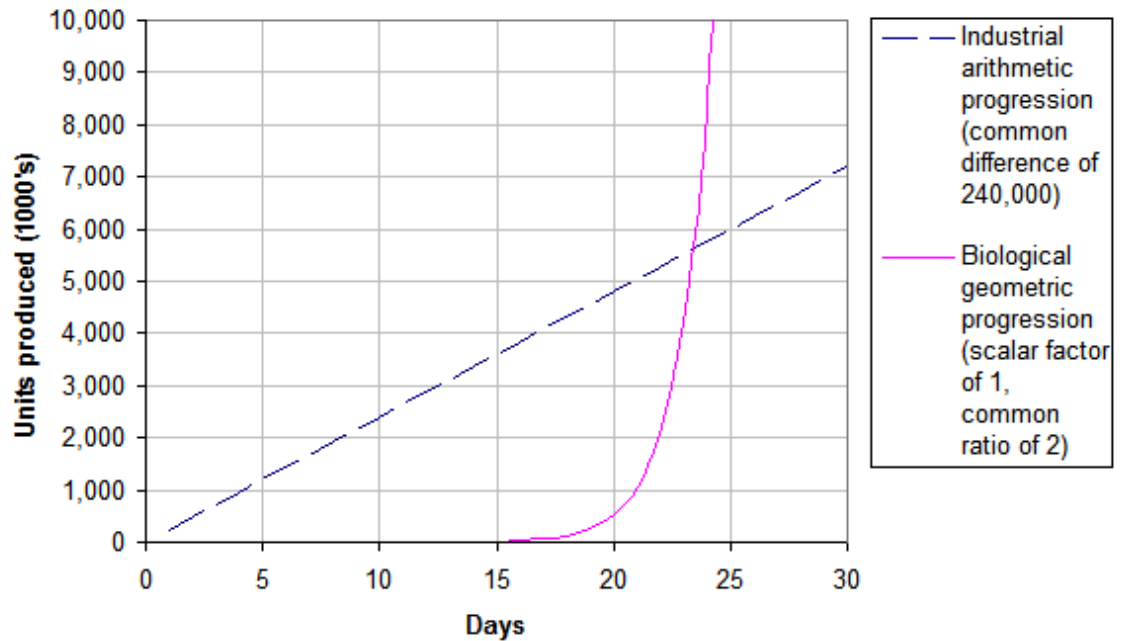
Figure 14: Comparison of production of combs for an injection moulding machine at 10,000 combs per hour against a biological machine which could only make one comb per day but also a copy of itself.

In this example the biological process exceeds industrial production at 24 days. Another ten days later and biological production has exceeded industrial production by a factor of approximately 1000. Clearly the number of machines required for the biological approach quickly becomes unfeasibly large if they are housed within a traditional centralised warehouse environment, but this is not a problem for the RepRap printer because its will be distributed amongst people's homes.

3.6.3   Cost trends for the RepRap printer against centralised manufacture

In the case of the RepRap printer the author expects geometric growth to reduce the cost of each manufacturing unit down to resources and assembly time. As summarised by Bowyer [58]: "the economics are driven by logic – once a system can copy itself (with a bit of help) it costs very little, other than the raw materials to produce unlimited numbers of it, which makes the added value approach zero". This puts the technology within reach of a household budget, enabling people to manufacture goods very cheaply in their own home.

Conversely, non-replicating centralised mass-manufacturing systems are dependant on high investment for refined, efficient, high-volume processes. The nature of these processes means that products are generally made in one location and then made available to the market via a distribution network. A significant drawback for a centralised manufacturing system is product transit. Product transit carries a host of inefficiencies:

massive investment in transport infrastructure, energy expenditure, delay and shelf life. This cost is passed on to the consumer.

3.6.4 Rapid evolution for the self-replicating RepRap printer through accelerated artificial selection

To explain the evolutionary benefits which the RepRap printer may inherit through self-replication, the author will first describe how mass-manufactured items usually evolve. A traditional, non-replicating mass-manufacturing process is represented on the right side of Figure 15. This might be a production line making and assembling mini-lathes. It shows production of fifteen units which all come off the same production line and belong to the same generation. These items will all be identical. Any improvements (or evolutions) in the product will not be implemented until it is economically beneficial to change the tooling of the manufacturing process. In reality, the new generation of products may be thousands of products later.
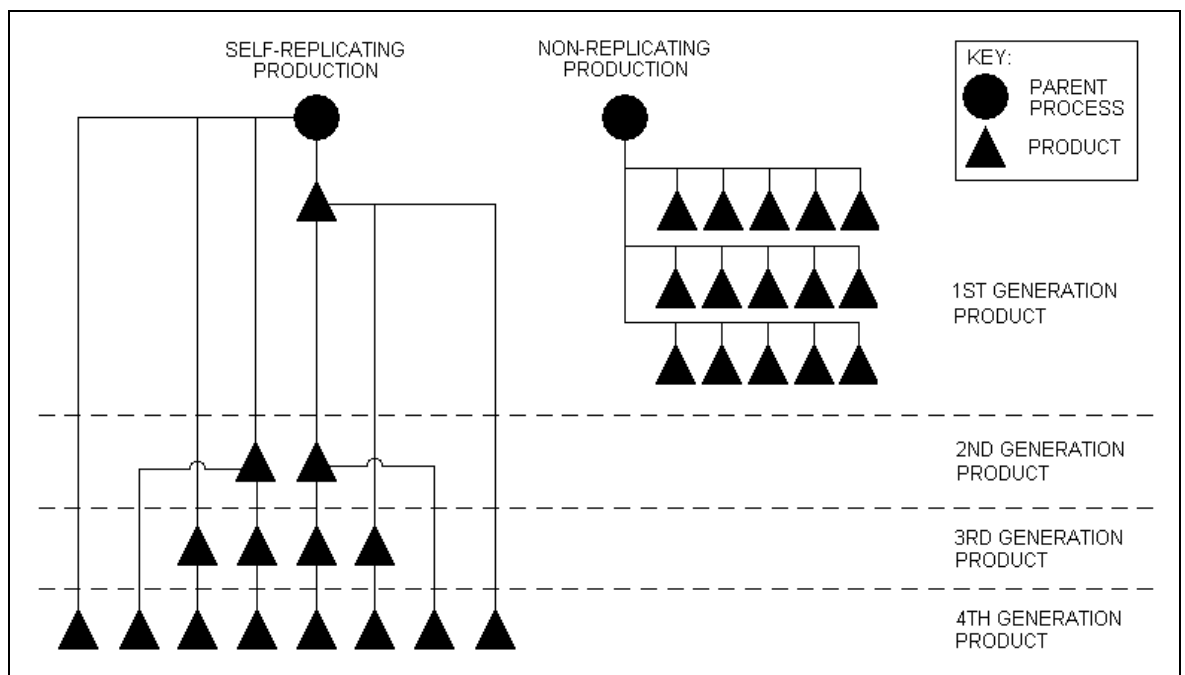
Figure 15: Comparison between self-replicating and non-replicating production processes. To meet a production of 15 units the self-replicating process spans four generations.

The left side of Figure 15 shows how the RepRap printer would self-reproduce to a total of fifteen units, assuming the same replication rate for all machines. However, this machine does not suffer from the generational constraint found in traditional mass-manufacture. The RepRap printer's flexible tooling means that improvements to the machine's design can be implemented immediately with no costs incurred for tooling.

Each machine's description and fitness has the capability to be shared through the internet, and each new machine can benefit from successful attributes of the other machines (analogous to genetic cross-over through artificial selection[11]).

The author refers to this evolution as 'accelerated' for two reasons:

- The contribution to improvement is proportional to its growth *i.e.* the more machines there are, the more exposed the design is to development.

- Unlike traditional artificial selection, organisms from previous generations of breeding are capable of replicating the latest version, and can also contribute to growth and further evolution.

These factors make the RepRap printer's ability to evolve extremely powerful.

3.6.5   Self-repair vs. external maintenance

Because of their diverse manufacturing capabilities, biological organisms are able to make the parts they need to repair themselves. For example a cell is able to repair itself by manufacturing the myosin and actin scaffolds it needs for its own structure.

The RepRap printer is *designed* to manufacture its own printed spares for preventative maintenance. The vast majority of industrial, centralised mass manufacturing processes are unable to do this because they are limited to making one type of product.

3.6.6   Limitations of distributed manufacture

There are two obvious conditions for distributed manufacture to be successful:

- Distributed manufacture is only efficient when it is able to convert a low resource range into a high product range, like cells stringing a small range of amino acids into a large range of proteins. If the resource range is too large, delivery of resources to the manufacturing sites becomes inefficient, and if the product range is low (or specialized) then the manufacturing process may as well be centralised.

- Because of the required product flexibility, a distributed manufacturing unit is usually not as fast at producing one product as a centralized mass-manufacturing

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[11] Artificial selection is the intentional breeding of selected organisms to produce offspring with specific characteristics.

unit. If a location requires an unusually high demand, a centralized manufacturing system coupled with a good distribution network is more suitable. For example, consider a mammalian infection where large numbers of lymphocytes are made in the bone marrow and flooded to the infection site via the circulation system.

3.6.7   Discussion of the potential impact of the RepRap printer on society

This potential impact of the RepRap printer on society is explored in the discussion,

4   AIMS, HYPOTHESIS AND OBJECTIVES FOR THIS PHD

This chapter states the general aims of the work for the author's PhD, leading to a hypothesis and objectives for the work.

4.1   Aims

A short-term aim of the work was to make RP technology accessible to the public by designing a RP machine which was simple to assemble by hand and capable of self-manufacture. As discussed previously, in Sections 3.6.2 and 3.6.4 (pages 49 and 51), this later capability would qualify the machine as an assisted self-replicating machine, and, as with natural self-reproducing organisms, the printer could benefit from geometric growth and evolution. These characteristics could reduce costs, improve performance and make RP technology accessible to a broad range of the domestic market.

From a wider perspective it was hoped that the work would contribute further knowledge to the fields of RP, self-manufacture and self-replication.

4.2   Hypothesis

This PhD, in conjunction with the RepRap project, tested the following hypothesis:

The Fused Filament Fabrication process is sufficiently versatile to make a self-manufacturing Rapid Prototyping machine [59].

4.3 Objectives

In conjunction with other work from the RepRap team, the author attempted to achieve three goals:

1. Manufacture an RP machine designed in such a way that it is capable of making most* of the parts needed for a copy of itself (referred to in this thesis as the "RepRap printer") using FFF technology.

2. Repeatable performance of the machine within the specifications required to manufacture a copy of most* of its own parts.

3. Physical self-replication of most of the machine's parts to create a copy of itself. Assembly of the copy was to be done by hand.

* (excluding the imported parts listed in Section 3.1, page 43).

5 PHD WORK IN AN OPEN-SOURCE PROJECT

Before detailing the developments and results for this PhD it is important to stress they were made in an open-source environment - it is the open-source nature of the project which enables broad evolution for any self-reproducing results. The total developments and results of the RepRap project are a culmination of hard work and effort from the entire RepRap community, without which this project would be literally years behind where it is at the time of writing.

In the following chapters, the author will attempt to draw only on points which he was directly involved in, and will distinguish work contributed from other team members wherever necessary. A section in the Appendix (Section 13.7, page 220) has been included to detail the core team members who may be referenced in this thesis.

The majority of the work carried out by the author was focussed on the mechanical design and testing of the RepRap printer. Table 6 has been included in a bid to make the author's contribution clearer.

Table 6: An indication of the author's contribution towards different areas of the RepRap project

Category of work	Indication of Contribution (estimate)
Research into printer concepts	95%
Printer prototype developments	95%
Mechanical design for the printer	95%
Mechanical release and documentation	95%
Mechanical support and iteration	80%
Testing	25%
Software development	10%
Electronics	5%

6 MECHANICAL RESEARCH AND DEVELOPMENT ON THE REPRAP PRINTER

This chapter documents the mechanical research and development in making the first RepRap printer, undertaken during the author's PhD.

To give an overview of this development: research initially focused on the design of the machine's vertical axis. This would define the overall structure of the machine. Two different concepts were tested experimentally: Mk 1 used a cable transmission and Mk 2 used a screw-drive transmission. These concepts were then developed into two working prototypes. The screw-drive transmission worked considerably better than the cable transmission and was chosen for the final design of the RepRap printer. Many lessons were learnt during the development of Mk 1 and Mk 2 and this new knowledge was applied to a Mk 3 design, which became a fully functional prototype.

The author notes that a detailed methodology was not appropriate as the design had to be realised before it could be evaluated. Also, due to the limited types of materials which could be used in the design (listed in Section 3.1, page 43) many traditional engineering solutions could not be used. Some of the approaches documented in this chapter may therefore be considered to be extreme design methods.

6.1 Design brief and specification

The following brief was written:

"The RepRap Printer should be designed to manufacture its own mechanical parts using RP FFF technology (explored in Section 1.3.3.2, page 24). It should be considered a prototype test rig to:

- Test the characteristics of the RP FFF technology.

- Establish the key requirements for the required rig and identify elements which require further development."

Specifications were drawn up from this brief and have been listed in Table 7, below:

Table 7: Design specifications for the RepRap printer

Ref	Factor	Specification for the RepRap printer	Justification
1	Ergonomics	Machine should be controlled through a PC interface. Z-bed printing tray should be easy to replace. Form to follow function.	This machine will be design for private technical use (i.e. it is not to be a consumer product), therefore form should always follow function.
2	Standardization	Design should accommodate the use of standard materials.	Cheap, widely available imported components will aid self-replication.
3	Aesthetics/finish	Loose wiring should be neatly tied. RepRap logo should be prominent. No aesthetic required.	See 1.
4	Performance	M/c should manufacture parts in a volume of 300 x 300 x 300 mm. No speed requirements. X, Y and Z axis movements must be repeatable to ±0.05 mm, and accurate to a resolution of 0.1 mm.	Volume specified to meet the current specifications of commercial rapid prototyping machines. No speed requirements are made because this is dependant on the final design of the machine and performance testing. Accuracy specifications have been made to yield basic engineering quality parts.

Ref	Factor	Specification for the RepRap printer	Justification
5	Product cost	Part cost limit: £500. Assume no labour cost for assembly.	£500 is considered an affordable expense for hobbyists to purchase a machine which is, to some extent, necessary to participate in the project. The owner of the machine is expected to assemble the machine, hence zero assembly cost.
6	Materials	Imported parts: Self tapping screws Brass bushes & simple linear bearings Studding Lubricating grease Standard electronic chips (*e.g.* microcontrollers and optical sensors) Standard plug in low voltage power supply Stepper motors Timing belts	See Section 3.1, page 43.
7	Quantity	3 off: 1st generation machine replicates the 2nd generation machine. 2nd generation machine generates the 3rd generation machine to prove the concept.	See Section 3.1, page 43.

Ref	Factor	Specification for the RepRap printer	Justification
8	Life span	3 years experimental use.	This is the term of the PhD, and an appropriate length considering the likelihood that the first version will be superseded by developments throughout the course of the project.
9	Production timescale	The RepRap printers should be completed by October 2008.	This is the end date of the PhD.
10	Manufacture process	FFF process	See Section 3.1, page 43.
11	Size	M/c should be small enough to fit on top of an average bench.	Development will be carried out in a lab.
12	Disposal	Bespoke parts must be simple to remove for scavenging purposes on later designs.	The machine is likely to evolve and therefore it would be ideal to reuse imported parts for an upgrade build.
13	Market constraints	None.	-
14	Weight	M/c should be light enough to be supported on the average bench.	See 11.
15	Maintenance	At this stage of research it is acceptable for maintenance before each use.	See 1.

Ref	Factor	Specification for the RepRap printer	Justification
16	Packing and shipping	No physical shipping. Software must be arranged in a bundle for simple distribution of files.	No specialist parts and due to the nature of the project, shipping is not a consideration. The only centralised element is likely to be the information. This must, therefore, be packaged for open distribution.
17	Reliability	See 'performance'.	-
18	Patents	Designs should be published open-source on the RepRap site to make the m/c unpatentable.	One of the aims of the RepRap project is to foster an assisted self-replicating machine. It is important, therefore, that its population growth is not restricted by patents.
19	Safety	Sharp edges, nips and points must be avoided. However, this will not be CE marked and will not be examined as such.	Machinery should always be safe.
20	Colour	No requirements.	See 1.
21	Assembly	Assembly to be completed by an untrained, but technically competent, human with basic tools.	An important objective for the project is that that the printer will eventually be assembled by hand by members of the general public. Achieving this at this early stage is a crucial indicator as to whether the project is likely to be possible or not.
22	Trade Marks	None.	-
23	Value analysis	None.	-

Ref	Factor	Specification for the RepRap printer	Justification
24	Competing products	None – this is a contribution to science.	-
25	Environmental factors	None.	-
26	Corrosion	None.	-
27	Noise levels	Avoid loud noise where possible.	The machine is likely to be used around humans.
28	Documentation	Technical Construction File required.	Such documentation would aid the design's evolution in the future.
29	Balance and inertia	M/c must be stable enough to run without supervision.	The purpose of a rapid prototyping machine is to manufacture 3D components automatically. Supervision would, therefore, negate the purpose of the machine. Also, an unstable machine would be considered dangerous.
30	Storage	M/c to survive open bench top environment for lifespan.	The machine will be in constant development/use throughout its lifespan.
31	Machine head	It is expected that the final machine design will use multiple (approximately 4) material distribution heads. These heads also require development.	Multiple tool heads will be needed to achieve a high level of versatility.

Ref	Factor	Specification for the RepRap printer	Justification
32	RP head	Use Bowyer and Olliver's design (Section 6.6.1.6, page 89). Stock ABS dimensions: ø 3 mm.	An extruder design has already been completed.
33	Metal head	To be designed. Stock alloy dimensions to be undefined.	See 31.
34	Power Supply	Run on 12V.	A useful characteristic for the machine (especially in rural areas) would be its ability to be powered from a car battery.

6.2   Concepts for the machine's architecture

For the RepRap printer to print 3D mechanical parts the deposition head must access all points within a three dimensional space. This can be done using either Polar or Cartesian geometries. The pros and cons of the different geometries are analysed in the Appendix (Section 13.3, page 192).

A Cartesian geometry structure was chosen for three major reasons:

1. The control systems required are relatively simple. This would speed up the development phase.

2. Cartesian technology in machine design is more common than polar technology. Therefore less work would be needed to implement the Cartesian geometry, allowing research to follow the key aims and objectives outlined in Chapter 4 of this thesis.

3. Polar technology requires a very fine resolution transmission when depositing at the extents of the build volume. Whilst this is achievable at high cost, it would go against the RepRap project's principle of making affordable machines.

6.3   Concepts for implementing a Cartesian geometry

Different concepts are shown in the figures below: the X/Y table would be an extension of a simple axis previously designed by the author [60], illustrated in Figure 16, and the vertical movement of the printing tray (referred to in this thesis as the Z-bed) could be driven either by a screw drive (Figure 17) or a cable transmission (Figure 18).
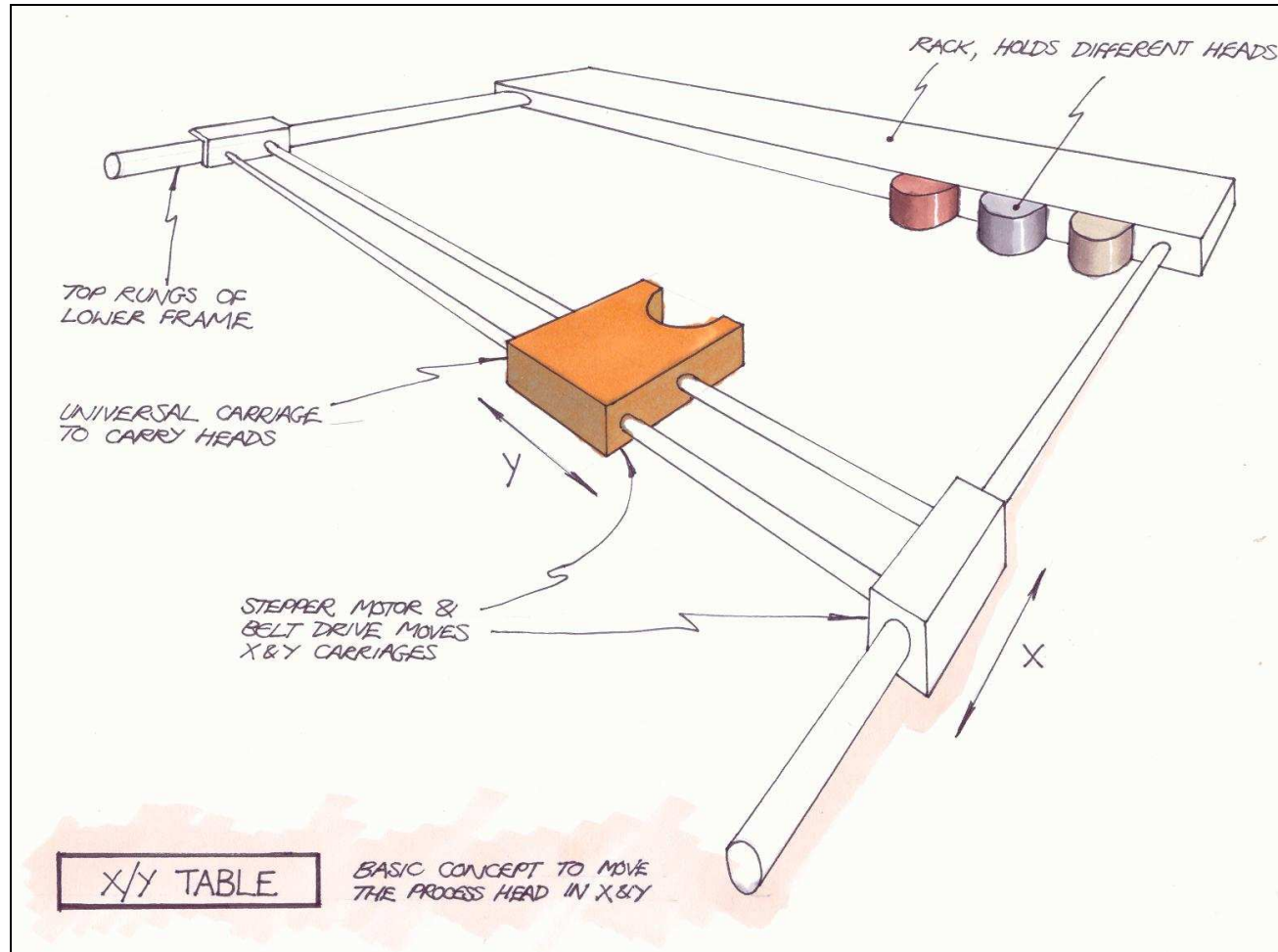
Figure 16: Illustration of a concept to move the deposition head in the X and Y planes.
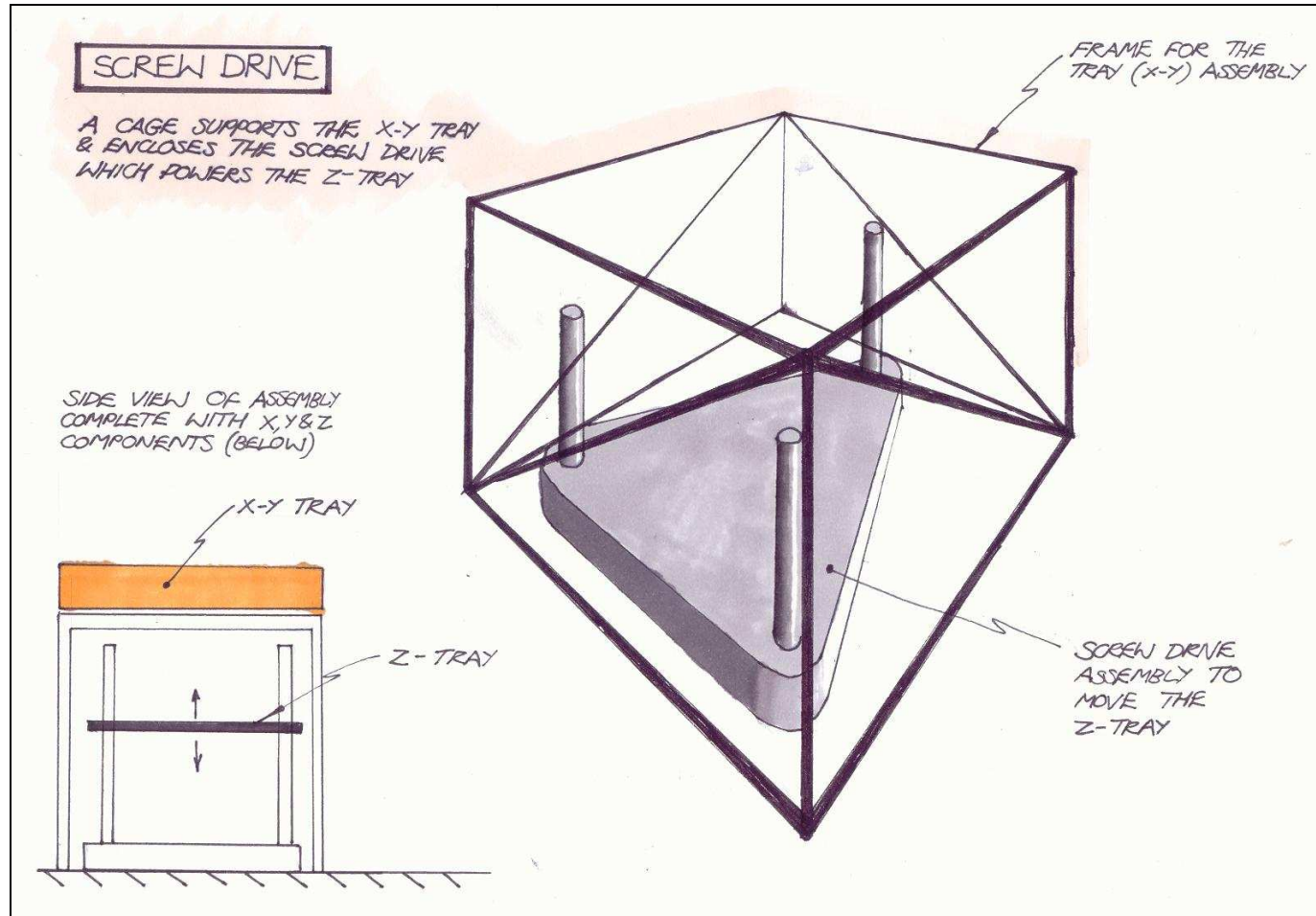
Figure 17: Illustration of a screw drive concept to move the Z-bed in the vertical plane.
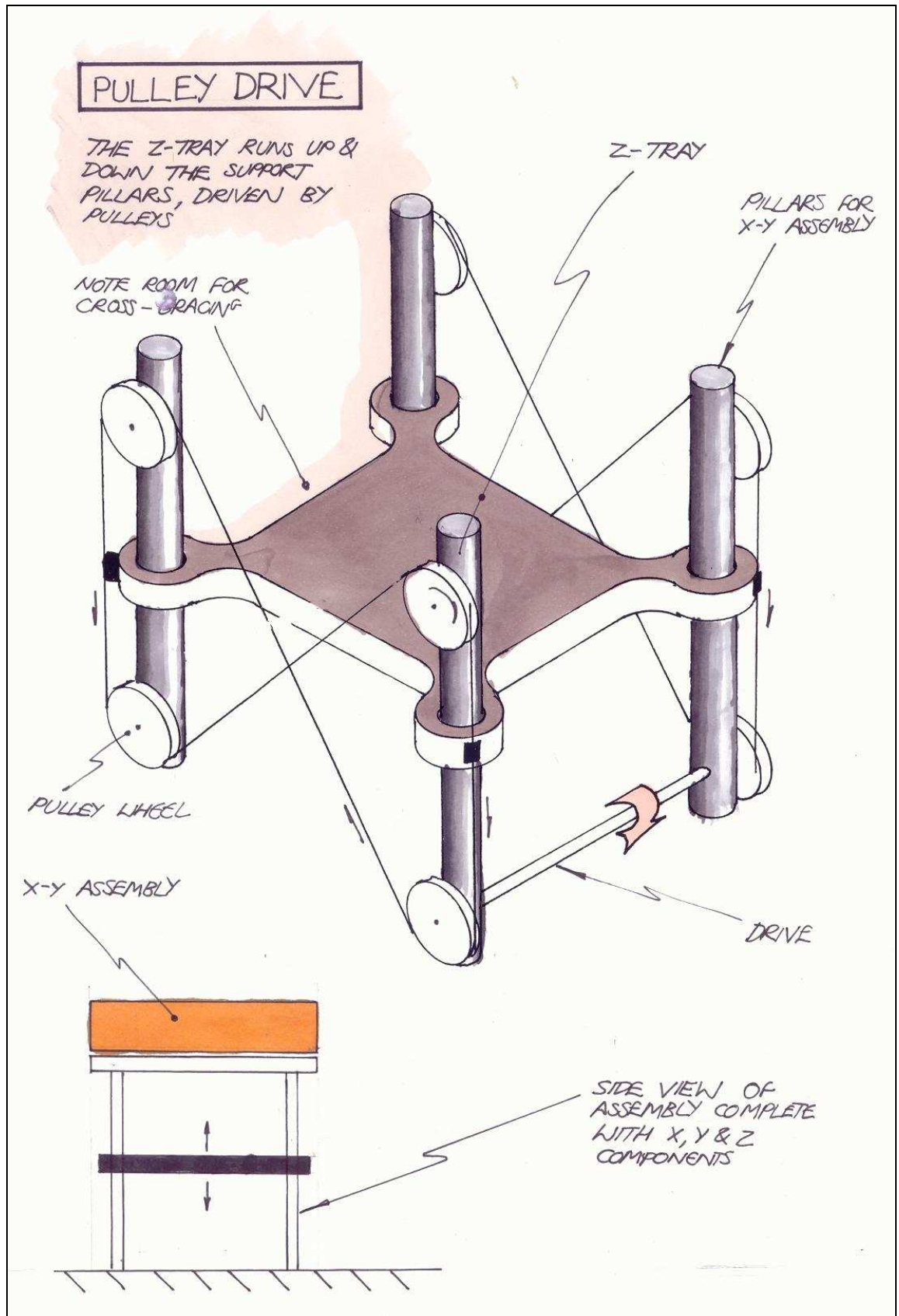
Figure 18: Illustration of a cable transmission to move the Z-bed in the vertical plane.

6.4   The RepRap printer Mk 1 (cable transmission)

A brief analysis (summarised in the Appendix, Section 13.4, page 192) was made between the two different vertical transmission concepts shown in the previous section. The cable concept was considered first because it only used cable for its transmission – this was a major advantage because it would reduce additions to the imported parts list.

6.4.1   Initial Research: cable test rig

From the concept illustrated in Figure 18 an experiment was done to prove the repeatability of a simple, two-point cable transmission. A measurement rig was made (Figure 19, below) and the carriage's travel distance was measured for a set number of motor revolutions. The first attempt sought to use a cheap, widely-available transmission cable to match that of RepRap's imported parts list.

The best transmission cable was found to be steel fishing wire (nylon cord, although better for grip, was found to be too elastic).
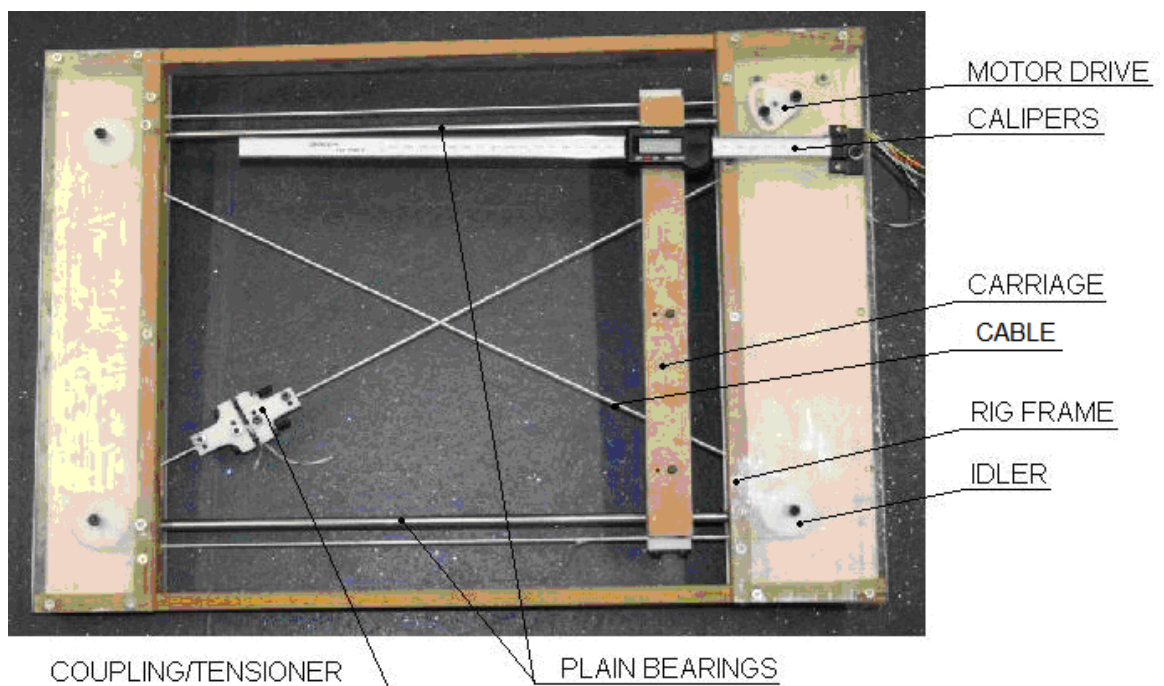
Figure 19: 2-bearing test rig
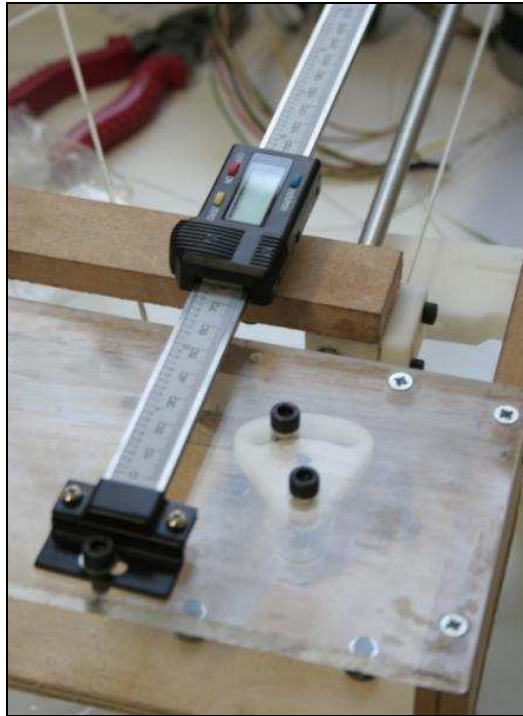
Figure 20: Calliper mount for calibration
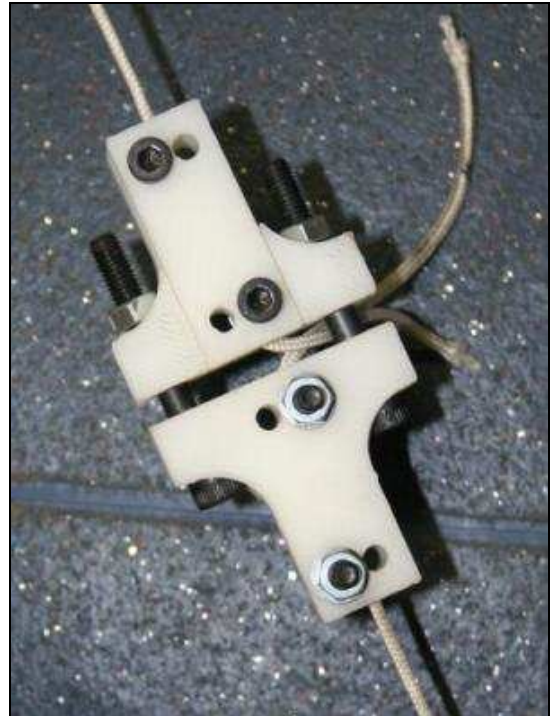
Figure 21: Tensioner & coupler

The rig highlighted some problems with the cable transmission. The biggest problem was the coupling mechanism between the motor and the line. Wrapping the wire completely around the drive wheel was necessary to ensure grip (a pinch idler assembly to increase the contact angle to 210° was not enough). However, once the wire made a complete revolution the wrap would ride up and down the length of the drive wheel. All attempts to constrain this ride resulted in jamming (see the Appendix, Section 13.5, page 194).

The best solution was found to be a plain drive wheel with a heat shrink grip (Figure 22). The wire was turned around the drive wheel three times and was allowed to ride up and down the length of the drive wheel.
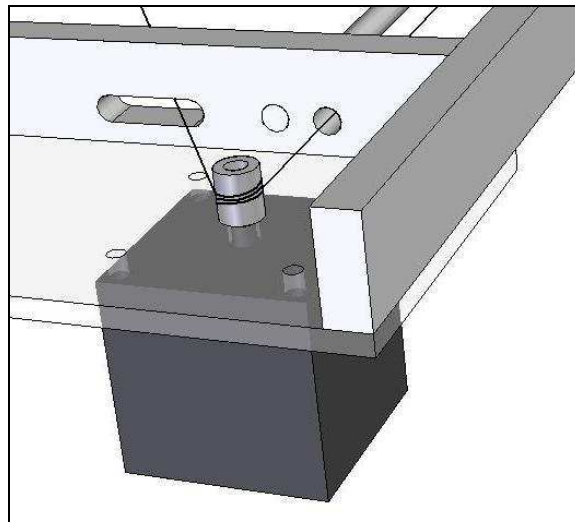
Figure 22: The best drive wheel solution – a heat-shrinked plain drive wheel (push fit onto motor shank) pulling a transmission line wrapped three times.

The results for the arrangement are shown below, in Figure 23. To further illustrate the figure a brief example has been included below:

On the first run, with the calliper in the centre position, the carriage retreated 1025 steps from the home position (set to 0.00 mm) to an end position of -99.51 mm. To begin the second run, the carriage then returned 1025 steps achieving a home position of 0.01 mm. The end position for the carriage after the second run was recorded to be -99.52 mm, and so forth.

Despite encouraging data for two of the calliper positions, the figure below demonstrates transmission failure: when the calliper was mounted at the bottom of the carriage (*i.e.* the carriage was loaded asymmetrically) the results were unrepeatable. This was thought to be

because of slip in the transmission system. At this point attempts using the fishing wire were abandoned.
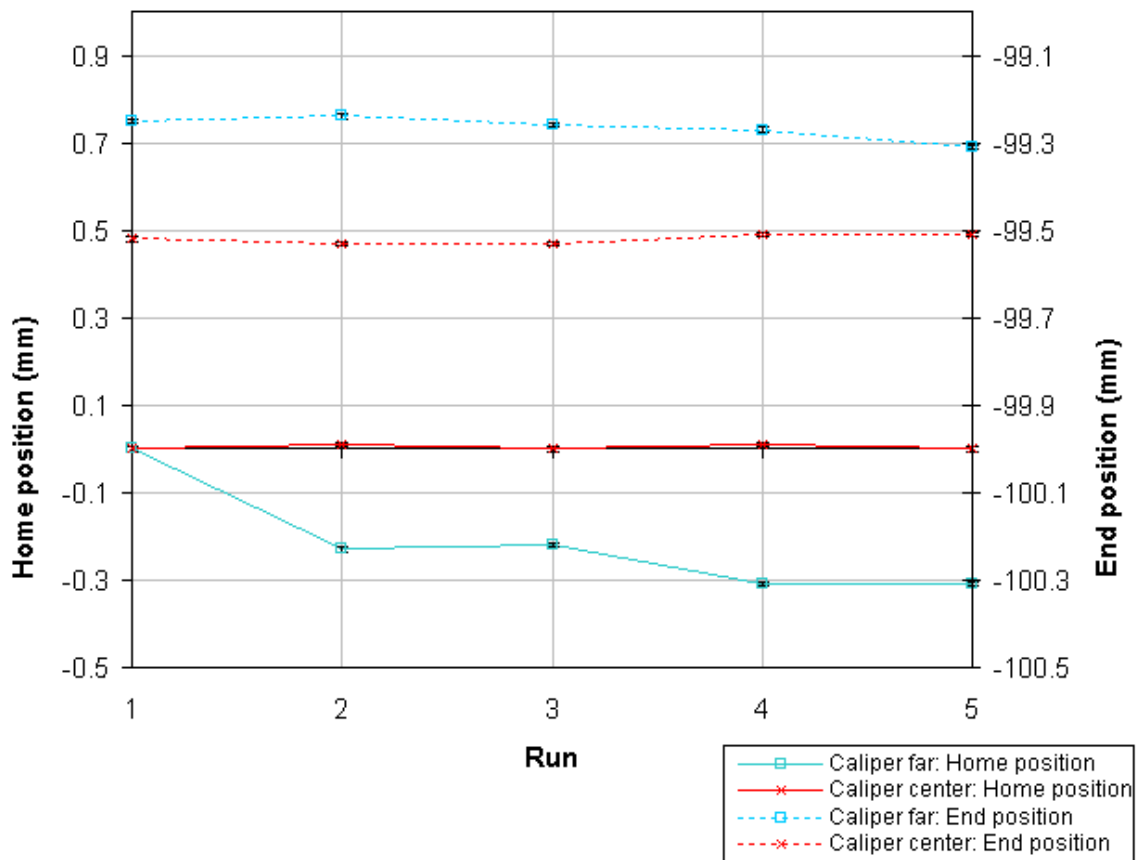
Figure 23: Carriage positions for runs up and down the bearings. There were 1025 stepper motor steps for each run. The test rig used a fishing wire transmission and a plain shrink wrapped drive wheel. 'Calliper centre' refers to the calliper being in the centre of the carriage, 'far' refers to the calliper at the end of the carriage furthest from the drive wheel.

A toothed transmission belt was introduced to replace the fishing wire (Figure 24). A toothed drive wheel eliminated the slip. Test results are shown in Figure 25.
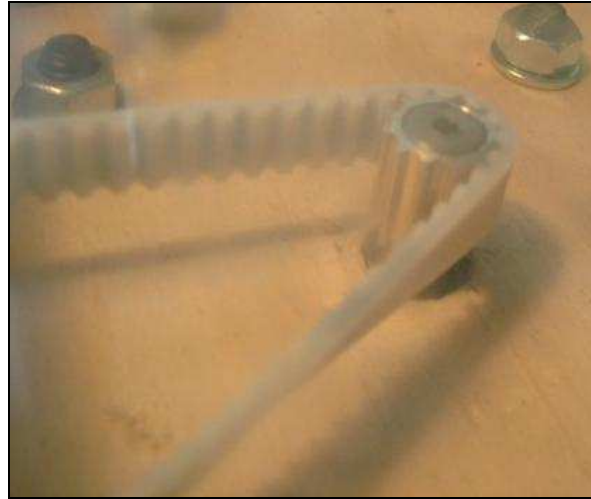
Figure 24: Timing belt transmission with toothed drive wheel
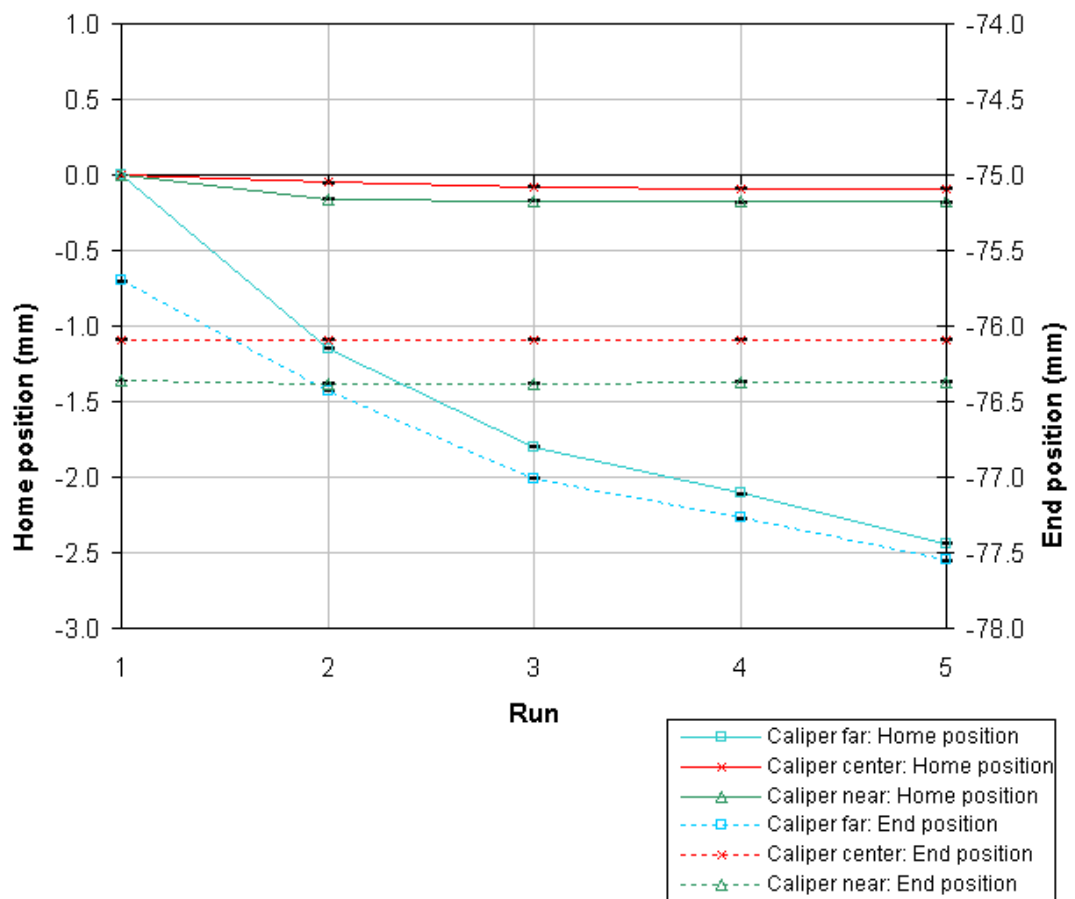
Figure 25: Carriage positions for runs up and down the bearings. There were 1025 motor steps for each run. The machine used a tooth belt transmission. 'Calliper centre' refers to the calliper being in the centre of the carriage, 'far' refers to the calliper at the end of the carriage furthest from the drive wheel and 'near' nearest the drive wheel.

The timing belt yielded better results but demonstrated that repeatability for asymmetrical loading was asymptotic. This meant that while the grip issue had been solved, a different issue still pervaded. This is discussed further in Section 6.4.4 (page 77). However, results were considered encouraging enough to begin work on a prototype Z-axis using a toothed-belt transmission.

6.4.2   Prototype design (toothbelt transmission)

Once the fastening technique had been finalised designs were started on the RepRap Printer Mk 1. Figure 26 illustrates the final design. The design catered for either a timing belt or cable which was looped around the external frame and coupled to the Z-bed at four points. The belt was driven by a stepper motor.

6.4.2.1   CAD model

Figure 26 illustrates the design for the Z-axis with tooth-belt transmission.
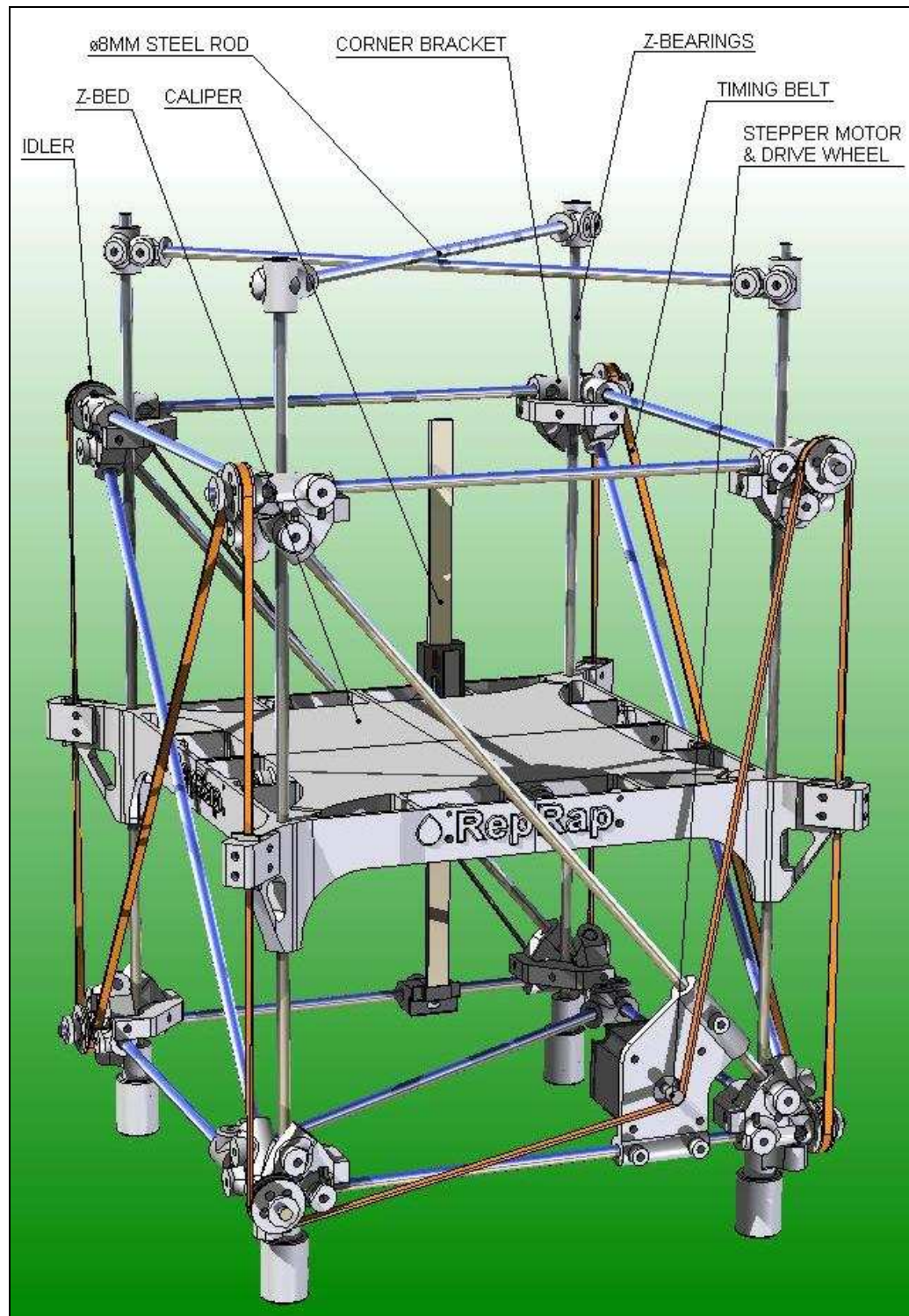
Figure 26: Assembly design for the RepRap Printer Mk 1 with belt driven Z-axis

6.4.2.2 Mk 1 feature: threaded inserts

During testing it was noticed that the build structure from the Stratasys FDM RP machine (which was to be used to make the prototype parts and to prove the principle of making a machine using FFF RP technology) was not ideal for robust tappings. Whilst sufficient for single use, the threaded holes would strip easily with frequent use.

To prevent this from happening nuts were mounted into the ABS by way of a counterbored push fit. Experiments were designed to determine the size and profiles of the counterbores needed to guarantee a sound push fit to house a metric nut.

A matrix of tests was run to establish the best geometries for the counterbores. Figure 28 illustrates the best counterbore profile: a rounded hexagon. The idea used a clearance fit between the flats of the nut and the flats of the counterbore to allow the nut to be inserted (dimension C) but the edges between the flats were forced into an interference fit with the rounded corners (dimension B). This trapped the nut. Dimension A defines the through hole diameter for the bolt. The simple insertion of robust threads greatly increased the strength and reliability of using fasteners during assembly.
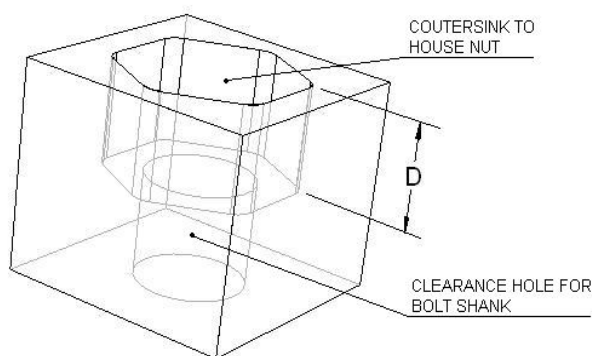
Figure 27: Counterbore geometry in the RP part to trap a metric nut in the RP part body, thus providing robust threading for bolts.
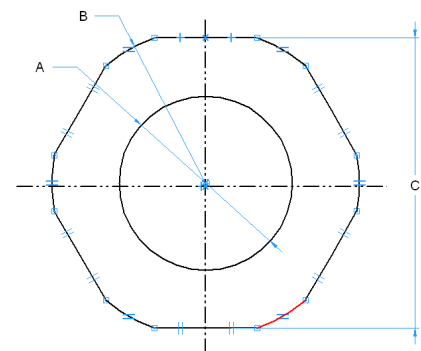
Figure 28: Counterbore profile including through hole diameter (A), rounded hex radius (B) and hexagon flat-to-flat distance (C).

6.4.3   Results for the Mk 1 concept

Figure 29 shows the finished prototype for the tooth-belt transmission. Note all of the white parts were manufactured using a commercial Stratasys Dimension RP machine.
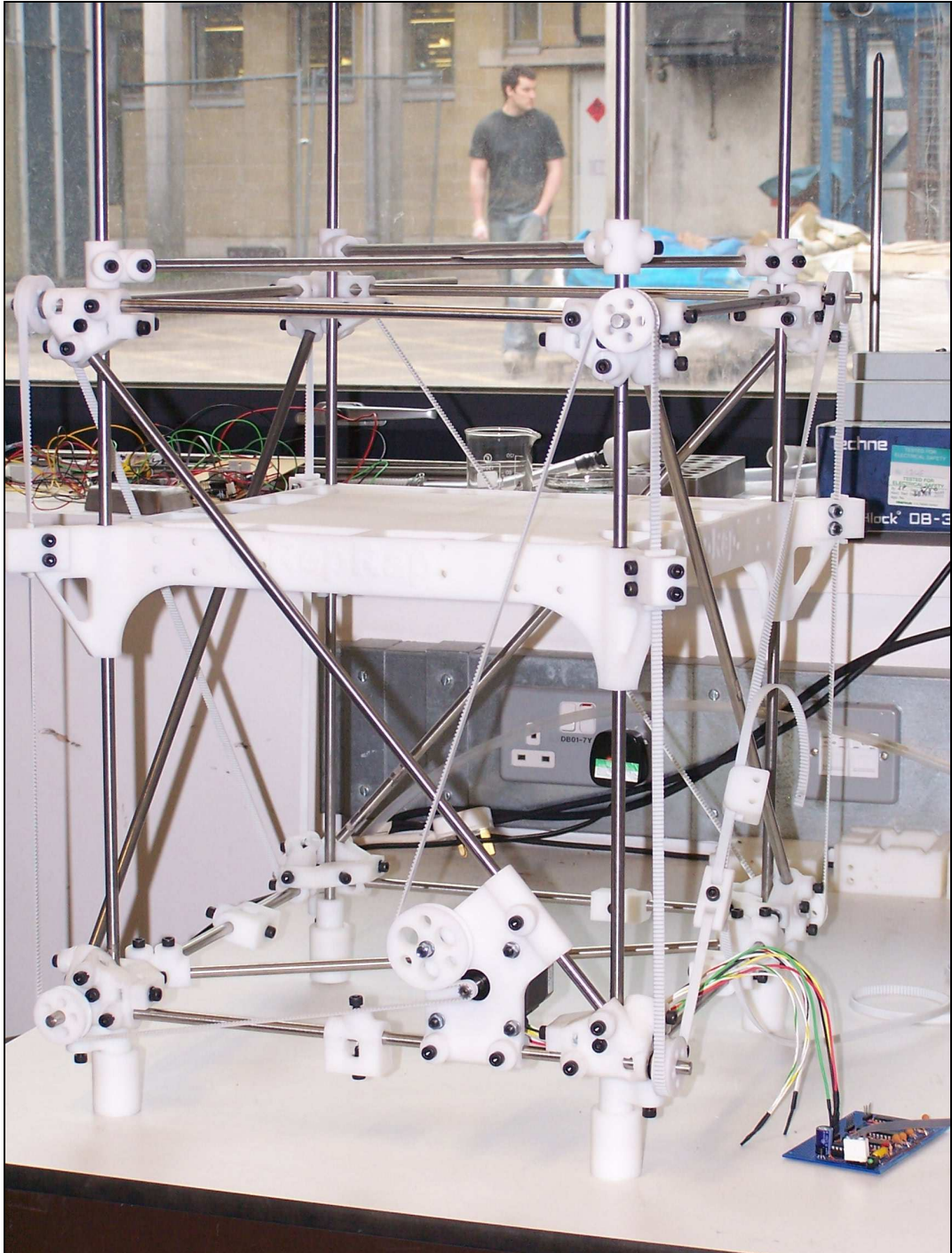
Figure 29: Photograph of the completed RepRap Printer Mk 1 with belt driven Z-axis

Unfortunately the transmission design failed: the Z-bed would jam when moving upwards.

6.4.4   Design evaluation

At the start of each run on the upward stroke the carriage would immediately yaw. This yaw was the primary cause of the bearing jams which caused the transmission to fail. A likely explanation for the yaw was imbalance in the transmission cables on rotation of the drive wheel. Figure 30 illustrates this in a two-point cable transmission.
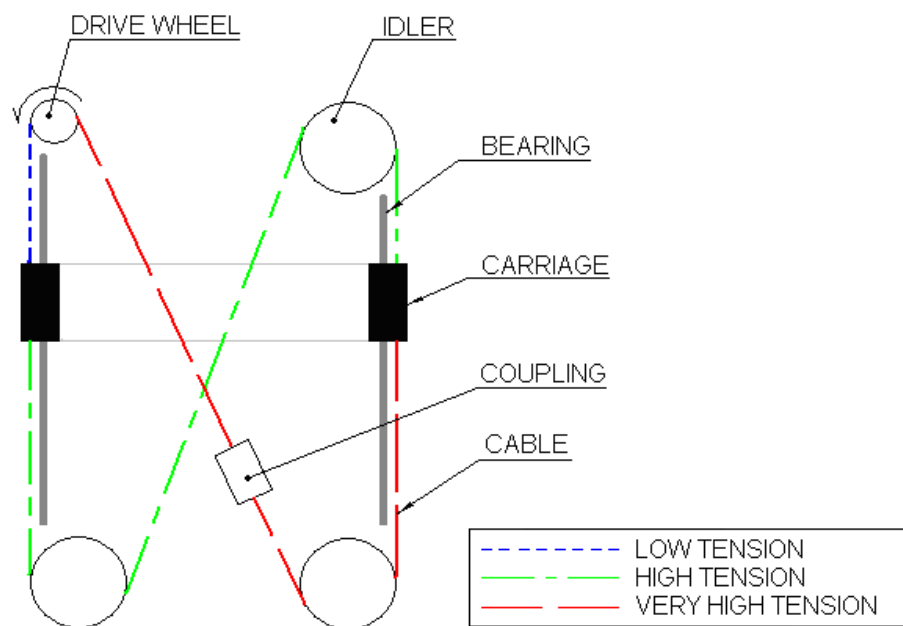
Figure 30: Tensions in the cable at the beginning of drive wheel rotation for a two-point transmission.

Aside from transmission failure, two problems were observed with the Mk 1 build:

- Poor strut constraint: by designing the vertical struts to be adjustable using a pincer arrangement of bolts, the support for the structure was reduced and made the bearing structure especially weak.

- The Z-bed suffered from over-constraint. Full contact against all four vertical posts (which can be seen in Figure 26, page 74) increased the chance of axis jams.

- Weak housing for threaded inserts: FDM RP parts were especially weak when forces were applied perpendicular to a layer plane, rather than along the length of it. No consideration was given to the orientation of the build for any of the parts and a few delaminated when the bolts were over-tightened (delaminations are shown in Figure 31).
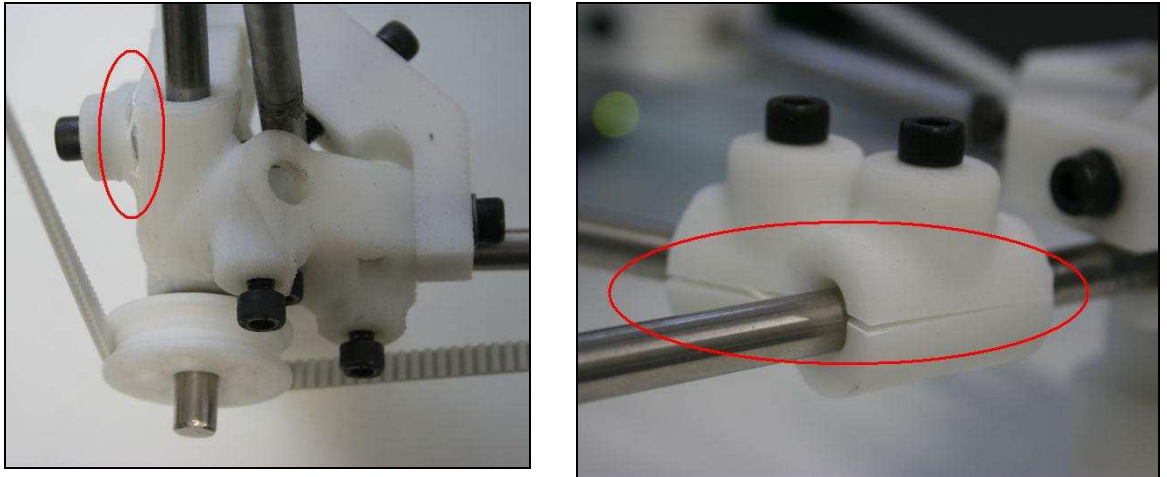
Figure 31: Cracked parts because of force imparted by the bolts across layer welds in the RP structure.

Positive observations included:

- The use of threaded inserts prevented any cases of stripped threads.

- Rapid prototyped parts, when made with proper consideration to build orientation, proved robust enough for a machine design on the scale of the RepRap printer.

6.5   The RepRap Printer Mk 2 (screw drive transmission)

After the failure of the tooth-belt transmission prototype, development continued towards a screw driven prototype. It is worth noting that for the FFF process (indeed, for most RP processes) the total distance of travel made in the Z-axis is insignificant in comparison to the total travel made in the X/Y plane[12]. Therefore, whilst a screw drive is much slower than a belt drive, its effect on the total build time is negligible.

6.5.1   Initial Research: screw drive test rig

Following the screw drive concept illustrated in Figure 17 (page 66) an experiment was run to prove the repeatability and accuracy of a simple nut and standard studding assembly. A measurement rig was made (Figure 32, below) and the nut's travel distance was measured for a set number of revolutions (Figure 33).
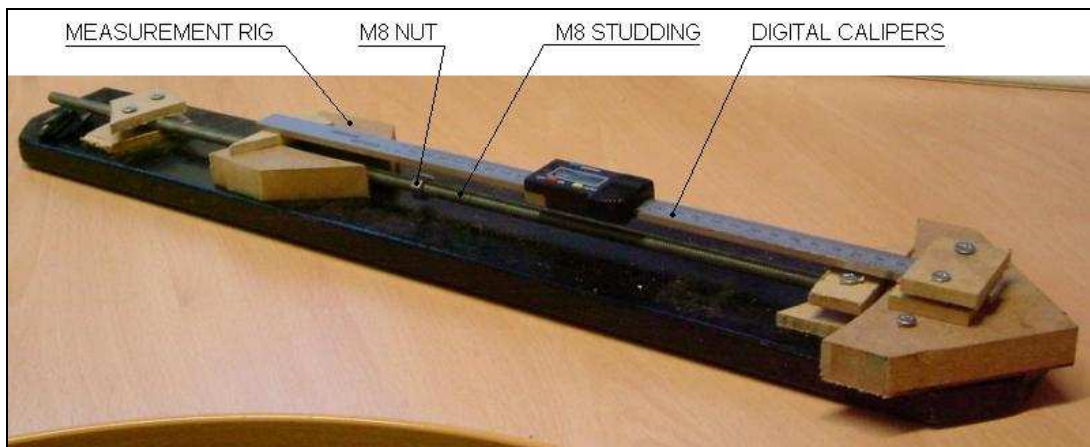
Figure 32: Screw drive repeatability measurement rig

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[12] To build a 50 mm cube with a typical FFF process using a 0.5 mm diameter filament the toolhead would need to move approximately 5000 mm in the X-Y plane per layer. Each layer would be separated by only a 0.2 mm increment in the Z-axis.
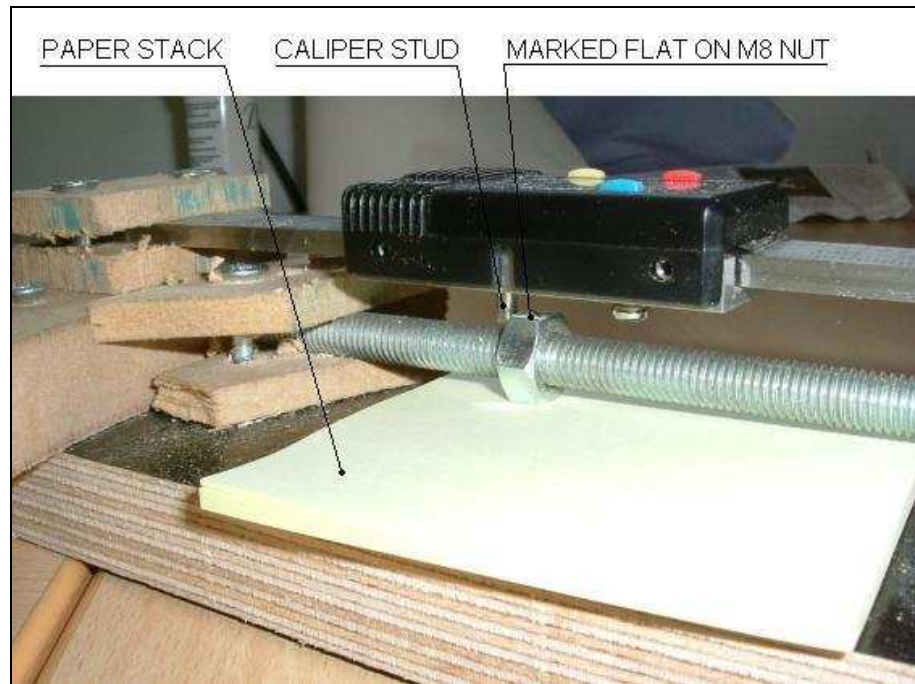
Figure 33: Offering up the calliper head up to the M8 nut face. The M8 nut had the marked face on the top horizontal plane and was levelled by the paper stack placed underneath it.

The best results were achieved using a simple travelling sprung nut arrangement, shown in Figure 34. This improved repeatability by reducing backlash. Results are shown in Figure 35.

Figure 34: Travelling sprung nut arrangement
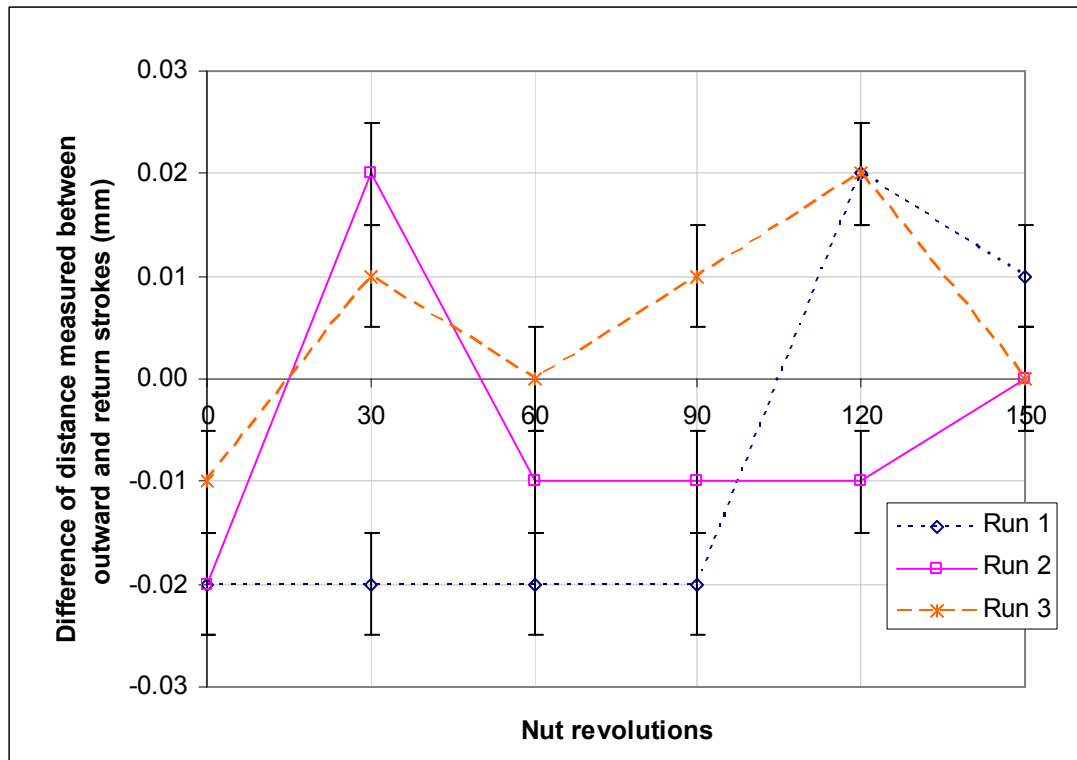
Figure 35: Graph to demonstrate the repeatability of the sprung nut screw drive

The test rig demonstrated a repeatability in movement for the screw drive of ± 0.025 mm. This was considered acceptable, as the general repeatability target in the printer specifications was ± 0.05 mm.

6.5.2   Prototype design (screw drive transmission)

The tooth-belt transmission prototype was used as a harness for the screw drive transmission (Figure 36). A stepper motor rotated a stud which was threaded through a trapped nut on the Z-bed. This principle was copied on the 3 remaining corners of the Z-bed using a drive belt transmission.

6.5.2.1 CAD model

Figure 36 illustrates the design for the Z-axis with screw drive transmission.

POSITION FOR
INJECTION HEAD
ON X/Y CARRIAGE

OLD MK1 CHASIS

STUDDING
TRANSMISSION

Z-BED

DRIVE BELT

STEPPER MOTOR
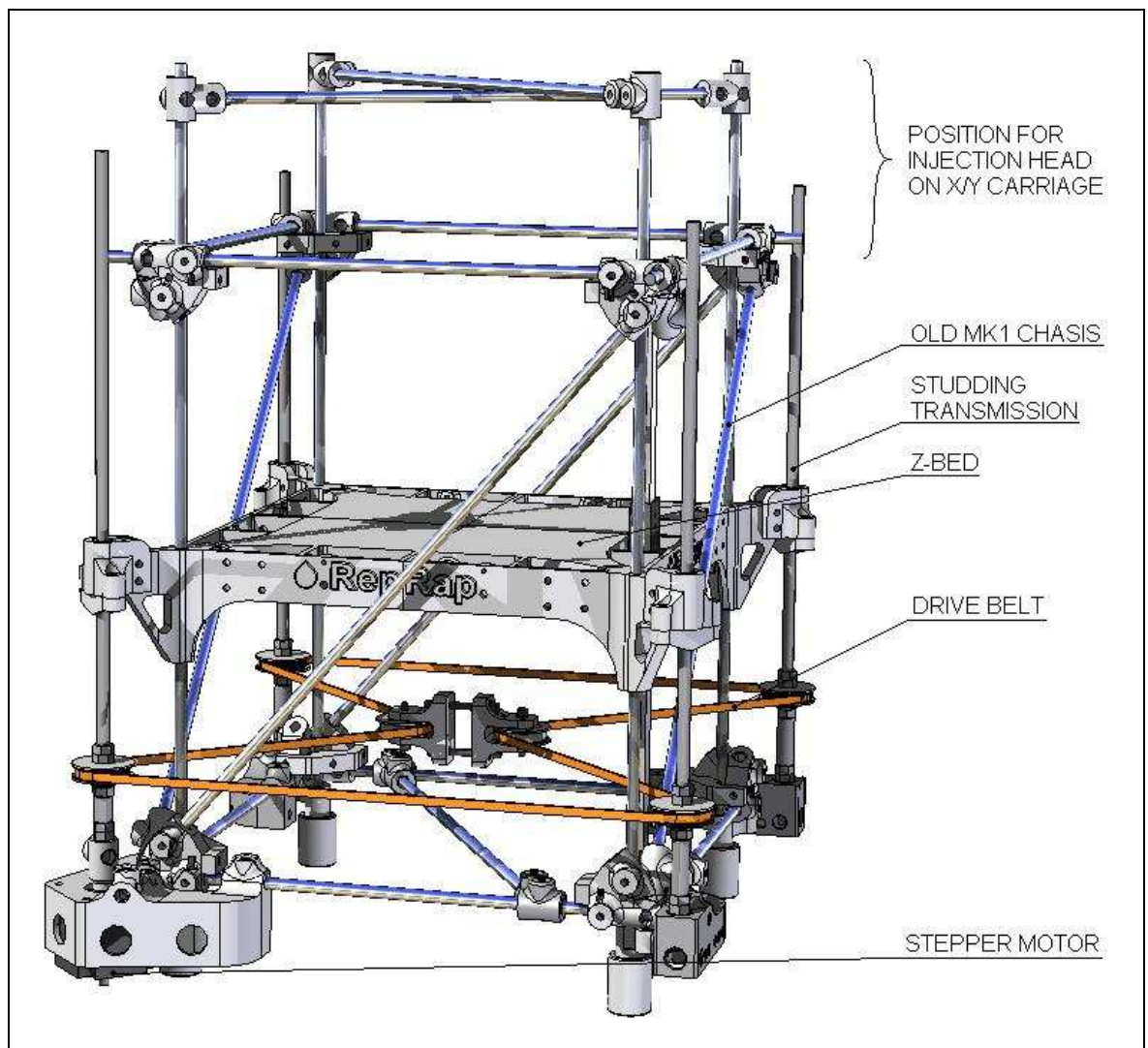
Figure 36: Design of the RepRap Printer Mk 2 assembly. This is the Mk 1 assembly with a retro-fitted studding transmission

6.5.2.2 Mk 2 features

Ideas from the initial studding experiments were used to counteract the backlash using two nuts separated by a spring, as shown in Figure 37, below.
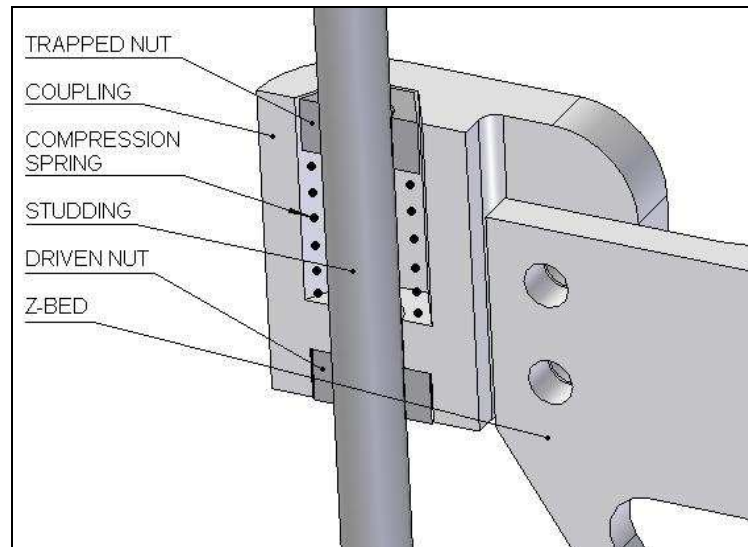
Figure 37: Section through the anti-backlash mechanism. The trapped nut acts as a mobile anchor for the compression spring to force the base of the coupling against the top of the driven nut, and simultaneously keeps a consistent contact at the interface of the driven nut thread and the studding thread.

It is interesting to note that the Stratasys Dimension RP machine's resolution was good enough to successfully manufacture the toothed pulleys used to transmit the power between the studding posts (Figure 38).
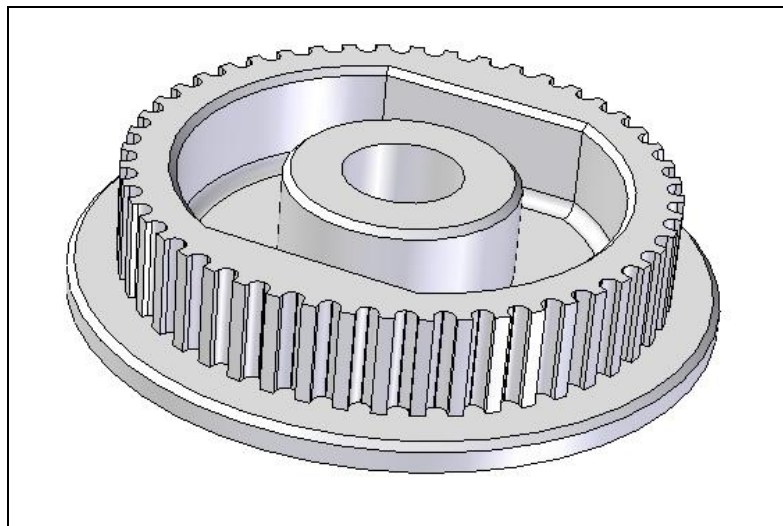
Figure 38: CAD model for a toothed pulley (40 mm PCD) to be made on the Stratasys Dimension RP machine

6.5.3   Results for the Mk 2 concept

Figure 39, below, shows the finished prototype for the screw drive transmission.
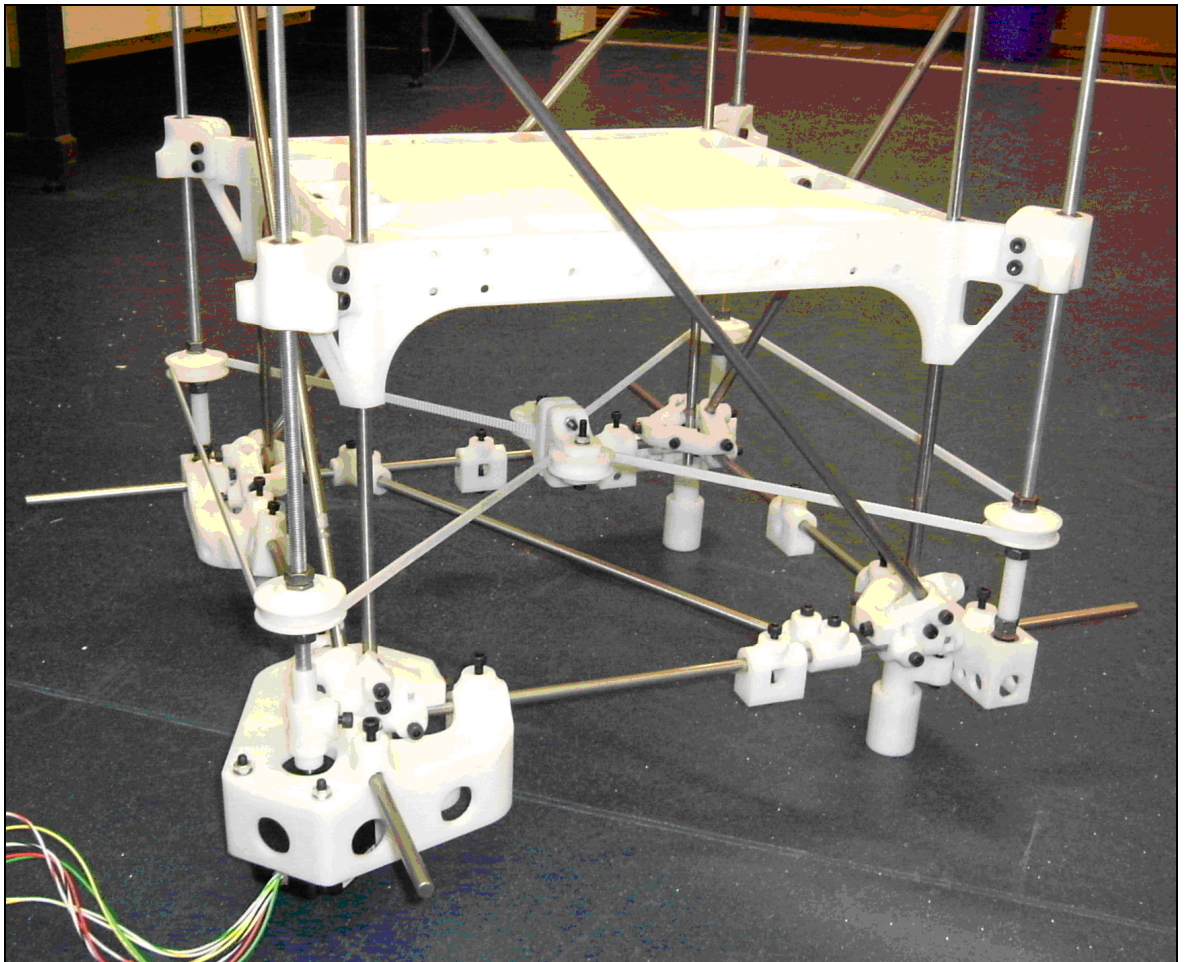
Figure 39: Photograph of the completed the RepRap Printer Mk 2, driven by a 400 step per revolution stepper-motor concealed in the bottom left bracket.

The 400 step per revolution stepper-motor was instructed to move the bed 4000 steps forwards and backwards 10 times at a speed of 60 steps/second (a speed at which motor resonance was lowest). A calliper was used to measure the position of the Z-bed at the start and end of each run. Figure 40, below, shows the results for this test.
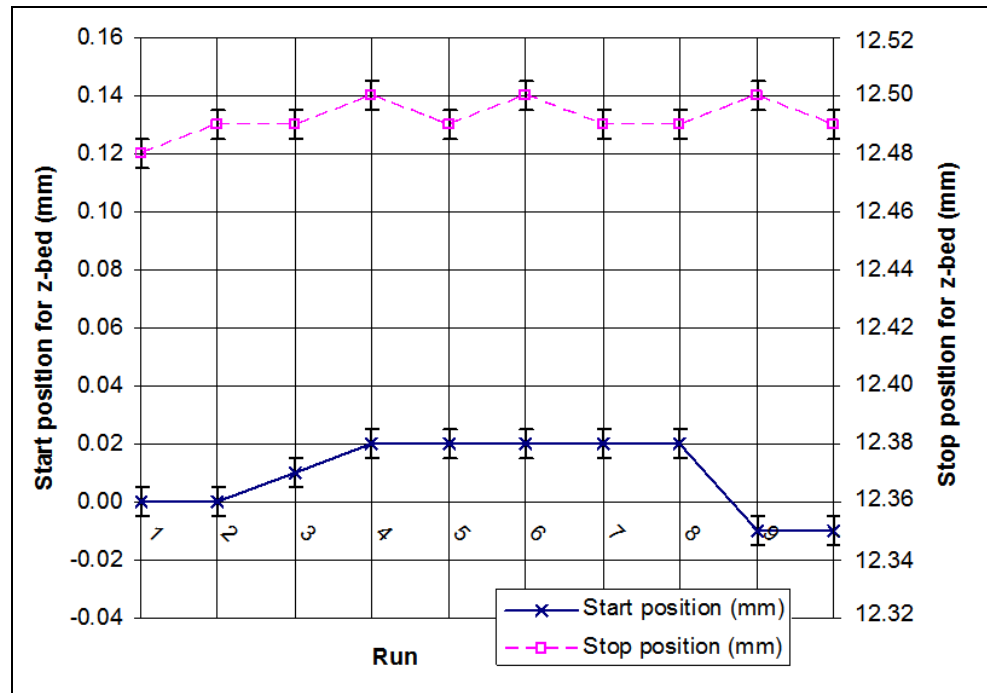
Figure 40: Start and end positions of the Z-bed after moving it over a stroke of 2000 steps, ten times at a speed of 60 steps/second.

6.5.4   Design evaluation

The screw drive transmission was a success, proving to be repeatable on the prototype rig to within ± 0.02 mm.

Learning from the evaluation after Mk 1 (Section 6.4.4, page 77), RP parts for the Mk 2 were all made with build orientation in mind. This successfully prevented delamination in all cases.

6.6   The RepRap Printer Mk 3: Darwin

A new prototype was designed to incorporate all of the lessons learnt in previous developments. The prototype included an X/Y table and consideration was also given to design for self replication. This Mk 3 design, which was to become a fully operational self-replicating RP machine, came to be known as "Darwin".

A bill of materials for Darwin's design is included in Section 13.6 (page 196), and all self-manufactured parts are identified and illustrated in Section 13.10 (page 235). Complete design data and assembly instructions are included in the DVD which accompanies this thesis.

6.6.1   Darwin's prototype design

Figure 41 illustrates the concept for Darwin. Key features of the design are discussed below this.
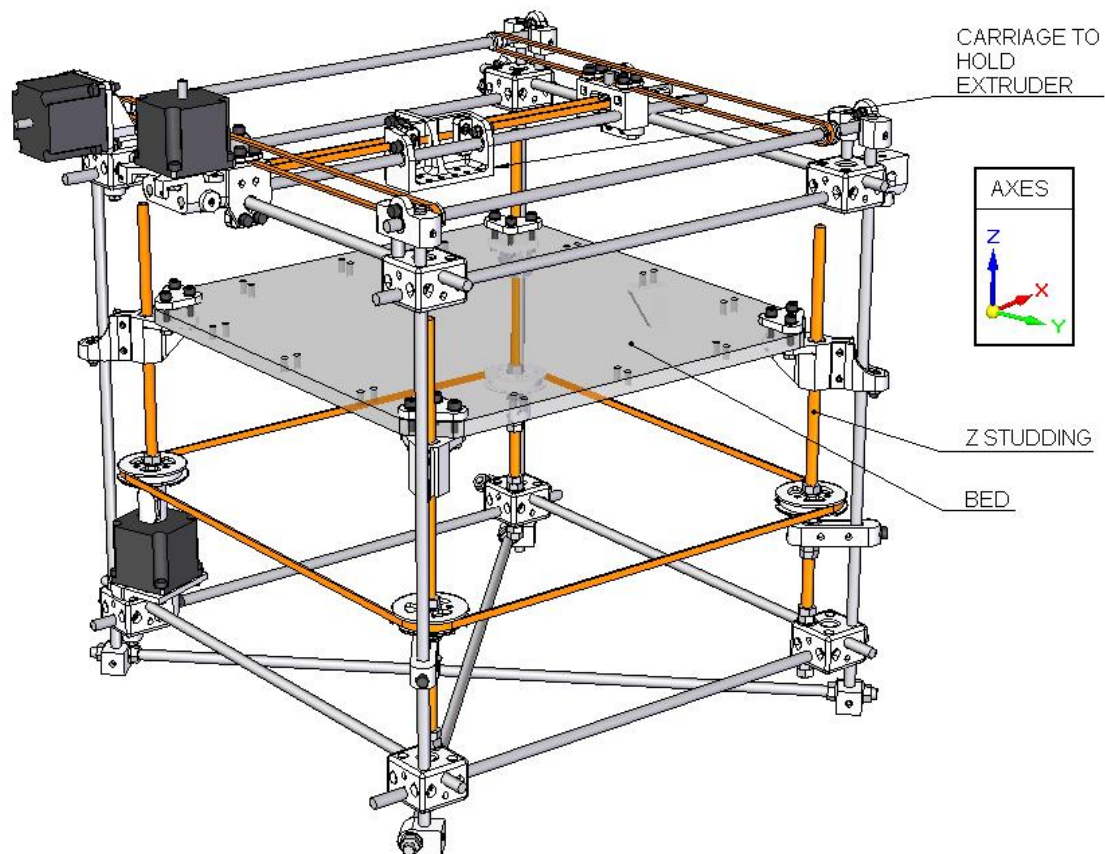
Figure 41: Concept for the RepRap Printer Mk 3

6.6.1.1   Screw drive

After the success of the Mk 2 design, Darwin used a similar screw drive transmission to move the Z-bed.

6.6.1.2   Corner brackets

Mk1 demonstrated poor strut constraint at its corners. The corner bracket was redesigned for Mk 3 to improve strength. The design was symmetrical for all eight corners and redundant features were included to facilitate future development work. Figure 42, below, is a section diagram of how the corner bracket had the capacity to clamp four vertical struts and two horizontal struts.
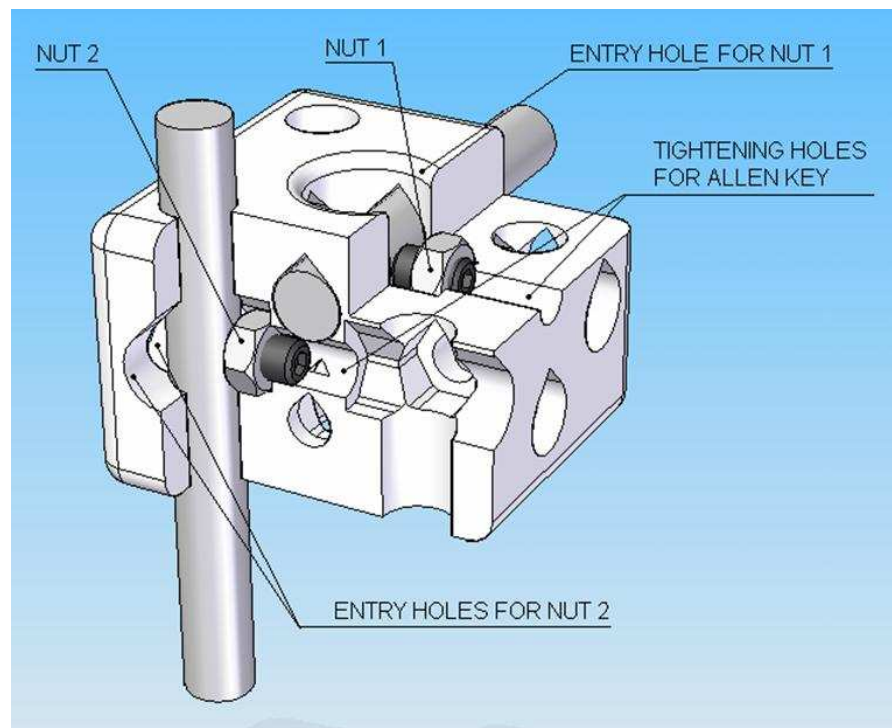
Figure 42: Section of Mk 3 corner bracket. Grub screws were used with trapped nuts to clamp the struts.

6.6.1.3   Z-bed constraint

In previous designs the Z-axis jammed due to over-constraint: the bed ran along all four vertical posts. Figure 43 illustrates how Mk 3 used only two vertical posts to eliminate over-constraint. A bearing made full 360° contact against the first post. Rotation around this point was constrained with two opposing flats against the diagonally-opposite post.
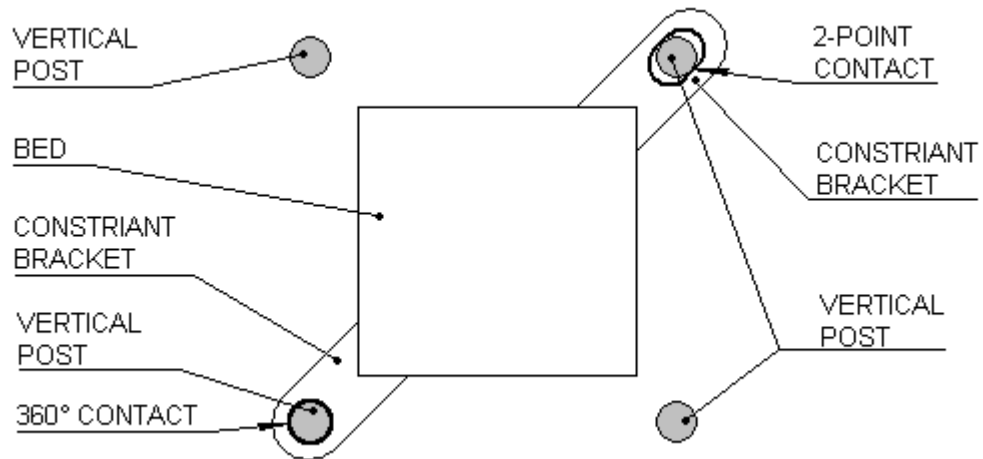
Figure 43: Diagram to show how the Mk 3 bed was constrained in the X/Y plane. Only two vertical posts were used for constraint. A bearing makes full 360° contact against the first post. Rotation around this point was constrained with two opposing flats against the diagonally opposite post.

6.6.1.4   X/Y table

Figure 44, below, illustrates the X/Y table assembly. Timing belts were chosen instead of a screw drive because they made for a faster transmission. Using a direct drive from 400 step per revolution stepper-motors and gears with a PCD of less than 12.7 mm, it was possible to achieve a linear resolution of 0.1mm.
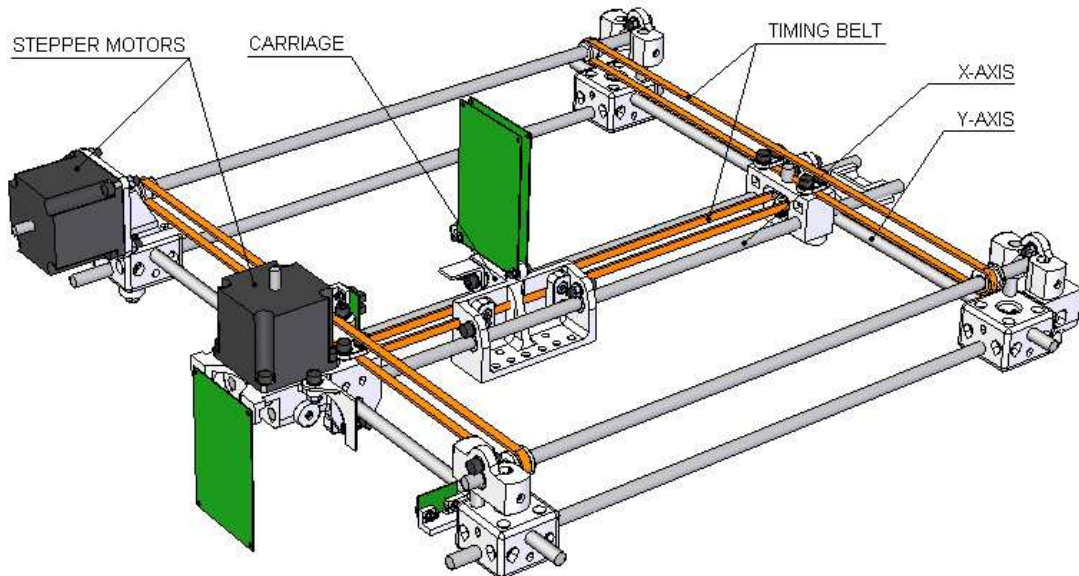
Figure 44: The X/Y table assembly used a timing belt transmission and direct drive from two stepper motors. This moved the carriage (which holds the extruder) to all positions in the X/Y plane. The thin green rectangles represent circuit boards.

6.6.1.5 *Use of optoswitches for automatic axis homing*

Figure 45, Figure 46 and Figure 47 illustrate how optoswitches were used with RP flags to home the X, Y and Z axes. Aluminium foil was glued over the flags because the RP build material (ABS) was transparent to the optoswitches' infrared signal lights.
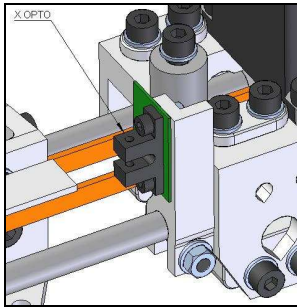
Figure 45: X-axis optoswitch
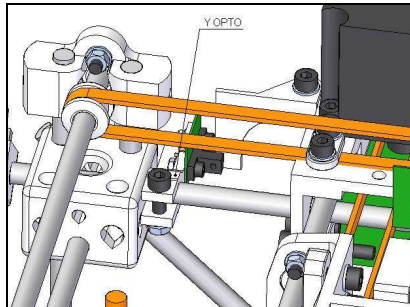
Figure 46: Y-axis optoswitch
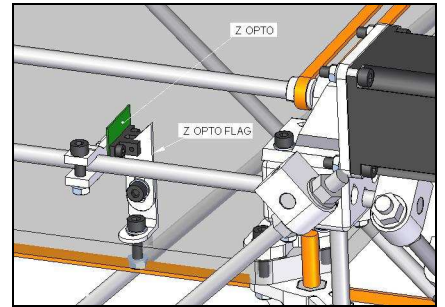
Figure 47: Z-axis optoswitch

6.6.1.6 *Extruder*

Figure 48 and Figure 49 illustrate a thermoplast extruder design developed by Bowyer and Olliver. The X/Y table was designed to manoeuvre two of these extruders. This extruder was the toolhead which the FFF technology used to print the layers of polymer to produce a part.
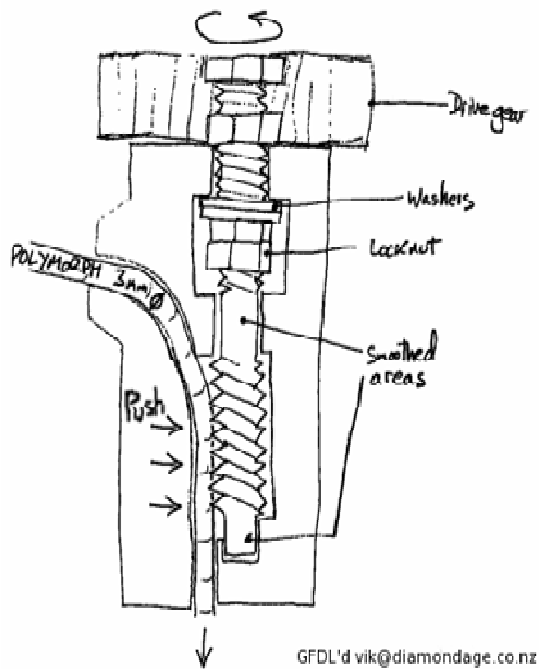
Figure 48: Extruder principle, a length of studding drove a polymer filament into a heated barrel.
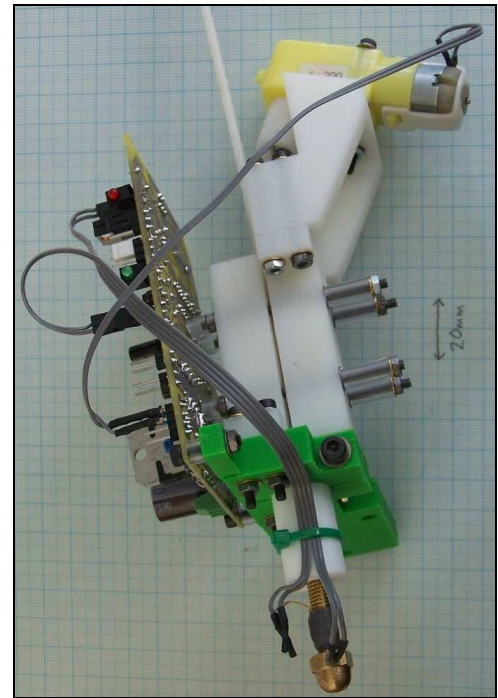
Figure 49: Working extruder. A standard dome nut, with a small hole in the end, acted as a nozzle.

6.6.1.7   Electronic housing

Darwin was designed to house the PCBs designed by the rest of the RepRap team. Parts were arranged in such a way that the both the communications ring (detailed in Figure 63, page 111) and the power lines were kept to a single side of the machine, as shown in Figure 50. This made the wiring simpler and tidier and reduced the risk of cables getting caught in moving parts.
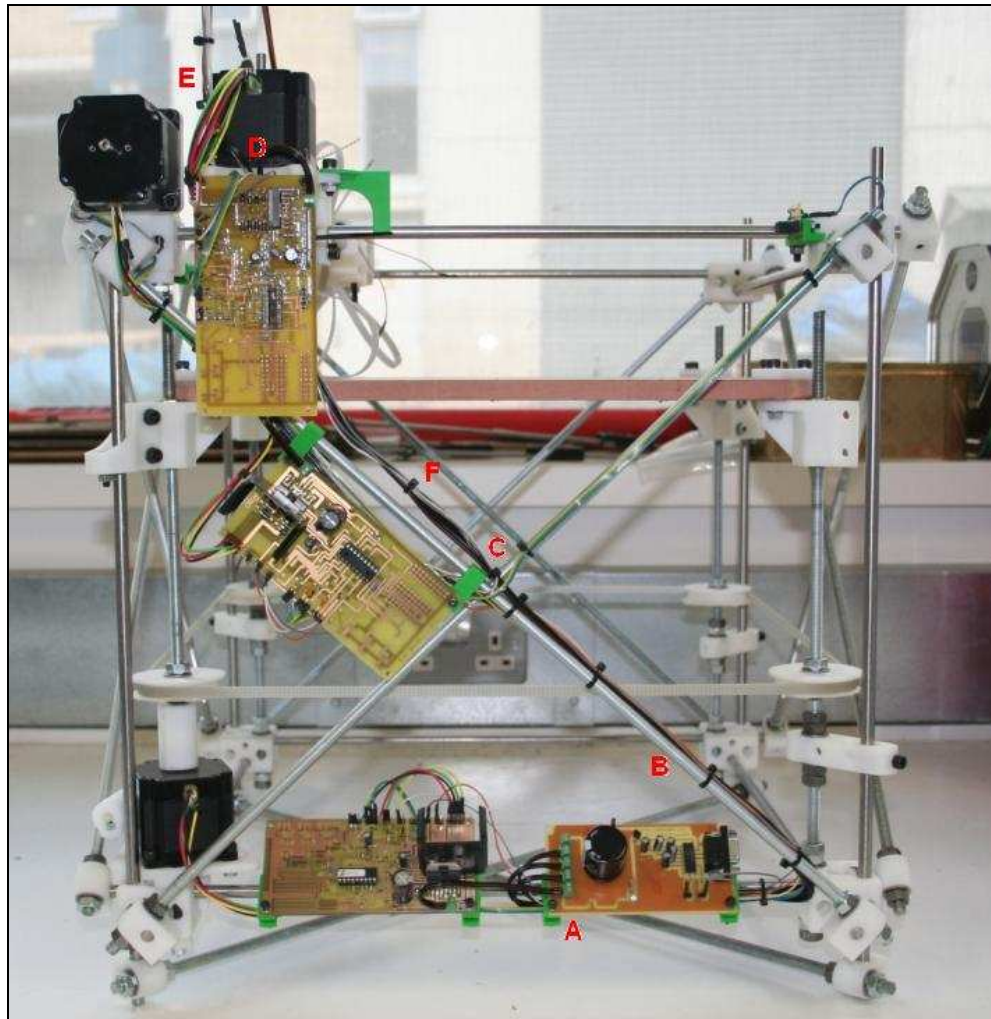
Figure 50: Parts on Darwin were arranged to limit the power and communications wiring to one side of the machine.

6.6.2   Design for a self-manufacturing RP process

After the essential concepts for Darwin were defined, consideration was given to 'design for self-manufacture'.

As defined in Section 1.1.10 (page 6), for the machine to achieve self-manufacture it had to be able to manufacture its own parts using its own manufacturing process. The FFF process, defined in Section 2.2 (page 26) has the potential to be extremely versatile, which is why it was selected for the RepRap printer. However, at the time of printing, there were a few limitations. Table 8 makes the point that the part was either made on the machine or, if the part exceeded the capability of the process, the part had to be imported. Obviously the latter case was a step away from a pure, self-manufacturing machine, so parts needed to be made by the machine wherever possible. This meant that some parts made on the machine tested the limitations of the manufacturing process. For these parts a compromise was made in their design to ensure reliable self-manufacture.

Table 8: Scenarios for machine's part replication

	Suitability of SRM's manufacturing process for replicating a functional part	Example	Outcome
1	Suitable	Most parts printed parts for Darwin's design, shown in white in Figure 41, page 86	Part was replicated using the machine's manufacturing process
2	Only just suitable	Plain bearings	A compromise was made in the design of the part to enable it to be replicated on the machine
3	Completely unsuitable	All parts on the imported parts list, Section 3.1, page 43	Part was imported

The rest of this section details some of the compromises made in Darwin's design to cater for the few limitations of the FFF process.

6.6.2.1 Design for adjustability to meet higher-than-specification accuracies

The specifications for the machine required parts to be made to a tolerance of 0.1 mm. This met the needs of most mechanical parts in the design. However, there were some situations where this tolerance was not tight enough. In these situations the design incorporated an element of adjustability, either relying on:

- location, or

- fine screw thread control

to meet the required tolerance.

An example of location controlled adjustability on Darwin was the bearing surface at the back of the carriage. The carriage required a running fit on the rear axis bar which needed a resolution better than 0.1 mm. Figure 51, below, illustrates how an adjustable bracket (housed in slots) was moved upwards to pin the rear axis bar against the carriage wall as the bracket was clamped. This demonstrated how adjustability was used to achieve a precision fit via location.
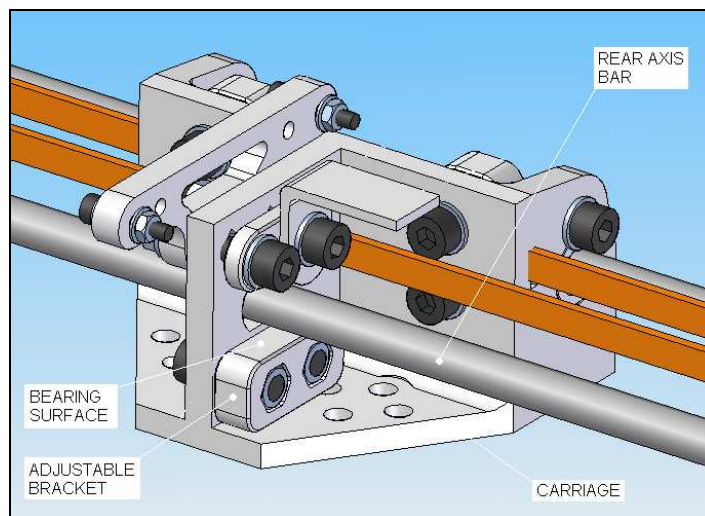
Figure 51: Illustration of an adjustable bracket used to achieve a 'better than 0.1mm' fit. The bracket was pushed up towards the rear axis bar, pinning it against the carriage wall. Thus the fit was achieved through location.

The design of the Z-optoswitch flag illustrated screw-thread-controlled adjustability. The position of the bed for the first build layer was critical, and the printer's resolution was not good enough to make a flag at a height of suitable tolerance. Figure 52, below, shows how a screw thread from a bolt was used to position a floating flag. The pitch on the M5 thread was 0.8 mm, therefore rotation of the bolt by 10° yielded a linear movement of 0.022 mm.
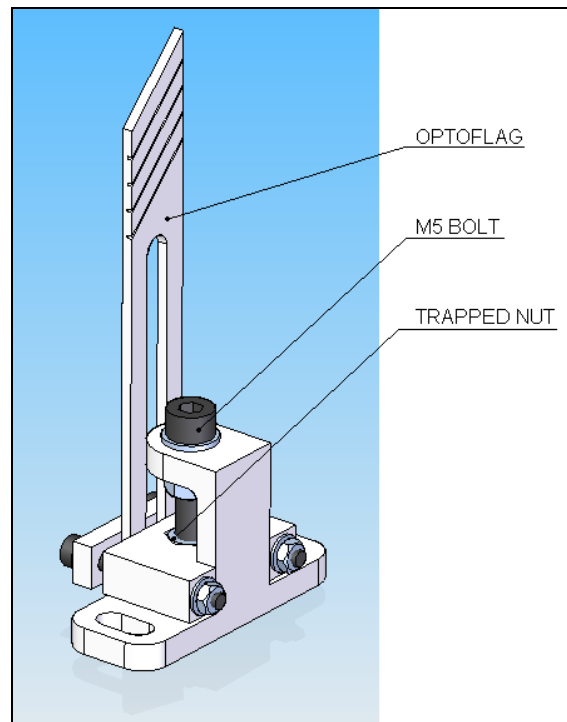
Figure 52: The Z-optoswitch flag's height was adjustable, using a screw thread from a bolt to achieve high precision positioning

6.6.2.2 Subdivision of large parts to exceed the bounds of the working volume

As with most manufacturing processes, the FFF process had a working volume. This presented a problem if the Darwin needed to make any parts larger than its working volume. A typical example of this is the bed which it printed on.

This problem was solved in the Mk1 design by subdividing the total bed design into quadrants. Figure 26, page 74, shows how the large bed was assembled from four quadrants, each quadrant small enough to be made within the working volume. Subdivision in this case was relatively simple because the part was symmetrical. For more complex large components however, the author refers the reader to the work of Medellin *et al.* [45] who have developed techniques to automate the method of decomposition with due consideration to wall thickness, overhanging features and male/female assembly features.

6.6.2.3 Design to compensate for weakness from layered FFF manufacture

The process of welding filaments together in the FFF process meant that the final part volume was weaker than that of an entirely solid lump of material (for example a cast part, or a machined part). This did not cause a problem for most of the parts. However, some parts had to cater for high stress.

The corner bracket shown in Figure 42, page 87, was a good example of a part which needed to be redesigned to use higher second moment of areas to compensate for the slightly weak manufacturing process.

Also, as detailed in Section 6.4.4, page 77, the process of building the part up in layers meant that RP parts were weaker when forces were applied normal to the layer plane. Consideration to build orientation, as demonstrated in the Mk 2 prototype, was given to ensure that parts did not delaminate.

6.6.2.4   *Design to permit thin walled parts*

Because the FFF process effectively drew the part, the minimum part dimensions were constrained by the width of the filament extruded by the print head. The thickness of the filament made thin walls difficult to build in the printer's vertical plane. Therefore all thin walled parts in Darwin's design were designed to be built on the horizontal plane.

6.6.2.5   *Design for secondary processing*

As mentioned earlier in this section, FFF performance struggled when part features approached the resolution of the machine, which is why the manufacture of toothed gears posed a problem. Whilst the principle of using RP to create toothed gears had already been proven on a commercial machine (Section 6.5.2.2, page 82) it was estimated that Darwin would not be able to achieve such performance at its early stages.

Olliver (from the RepRap team) realised that a toothed gear could be cast using the toothed belt to form a mould. This brought about an interesting idea: that the printer could be used to enable a secondary manufacturing process, such as casting. Figure 53 and Figure 54, below, show a simple RP mould designed by the author to cast detailed toothed gears on the screw drive transmission using a section of toothed belt.
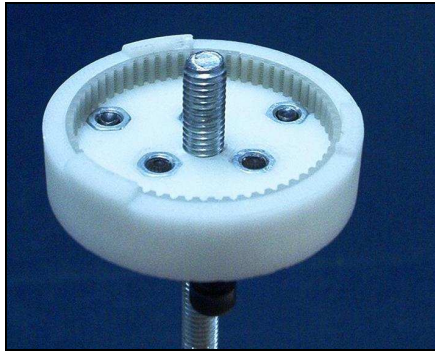
Figure 53: RP mould created to house a section of toothed belt. Bolts were used to eject the casting after it solidified.
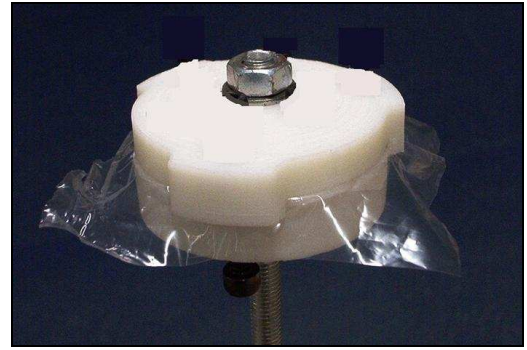
Figure 54: Mould closed (with Polycapralactone inside) clamped shut using the threaded studding. Polythene sheet was used as a release agent.

Figure 55 and Figure 56 illustrate how this approach was also adapted for the tooth-belt drive gears used on the X/Y table.
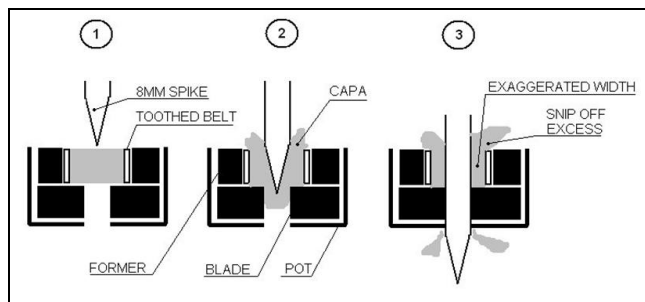
Figure 55: Sequence for casting the X/Y tooth-belt drive gears
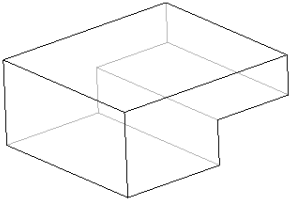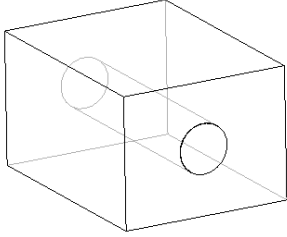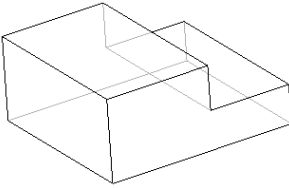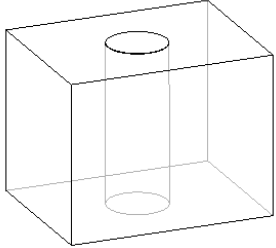
Figure 56: Moulds and casting (on motor shaft)

6.6.2.6 *Design for single build head manufacture*

Most SFF techniques traditionally use a second print head to lay down support material for critical overhangs (described in Section 2, page 26). At this stage in Darwin's development, however, there was no support material print head available. However, after the initial design of all of the parts it was realised that replication would be possible without the use of a second print head if the designs were modified slightly. This was done as a collaborative effort between the author and Olliver.
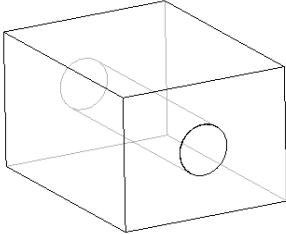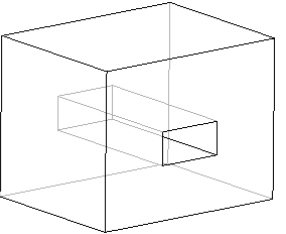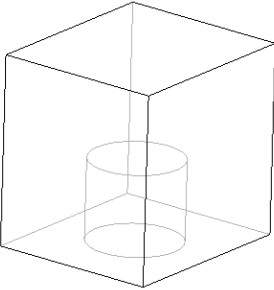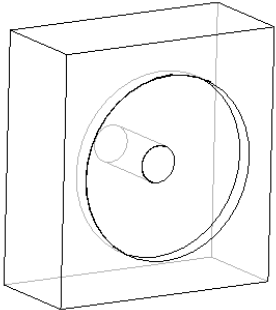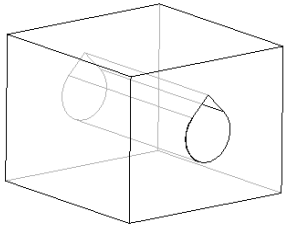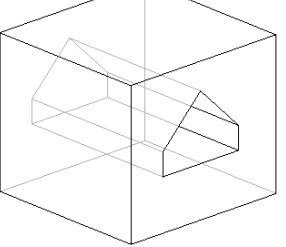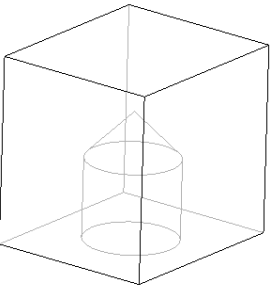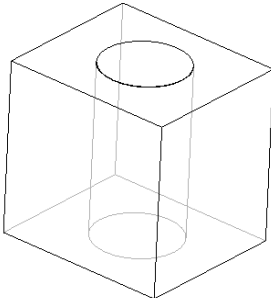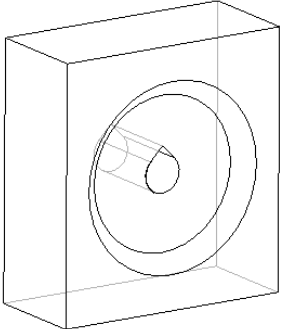
The modification strategy, devised by the author, was to reconsider the build orientation of the parts. In some instances this was enough to eliminate the need for support material altogether. Table 9 illustrates this approach.

Table 9: Examples of solutions to avoid the use of support material using appropriate orientations

	Example 1	Example 2
Part		
Support material	Support material induced below overhang	Support material induced into the hole. Difficult to remove and reduces the quality of the finish.
Orientation solution		
	Build with largest flat at the bottom	Build with hole axis in the vertical plane

For most parts, however, simply changing the build orientation was not enough, so modifications were made to the overhanging features. In the FFF process it was discovered that overhangs which ranged from 0 ° to 45 ° were self supporting. With this knowledge, it was possible to use a range of approaches to completely eliminate the need for support material for all parts. Table 10 illustrates the approaches made, assuming that the orientation of the features could not be changed. The consequent teardrop profile for horizontal holes (illustrated in the first example) became the logo for the project.

Table 10: Example of design solutions to avoid the use of support material for different features

	Example 1	Example 2	Example 3	Example 4
Feature	Horizontal hole	Horizontal slot	Blind hole (inverted)	Vertical counter-bored
Design solution	Pointed (45 °) hole	Pointed (45 °) slot	Coned (45 °) roof / Through hole	Chamfered (45 °) countersink

6.6.3   Design for an assisted SRM

It was assumed that, with further development, the RepRap printer would approach pure self-manufacture, and that it would eventually qualify as an assisted SRM. Section 3.6 (page 46) discusses how this may enable geometric growth and evolution. The design specifically catered for these characteristics.

6.6.3.1   Design for evolution

Evolution was encouraged by:

- Open design: the RepRap printer is entirely open-source, as detailed in Section 3.1 (page 43). The original design was fully documented on the web so that anybody who wanted to could master the design and take it in whichever direction they desired.

- Modular design: parts were deliberately modular to separate out different machine functions. Whilst this made assembly a little more arduous, and tarnished the aesthetics of the machine, this enabled different functions to be developed easily. Darwin's modular chassis, for example, was expandable to the user's own requirement. The modular corner blocks themselves could also be modified without affecting any other functions in the machine.

- High redundancy: the inclusion of non-critical features enabled easy mechanical development. A good example of redundancy in Darwin's design was the extra fastening holes in the structural parts, and capacity for a second toolhead in the X-carriage.

6.6.3.2   Design for growth

Growth was encouraged by:

- Reducing the complexity of the machine where possible: designing the machine with a minimum number of parts speeded up the replication cycle, both in terms of manufacturing time and assembly time. A good example in Darwin's design was the use of the steel bars in the X-axis to avoid the need for vertical support bearings.

- Ease of assembly: assembly time takes up a significant portion of the replication cycle so it was beneficial to make the assembly as simple as possible. Approaches

like common bolt diameters, socket head bolts and design parts for jigs were all used to speed up assembly time.

- Design for simple maintenance prolonged the lives of the machines. For example, Darwin used plain bearings on the bars to achieve movement. Whilst printing in polymer gave excellent characteristics for most mechanical parts, polymer bearings wore out quickly. Figure 57, below, illustrates a quick-fit design used for Darwin's five plain polymer bearings – each bearing was constrained by a single bolt to simplify bearing replacement. This made polymer bearings (which the printer could make itself) viable for use in Darwin.
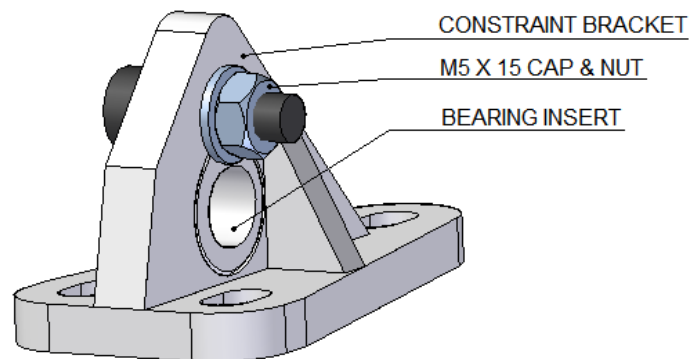
Figure 57: An illustration of how most plain bearings were designed to be constrained with one bolt, thus making replacement easier.

6.6.4   Results for the Mk 3 concept

Figure 58 shows the finished prototype for Darwin.
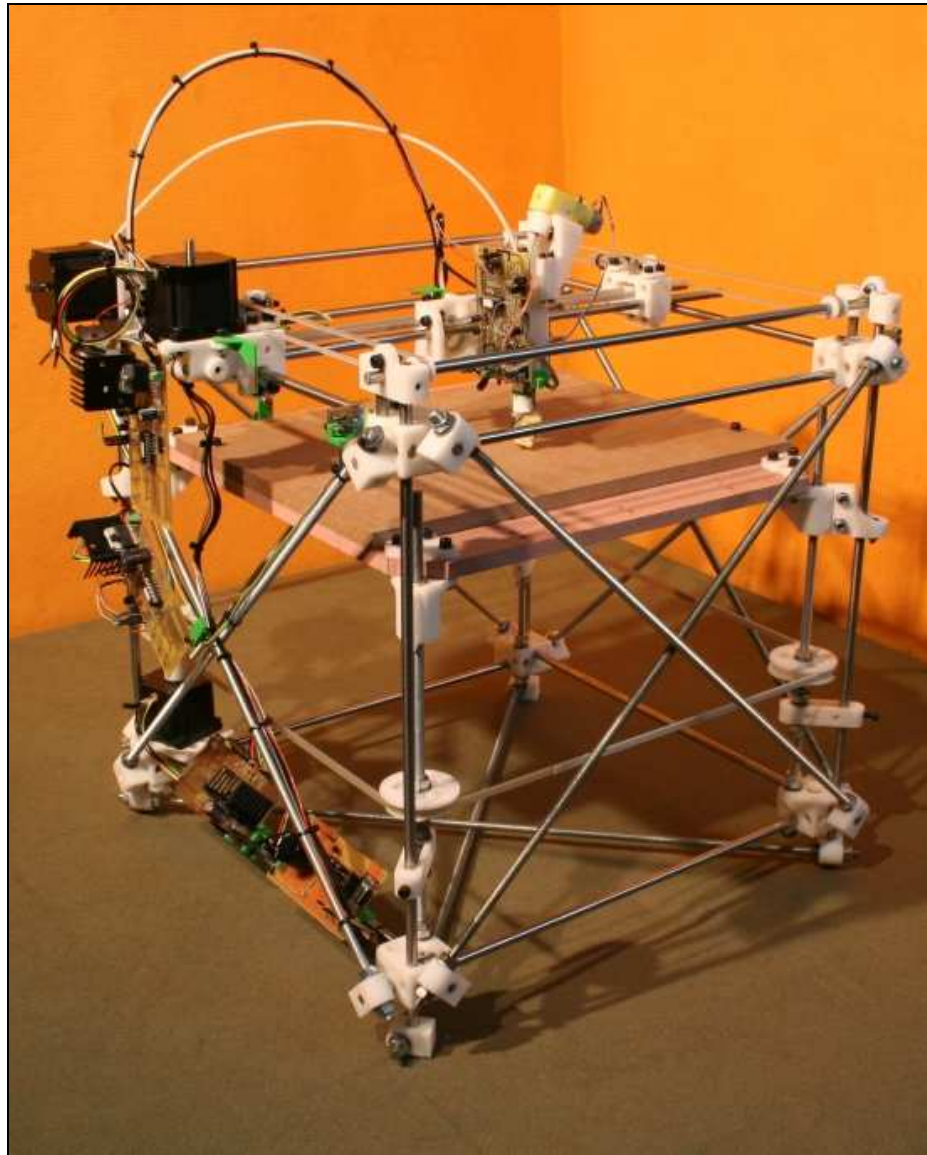
Figure 58: Photograph of the completed Mk 3 design: "Darwin".

6.6.4.1   Mechanical strength

The use of the new corner bracket design proved very successful. This significantly strengthened the structural problems encountered in the Mk1 Z-axis design.

To test the strength of the assembly, a small child (Johnny Adkins, 15.0 kg) was mounted on the bed of the machine and driven up and down at a speed of 30 mm/s.

Figure 59: The strength of the design was tested by placing a small child (Johnny Adkins, 15.0 kg) on the Z-bed. Ian Adkins (father) used dedicated stepper driver chips with MOSFET technology to move Johnny up and down at a speed of 30 mm/s.

6.6.4.2   General reliability

The X/Y table worked reliably and up until the time of writing, has never jammed.

The Z-axis was also reliable, when set up correctly. However, there were problems with machines (in New York, New Zealand and in the United Kingdom) which were not setup correctly. The most common reason for jamming was incorrect belt tensioning. Friction in the transmission was directly proportional to belt tension; therefore too much belt tension caused the axis to seize. The incentive for increasing belt tension was to guarantee the belt would not skip, so many of the builders' instincts were to install the belt with a very tight fit, thus jamming the axis.

A belt tensioner was retro-fitted to the design so that the builder was able to assemble the transmission with a loose belt and then set it to an optimum tension. This solved the problem in all cases.

6.6.4.3 Repeatability

Figure 60 illustrates the results for repetitive movement of the Z-axis, using optoswitches to home the axis. This suggests that Z-axis movement was repeatable to $\pm$ 0.01 mm.
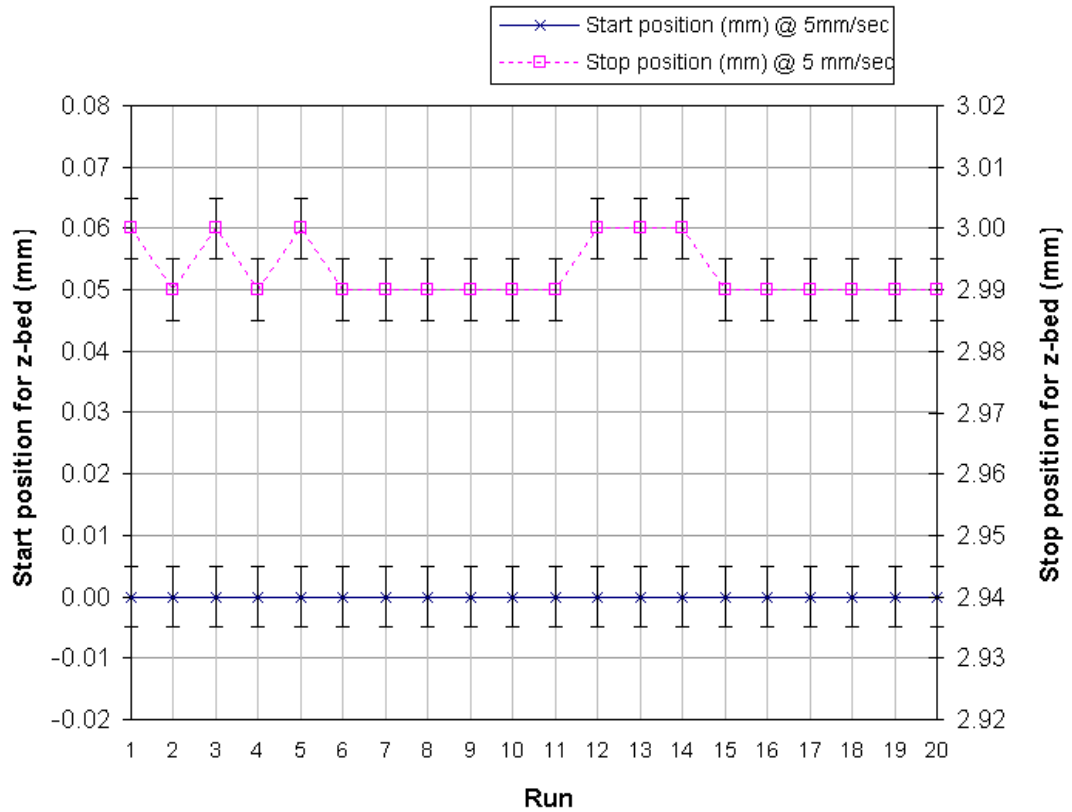
Figure 60: Repeatability for Darwin's Z-axis

Figure 61 illustrates the results for repetitive movement of the Y-axis, using optoswitches to home the axis. This suggests that X/Y table movement was repeatable to ± 0.06 mm.
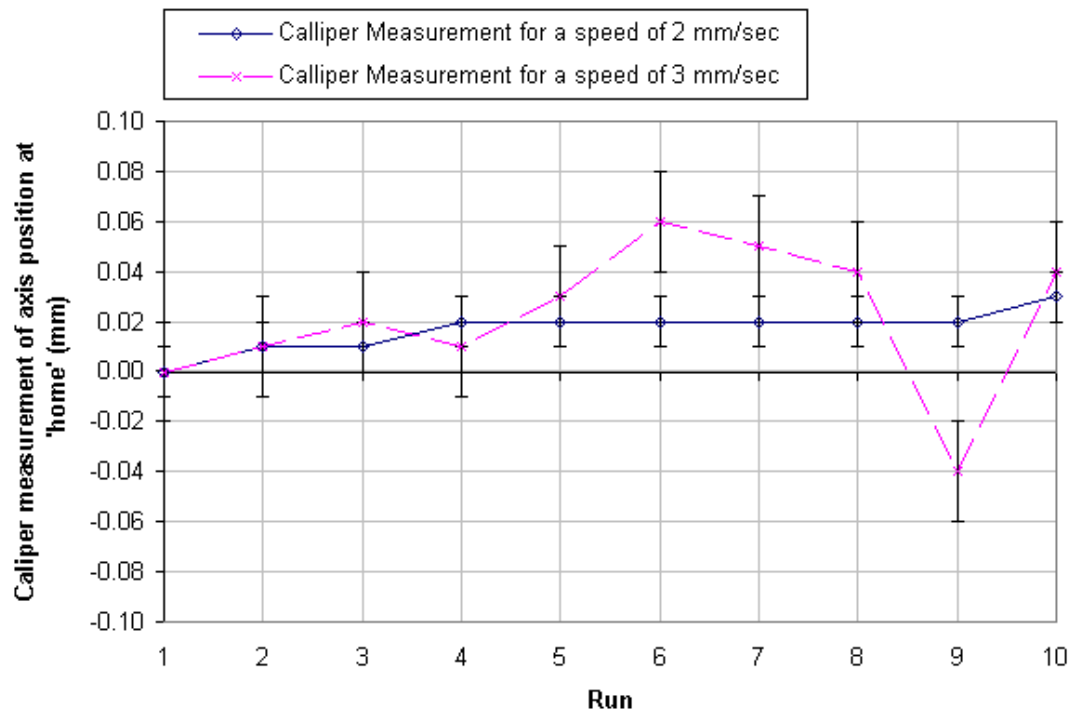
Figure 61: Accuracy tests for returning the Y-axis to the home position using the optoswitch

6.7   Final design evaluation

Overall, the Mk 3 design met the original specifications for the RepRap printer. Table 11 compares Darwin to the original specification.

Table 11: Specification for the RepRap printer and evaluation of the Darwin design

Ref	Factor	Specification for the RepRap printer	Darwin's notes
1	Ergonomics	Machine should be controlled through a PC interface Z-bed printing tray should be easy to replace This machine will not be for non-technical public use, therefore form should always follow function	Specification met.
2	Standardization	Design should accommodate the use of standard materials	Specification met.
3	Aesthetics/finish	Loose wiring should be neatly tied RepRap logo should be prominent No aesthetic required	Specification met.
4	Performance	M/c should manufacture parts in a volume of 300 x 300 x 300 mm No speed requirements (this will be a product of m/c testing) X, Y and Z axis movements must be repeatable to ±0.05 mm, and accurate to a resolution of 0.1 mm.	Working volume: 160 x 160 x 150 mm X & Y axes repeatable to ±0.06 mm, Z axis repeatable to ±0.01 mm.
5	Product cost	Part cost limit: £500 Assume no labour cost for assembly	Cost: £300

Ref	Factor	Specification for the RepRap printer	Darwin's notes
6	Materials	Imported parts: Self tapping screws Brass bushes & simple linear bearings Studding Lubricating grease Standard electronic chips (*e.g.* microcontrollers and optical sensors) Standard plug in low voltage power supply Stepper motors Timing belts	All used, with the following additions: Darwin imports: drive belt, bar, springs, MDF bed, cable ties, foil, super glue Extruder imports: servo motor, solenoid, gearbox gears, steel cable, brass bushes, solder, PTFE bar, brass heating barrel, Nichrome heating wire, nozzle, insulation: JB weld & fibre glass, valve wire, fan, springs Secondary process required for toothed pulleys
7	Quantity	3 off: 1st generation machine replicates the 2nd generation machine. 2nd generation machine generates the 3rd generation machine to prove the concept.	1st and 2nd generations complete. 3rd generation underway at the time of writing.
8	Life span	3 years experimental use	At the time of writing, the first Darwin had survived 12 months with no major problems.
9	Production timescale	The RepRap printers should be completed by October 2008	Specification met.
10	Manufacture process	Custom parts (parts outside the stock list) must be either: - a reasonable contender for the stock list	Specification met.

Ref	Factor	Specification for the RepRap printer	Darwin's notes
		- a labour saving necessity which can be circumvented in a later design	
11	Size	M/c should be small enough to fit on top of an average bench	Specification met.
12	Disposal	Bespoke parts must be simple to remove for scavenging purposes on later designs	Specification met.
13	Market constraints	None	-
14	Weight	M/c should be light enough to be supported on the average bench	Total weight: 13 kg
15	Maintenance	At this stage of research it is acceptable for maintenance before each use	Axes require greasing on a weekly basis
16	Packing and shipping	No physical shipping Software must be arranged in a bundle for simple distribution of files	Specification met.
17	Reliability	See 'performance'.	-
18	Patents	Designs should be published open-source on the RepRap site to make the m/c unpatentable	Specification met.
19	Safety	Sharp edges, nips and points must be avoided. However, this will not be CE marked and will not be examined as such	Specification met.
20	Colour	No requirements	Filament dependant

Ref	Factor	Specification for the RepRap printer	Darwin's notes
21	Assembly	Assembly to be completed by an untrained, but technically competent, human with basic tools	Specification met.
22	Trade Marks	None	-
23	Value analysis	None	-
24	Competing products	None – this is a contribution to science	-
25	Environmental factors	None	-
26	Corrosion	None	
27	Noise levels	Avoid loud noise where possible.	Specification met.
28	Documentation	TCF required	This thesis serves as a summary for the technical construction file, as does the online documentation at reprap.org
29	Balance and inertia	M/c must be stable enough to run without supervision	Specification met.
30	Storage	M/c to survive open bench top environment for lifespan	Specification met.
31	Machine head	It is expected that the final machine design will use multiple (approximately 4) material distribution heads. These heads also require development. See below for a build strategy.	Darwin supported the use of 2 heads. Only 1 head was necessary for replication.

Ref	Factor	Specification for the RepRap printer	Darwin's notes
32	RP head	Use Bowyer and Olliver's design (Section 6.6.1.6, page 89) Stock ABS dimensions: ø 3 mm	Specification met.
33	Metal head	To be designed Stock alloy dimensions to be undefined	Metal deposition head being prototyped at the time of writing
34	Power Supply	Run on 12V	Specification met.

6.8   Releasing Darwin's mechanical design and supporting its developments

When Darwin's design was completed it was made available on the web. This involved:

- Processing the parts files and packaging them as a release on the SourceForge server.

- Documenting the assembly process and putting it on the project's wiki.

- Creating a collection structure on the project's wiki for improvements and developments.

- Maintaining the release packages to ensure they were current.

6.9   Software and electronics

During mechanical development the rest of the RepRap community had worked hard to deliver a working set of software and electronics. Whilst these areas of work were done by others, the author will continue to summarise these contributions because they were essential to the operation of the machine, and essential to reproducing the author's work.

6.9.1   Software

Darwin was operated through a host computer. The program which did this was small enough to be run on a home PC, and was written in Java to ensure cross-platform compatibility. Figure 62 shows how the software took a solid model file (of STL format) and sliced it into layers. The original core software was written by Bowyer. The program then sent Darwin the information it needed to print each layer, developed by Bowyer and McAuliffe.

A copy of the program, in both binary and source files, has been included on the DVD which accompanies this thesis.
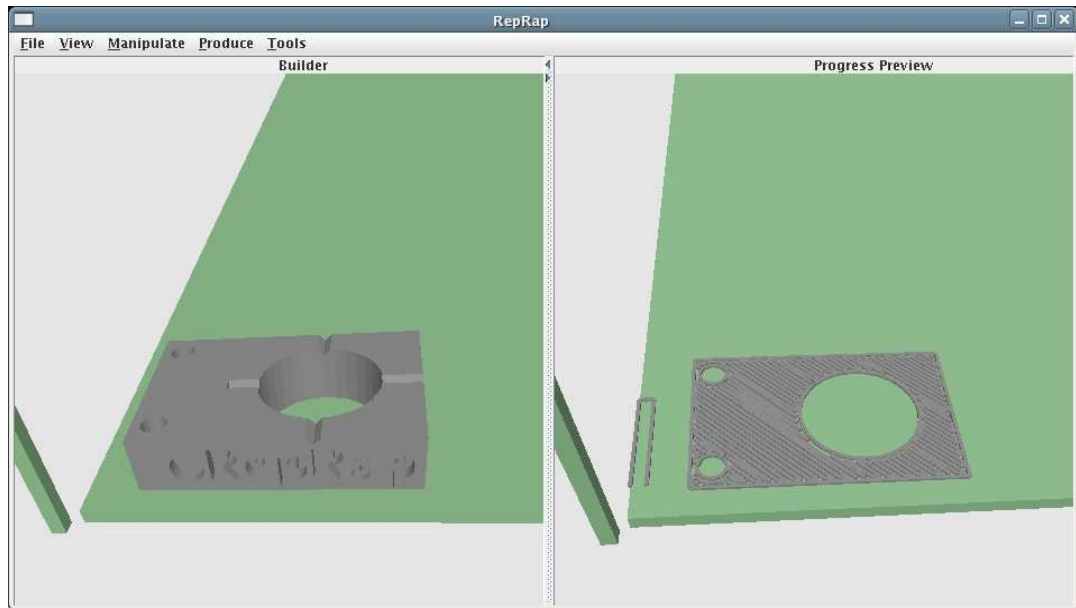
Figure 62: Graphical User Interface for the RepRap software. This software analyses a geometric model, splits it into layers and sends instructions to Darwin.

6.9.2 Electronics and firmware

Figure 63 illustrates the first version of electronics which was used to run the machine, developed by Bowyer and McAuliffe. Each module (*e.g.* motor controller, or extruder controller) was linked together in a ring and information was passed around in a ring network. This had the advantage that it was extensible (*i.e.* new modules could easily be added).
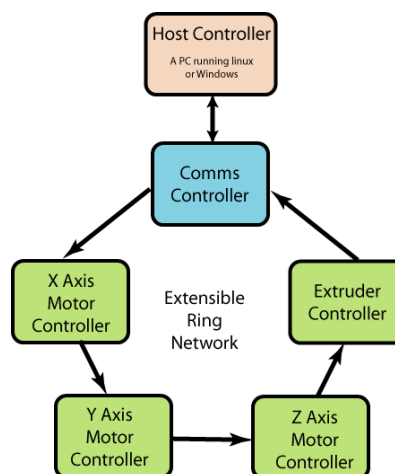
Figure 63: Instructions are passed around the printer via a token ring of microprocessors.

The current version of electronics uses an Arduino Diecimila microcontroller board [61] designed by Banzi *et al.* [62], and Arduino-specific modules (developed by Smith from the

RepRap project) are arranged in a star network. The wiring diagram for this network is shown in Figure 64 (overleaf).

A copy of the firmware for each module and the PCB designs has been included on the DVD which accompanies this thesis.
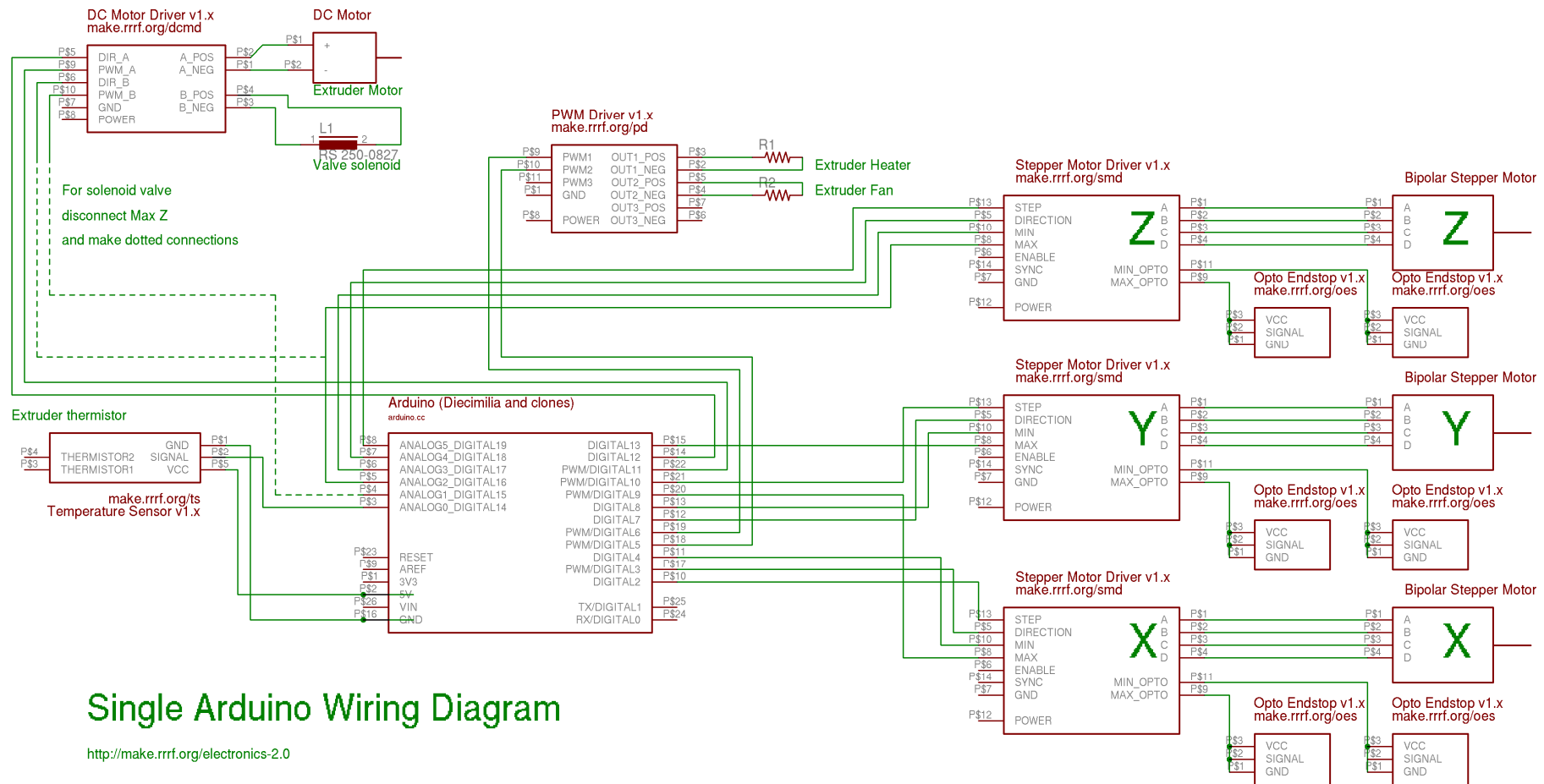
Figure 64: Wiring diagram for the current electronics version. This uses an Arduino microcontroller board as the hub for a star network.

7   OPTIMISING THE SELF-MANUFACTURING PROCESS

This chapter describes some of the development which went into setting up the FFF process and improving Darwin's manufacturing performance. This was done to a point where design specifications could be met and self-manufacture could be achieved.

The author notes that test components exist to measure specific qualities of an RP machine, for example that of J.-P. Kruth *et al.* [63]. Whilst self-manufacture was achieved without the use of these components, the author acknowledges that future analysis would be useful to compare the RepRap printer's performance with other RP technologies.

7.1   How the FFF process works, and initial results

Darwin's manufacturing performance relied on the FFF process parameters which were controlled in the software. For example, there was a parameter for the rate at which the polymer was extruded and a parameter for the extruder's nozzle speed in the X/Y plane. A complete list of the parameters has been included in the Appendix (Section 13.9, page 223). These parameters needed to work together to produce a good build. This was a challenge because 51 of the parameters were critical to build quality and most were inter-dependant. The very first prints from Darwin, unsurprisingly, did not meet specifications. Typical symptoms included collapsed walls, filled holes and poor surfaces.

7.2   Collaboration from the rest of the RepRap project team

Whereas mechanical research and development in the previous chapter was the near-sole product of the author, optimising the FFF technology was much more of collaborative effort. By making several copies of the Darwin design for the rest of the team (using a commercial Stratasys FDM RP machine) other developers were able to contribute in this area. Aside from the collaborative technologies described in Section 3.3, page 45, an online Google spreadsheet was set up to collect process parameters from different parts of the world.

7.3   Learning and using Java™ to develop the self-manufacturing process

Improving the performance of the machine required a significant amount of software development to manipulate different process parameters.

As mentioned in the previous chapter, the core software which ran the RepRap printer was written in the Java™ programming language by the RepRap team, significantly Adrian Bowyer (for geometry) and Simon McAuliffe (for communications). To improve the performance of the machine the author needed to learn Java™, specifically language basics, class design and the concepts of inheritance and polymorphism. This allowed the author to edit the software to effect necessary changes indicated from physical testing. A graphical user interface was designed and implemented by the author to make general testing of the machine easier (Figure 65, below).
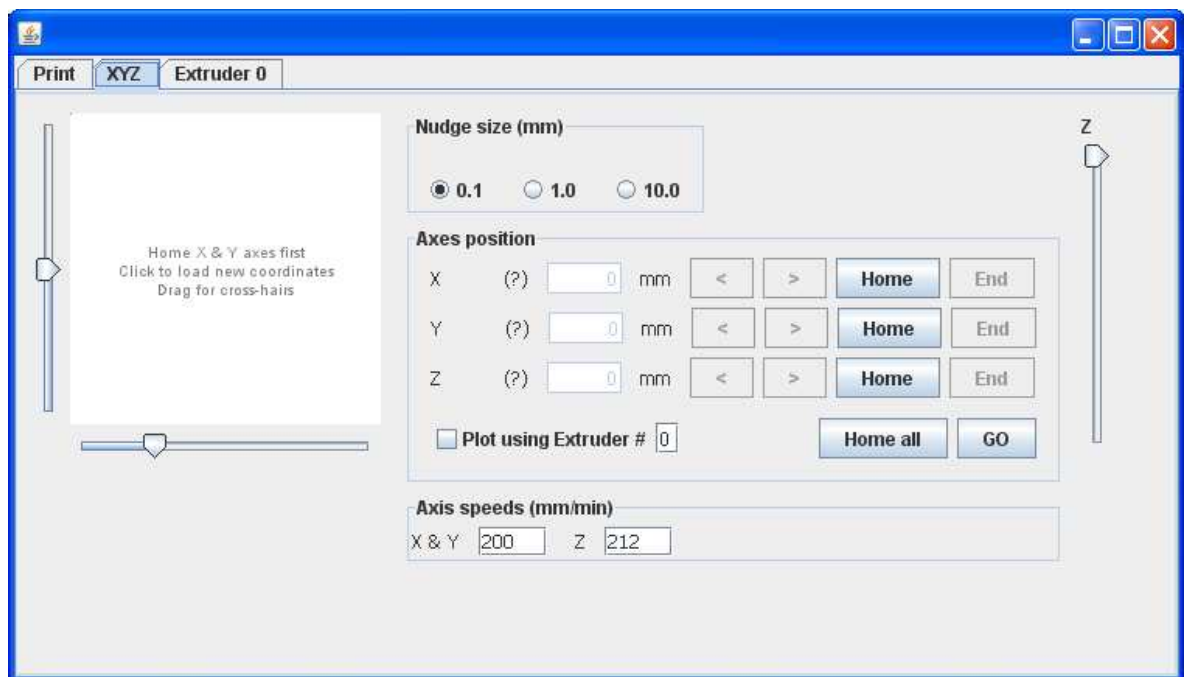
Figure 65: Graphical User Interface designed to make testing simpler. This was designed to give the user simultaneous control of the printer's mechanisms.

7.4   Basic calibration

This section is a summary of the final approach used to make sure the process parameters, and their respective hardware elements, worked together.

7.4.1   Filament stressing

The first test extruded an unstressed filament (this refers to a filament which leaves the extruder nozzle and lands at is designated deposition point without being put under tension or compression). Two parameters defined this quality: extrusion speed (the speed at which the polymer exits the nozzle) and nozzle speed (the speed at which the extruder moves in

the X/Y plane), illustrated below in Figure 66. The effect of these two speed parameters on the filament are illustrated in Figure 67.
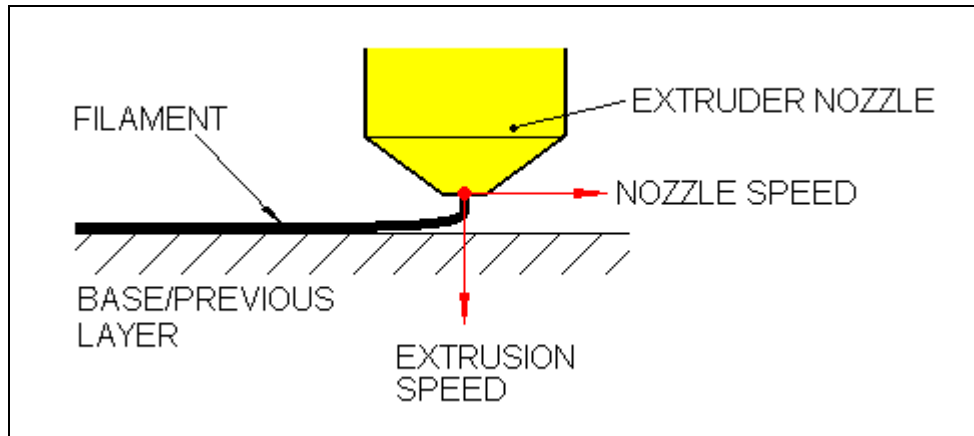
Figure 66: Illustration of nozzle and extrusion speeds
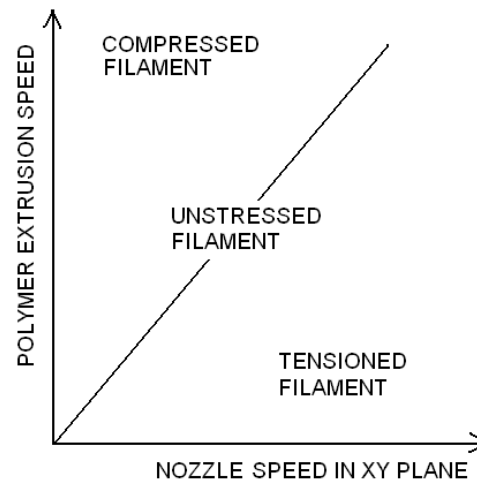
Figure 67: Illustration of how the extrusion and nozzle speeds related to different qualities of filament. An ideal unstressed filament was achieved at a specific ratio of parameters.

A long cuboid (Figure 68, below) was modelled to test these parameters, and the code was edited to force the printer to extrude long straight tracks for the infill sections.
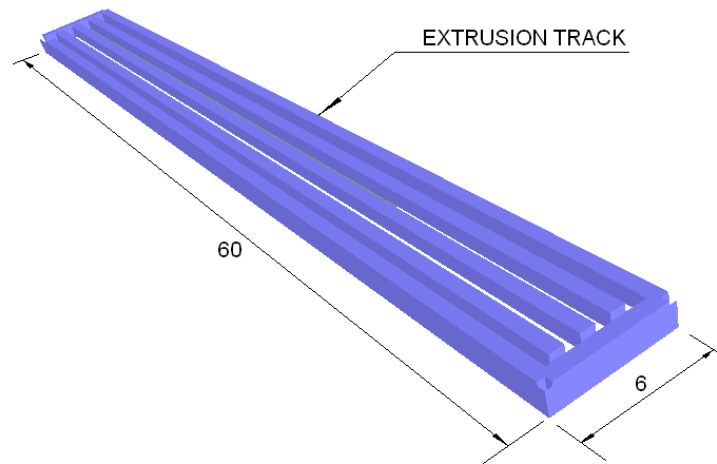
Figure 68: The 'Long-bar' test piece was created to force the printer to extrude long tracks, modelled here in blue. This test was designed to observe the stressing of the filament during the deposition of long straight segments.

A filament under tension produced a very thin, strung-out polymer track, while a filament under compression would produce a fat, bunched polymer track (Figure 69).
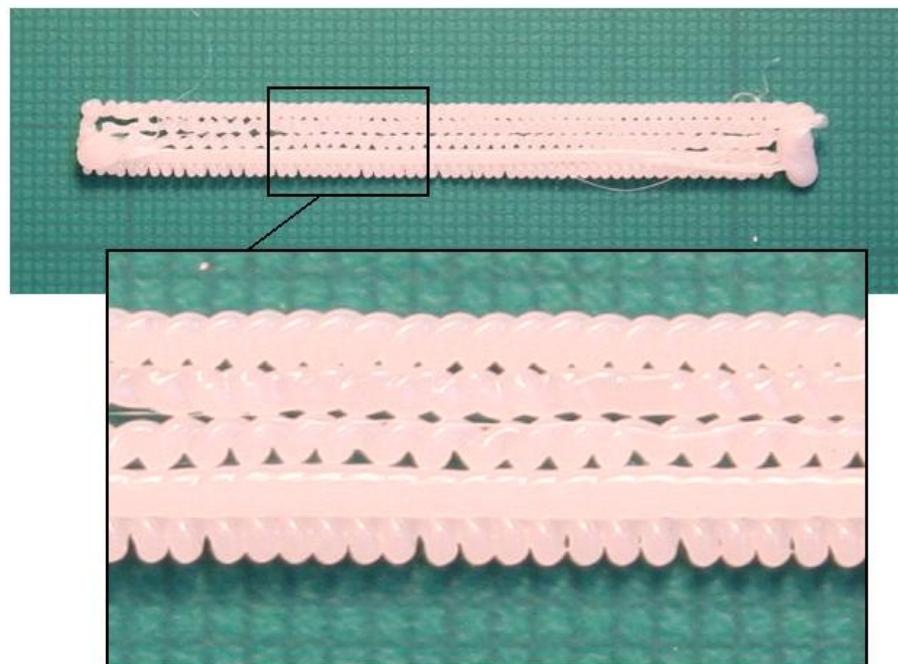
Figure 69: Poor print parameters – the bunched filament indicated that the deposition was under compression: either the extruder speed was too fast, or the nozzle speed was too slow.

'Bunching' was eliminated by either increasing the nozzle speed or decreasing the extruder speed. Sections of the filament were then measured using calipers and compared with the nozzle diameter.

7.4.2 Layer height adjustment

The position of the Z-bed was adjusted to ensure that the first layer bonded securely. This was important because the first layer formed the foundation of the build. A 10 mm cube was then printed to calibrate the layer height. This completed the basic calibration process.

7.5 Problems and solutions to "printing on air"

After basic calibration, several problems were encountered which made the process unreliable at the start. All build failures were reduced to one simple cause: "printing on air". This referred to the extruder depositing a segment, but due to a previous problem there was no segment beneath to weld to. The deposition would then curl and weld to the wrong area of the part and errors would stack up to cause a build failure (manufacture out of specification).

In short, printing on air was due to an erroneous absence of a segment in the layer below. The following subsections detail some of the causes for this segment absence and the developments to make sure this didn't happen.

7.5.1 Extruder motor stalling

One of the simplest reasons for segment absence was a stalling extruder. The original extruder transmission, shown in Figure 48 and Figure 49 on page 90, was a direct drive from a servo motor (the 'GM3' motor by Solarbotics, supply details of which are listed in Section 13.7, page 220). In this arrangement the motor was occasionally unable to overcome friction and compression forces at the interface between the feedstock and the drive screw. To remedy this, a gear train was designed which increased the output torque from the motor by a factor of 3.0 (Figure 70, below).
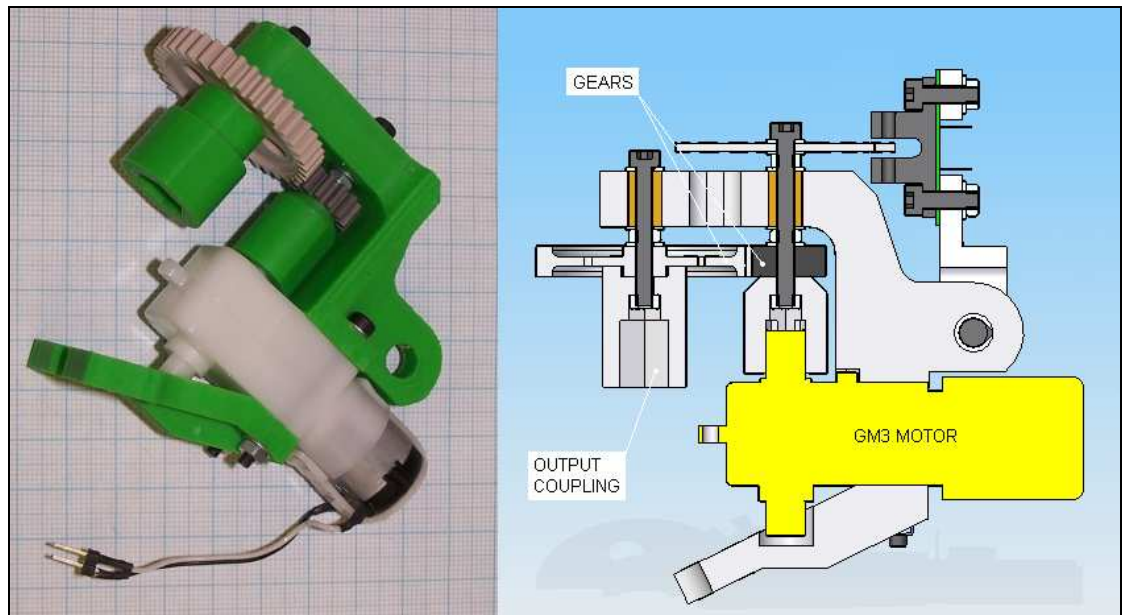
Figure 70: Gear train designed for the extruder motor to overcome stalling issues. This increased the output torque by a factor of 3.0. The design incorporates an encoder disc for future speed control.

7.5.2   Uneven layers due to over-printing and segment pausing

To fill a layer, a cross hatch was deposited in the space within the boundary filament. Figure 71 shows how this caused bulging at the point where the hatching met the boundary. This was because the change in the nozzle direction caused over-printing, as illustrated in the figure below. This was true for all changes in nozzle directions, and became significant when the angle change was acute. The resultant bulging caused the layer to become uneven.

To make matters worse, a phenomena known as 'segment pausing' prevailed throughout most of this development phase. This was because of the momentary pausing of the nozzle before beginning a new segment (red circles in Figure 71 denote 'segment pausing' positions). Segment pausing was caused by a delay in electronic communications between segments. During this pause, filament would ooze from the nozzle, further adding to the bulge.
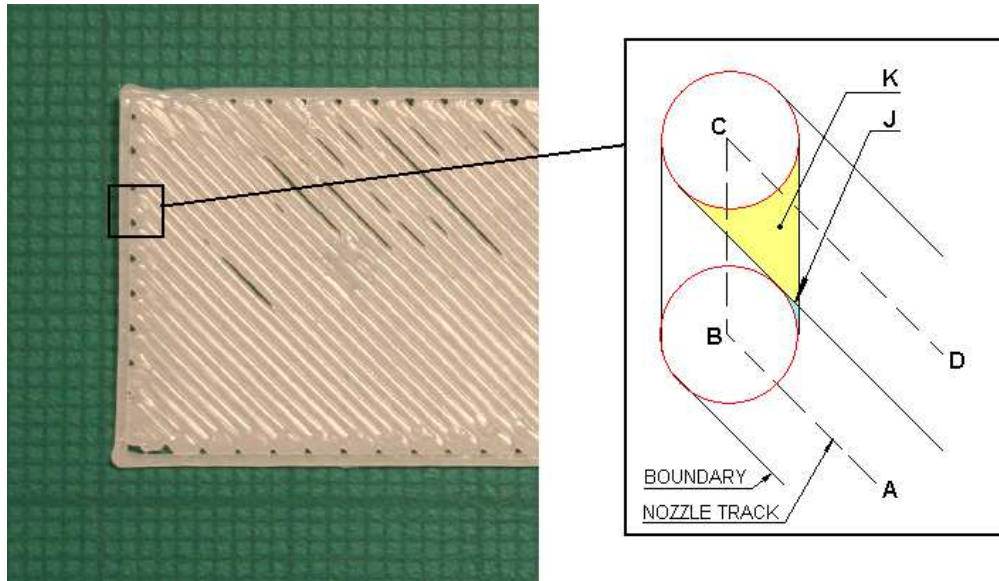
Figure 71: Photograph of a single print layer for a wide bar (left). Bulging was observed where the hatching segments met the edge segment. This is explained in the nozzle schematic (right): The nozzle prints A-B. From B-C the nozzle over-prints area J and from C-D the nozzle overprints area K. Note that over-printing is most severe during acute track change angles. It is this over-printing which causes the bulge, creating uneven layers. The circles on the schematic denote 'segment pausing' positions, where the nozzle resides momentarily as it receives its next instruction to print the next segment.

As uneven layers were stacked on top of each other, the disparity increased and it became increasingly difficult to pick a successful increment for layer height. An average value eventually caused the nozzle to smudge high-spots yet be so high that it printed on air over the low-spots.

Bowyer solved most of this problem by using an algorithm which increased the nozzle speed relative to track change angle over a short distance (approximately 2 mm) after every change. This reduced the impact of over-printing because it meant that less material was being deposited in total for these sections. He also eliminated the 'segment pausing' which formed a significant part of the problem by buffering segment information in the microcontroller.

Whilst these measures certainly improved performance, it was noted that overprinting was an unavoidable limitation for FFF. However, more control was gained by reducing the nozzle diameter.

7.5.3   Segment drag

One of the biggest causes for segment absence was segment drag. This is where the segment had literally been dragged out of position during the course of the build. There were a few reasons for this identified during testing.

7.5.3.1   Nozzle debris

Nozzle debris refers to excess filament which collected on the nozzle. This was damaging during a print because the debris was likely to catch a printed segment and pull it out of position. Four things were done to eliminate nozzle debris:

- An 'anti-ooze' nozzle valve was added. After the extruder motor was turned off, filament would continue to ooze from the nozzle due to the pressure in the chamber. This was a primary source of debris. Figure 72 and Figure 73, below, illustrate the author's concepts on how this might be have been counteracted using a nozzle valve. These concepts were later implemented by Bowyer and Adkins.
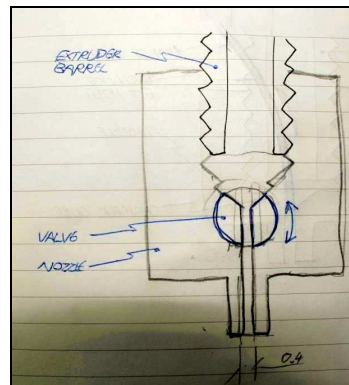
Figure 72: Nozzle cylinder valve. A solenoid rotates the cylinder to allow filament to leave the nozzle
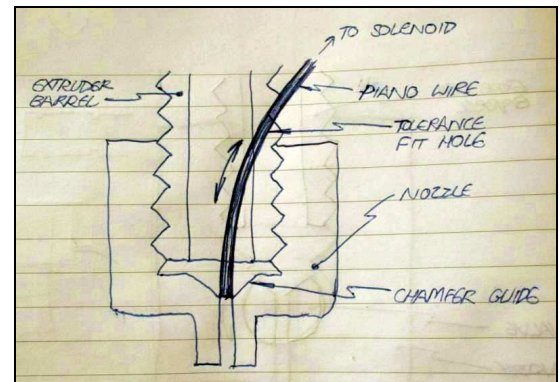
Figure 73: Nozzle piano wire valve. A solenoid lifts the wire to allow filament to leave the nozzle

- The nozzle profile was changed. The extruder had been originally designed to use a dome nut as a nozzle. This profile exposed a lot of surface area to the build which attracted debris. A turned nozzle was designed to reduce the exposed area, thus attracting less debris (both are shown in Figure 74).

Figure 74: The original extruder nozzle was made from a bored dome nut (left) which exposed a lot of surface area to the build. The turned spigot nozzle (right) exposed less area to the build and attracted less debris.

- Addition of a nozzle wipe. After each layer, depending on the material, the nozzle was moved away from the build to allow the part to cool. A wipe was designed to allow the nozzle to clean itself during this period, freeing it of any debris.
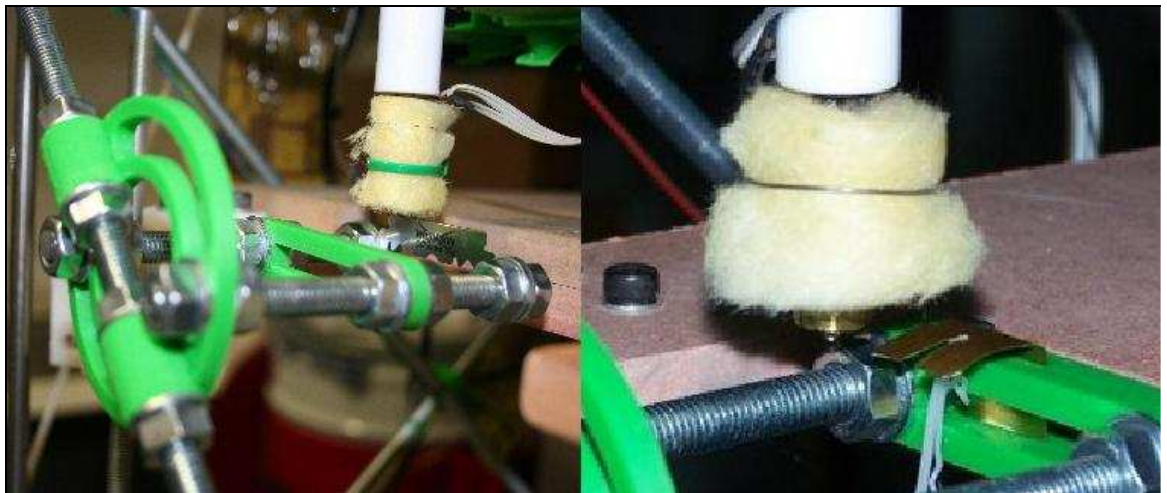
Figure 75: Nozzle wipe. The print routine was to move the nozzle backwards and forwards over a doctor blade during the cooling period. Different blade orientations and designs were tried with varying degrees of success. Bowyer also implemented a lever which, when pushed by the nozzle, cleaned the doctor blade.

- The need for nozzle wiping was eliminated. An option was built into the software to skip the cooling procedure. The rational behind this was that if the debris control was already good enough with the nozzle valve and anti-debris nozzle profile, and the build material did not need inter-layer cooling, excessive movement of the nozzle created a debris collection risk, similar that detailed in Section 7.5.3.2.

7.5.3.2   Dry movement ripping

Occasionally the extruder needed to stop extruding and move to a different area of the layer. The bed dropped down a certain distance to give the nozzle clearance to move over pre-printed material. However, if the angle to the next point was too acute (*i.e.* the nozzle moved backwards over the freshly deposited segment) this would sometimes rip the freshly deposited segment away.

7.5.4   Excess

Excess deposition was a symptom of over-printing (detailed previously in Section 7.5.2) or poor parameters. Excess material caused segment absence by flowing into molten segments and pushing them out of position.
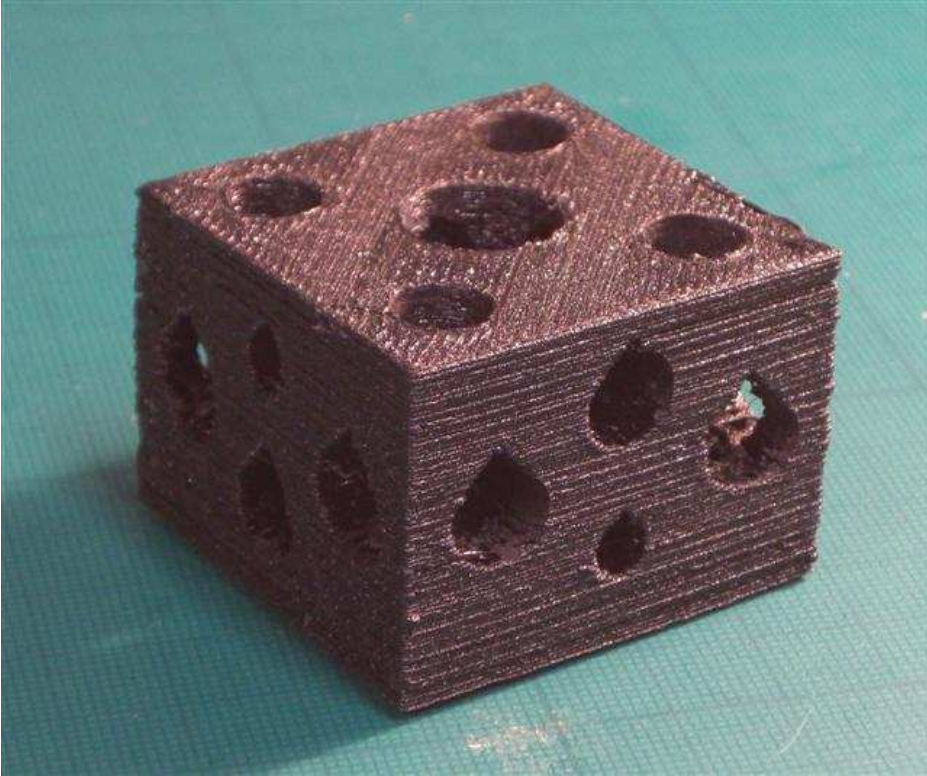
7.6   Summary
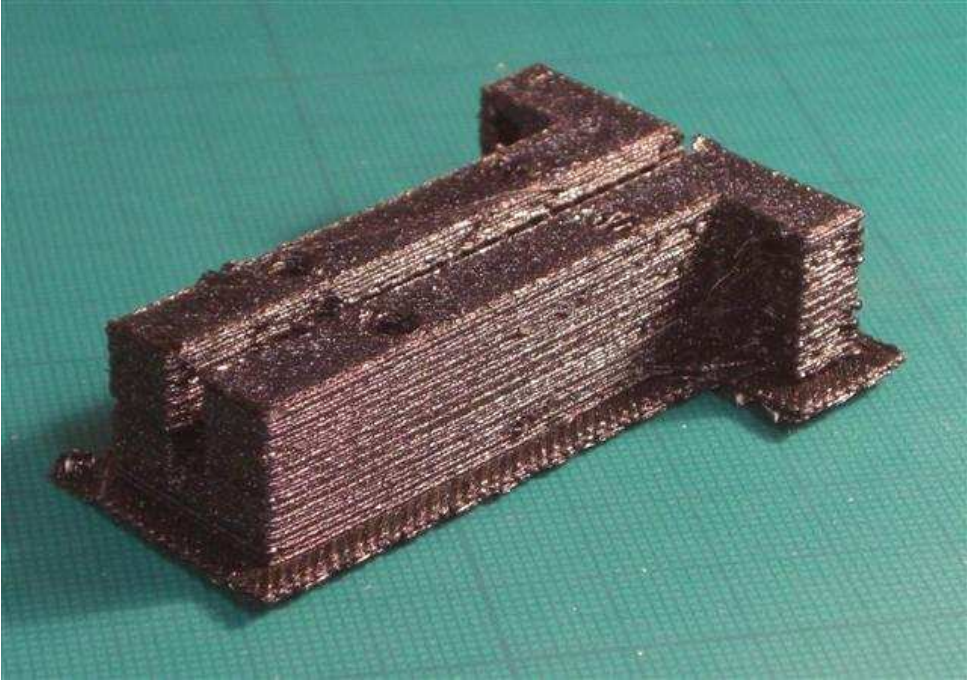
This chapter has documented how the FFF process worked, how it was calibrated and the developments needed to make the process reliable. The next chapter documents printing results at the time of writing, and demonstrates self-manufacture and assisted self-replication.
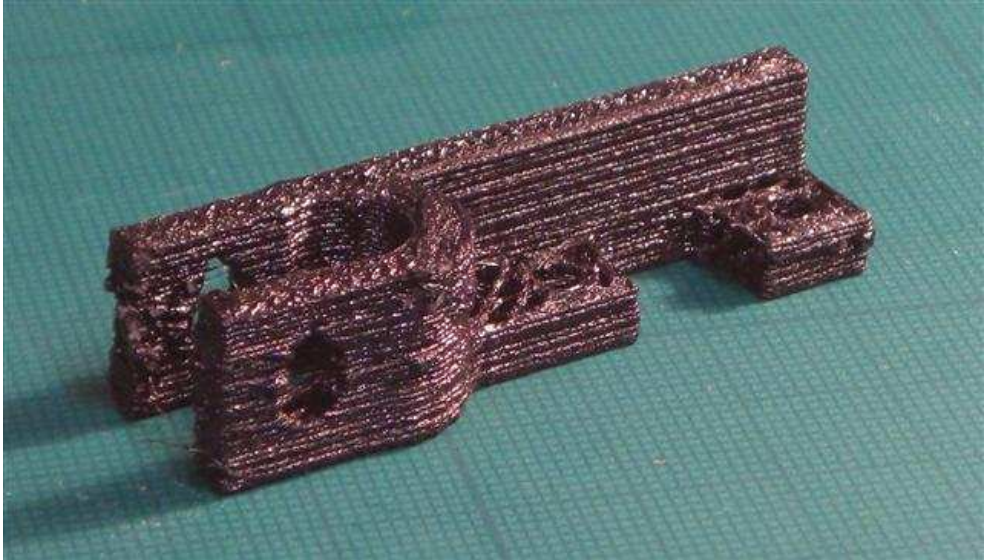
8   RESULTS

This chapter illustrates the print quality achieved at the time of writing, and documents the first instance of assisted self-replication for the RepRap printer. The examples of prints shown below were done in three different types of material: polycaprolactone (PCL), acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). In addition to examples presented from the author, examples of prints from other RepRap team members (Section 13.8, page 221) have also been included. These other team members were also using Darwin, to the author's design.
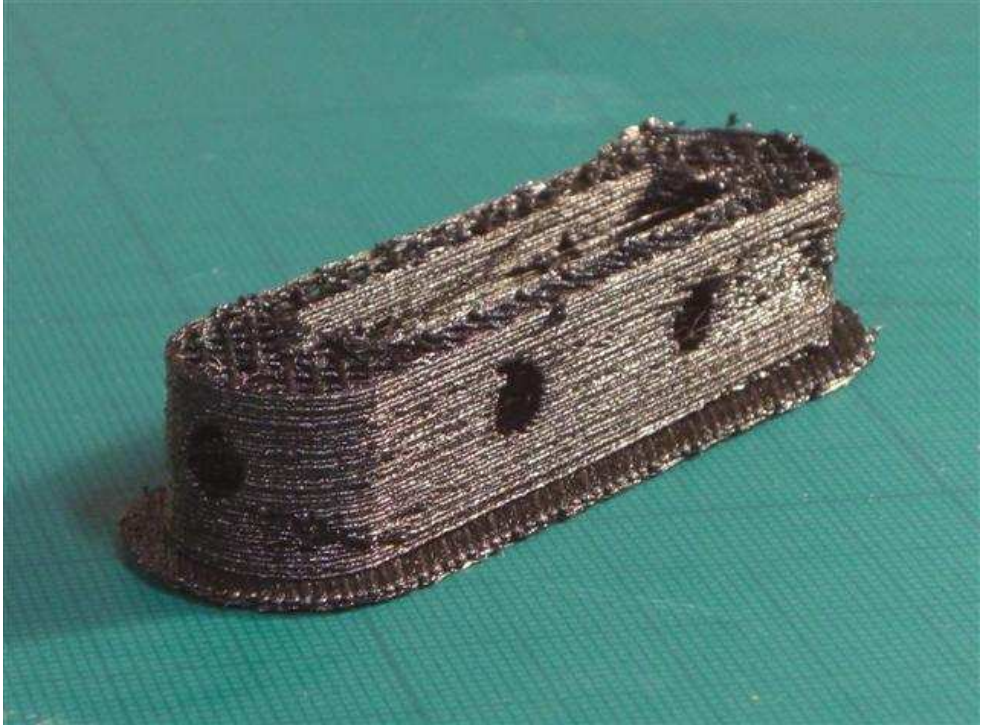
8.1 Illustrations of print quality at the time of writing
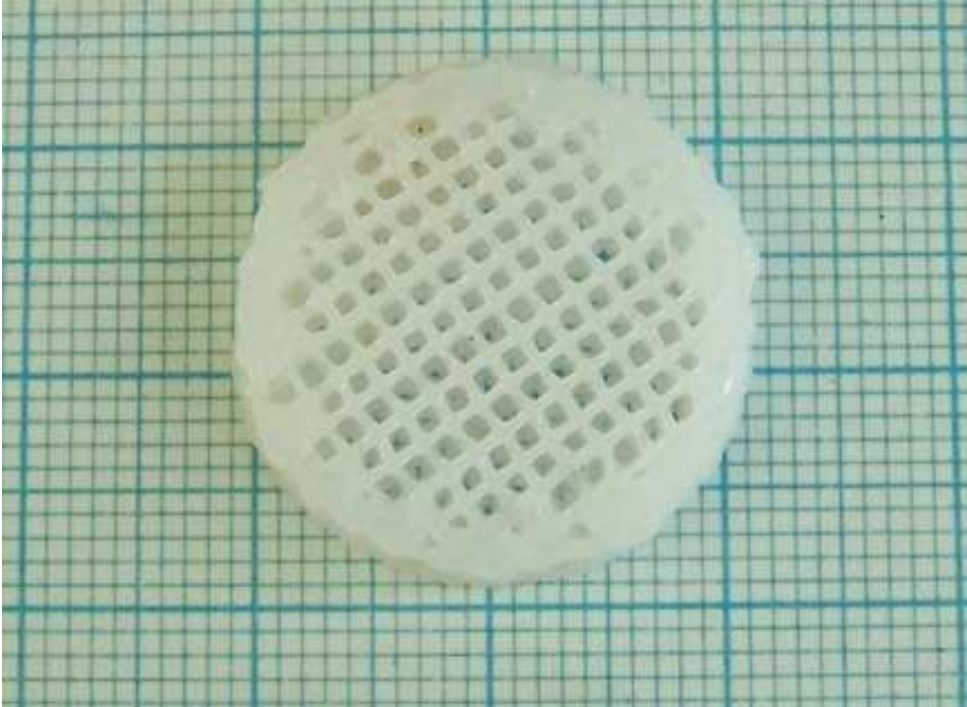
Model Description	Printer and Material	Photograph (small squares on the base represent 1 mm^2)	Notes
The corner bracket for the Darwin design (see Section 13.10.2, page 261).	Author, ABS		The corner bracket is one of the most intricate parts in the Darwin design with twelve captive nut cavities, eight horizontal through holes and five vertical through holes. This was a good test of the FFF technology.

Model Description	Printer and Material	Photograph (small squares on the base represent 1 mm^2)	Notes
Part of the thermoplast extruder housing used in the Darwin design (see Section 6.6.1.6, page 89).	Author, ABS		Smaller holes which needed to be cleaned up with a drill. The part was printed on a raft which prevented warping as the lower layers cooled. The raft was then peeled off when the build was finished.
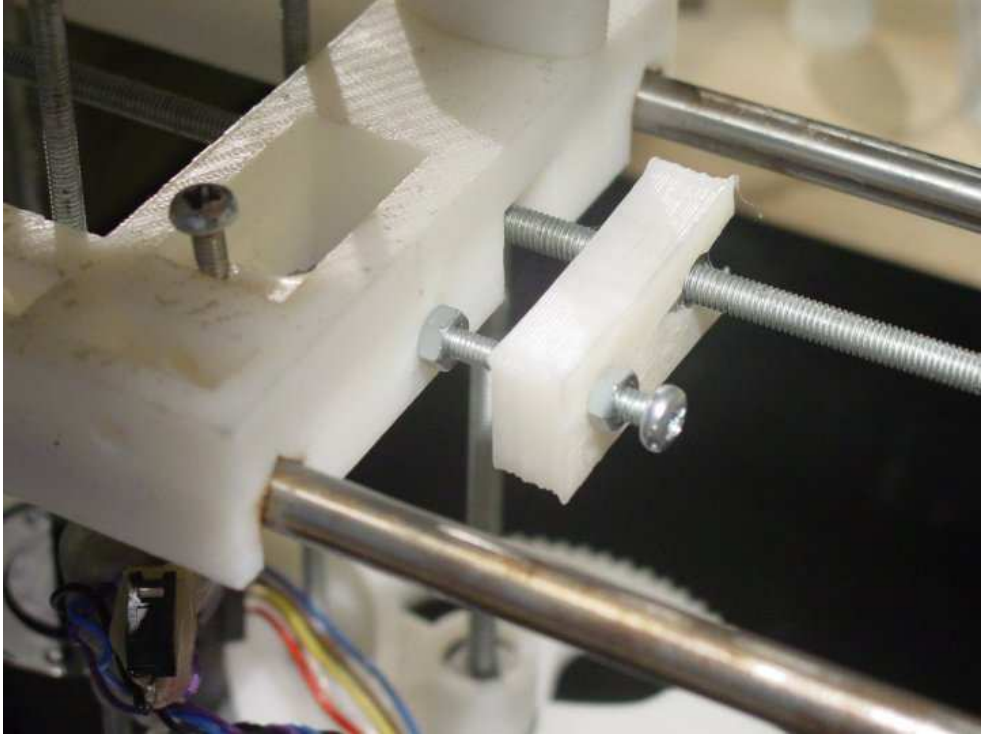
Model Description	Printer and Material	Photograph (small squares on the base represent 1 mm^2)	Notes
The optoswitch bracket for the Darwin design (see Section 13.10.2, page 261).	Author, ABS		-
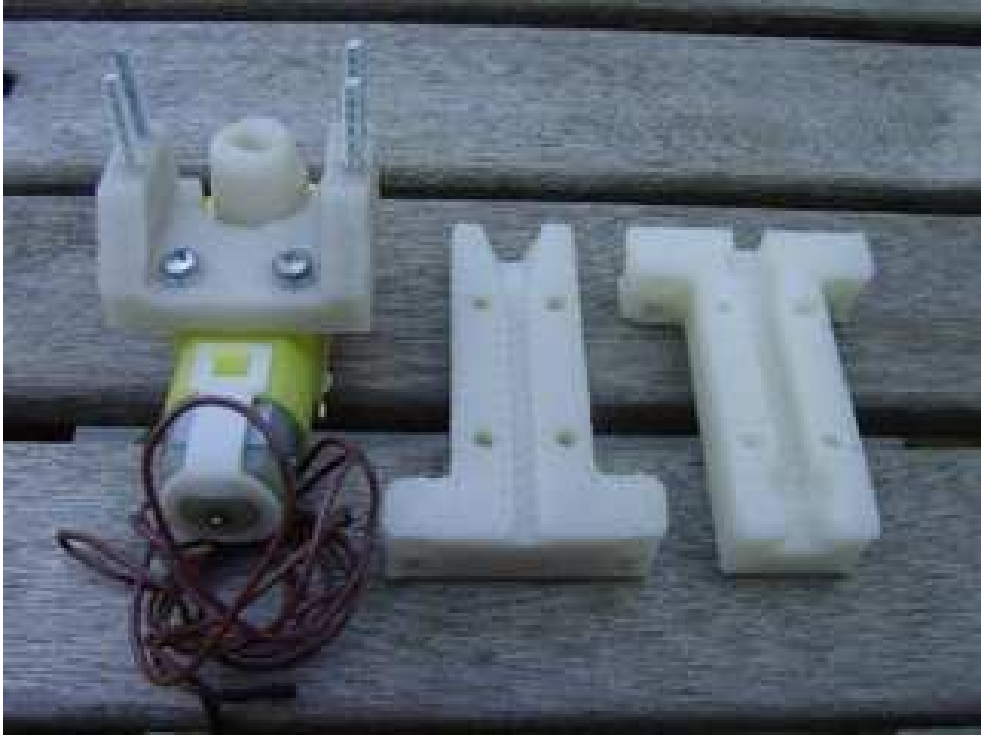
Model Description	Printer and Material	Photograph (small squares on the base represent 1 mm^2)	Notes
Coat-hook.	Author, ABS		-

Model Description	Printer and Material	Photograph (small squares on the base represent 1 mm^2)	Notes
Studding tie bracket for the Darwin design (see Section 13.10.2, page 261).	Author, ABS		Poor surface finish at the top of this part is the result of the printer running out of feedstock near the end of the build. This model has been included, however, to illustrate the sparse infill used within the component.
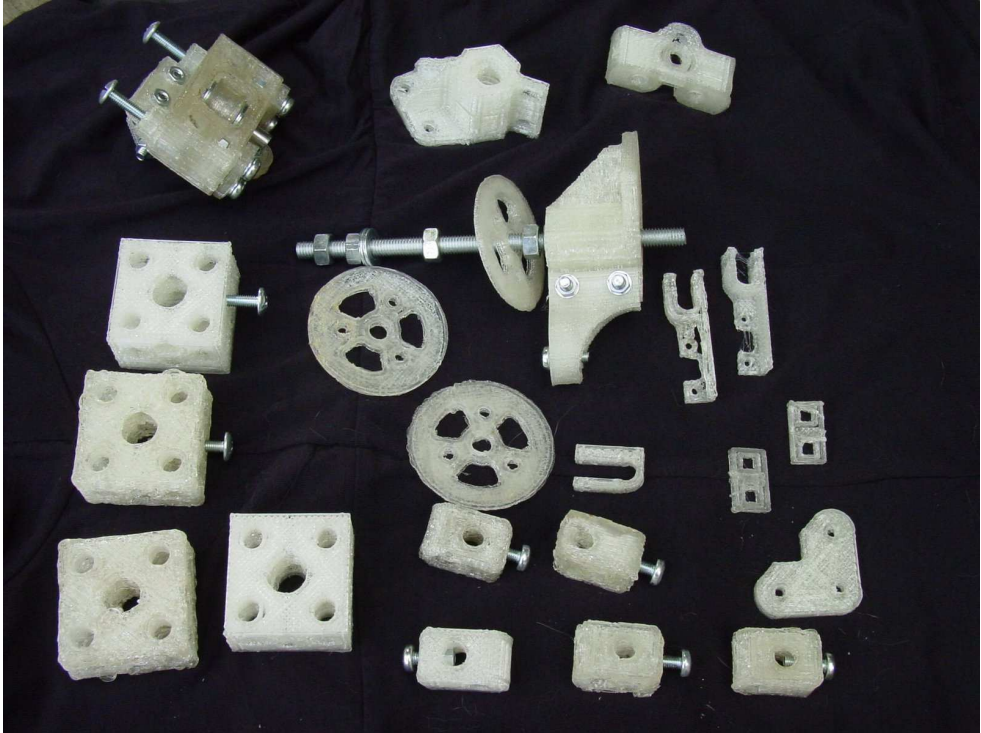
Model Description	Printer and Material	Photograph (small squares on the base represent 1 mm^2)	Notes
Water filter.	Bowyer, PCL		-

Model Description	Printer and Material	Photograph (small squares on the base represent 1 mm^2)	Notes
Pair of sandals.	Bowyer, PCL		The use of PCL here illustrates how flexible products can be printed.

Model Description	Printer and Material	Photograph (small squares on the base represent 1 mm^2)	Notes
Nut constraint bracket (shown in the right of the photograph). This is the first part made by the FFF machine, for the FFF machine.	Oliver, PCL		-

Model Description	Printer and Material	Photograph (small squares on the base represent 1 mm^2)	Notes
A full set of parts for the thermoplast extruder used in the Darwin design (see Section 6.6.1.6, page 89).	Olliver, PCL		-

Model Description	Printer and Material	Photograph (small squares on the base represent 1 mm^2)	Notes
Glass	Olliver, PLA		The use of PLA here is interesting because it is a polymer which has the potential to be made locally from starch.

Model Description	Printer and Material	Photograph (small squares on the base represent 1 mm^2)	Notes
A collection of some of the parts need to create a self-manufactured copy of the Darwin design	Olliver, PLA		These are some of the parts which were used to achieve self-manufacture (documented in the next section).

8.2   Assisted replication through self-manufacture

Thanks to the open source nature of the project, Olliver in New Zealand was able to demonstrate assisted self-replication for the author's mechanical design of the RepRap printer. Figure 76 is a photograph of the fully functional child printer. Its printed parts were all printed in Polylactic acid (PLA) and were made using Darwin as the parent. The child machine then went on to make its first successful grand-child part at 14:00 UTC on 29 May 2008 at Bath University in the UK.
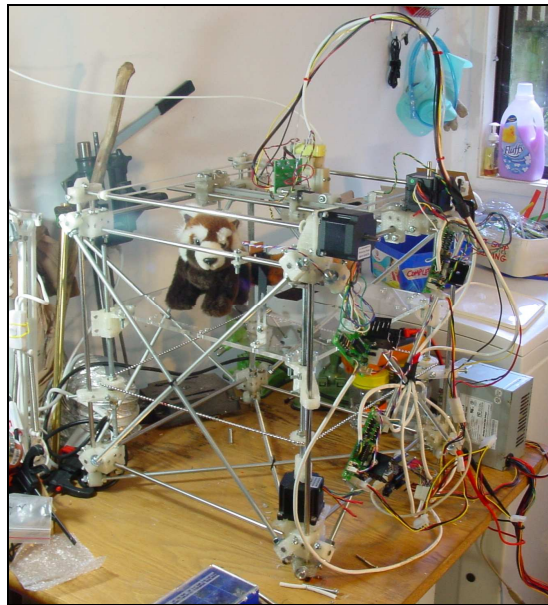
Figure 76: The child machine, made to the author's mechanical design from the parent RepRap printer: Darwin.
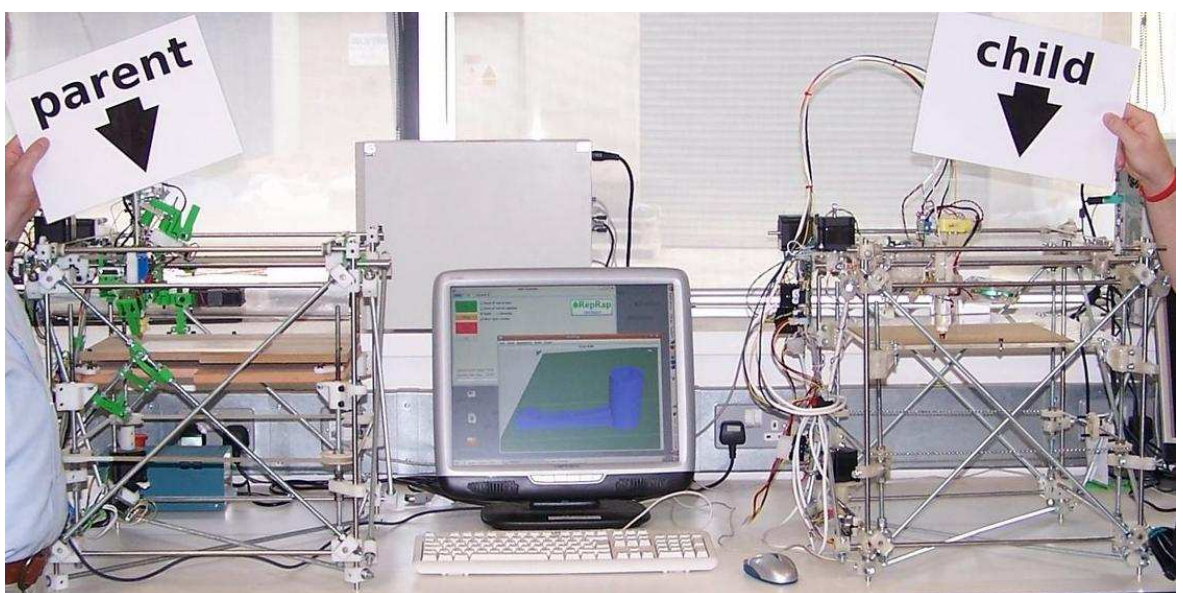
Figure 77: Child machine with parent machine.

A bill of materials for Darwin's design is included in the Appendix, Section 13.6 (page 196), and all self-manufactured parts are identified and illustrated in Section 13.10 (page 235).

8.3   Replication time and cost

Darwin took approximately 100 hours to manufacture its own printed parts. It then took approximately 20 hours for Olliver to assemble. The total cost was approximately £300.

8.4   Replication percentage

Figure 78 and Figure 79 illustrate a part count analysis for Darwin's assembly, including one extruder. The raw data for this analysis has been included in the Appendix, Section 13.6 (page 196). The analysis considers each electronic subassembly (*e.g.* PCB, motor *etc.*) as one electronic part. Figure 79 excludes fasteners to examine the proportion of parts from the other categories. These results are discussed further in the next chapter.
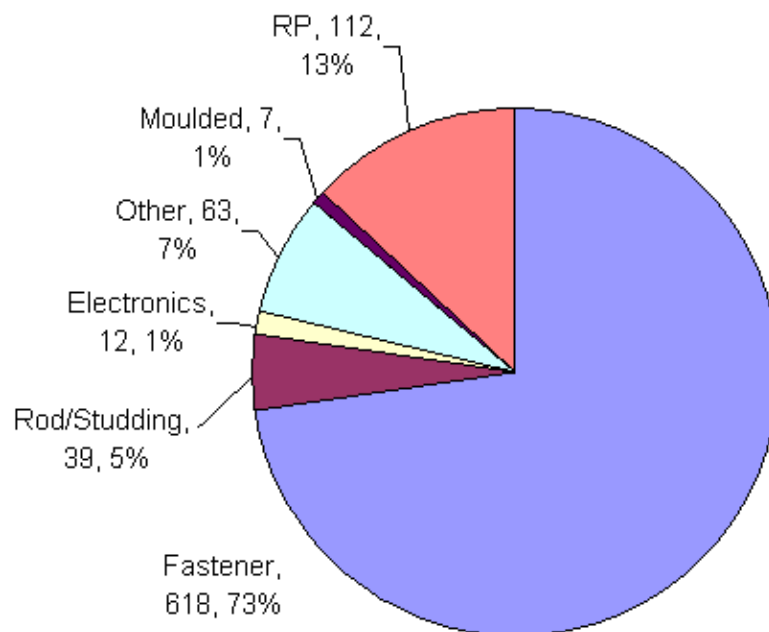
Figure 78: Part count, by type, for Darwin including one extruder.
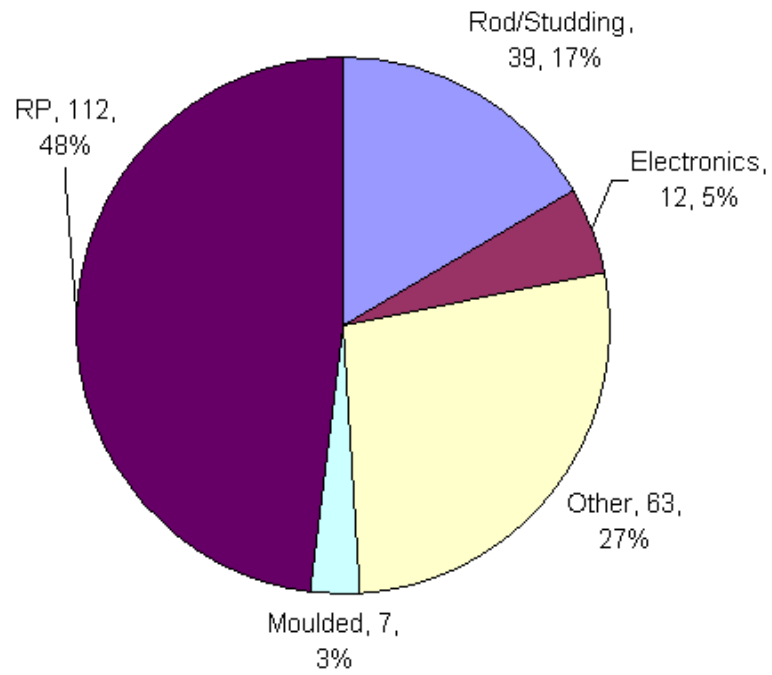
Figure 79: Part count, by type, for Darwin including one extruder. Excludes all fasteners.

9   DISCUSSION

To summarise, Chapter 1 introduced the topic of self-replicating machines by suggesting definitions and reviewing prior art. It was suggested that a recent technology, Rapid Prototyping (RP), might be versatile enough to achieve the self-manufacturing element for an organismic self-replicating machine. RP technology was examined further in Chapter 2, and the FFF process was justified as the most suitable variant. Chapter 3 detailed the RepRap project which is focussed on the production of an assisted self-*rep*licating *rap*id-prototyper (the RepRap printer). The idea behind this printer is that it should manufacture its own parts using the FFF process. Chapter 4 summarised the aims and objectives of the author's PhD which centred on the mechanical design of the RepRap printer. Chapters 5, 6 and 7 summarised the mechanical research and development towards the first version of this self-manufacturing machine (referred to as 'Darwin'). Darwin then went on to achieve assisted self-replication, shown in Chapter 8.

9.1   Review of progress with respect to objectives and aims

9.1.1   Progress with respect to objectives

In conjunction with other work from the RepRap team, the author attempted to achieve three objectives (Section 4.3, page 55). For convenience these are repeated below:

1. Manufacture an RP machine designed in such a way that it is capable of making most* of the parts needed for a copy of itself using FFF technology.

2. Repeatable performance of the machine within the specifications required to manufacture a copy of most* of its own parts.

3. Physical self-replication of most* of the machine's parts to create a copy of itself. Assembly of the copy was to be done by hand.

* (excluding the imported parts list mentioned in Section 3.1, page 43).

This thesis has documented the successful achievement of all three objectives, contributing to a RepRap printer which is capable of self-manufacture. The extent of this self-manufacturing capability is the subject of Section 9.2 in this discussion (page 142).

9.1.2   Progress with respect to aims

9.1.2.1   Completion of short term aims

As stated in Chapter 4, the aim of the author's work was to make RP technology accessible to the public by designing an RP machine which can self-manufacture. This would qualify the machine as an assisted self-replicating machine, and, as with natural self-reproducing organisms, the machine could benefit from geometric growth and evolution (discussed further in Sections 3.6.2 and 3.6.4, pages 49 and 51 respectively). These characteristics could reduce costs, improve performance and make RP technology accessible to a broad range of the domestic market.

With respect to making RP technology accessible, the development phase of the printer alone has already enabled the public to manufacture their own FFF RP machines for free, enabling growth at the 'parent' level. At the time of writing the author estimates there to be over 1000 Darwin machines of his design in circulation around the world, and this number continues to grow. This is largely due to a company which is now selling kits based on the machine's original design and support from the RepRap Research Foundation.

The total process of making Darwin available (including documentation of progress on a blog, support for downloads through SourceForge, maintenance of documentation on a wiki *etc.*) has proven how an open-source structure can foster printer evolutions through the general public. For example, Oliver has redesigned the Z axis transmission to use a ball chain. This is cheaper and allows the toothed pulleys to be self-manufactured (Figure 80). Also, Adkins has redesigned the 'printed parts' for Darwin (which were initially designed for the FFF process to prove that the process was capable of building mechanically robust components) so that they could be made from acrylic on a laser cutter (Figure 81), further reducing the cost of the parent design. These parts can also, of course, be made on a RepRap printer. These are just two examples. The project's blog is replete with descriptions of evolution-steps which have strengthened the design of the RepRap printer in all areas.

Figure 80: Evolution of Z axis transmission - the toothed belt has been replaced by a cheaper bath-plug ball chain.

Figure 81: Evolution of Darwin's 'printed parts' design to enable them to be laser cut for a cheaper assembly.

Geometric growth through replication has yet to happen because replication was only achieved just prior to the time of writing. Therefore, the extents to which this, and evolution through replication, occur have yet to be observed. However, this thesis has documented the successful development of the mechanical foundations from which geometric growth may now occur.

Sections 6.6.3.1 and 6.6.3.2 (page 99) document how Darwin was designed to facilitate both evolution and growth. With respect to replication time and cost, which largely determines public accessibility, Section 8.3 (page 137) has stated that the replication cycle takes a week and carries a mechanical material cost of approximately £300. The author considers this to be encouraging for the first replication and expects both replication time and cost to improve with development.

9.1.2.2   *Completion of long term aims*

Longer term aims included contributions to further the knowledge of RP, self-manufacture and self-replication. With respect to RP, enabling people to experiment with the FFF process has attracted some dramatic contributions from the public. Of particular note is Palmer's recent idea that a support material head is not necessarily critical to print horizontal overhangs, shown here in Figure 82. Again, the project's blog documents more ideas which challenge the traditional pre-conceptions of the FFF process.
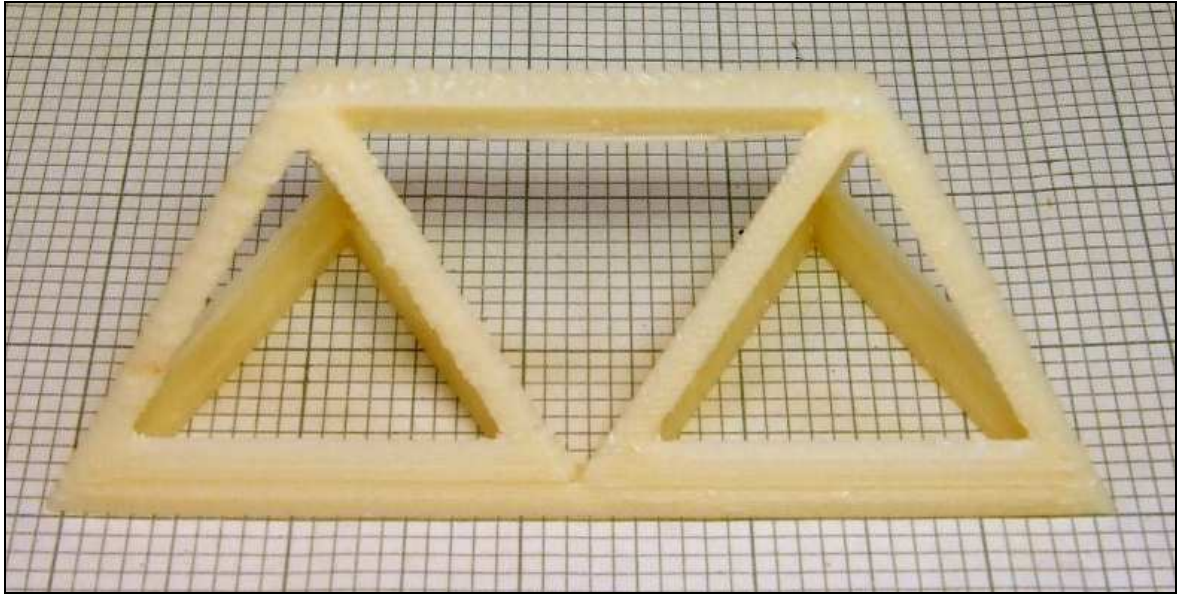
Figure 82: Truss printed in ABS by Palmer using the FFF process, without any support material. The segments for this spar were extruded at a speed which allowed the filament to freeze whilst the extruder nozzle maintained enough tension to keep the segment horizontal.

With respect to furthering the knowledge in the field of self-manufacture Section 6.6.2 (page 91) has documented many mechanical considerations for designing a self-manufacturing machine using FFF technology. Some of these design principles may be applied to other self-manufacturing technologies should they arise, particularly design for adjustability, design for modular components to exceed the bounds of working volumes and design for the maintenance of high wearing parts.

Knowledge of mechanical self-replication will be proportional to the growth of the machine through its generations, which remains to be seen. However, Section 6.6.3 (page 99), has documented design principles to cater for the evolutionary and growth characteristics expected to come with assisted self-replication. It is also hoped that the terms defined in Section 1.1 (page 4) will serve to promote discussion of the field of SRMs.

9.2   Proof of hypothesis

As stated in Chapter 4, this PhD, in conjunction with the RepRap project, tested the following hypothesis:

The Fused Filament Fabrication process is sufficiently versatile to make a self-manufacturing Rapid Prototyping machine [59].

'Versatility' in this context is equivalent to the proportion of parts which the process can replicate to make a copy of its mechanical infrastructure. There are a few metrics available to us for measuring this proportion: part count, part mass and part volume. Of these three, the author considers part count to be the most suitable metric because it represents the distinct design elements of the machine.

9.2.1   Limitations of a part count analysis for the RepRap printer

Whilst considered to be the most suitable metric to assess the RepRap printer's self-manufactured part ratio, it is necessary to understand the limitations of a part count analysis and how these limitations were taken into account.

As stated in Section 1.1.3 (page 4) a 'part' refers to a physical entity of specific geometry which performs a specific function in an assembly. This definition is appropriate for most mechanical elements in a part count analysis, but it is problematic when representing electronic subassemblies made up of many smaller components. Electronic subassemblies are therefore treated as single components: for example, a complete PCB is considered to be one part.

A part count analysis can also be misleading when including fasteners: there are at least two fasteners required for each mechanical interface, and each fastener is usually made up of four parts (one nut, one bolt and two washers). This totals a minimum of eight fastener parts per interface. The author therefore considers it fair to view results from the study both with and without fasteners. This is especially useful when viewing the part count of the RepRap printer as a product rather than a prototype: most of the nuts and bolts in the design are merely to facilitate research - if the design was made towards a product, most of these fasteners could simply be replaced by adhesive. This is discussed further in Section 9.3.3, page 165.

9.2.2   Part count analysis for the self-replicated child machine

Raw data from Darwin's part count analysis has been included in the Appendix (Section 13.6, page 196) and the results are summarised in Section 8.3 (page 137). As expected, the fastener count dominates the analysis – it indicates that Darwin is 73% fasteners and can only make 13% of its own parts! It is encouraging to note, however, that if all the fasteners were to be replaced by adhesive, the total number of self-manufactured parts would constitute 48% of the design.

It is the author's opinion that this ratio belies the RepRap printer's true potential for self-manufacture because the project is in the research phase, adopting modularity and redundancy principles to encourage development. The remainder of this section will attempt to show that if the machine's design were adapted to fully demonstrate self-manufacture, a much higher ratio may be achieved.

9.2.3   RepRap research activity

In the following sections the author projects Darwin's development in the future. It is, therefore, important to note the level of research activity on the printer at the time of writing.

Since the RepRap project became accessible on the internet in March 2005, activity has steadily grown. At the time of writing (5th January 2009) Alexa.com[13] estimated the main web page for the RepRap project (www.reprap.org) to have a traffic rank of 191,052, and the project forums (conceived in January 2007) had attracted 19,640 posts.

Perhaps the best indicator of research efforts towards the printer is the progress of the RepRap Research Foundation (RRRF). The RRRF is a foundation "to promote research in self-replicating manufacturing systems and to distribute the results of that research freely to everybody using open-source licensing" [64]. Director and Treasurer of the RRRF, Zach Smith, reported the RRRF's total revenue (in US dollars) over 2008 in Figure 83, below.

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[13] Alexa ranks sites based on visits from users of its associated toolbars in internet browsing programs (from integrated sidebars in Mozilla and Netscape, and the Alexa toolbar in Microsoft's Internet Explorer). Whilst there is some controversy over unknown sample sizes and sampling biases, Alexa does acknowledge these weaknesses and has attempted to improve reliability by taking into account more data sources in their most recent ranking system.
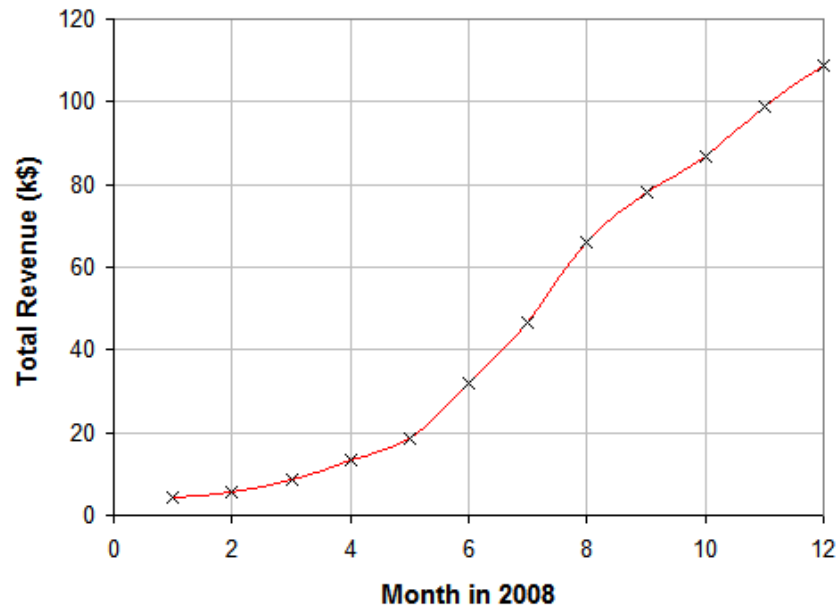
Figure 83: Total revenue received by the RRRF over 2008. Data supplied by Smith, Director and Treasurer of the RRRF.

Figure 83 illustrates the RRRF's growth. Smith also noted that periods of growth were spurred by the project's achievement of milestones. For example, in 2008 an increase in monthly revenue can be observed from the fifth month onwards – this coincides with the announcement of successful self-replication (documented in Section 8.2, page 136).

Six months prior to the time of writing (*i.e.* from June 2008), the average revenue per month was $15,000. The trend illustrated in Figure 83 indicates a strong and consistent level of research activity on the printer over the last six months, from contributors worldwide. The author can see no reason why this activity should not continue, on the provision that project milestones are consistently met. The reader should bear this in mind when considering the justifications of timescales for future developments made in the following sections.

9.2.4 Future development towards pure self-manufacture

The following table assesses the future of the parts which Darwin could not make for itself (including the extruder design) forming part of an analysis which projects Darwin's self-manufacturing capability in the future. The final column in the table refers to the estimated term of future (near, mid or far) in which the parts might be eliminated from RepRap's imported parts list. These estimations are justified in Table 13 and Table 14 in the following sections. Estimations rely on future developments of the FFF process, which are

documented in Section 9.3, and the level of research activity mentioned in the previous section.

Table 12: Estimated future for the non-printed parts imported into Darwin's design. The final column refers to the estimated term of future in which the parts might be eliminated from RepRap's imported parts list. These estimations are justified in Table 13 and Table 14 in the following sections.

Non-printed part imported into Darwin's design	Location	Reason why the FFF process could not manufacture the part	Possible solutions	Estimated term of future to develop (see caption)
Springs	Z-bed and extruder	The eight springs in Darwin's design have only been used out of convenience for research.	Sprung parts can already be printed, detailed in Section 9.3.1 (page 161).	Near
Foil	Optoswitch flags	Foil is only included out of convenience - it is dense enough to trigger the optoswitches.	Foil can be replaced by another dense resource, or an infra-red-opaque polymer could be used.	Near
Adhesive	Optoswitch flags	Adhesive was only used to glue the foil to the optoswitch flags out of convenience.	The flag can be redesigned to use an alternative fastening technique.	Near
Cable ties	Global	Cable ties are simply convenient to gather the cable. None of them perform any structural functions.	Clips can be printed.	Near
MDF bed	Z-bed	The FFF process is capable of printing its own bed.	The Mk 1 and Mk 2 designs demonstrate a printed Z-bed (Figure 29, page 76, illustrates this).	Near

Non-printed part imported into Darwin's design	Location	Reason why the FFF process could not manufacture the part	Possible solutions	Estimated term of future to develop (see caption)
Toothed pulleys	X, Y & Z axis	The required print resolution for toothed pulleys lies just outside the specification of the RepRap printer.	Improving build quality may enable self-manufacture of toothed pulleys. Section 9.3.5 (page 166) details continuing development on build quality. The Stratasys Dimension (FDM RP machine) is already capable of printing toothed pulleys, as illustrated in Figure 38 (page 83).	Near
Bearings in gearbox	Extruder	Gearbox bearings were imported out of convenience.	Use of polymer bearings has already been demonstrated elsewhere in the design: both in the extruder and in all printer axes.	Near
Gearbox gears	Extruder	See 'Toothed pulleys'.	-	Near
Hawser (steel twisted cable)	Extruder	The FFF process cannot print steel twisted cable.	This element is non-critical to the concept of a screw driven extruder and can be designed out.	Near
Solder	Extruder	An alloy deposition print head is yet to be developed and fully automated.	This is necessary for the assembly of the hawser, and therefore is also not strictly critical for the concept of a screw driven extruder.	Near

Non-printed part imported into Darwin's design	Location	Reason why the FFF process could not manufacture the part	Possible solutions	Estimated term of future to develop (see caption)
Fan	Extruder	An off the shelf fan unit was imported out of convenience.	Fan fins would be simple to print. For the motor, however, see 'Stepper motors'.	Near
Fasteners: bolts, washers, nuts, grub screws	Global	Section 9.3.3, page 165 details how most fasteners have only been included in Darwin's design for the convenience of research. Some fasteners, however, are critical. Fasteners cannot be made immediately because they need to be accurate and need high strength.	A redesign towards a product would reduce the number of fasteners needed. Improving build quality and use of a resin print head (Section 9.3.4, page 165) will enable self-manufacture of fasteners, and their elimination in most cases. Section 9.3.5 (page 166) details continuing development on build quality. Alternatively, much of the design could simply be glued together, assuming the design didn't need to be repaired or modified.	Near and mid
Transmission belt	X, Y & Z axis	A flexible polymer deposition print head is yet to be developed and fully automated.	It conceivable that, printing with a flexible substrate, the machine might be able to print its own V-belt. Section 9.3.4 (page 165) details the future use of different print heads.	Mid

Non-printed part imported into Darwin's design	Location	Reason why the FFF process could not manufacture the part	Possible solutions	Estimated term of future to develop (see caption)
PCBs	Global	An alloy deposition print head is yet to be developed and fully automated.	Circuit inclusion techniques are available if an alloy print head were developed. Section 9.3.2 (page 162) details circuit inclusion techniques.	Mid
Grease	Z axis and extruder	The FFF process cannot manufacture grease.	Lubricant could be eliminated from the design if the bearing properties had a low enough friction to eliminate jamming and significant wear. This could be achieved with resin bearings. Section 9.3.4 (page 165) details the future use of different print heads.	Mid
Bar	Global	Bars are essential for linear bearing surfaces, but only convenient for the chassis design. The FFF process cannot currently manufacture to such tight bearing tolerances.	Improving build quality may enable self-manufacture of linear bearing surfaces. Section 9.3.5 (page 166) details continuing development on build quality. Alternatively, the design could be altered to use linkages to eliminate sliding bearings. An example of how this could be implemented for the Z-axis is illustrated in the Appendix (Section 13.11, page 277).	Mid

Non-printed part imported into Darwin's design	Location	Reason why the FFF process could not manufacture the part	Possible solutions	Estimated term of future to develop (see caption)
Studding	Global	Essential for transmission, but only convenient for the chassis design. The FFF process lacks a print head which can manufacture anything hard enough to replace a length of studding.	If a resin print head were developed, hardness properties could be achieved. Section 9.3.4 (page 165) details the future use of different print heads.	Mid
Brass Heating barrel	Extruder	The brass heating barrel is needed for its thermal properties. A resin deposition print head is yet to be developed and fully automated.	If a resin print head were developed, insulation properties could be achieved. Section 9.3.4 (page 165) details the future use of different print heads.	Mid
PTFE barrel	Extruder	PTFE is needed for its thermal properties. A resin deposition print head is yet to be developed and fully automated.	If a resin print head were developed, insulation properties could be achieved. Section 9.3.4 (page 165) details the future use of different print heads.	Mid
Brass nozzle	Extruder	The brass nozzle is needed for its thermal properties. A resin deposition print head is yet to be developed and fully automated. This also carries the problem of making a small extrusion hole.	If a resin print head were developed, insulation properties could be achieved. Section 9.3.4 (page 165) details the future use of different print heads.	Mid

Non-printed part imported into Darwin's design	Location	Reason why the FFF process could not manufacture the part	Possible solutions	Estimated term of future to develop (see caption)
Capacitors, resistors, LEDs, optoswitches, heat-sinks, chips, voltage regulator, and oscillators.	Global	Printing electronic components is an advanced technology which has not yet been adapted for the FFF process.	Section 9.3.2 (page 162) offers some suggestions towards the manufacture of these components.	Far
Stepper motors	X, Y & Z axis	The FFF process is currently unable to manufacture the wiring and magnetic resources required to build a motor.	If efficient cabling can be achieved (perhaps using a conductive polymer, as mentioned in the circuit inclusion techniques in Section 9.3.2, page 162) only magnets and a core would be needed.	Far
Cable (power and communications)	Global	The FFF process is currently unable to print cables.	Section 9.3.2 (page 162) details circuit inclusion techniques. This suggests how the FFF process may be able to print conductive, flexible cable with conductive polymer.	Far
Servo motor	Extruder	See 'Stepper motors'.	-	Far

Non-printed part imported into Darwin's design	Location	Reason why the FFF process could not manufacture the part	Possible solutions	Estimated term of future to develop (see caption)
Solenoid	Extruder	See 'Stepper motors'.	The solenoid currently acts as the actuator for the valve. If the need for a valve is eliminated by optimising the parameters (and perhaps by reversing the extruder motor) the solenoid may be eliminated from the design. It should be noted that the printing results in Section 8.1 (page125) were done without a valve (*i.e.* solenoid was not used).	Far
Nichrome heating wire	Extruder	The FFF process is currently unable to manufacture a heating element.	Unknown.	Far

9.2.5   Projected part count analysis for Darwin in the near-future

As mentioned previously, the existing Darwin design caters for the research stage of the development. The modular design and deliberate redundancy serve evolution rather than a specific demonstration of self-manufacture. However, if some of the simpler mechanical changes identified in Table 12 were made to the design, Darwin would quickly be able to demonstrate a much better self-manufacturing ratio using the current state of FFF technology. Table 13, below, summarises these immediate developments and justifies the timescales.

Table 13: Summary of potential developments to Darwin which can be effected in the near-future, and justification of individual timescales.

Proposed development	Estimated time to effect, including contingency	Justification of time to effect
Use of the existing FFF process to manufacture springs, cable clips, bed and fan fins.	1 month	Requires design, manufacture and testing of said parts. Typical turnaround for small parts is one or two days, however, the build of the bed may take a few days as it is a large sub-assembly.
Minor improvement to the FFF process parameters for the manufacture of toothed pulleys and bearings (discussed further in Section 9.3.5, page 166).	6 months	Figure 94 (page 167) illustrates a significant improvement in printing to a quality capable of printing gears over a period of approximately six months using RepRap machines. The author grants another six months of development in extruder reliability and software development before this performance becomes common place.
Use of a dense resource (*e.g.* washers) to replace the foil optoswitch flags.	1 week	Replacement of this part can be immediate.
Redesign of the extruder to eliminate the flexible drive.	0 weeks	At the time of writing, Bowyer has designed and successfully implemented an extruder with direct drive.
Elimination of general mechanical redundancy and modularity, hence elimination of fasteners and design for adhesive interfaces (a chassis redesign to reduce the machine's structural requirements and associated fasteners is proposed in Section 9.3.7, page 167).	6 months	The author took approximately two months to design the final version of Darwin, and another two months to test it. An extra two months contingency should secure a working re-design.

The author expects these changes to take approximately one year, on the condition that the current level of research activity detailed previously in Section 9.2.3 (page 144) is focussed towards these changes. Figure 84 is a summary of Darwin's parts ratios after these changes have been effected (the raw data for this part count analysis has been included in the Appendix, Section 13.6, page 196).
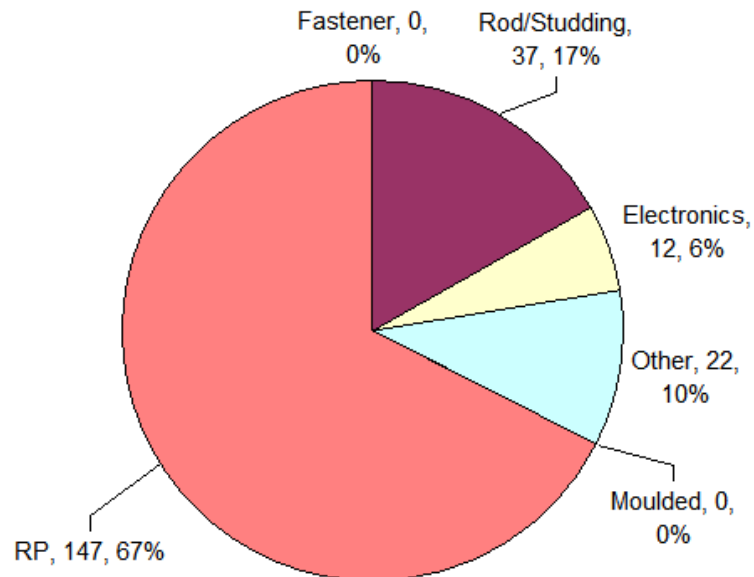
Figure 84: An estimation of the parts ratio after near-future mechanical development towards pure self-manufacture, using adhesive to replace fasteners.

After these developments the part count estimates Darwin's self-manufacturing ratio to be 67%. The most significant of these changes would be an adaptation of the design towards a product by replacing fasteners with adhesive.

9.2.6   Projected part count analysis for Darwin in the mid-future

Beyond adaptations of the design, the FFF process needs to print in different materials. This would enable Darwin to manufacture many more of its own parts. Table 14, below, summarises the developments suggested in Table 12 for the mid-future, and justifies individual timescales.

Table 14: Summary of potential developments to Darwin which can be effected in the mid-future, and justification of individual timescales.

Proposed development	Estimated time to effect	Justification of time to effect
Use of a resin print head (for bearing surfaces, studding, threaded elements, bar and high temperature elements) as described in Section 9.3.4, page 165.	24 months	Note 1: A design for a resin extruder toolhead has already been implemented by the Fab@home project (described in Section 9.3.4, page 165). Note 2: The author has designed two syringe extruders which can be used for resin in the RepRap project. These designs have been included in the Appendix (Section 13.12, page 278). Note 3 – General: Extruder head development time varies. It took the author three months to implement the first simple version of the alloy print head (detailed further in Section 9.3.2, page 162), yet the concept for a successful granule extruder has proven problematic for over 12 months (though Bowyer is now in the final stages). Speed of extruder development heavily depends on the materials used and the feed mechanisms implemented. Reliability is essential for all toolheads - it is therefore wise to allow a generous 24 months development to secure an extruder with repeatable performance.
Use of a flexible polymer print head (for transmission belts).	24 months	See 'Note 2' above: syringe extruders can also be used for flexible polymer pastes. Also, see 'Note 3 - General' above.
Use of an alloy print head (for PCBs, as described in Section 9.3.2, page 162)	24 months	See 'Note 3 - General' above. The alloy print head mentioned uses hot air as a heating mechanism. This needs to be developed to use more compact direct heating method (detailed further in Section 9.3.2, page 162).

The author expects the development of these print heads (detailed in Section 9.3.4, page 165) to take approximately two years, on the condition that the current level of research activity detailed previously in Section 9.2.3 (page 144) is focussed towards this development.

Figure 85 is a summary of the self-manufactured parts ratio after these changes have been effected (the raw data for this part count analysis has been included in the Appendix, Section 13.6, page 196).
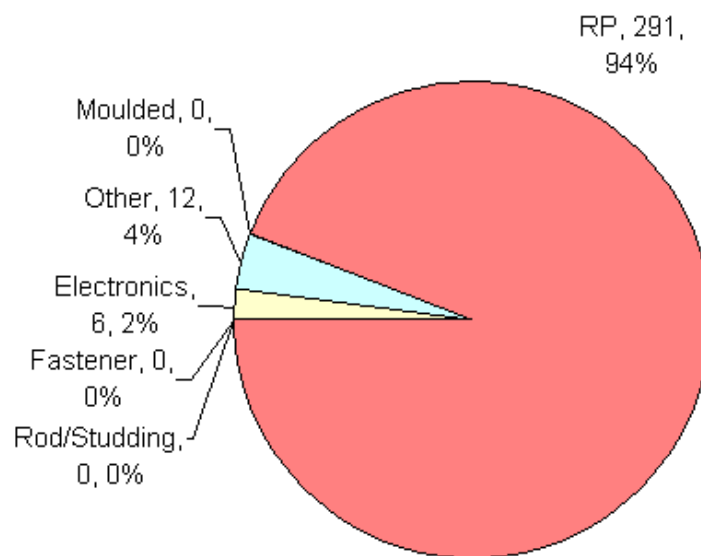
Figure 85: An estimation of the parts ratio after mid-future development towards pure self-manufacture.

The most significant of these developments would be the development of a resin head as its hard wearing, stiff, high-temperature-resistant parts would allow the manufacture of many critical mechanical components (specifically bearing surfaces, studding, threaded section, bar and extruder elements). The polymer and alloy heads would also contribute towards self-manufacture, and, whilst less significant, they would improve the RepRap printer's general production range. This study is again encouraging, indicating that the RepRap printer may be capable of making 94% of its own parts in the mid-future.

9.2.7   Remaining challenges for pure self-manufacture

Table 12 identifies some parts which will remain a challenge for the RepRap printer to self-manufacture: electronic components, motors, conductive cable, solenoids and the heating element. Whilst some suggestions for how these might be approached are given in

Section 9.3 (page 161) it is unlikely the machine will be able to self-manufacture these parts for at least a couple of years.

However, hope does lie in the potential geometric growth of the RepRap printer's population, which may succeed in attracting a significant development community with a devotion towards pure self-manufacture. It may be that in the future these parts can be eliminated from the design, or technologies can be invented to self-manufacture these final parts.

It is worth noting, however, that organisms in nature do not rely on a single basic material to manufacture all of their own components. Animals, for example, rely on 20 amino acids to make their necessary proteins. Whilst most animal species can synthesise about half of these themselves (as long as their diet includes organic nitrogen), the remainder must be obtained through their diet [1].

The author acknowledges that if organisms from the biological world (which are products of millions of years of evolution) cannot reproduce without a supply of different materials, 100% pure self-manufacture for a machine may also be impossible. Freitas and Merkle also acknowledge this as a possibility in their 'Map of the Kinematic Replicator Design Space' [2], referring to critical imported parts as "vitamins".

9.2.8   Summary

To re-iterate, the author's PhD tested the following hypothesis:

The Fused Filament Fabrication process is sufficiently versatile to make a self-manufacturing Rapid Prototyping machine [59].

The work presented in this thesis has demonstrated an RP machine sufficiently versatile to demonstrate some degree of self-manufacture. If fasteners were to be replaced with adhesive, the percentage of self-manufactured parts is currently 48%. Whilst encouraging for the first attempt, this result is considered conservative with respect to the potential of the FFF process because the current RepRap printer design is geared towards the research and development phase. If the machine design was adapted to fully demonstrate self-manufacture using the current state of the FFF process, the self-manufactured part count could increase to 67%. This demonstration is possible in the near-future.

After this, improvements to the FFF process are required. The addition of new material heads, achievable in the mid-future, should further increase the process's versatility to achieve a self-manufacturing ratio of 94%.

These developments rely on further activity from the RepRap community and it is encouraging to note that activity has been consistently strong over the past 6 months.

Beyond these developments a few parts will remain as a challenge for the FFF process to make. However, it is hoped that the potential geometric growth rate of the printer, enabled through replication, will bring more effort towards pure self-manufacture.

Whilst the author accepts that the achievement of pure self-manufacture might be an impossible ideal, he notes that any development towards this goal is still a useful contribution to the field of autotrophic SRMs. Each new development to improve the RepRap printer's self-manufacturing ratio reduces the number of necessary 'vitamins'. The smaller the vitamin count the higher the feasibility of using such a self-manufacturing system in an autotrophic SRM. And because the range of an SRM is limited by the vitamins it needs to extract from its environment, a reduction in necessary vitamins will increase the SRM's range. Any development in this area is, therefore, good news for Dyson's Astrochickens.

9.3   Future developments on the FFF process for self-manufacture

This section details the near, mid and far-future developments required to manufacture the parts which are currently imported into Darwin's design.

9.3.1   Springs

Initial tests suggest that it is already possible to make spring parts using the FFF process. This can be done by building the parts in an orientation which ensures that the stress runs along the length of the RP layers rather than over the weaker interfaces between the individual layers. Figure 86 illustrates a prototype homing switch which uses a spring section.
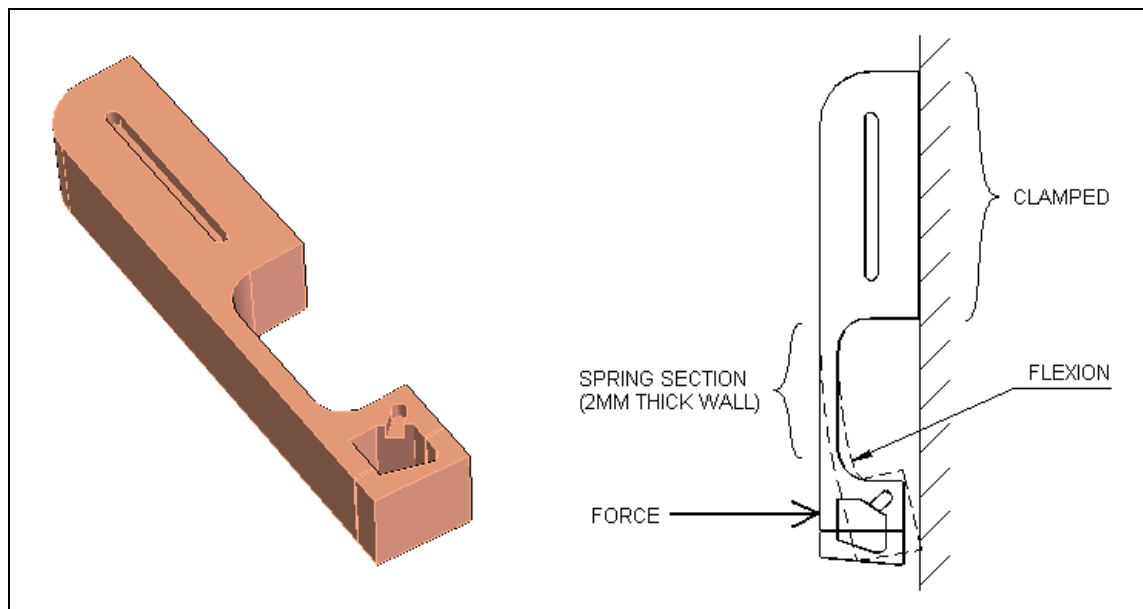
Figure 86: Example of an RP component using a spring section in its design

Figure 87 and Figure 88 illustrate correct and incorrect build orientations with respect to layer orientations for the above example.
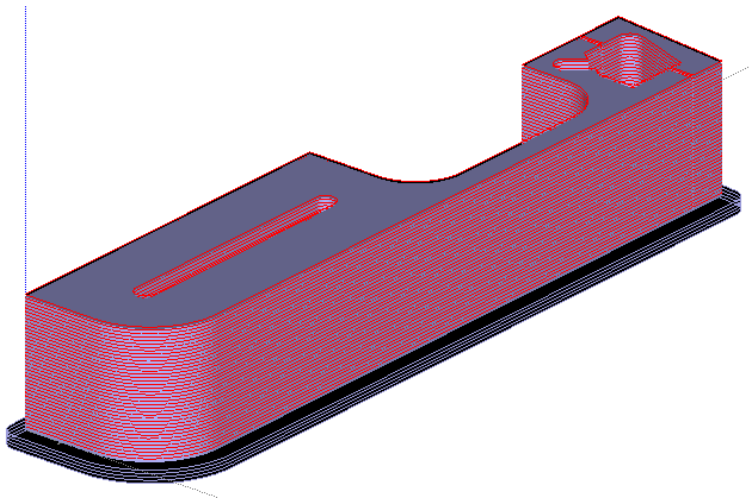
Figure 87: Correct build orientation. Layers run along the length of the sprung section. FFF components are weakest in the planes where layers are bound together (the interfaces) – this lay-up ensures that the stress is distributed along the layers and not the segment weld surfaces.
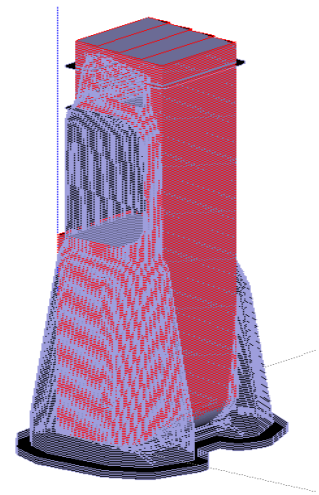
Figure 88: Incorrect build orientation (ignore support material). Layers cut across the sprung section.

9.3.2   Circuit inclusion

For the RepRap printer to print electromechanical components it must rely on the field of research which concerns itself with printing electronic circuits (into RP components or otherwise).

This is not a new field. Pain documents one of the first attempts to incorporate electronic circuits into mechanical components [65]. In 1944, British engineer, John Saargrove designed an automatic radio production line which he called ECME (Electronic Circuit-Making Equipment). In a bid to manufacture radios cheaply he dispensed with most of the hand-assembled parts by inventing a primitive chip – a slab of Bakelite with all the receiver's electrical components and connections embedded in it. This was something which could be easily made and assembled by machines.

The starting point was a piece of Bakelite, moulded with a pattern of grooves and depressions on each side (Figure 89). When these were filled with molten zinc, they formed all the conductors, inductors, capacitors and resistors and so on, that the receiver needed, all connected in exactly the right way. This process was fully automated to form the ECME production line (Figure 90).

Figure 89: ECME bakelite chip

Figure 90: The ECME production line in 1947

Using a similar approach to Saargrove, the author [50] showed that the FFF process can be adapted to make electronic circuits too. A metal deposition head is needed to lay molten alloy in casting channels designed into the part. Figure 91 and Figure 92 illustrate a print head used for a low melting point alloy (Wood's metal), and the resulting circuit.
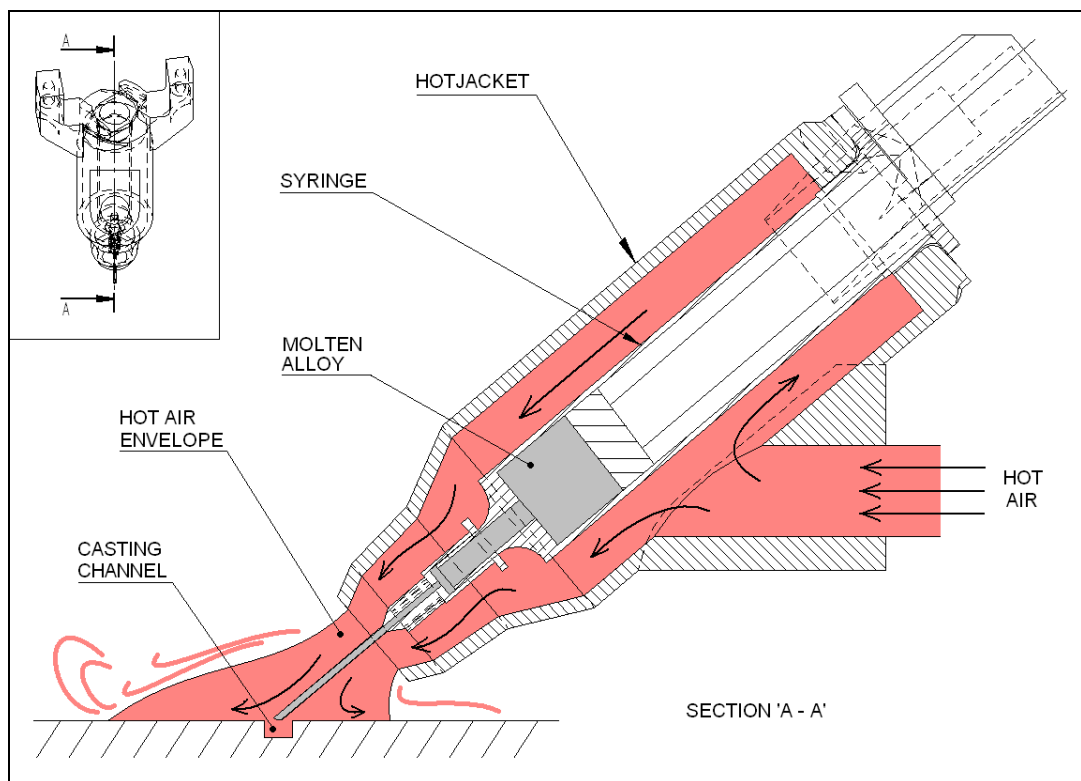
Figure 91: Alloy heating mechanism: hot air (at approximately 80 °C) was pumped into the heating jacket which in turn heated the alloy in the syringe above melting point. This enabled molten deposition. In addition the mechanism also provided a hot air envelope around the deposition area.

Figure 92: Magnification of a solidified circuit in a 2mm wide casting channel in an RP component.

This work is encouraging because it suggests that the FFF maybe able to manufacture some of its own electric components (*e.g.* circuits, resistors, capacitors *etc.*). Development to the head is required to replace the hot air heating mechanism with direct electrical heating from Nichrome wire. This principle is already used in the existing thermoplastic extruder, and Bowyer has already made a prototype for Wood's metal, the design for which has been included in the Appendix (Section 13.13, page 279).

Another encouraging factor in this area is the advent of RFID tags. Cheap, printable transistors are, at the time of writing, under development in many research groups around the world. For example Kovio (USA) in November 2007 declared that it could print low-grade transistors using high-end commercial ink jet printers [66] and in January 2008 scientists from the University of Massachusetts Lowell and Brewer Science, Inc. demonstrated carbon nanotubes as the basis for a high-speed thin-film transistors which were then printed onto sheets of flexible plastic [67]. The Organic Semiconductor Conference has been running since 2002 and on 30 September 2008 it presented for the first time an all-printed 13.56 MHz 1 bit RFID Tag. Using a gravure printer, a pad printer and an ink-jet printer the researchers were able to fabricate a complete operational 13.56MHz RFID tag including antenna, rectifier, and ring-oscillator (the author is awaiting conference proceedings). This bodes well for the future of printing circuits using the RepRap printer.

9.3.3 Elimination of interfaces

The majority of fasteners in Darwin's design are only necessary for the convenience of research. The most appropriate way to design a research technology is in modules, as noted in Section 6.6.3.1 (page 99). This means modules can be developed without affecting the rest of the design. Modular design implies the need for multiple interfaces, which, as mentioned earlier, require fasteners. However, as the design for the RepRap printer matures towards a product it will become less and less modular and the fastener count will diminish. For the interfaces which cannot be avoided, it is entirely conceivable that printed parts can be snap fitted, or glued together. Alternatively, fasteners could be made using a resin print head, discussed in the next section.

9.3.4 Addition of print heads

Darwin currently only uses one print head. A crucial advantage of the FFF process is that it lends itself towards the use of multiple print heads, which improves its versatility. Figure 16 (page 65) illustrates how the X/Y table is capable of docking different print heads, only using them when necessary. This author has suggested the development of the following print heads:

- Resin deposition, cured with UV light (Fab@home has recently achieved this [68], as shown in Figure 93)

- Flexible polymer deposition (*e.g.* silicone *i.e.* PDMS).

- Conductive deposition (*e.g.* low melting point alloy, or conductive polymer).
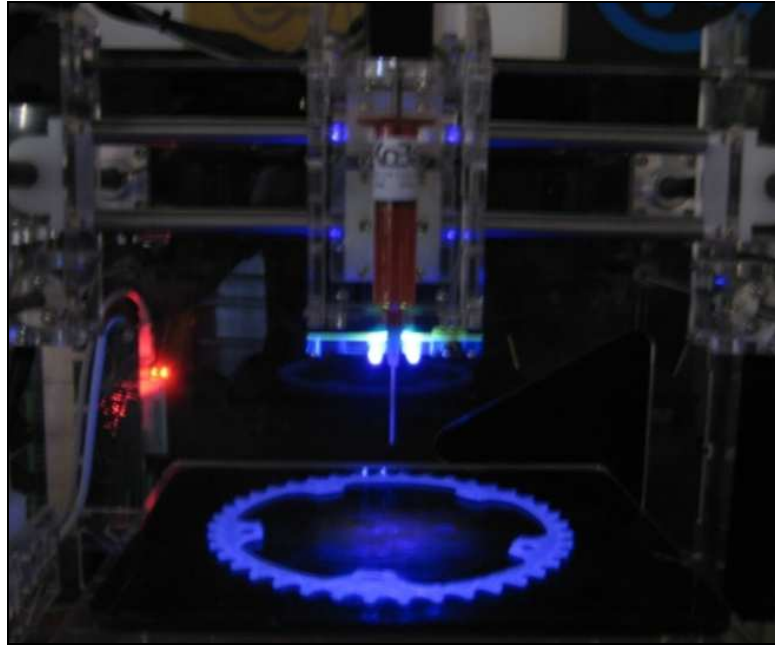
Figure 93: Resin print head developed for the Fab@home RP machine, by Koba Industries Inc. Image courtesy of Fab@home.

9.3.5   Improvement of build quality

Chapter 7 documents how the FFF process was optimised at a basic level. Since the self-manufacture of Darwin's child, build quality has continued to improve. Figure 94 illustrates this improvement. This improvement is crucial to replace some of the imported parts *e.g.* fasteners.
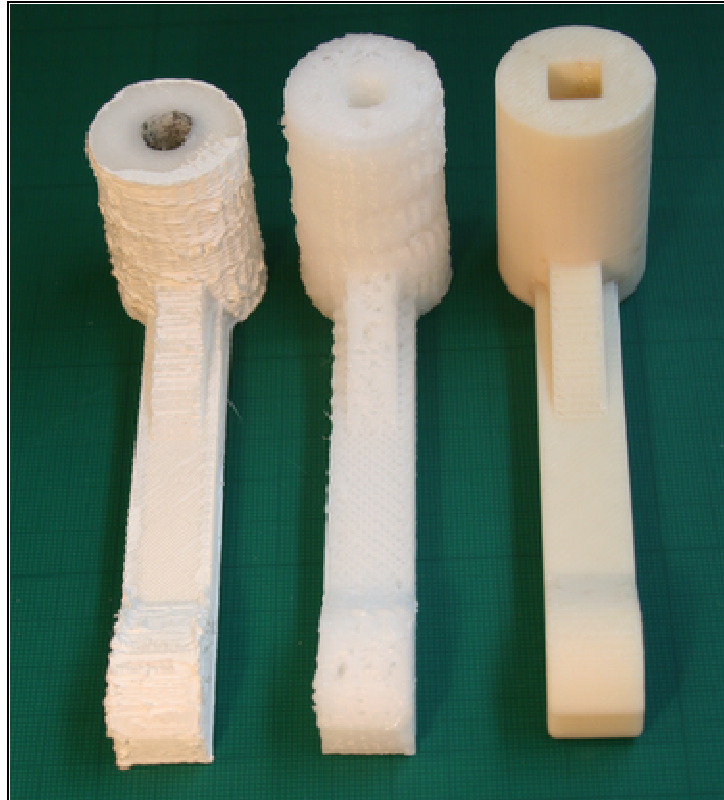
Figure 94: Demonstration of improving build quality over the last six months. Quality improves from left to right as the RepRap FFF process has been optimised (parts courtesy of Bowyer and Palmer).

9.3.6   Improving FFF technique

Hardware elements can be eliminated by developing the general FFF technique. An excellent example of this is Palmer's technique for printing horizontal overhangs which eliminates the support material print head mentioned earlier in this chapter (Figure 82, page 142). Another example would be the elimination of nozzle-wipe hardware if inter-layer cooling is not required (Section 7.5.3.1, page 121). The FFF process is still relatively young and there is plenty of opportunity for optimisation of the technique towards self-manufacture.

9.3.7   Optimising Darwin's design to reduce the requirements for self-manufacture

Case studies in "Theory of Inventor's Problem Solving", commonly known as TRIZ, can be used as a tool for product evolution. By taking data from patents, TRIZ predicts a rise in parts during the research and development phase [57]. The continued development of a design often leads to a reduction in part count, or 'trimming' (illustrated in Figure 95) as the product moves closer to the 'ideal final result'.
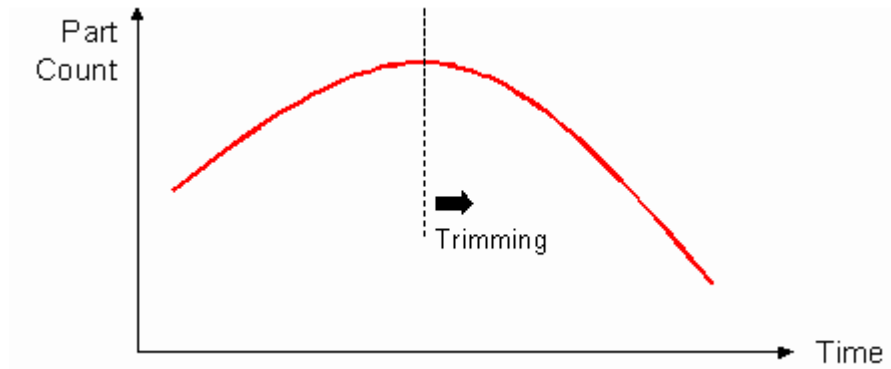
Figure 95: Part count curve for a developing system over time [69]. Trimming occurs as the technology matures.

Trimming, in this case, is likely to occur after the nuances of the FFF process have been finalised and the design moves towards a product, eliminating the redundancy and modularity mentioned in Section 6.6.3, page 99. This may be important for the development of the FFF process towards self-manufacture because trimming may eliminate some of the imported parts.

One potential for the elimination of redundancy would be a chassis redesign to remove dead space from the toolhead movement, reducing the machine's total volume. It is acknowledged by the author that there is a significant proportion of dead space in the design. Elements which could be re-organised to reduce dead-space are identified below, in Figure 96.

1 - NOZZLE WIPE AREA
2 - FAN
3 - EXTRUDER POSITION
4 - CARRIAGE SIZE
5 - EXTRUDER PCB
6 - X-AXIS END BRACKET
7 - Z-OPTOSWITCH

TOP VIEW

8 - EXTRUDER NOZZLE HEIGHT
9 - BED CORNERS
10 - Z-BED TRANSMISSION
11 - Z-MOTOR

EXTRUDER AREA

WORKING AREA

SIDE VIEW
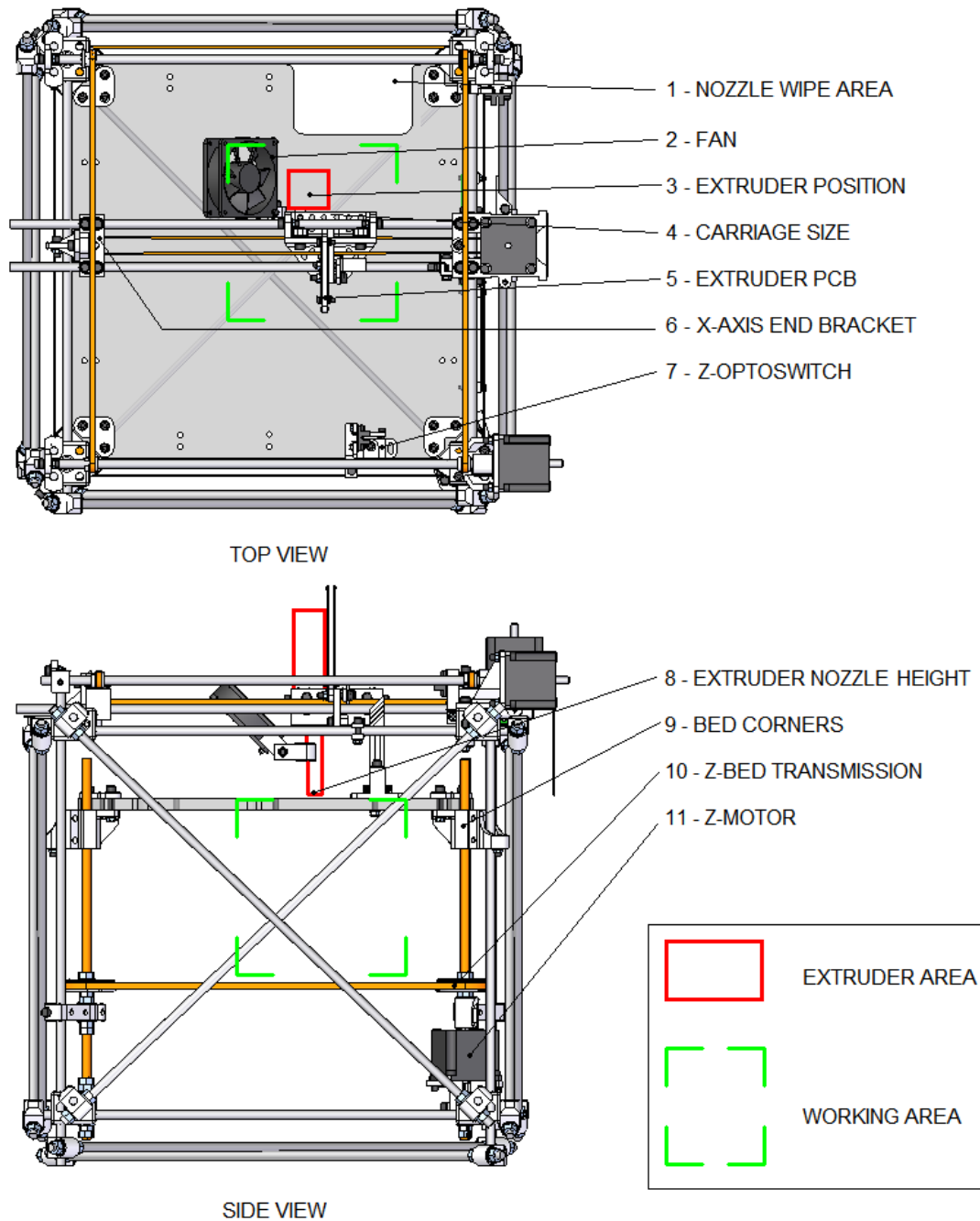
Figure 96: Elements of Darwin which could be re-organised to reduce dead-space.

Table 15 shows that if these elements were re-organised Darwin's volume could be reduced from a 500 mm cube to approximately 345 mm x 370 mm x 290 mm (X, Y and Z respectively). This would represent a 30% reduction in volume.

Table 15: Analysis of elements in Darwin's design which could be re-positioned to reduce dead-space

Element	Description	Improvement	Estimated saving (mm)		
			X-axis	Y-axis	Z-axis
1	Nozzle wipe area	Refine wipe area		10	
2	Fan	Position above carriage and channel air through conduit	80	80	
3	Extruder position	Position inside X-axis structure		(60 – accounted for with fan)	
4	Carriage size	Adapt for a single extruder	40		
5	Extruder PCB	Position above extruder		40	
6	X-axis end bracket	Position on the outside of the linear bearing	30		
7	Z-optoswitch	Position outside the working area	5		
8	Extruder nozzle height	Re-design extruder to put the nozzle at the carriage clamp point			70
9	Bed corners	Invert			20
10	Bed transmission	Position above X/Y table			50
11	Z-motor	Position above X/Y table			70
		Total	**155**	**130**	**210**

A more compact design would require less infrastructure (steel framework and associated fasteners) because loads would have less leverage.

Figure 97 illustrates a basic concept chassis which could be made using the FFF process. Whilst this concept is unproven, and does not detail how the working mechanisms would fit inside the chassis, it does serve to demonstrate how printed segments may be used to

form a part of the structure (as per Section 6.6.2.2, page 94). This would reduce the need for some of the imported structural parts.
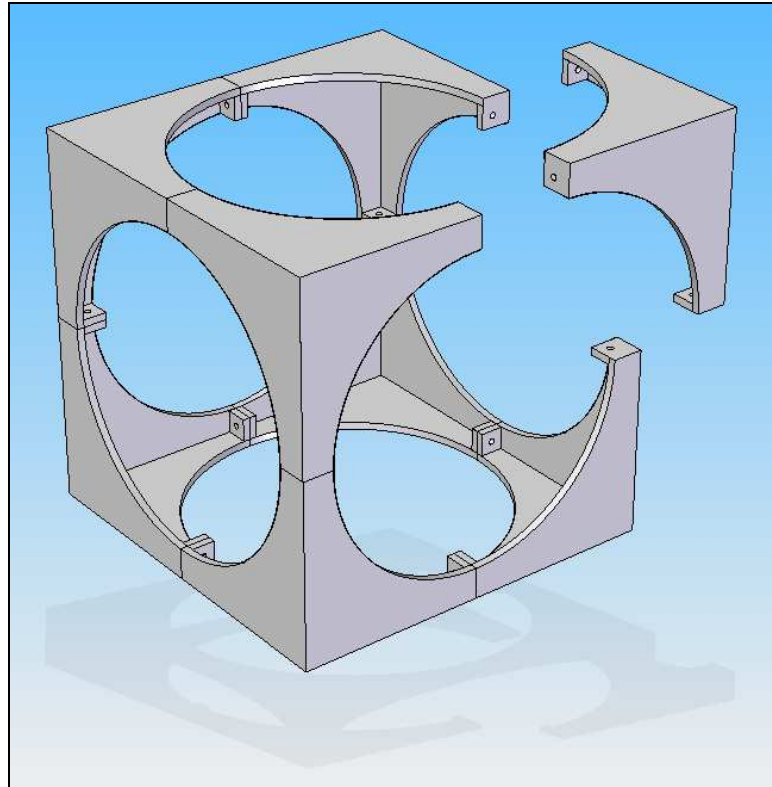
Figure 97: Concept chassis for a future redesign of the RepRap printer. A reduction in the machine's total volume, by eliminating dead space, would enable the machine to make segments for its own chassis. This would remove the need for many of the imported structural elements such as steel bars and fasteners.

9.4   Implications of the RepRap printer on society

One should remember that any discussion in a thesis should always include an element of science fiction: it is the next step. Cartoon strips from sixty years ago imagined much of the world in which we see ourselves today, from our conquests in space to the use of our mobile telephones. Technology has always been led, to some extent, by ideas and the ideas in this thesis should not be dismissed just because they present radical changes in the way we behave.

Chapter 3 suggests that a self-reproducing, distributed manufacturing system like the RepRap printer would offer lower product costs, accelerated evolution of manufacturing capability and self-repair of the manufacturing process. However, the technology must rely on a limited resource range, and the speed at which distributed manufacture occurs may be unsuitably slow for high demand situations. But if the RepRap printer succeeds it may offer an alternative to our current mass-manufacturing infrastructure, the consequences of which might be quite profound.

As demonstrated in Section 3.6.2 (page 49), any entity which can self-replicate has a geometric growth rate. The obvious advantage of geometric growth is that it quickly makes the machine widely available. Early machines are expected to have limited performance in comparison to their commercial competitors, but development of the open-source species will increase with the number of machines in circulation. This exposure will promote evolution which, in turn, will further the growth of the species.

Growth will drive the cost of the machine down to material costs and labour. As the imported technology set is reduced through development, the current £300 price tag is expected to decrease further. This compares favourably with the cost of existing commercial RP machines, the cheapest of which (at the time of writing) is available for around £12,500[14]. Geometric growth will also make the machine available to the public, making it possible for users to manufacture goods in their own home, enabling distributed manufacture.

The ability to self-repair will promote survival, perhaps by having a RepRap printer replicate its own spare parts before starting other production. But perhaps most interesting

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[14] This is the price at the time of writing for Stratasys' smallest desktop printer: the uPrint.

of all is the RepRap printer's powerful evolution characteristic: that of accelerated artificial selection, discussed in the previous section.

In the same way that cabbage, broccoli, cauliflower, brussels sprouts, collards, and kale have all been cultivated from the same species, *Brassica oleracea*, the RepRap printer will no doubt specialise to meet specific demands: optimum mechanical structure, optimum output, energy efficiency *etc*.

This would all add to the machine's ability to manufacture items cheaply, quickly and locally (often in the home) making it attractive to use, perhaps more attractive than the way we currently consume. It would reduce the relatively intense process of 'shopping' down to downloading a file from the internet and printing the item it represents.

Another exciting element of such a distributed manufacturing system would be its associated product information structure. As demonstrated with Darwin's current design, through the internet it is possible to centrally host the component descriptions and allow a collective to improve them. As mentioned earlier, the size of the collective contributing to the evolution can be as broad as the number of machines in circulation. This capability massively accelerates the evolution of not just the machine's parts but of any other public component description.

For example, you may download a coat-hook. It may not be exactly what you want, so you modify the design to fit your needs. If it proves useful you may then wish to post this modified design back on the web where it would enter the scrutiny of the coat-hook market. With this approach in mind, suddenly the product range for coat-hooks has extended beyond the capacity of any coat-hook shop's stock room.

Every person with an internet connection can contribute to the evolution of products in this mass-manufacturing system. No longer will products be bound to sluggish supply-chain forces: digital designs from anyone will be instantly accessible and free to flourish, or die depending on how well they have been designed. The range will not be determined by an elite, and energy will not be wasted by forcing physical products through an expensive supply chain before they are presented to the market. Giving people control over what they can make means they can get exactly what they want, and through the collective, designs can rapidly strengthen.

Whether RepRap will affect the world or not is a simple test of these ideas. Is the self-replicating nature of the machine powerful enough to permeate society as we know it? It is

difficult to escape the mathematical argument – the theoretical growth and evolutionary characteristics seem formidable.

9.5   The RepRap printer as a low risk analogy for a self-replicating mechanism in nanotechnology

Nanotechnology is a field which has the potential to offer many new materials and devices with wide ranging applications [70]. However, it is currently hampered by the lack of an efficient means of production at the atomic scale. Creation of such small structures is intensive and because they are so small, often many of them are needed to constitute a useful volume. One production solution would be to harness a self-reproducing mechanism, but this carries a large amount of risk. At this scale, reproduction would need to be fully automatic, therefore the possibility of mutation into a dangerous product is serious [10].

Whilst the RepRap printer operates at the macroscopic scale, it may serve as a useful parallel for a self-reproducing mechanism at the atomic scale. It has the advantage that it is a relatively safe experiment (discussed further in Section 9.6.5, page 177) and characteristics of replication will be relatively easy to observe.

9.6 Common criticisms of the RepRap idea

9.6.1 How is it self-replication if the RepRap printer still needs a computer?

Saying that the RepRap printer self-replicates is ambiguous. It is correct, however, to say that the RepRap printer achieves a level of self-manufacture, towards a form of *assisted* self-replication. To self-replicate it still needs a supply of power, resources, computing and assembly. Definitions which discuss this in more depth can be found in Section 1.1 (page 4).

9.6.2 Mechanical evolution happens anyway, what's so special about the RepRap printer?

Mechanical evolution for mass-manufacture is usually observed between physical generations of products. Each generation may spawn thousands or millions of products with identical characteristics over a period of months, or years, of production. This is necessary to satisfy the economics of inflexible tooling.

However, the RepRap printer has very flexible tooling. The manufacture of new designs incurs zero tooling costs. Its open source nature also fosters a collective information structure which is capable of using feedback from each individual product to strengthen each design. In this way the RepRap printer liberates evolution to happen at a rate at which ideas are conceived. This discussed further in Section 3.6, page 46.

9.6.3 The FFF process itself means that it does not have a physical feedback loop on the component it has made. How does the RepRap printer escape degeneracy?

Each part must be manufactured to meet its own design specification. Each part is checked manually by the human, using callipers. Furthermore, the engineering specification is designed to guarantee functionality by incorporating many adjustable parts. As long as the printed parts meet their specification the child machine will not suffer from degeneracy.

9.6.4 Is it irresponsible to put such a versatile technology into the hands of the people? What if my child decides to make a bomb?

If your child decides to make a bomb there are plenty of existing technologies he or she could use. First, perhaps we should tackle the issue as to why your child wants to manufacture a bomb casing. Second, FFF is not all that suited to weapon manufacture. A

second-hand lathe would be far more effective, and no-one, so far, has suggested that we shouldn't be able to own lathes.

9.6.5   What if the technology accidentally reproduces into a dangerous machine?

This is statistically very unlikely. Due to the number of parts it is highly improbable that a machine would accidentally reproduce a distinctly different *working* machine. The involvement of the human during the assembly stage also prevents a dangerous machine from being built accidentally.

9.6.6   How is the RepRap printer different to a CNC machine or a lathe in terms of self-manufacture?

Both CNC machines and lathes can manufacture some of their own parts. Unlike the RepRap printer however, they have not been designed from the ground up with self-manufacture in mind and are therefore far less likely to get as close to pure self-manufacture. Section 9.2 (page 142) has projected the RepRap printer's ability to self-manufacture to be 94% in the mid-future.

10   CONCLUSION

Fused Filament Fabrication (FFF) is a Rapid Prototyping (RP) process which can manufacture parts from digital descriptions, or CAD files, using a polymer extruder. The extruder prints layers of polymer filament which are built up to create a three dimensional component. This simple approach can be used to manufacture extremely complex parts to accuracies in the order of $\pm$ 0.05 mm and forms the basis of an extremely versatile manufacturing technology, capable of making highly complex components.

Realising this, Adrian Bowyer set up the 'RepRap'[15] project to make an assisted self-replicating RP machine. The RepRap project supports an on-line community, mostly volunteers, who develop this machine (referred to as the 'RepRap printer') under the GNU General Public Licence. The author's work focussed on the mechanical design of 'Darwin', the first version of the RepRap printer, testing the hypothesis that:

"The Fused Filament Fabrication process is sufficiently versatile to make a self-manufacturing Rapid Prototyping machine."

Concepts were tried and tested, and a final design was developed. The final result, combined with electronic and software modules completed by the rest of the RepRap project, was an FFF RP machine capable of making a significant fraction of it own fundamental components, using its own process. Self-manufacture was demonstrated by assembling a set of these components into a functional copy of the original machine, illustrated in Figure 76 (page 136). The replication cycle took about a week and the material cost was approximately £300. This child machine went on to disprove degeneracy by producing a functional third generation component of its own mechanical design.

The versatility of the process was assessed by using a part count analysis to determine how many of the child machine's parts had been made by the parent machine. It was noted that the inclusion of fasteners in the study unfairly distorted the results. If the fasteners were to be replaced with adhesive (*i.e.* the printer was assumed to be a product rather than a research and development prototype) the analysis would find the child machine to have a self-manufactured parts ratio of 48%.

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[15] Derived from *Rep*licating *Rap*id-Prototyper.

The author sees the results to be encouraging considering this was a first attempt. Also, it was noted that the design of the machine was directed towards the development phase of the FFF process: redundancy and modularity were incorporated to facilitate research, rather than to specifically demonstrate self-manufacture at every opportunity. With the current FFF technology the mechanical design could be adapted to demonstrate a self-manufacturing ratio of 67% in the near future. The author has suggested some short term developments to achieve this:

- Use of the existing FFF process to manufacture springs, cable clips, bed and fan fins.

- Improvement to the FFF process parameters towards the manufacture of toothed pulleys and bearings.

- Use of a dense resource (*e.g.* washers) to replace the foil optoswitch flags.

- Redesign of the extruder to eliminate the flexible drive.

- Elimination of general mechanical redundancy and modularity through printer redesign, using adhesive rather than fasteners at interfaces.

Improvements to the FFF technology could be made to increase this ratio further. The development of new tool heads to print in:

- resin

- flexible polymer, and

- conductive alloy

could bring the self-manufacturing ratio up to 94%. These developments are expected to be achieved by the RepRap project in the mid-future.

Beyond this, a few parts remain a challenge for the FFF process to self-manufacture: electronic components, motors, conductive cable, solenoids and a heating element. Whilst these are unlikely to be self-manufactured for at least a few years it is encouraging to note the development of new technologies which might aid self-manufacture. For example, the advent of RFID tags is driving a new effort towards printed electronics components, which may at some point be adopted into the FFF process to print transistors.

Also, it is hoped that as the machine gets more exposure to development, imported parts will gradually be eliminated from the design and the FFF process will be improved towards 100% versatility for self-manufacture. It is, however, accepted that pure self-manufacture

may be an impossible ideal. As with natural organisms, the RepRap printer may have to finally accept a small set of imported parts, but the author notes that future eliminations of imported parts are important contributions to the field of self-manufacture and autotrophic SRMs.

At the time of writing the author estimates there to be over 1000 Darwin machines in circulation around the world, and this number continues to grow. This is largely due to a company which is now selling mechanical kits based on the machine's original design and support for the electronics needed for the machine from the RepRap Research Foundation.

As the machine moves towards pure self-manufacture, the RepRap printer gradually qualifies as an *assisted* self-manufacturing machine. It will still require power, material, computation and assembly resources to self-replicate. However, humans may find it beneficial to trade these for versatile FFF manufacturing capability. Through this symbiotic relationship with humans the RepRap printer can self-replicate, enabling two powerful characteristics found in living organisms: geometric growth, and evolution.

The author has discussed how geometric growth can lower the price of the machine to materials and assembly costs. The open source nature of the project encourages development to the design of the printer, enabling fast improvements to the quality of the machine, akin to artificial selection. Both these factors would make the machine more accessible to the domestic market, and it is conceivable that such a machine could become a household item – an item which offers a radical alternative to the way the mass-manufacturing industrial system currently works.

The current system manufactures goods centrally, in factories, before shipping them out around the world, whilst the RepRap printer enables people to simply make the goods in their own home. The author has described how the latter, distributed approach, can transform the way we consume. An open-source approach to hardware can enable people to cheaply manufacture exactly what they need and, via the internet, collectives can rapidly strengthen designs.

In the course of demonstrating self-manufacture, the author has completed the aims set out at the beginning of his PhD. With respect to making RP technology accessible to the public, the design and release of the RepRap printer under the GNU General Public Licence has already enabled the public to make their own RP machines to the author's design. In turn this has enabled the design to evolve and furthered the knowledge of RP:

the project's blog is replete with significant improvements to the machine's design and to the FFF process from the RepRap community. This is expected to increase as the volume of machines begins to increase geometrically.

With respect to the aims of furthering the knowledge of self-manufacture, the author has documented many mechanical considerations for designing a self-manufacturing machine using FFF technology. Some of these design principles may be applied to other self-manufacturing technologies should they arise: specifically design for adjustability, design for modular components to exceed the bounds of working volumes and design for the maintenance of high-wearing parts.

With respect to the aims of furthering the knowledge of self-replication, the author has documented design principles to cater for the evolutionary and growth characteristics expected to come with assisted self-replication: specifically the inclusion of redundancy in a modular design. It is also hoped that the terms used in this thesis will serve to better discuss the field of self-replicating machines.

To conclude, this thesis has documented the mechanical development of a prototype for a self-manufacturing machine, contributing knowledge to the fields of RP, self-manufacture and self-replication. Whilst still in the development phase, its Fused Filament Fabrication manufacturing process is currently capable of manufacturing 48% of its own parts (excluding fasteners); however this proportion is likely to improve to 94% in the mid-future. As an assisted self-replicating machine it will benefit from the biological traits of geometric growth and rapid evolution which will reduce cost and improve performance respectively. These factors will make the manufacturing technology more accessible to the domestic market. The resultant distributed manufacturing system offers a radical alternative to the way our centralised mass-manufacturing system works – in the near future we may be printing customised iPods in our own living room.

11 GLOSSARY

3D printing (3DP)	A subtle distinction which refers to the category of RP processes which implement the simplest of the SFF technologies to achieve fast and affordable 3D printers.
Acrylonitrile butadiene styrene (ABS)	A common plastic found in many moulded products.
Blog	An online diary where people can post messages and others may view and respond to the posts.
Computer Aided Design (CAD)	An automated system for the design, drafting, and display of graphically oriented information.
Deposition	The extrudate after it has been printed onto a layer during the FFF process.
Darwin	The name given to the first version of the 'RepRap printer', inspired by the English naturalist Charles R. Darwin.
Filament	The material output from the polymer extruder in the FFF process.
Fused Filament Fabrication (FFF)	The deposition of molten filament to create a thin layer of a specific shape. Layers are printed on top of each other to create a tree dimensional object.
Self-Manufactured Part (SMP)	Used in the context of a self-manufacturing machine, an SMP is a part of the machine which the machine can manufacture for itself.
Infill	Areas of printing done during the FFF process which fills in the boundaries of each layer.
Kinematic Cellular Automata (KCA)	Automata which are made up of identical mechatronic modules.
PCB	Printed Circuit Board
Polycaprolactone (PCL)	A biodegradable thermoplastic (polyester) with a low melting point: 60°C.
Polylactic acid (PLA)	A biodegradable thermoplastic derived from renewable resources, such as corn starch or sugarcanes.

Rapid Prototyping (RP)	A process which uses a Solid Freeform Fabrication (SFF) process to automatically construct physical objects from CAD files.
RepRap printer, The	The self-manufacturing machine developed by the RepRap project.
Room Temperature Vulcanisation (RTV)	Casting resins at room temperature to achieve moulded parts. Moulds are commonly made from a silicone compound.
Segment	A straight line of filament deposition. Multiple segments are linked together to form each layer in the FFF process.
Segment pausing	A slight pause of print head movement during the FFF process which can occur between printed segments.
Self-Replicating Machine (SRM)	A machine which can make a copy of itself.
Solarbotics	Supplier of extruder motors used in the RepRap printer (See Section 13.7, page 220).
Solid Freeform Fabrication (SFF)	A collection of techniques for manufacturing solid objects by the sequential delivery of energy and/or material to specified points in space to produce that solid.
SourceForge	An open source software development web site, providing free hosting to open source projects.
Stratasys RP machine	A commercial rapid prototyping machine which uses Fused Deposition Modelling (FFF in this thesis) to manufacture components.
The RepRap Project	A project founded and led by Adrian Bowyer towards making a self-manufacturing machine using FFF technology.
TWiki	A structured wiki, typically used to run a collaboration platform, knowledge or document management system, a knowledge base, or team portal.
Wiki	A type of website that allows the visitors to add, remove, and edit the available content.
Wood's metal	A low melting point (70 °C) eutectic alloy of 50 % bismuth, 26.7 % lead, 13.3 % tin, and 10 % cadmium by weight. A non-toxic alternative is Field's metal which melts at 62 °C and is made up of 32.5 % bismuth, 51 % indium and 16.5 % tin.

12   REFERENCES

1.   CAMPBELL, N.A. and J.B. REECE, 2005. *Biology*. ed. 7. San Francisco: Benjamin Cummings.

2.   FREITAS, R.A. and R.C. MERKLE, 2004. *Kinematic Self-Replicating Machines*. Georgetown, Texas: Landes Bioscience.

3.   VON NEUMANN, J., 1966. *Theory of Self-Reproducing Automata*. Illinois: University of Illinois Press.

4.   NEHANIV, C.L. and K. DAUTENHAHN, 1998. Self-Replication and Reproduction: Considerations and Obstacles for Rigorous Definitions. *In*: *Third German Workshop on Artificial Life: Abstracting and Synthesizing the Principles of Life*, C. WILKE, S. ALTMEYER, and T. MARTINETZ, eds, Sep 17-18 Bochum. Frankfurt: Verlag Harri Deutsch. pp.283–290.

5.   ZYKOV, V., E. MYTILINAIOS, B. ADAMS, and H. LIPSON, 2005. Self-reproducing machines. *Nature*, 435, pp. 163-164.

6.   SHANNON, C.E., 1949. *The Mathematical Theory of Communication*. Urbana, IL: University of Illinois Press.

7.   MILLER, J.G., 1978. *Living Systems*. New York: McGraw-Hill Book Company.

8.   TAYLOR, T., 1999. *From Artificial Evolution to Artificial Life*. Thesis (Ph.D.), University of Edinburgh.

9.   ADAMS, B. and H. LIPSON, 2003. *A Unifying Framework for Self-Replication Phenomena*. Cornell university preprint.

10.   FORESIGHT INSTITUTE, 2006. *Foresight Guidelines for Responsible Nanotechnology Development: Draft Version 6.* [online] Available at http://www.foresight.org/guidelines/ForesightGuidelinesV6.pdf

11.   SIPPER, M., E. SANCHEZ, D. MANGE, M. TOMASSINI, A. PÉREZ-URIBE, and A. STAUFFER, 1997. A phylogenetic, ontogenetic, and epigenetic view of bio-inspired hardware systems. *IEEE Transactions on Evolutionary Computation*, 1 (1), pp. 83-97.

12.   LUISI, P.L., 1998. About Various Definitions of Life. *Origins of Life and Evolution of Biospheres (Formerly Origins of Life and Evolution of the Biosphere)*, 28 (4 - 6), pp. 613-622.

13.   SIGNORINI, J., 1989. How a SIMD machine can implement a complex cellular automaton? A case study: von Neumann's 29-state cellular automaton. *In*: *Supercomputing '89: Proceedings of the ACM/IEEE Conference*, Nov 12 - 17 Reno. pp.175-186.

14.   PESAVENTO, U., 1995. An implementation of von Neumann's self-reproducing machine. *Artificial Life*, 2 (Summer 1995), pp. 337-354.

15.   FREITAS, R.A. and W.P. GILBREATH. 1982. Advanced Automation for Space Missions. Proceedings of the *NASA Conference Publication CP-2255 (N83-15348)*, Summer 1980.

16. A.H. TAUB, ed., 1963. *John von Neumann: Collected Works, Volume V: Design of Computers, Theory of Automata and Numerical Analysis*. New York: Pergamon Press. pp. 288-329.

17. KEMENY, J.G., 1955. Man viewed as a machine. *Scientific American*, 192, pp. 58-67.

18. CAIRNS-SMITH, A.G., 1971. *The Life Puzzle*. Toronto: University of Toronto Press.

19. MOORE, E.F., 1956. Artificial living plants. *Scientific American*, 195 (October), pp. 118-126.

20. DYSON, F.J. 1972. The World, The Flesh, and the Devil. V. Self-Reproducing Machinery. Proceedings of the *Third J.D. Bernal Lecture*, 16 May London. London: Birkbeck College.

21. CALDER, N., 1978. *Spaceships of the Mind*. New York: Viking Press.

22. MCKAY, D.S., H.P. DAVIS, and M. BURNS. 1995. Using fabricators to reduce space transportation costs. Proceedings of the *Solid Freeform Fabrication Symposium*, 14 August University of Texas, Austin.

23. HINZMANN, B. 1996. The Personal Factory. Proceedings of the *MCB Internet Conference on Rapid Prototyping*.

24. A. PIQUE and D.B. CHRISEY, eds., 2001. *Direct Write Technologies for Rapid Prototyping Applications: In Sensors, Electronics and Integrated Power Sources*. New York: Academic Press.

25. FREITAS, R.A., 1980. A self-reproducing interstellar probe. *J. Brit. Interplanet. Soc.*, 33 (July), pp. 251-264.

26. CHIRIKJIAN, G.S., Y. ZHOU, and J. SUTHAKORN, 2002. Self-replicating robots for lunar development. *Special Issue on Self-Reconfiguration Robots, ASME/IEEE Transactions on Mechatronics*, 7, pp. 462-472.

27. STEPHENS, R. 1999-2003. *Self-Replicating Robotic Lunar Factory* [online]. Available from: http://thepreparation.net/SRRLF.html [Accessed 5 Feb 2009].

28. DYSON, F.J., 1979. *Disturbing the Universe*. New York: Harper and Row Publishers.

29. PENROSE, L.S., 1958. Mechanics of self-reproduction. *Ann. Human Genetics*, 23, pp. 59-72.

30. PENROSE, L.S., 1959. Automatic mechanical self-reproduction. *New Biology*, 28, pp. 92-117.

31. JACOBSON, H., 1958. On models of reproduction. *American Scientist*, 46 (September), pp. 255-284.

32. MOROWITZ, H.J., 1959. A model of reproduction. *American Scientist*, 47 (June), pp. 261-263.

33. LOHN, J.D., G.L. HAITH, and S.P. COLOMBANO. 1998. Two electromechanical self-assembling systems. Proceedings of the *Sixth Foresight Conference on Molecular Nanotechnology*, 13-15 November.

34.   TOTH-FEJEL, T., 2000. *Modeling kinematic cellular automata: An approach to self-replication*. Ann Arbor: Environmental Research Institute of Michigan.

35.   MOSES, M., 2002. *A Physical Prototype Of A Self-Replicating Universal Constructor*. Thesis (Masters). Mechanical Engineering, University of New Mexico: New Mexico.

36.   SUTHAKORN, J., A.B. CUSHING, and G.S. CHIRIKJIAN. 2003. An autonomous self-replicating robotic system. Proceedings of the *IEEE/ASME Intl. Conf. on Advanced Intelligent Mechatronics (AIM 2003)*, December Kobe, Japan.

37.   BRADLEY, W.E., 1980. First attempt to define a self-replicating system. *In*: *Advanced Automation for Space Missions (NASA Conference Publication CP-2255)*, R.A. FREITAS and W.P. GILBREATH, eds, 1982 pp.265-267.

38.   FANUC. April 1998. *New Robot Factory started the full Operation* [online]. Available from: http://www.fanuc.co.jp/en/news/h10/h10_04.htm [Accessed 12 Feb 2007].

39.   CHALMERS, R., 1998. Marrying CNC with the PC is the heart of the Cyber Factory. *Manufacturing Engineering*.

40.   BOGART, M., 1979. *In art the ends don't always justify means*.Smithsonian, pp. 104-110.

41.   BLANTHER, J.E. 1892: US Patent: 473,901.

42.   KODAMA, H., 1981. Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer. *Rev. Sci. Instrum.*, pp. 1770-73.

43.   PRINZ, F.B., C.L. ATWOOD, R.F. AUBIN, J.J. BEAMAN, R.L. BROWN, P.S. FUSSELL, A.J. LIGHTMAN, E. SACHS, L.E. WEISS, and M.J. WOZNY, *Rapid Prototyping in Europe and Japan*

VOLUME I. ANALYTICAL CHAPTERS. 1997, Japanese Technology Evaluation Center/World Technology Evaluation Center. p. 21-31.

44.   CHUA, C.K., K.F. LEONG, and C.S. LIM, 2003. *Rapid Prototyping: Principles and Applications, World Scientific Publishing*. ed. 2. Singapore: FuIsland Offset Printing (S) Pte Lts.

45.   MEDELLIN, H., T. LIM, J. CORNEY, J.M. RITCHIE, and J.B.C. DAVIES, 2007. Automatic decomposition and refinement of oversized components for rapid prototyping. *Journal of Computing and Information Science in Engineering*, 7.

46.   GRENDA, E. 2006. *Worldwide Guide to Rapid Prototyping* [online]. Available from: http://home.att.net/~castleisland/ [Accessed 21 September 2006].

47.   GRIFFITH, S., 2001. *Towards Personal Fabricators: Tabletop tools for micron and sub-micron scale functional rapid prototyping*. Thesis, Massachusetts Institute of Technology.

48.   MALONE, E., K. RASA, D. COHEN, T. ISAACSON, H. LASHLEY, and H. LIPSON, 2004. Freeform fabrication of 3-D zinc-air batteries and functional electro-mechanical assemblies. *Rapid Prototyping Journal*, 10, pp. 58-69.

49.   BOWYER, A. 2006. *The RepRap Project* [online]. Available from: http://reprap.org/ [Accessed 14 September 2006].

50.   SELLS, E. 2006. Directly incorporating electronics into conventional rapid prototypes. Proceedings of the *Rapid Design, Prototyping and Manufacturing*. Lancaster University: Bucks: MJA Print, pp.37-45.

51.   AGARWALA, M., A. BANDYOPADHYAY, R.V. WEEREN, V. JAMALABAD, P. WHALEN, N.A. LANGRANA, A. SAFARI, and S.C. DANFORTH, 1996. Fused deposition of ceramics. *J. Rapid Prototyping*, 2, pp. 4-19.

52.   TENG, K.F. and R.W. VEST, 1988. A microprocessor-controlled ink jet printing system for electronic circuits. *IEEE Trans. Indust. Electron.*, 35, pp. 407-412.

53.   HAYES, D.J., W.R. COX, and M.E. GROVE, 1998. Microjet printing of polymers and solder for electronics manufacturing. *J. Electron. Manufact.*, 8, pp. 209-216.

54.   COMISKEY, B., J.D. ALBERT, H. YOSHIZAWA, and J. JACOBSON, 1998. An electrophoretic ink for all-printed reflective electronic displays. *Nature*, 394, pp. 253-255.

55.   RIDLEY, B.A., B. NIVI, and J.M. JACOBSON, 1999. All-inorganic field effect transistors fabricated by printing. *Science*, 286, pp. 746-749.

56.   GRAHAM-ROWE, D., 2003. Gadget printer promises industrial revolution. *New Scientist*, 8 (January).

57.   SALAMATOV, Y., 1999. *TRIZ: the right solution at the right time: a guide to innovative problem solving.* Netherlands: Insytec BV.

58.   BOOTHROYD, D., 2006. Replication revolutionary. *New Electronics*, 12th December 2006, p.15.

59.   BOWYER, A. 2006. The Self-replicating Rapid Prototyper - Manufacturing for the Masses. Proceedings of the *7th national conference on rapid design, prototyping and manufacture*, 16th June 2006. Department of Engineering, Lancaster University, Lancaster, UK.

60.   SELLS, E., 2005. *Towards a self-replicating machine*. Thesis (MEng). Department of Mechanical Engineering, University of Bath: Bath.

61.   BANZI, M., D. CUARTIELLES, T. IGOE, G. MARTINO, D. MELLIS, and N. ZAMBETTI, 2008. *Arduino 0010 software.* Available from http://www.arduino.cc/en/Main/ArduinoBoardDiecimila [Accessed 6 Jan 2009].

62.   THOMPSON, C., 2008. Build It. Share It. Profit. Can Open Source Hardware Work? *Wired*, 10.20.08

63.   KRUTH, J.-P., B. VANDENBROUCKE, J.V. VAERENBERGH, and P. MERCELIS, *Benchmarking of different SLS/SLM processes as rapid manufacturing techniques*, in *International Conference of Polymers and Moulds Innovations (PMI)*. 2005: Gent, Belgium.

64.   SMITH, Z., A. BOWYER, S. MCAULIFFE, V. OLLIVER, and E. SELLS. 2008. *About the RRRF* [online]. Available from: http://www.rrrf.org/about/ [Accessed 23 Jan 2009].

65.   PAIN, S., 2002. The chunkiest chip. *New Scientist* (2365), pp. 60-61.

66.   LAMMERS, D., 2007 *Kovio Inkjet Prints Fast Silicon Transistor*. Semiconductor International [online], Available from: http://www.semiconductor.net/article/CA6500580.html [Accessed 23 Jan 2009].

67.   HAN, X., D.C. JANZEN, J. VAILLANCOURT, and X. LU, 2007. *Printable high-speed thin-film transistor on flexible substrate using carbon nanotube solution*. Micro & Nano Letters [online], 2 (4). Available from: http://scitation.aip.org/dbt/dbt.jsp?KEY=MNLIBX&Volume=2&Issue=4 [Accessed 23 Jan 2009].

68.   MALONE, E. 2008. *Fab@Home:News* [online]. Available from: http://fabathome.org/wiki/index.php?title=Fab%40Home:News [Accessed 23 Jan 2009].

69.   MANN, D. 2000. *Influence of S-Curves on Use of Inventive Principles* [online]. Available from: http://www.triz-journal.com/archives/2000/11/c/index.htm [Accessed 06 Jan 2008].

70.   DREXLER, K.E., 1990. *Engines of Creation*. London: Fourth Estate.

13 APPENDIX

13.1 Accompanying data

A DVD of data accompanies this thesis. Table 16 describes these data.

Table 16: Description of data included in the accompanying DVD

Data Folder	Data Description
Design files for Darwin	Digital descriptions of the parts used in Darwin's assembly. Available in STL, STEP, and Solid Edge v19 format.
Snapshot of the project wiki	All the data on the project's website at the time of writing. The main purpose of this is to supply the substantial documentation on how to make the RepRap printer with respect to software, electronics, mechanics and calibration.
Snapshot of the RepRap software source code	A copy of the RepRap software source code, written in Java, at the time of writing.

13.2   Rapid Prototyping Technology comparison chart

Table 17: Rapid Prototyping Technology comparison chart [46] as of 8/2/06

	Stereo-lithography	Jetted Photopolymer	Selective Laser Sintering	Laminated Object Manufacturing	Fused Filament Fabrication	Single Jet Inkjet	Solvent jet printing
Acronym	SLA	J-P	SLS	LOM	FFF/FDM	MM	Solvent jet
Representative Vendor	3D Systems				Stratasys	Solidscape	Z Corp.
Maximum Part Size (mm)	508 x 508 x 610	298 x 185 x 203	381 x 330 x 457	160 x 210 x 135	610 x 508 x 610	305 x 152 x 229	508 x 610 x 406
Speed	Average	Good	Average to fair	Good	Poor	Poor	Excellent
Accuracy	Very good	Good to very good	Good	Fair	Fair	Excellent	Fair
Surface Finish	Very good	Good to very good	Fair	Fair	Fair	Excellent	Fair

	Stereo-lithography	Jetted Photopolymer	Selective Laser Sintering	Laminated Object Manufacturing	Fused Filament Fabrication	Single Jet Inkjet	Solvent jet printing
Strengths	Large part size, accuracy	Accuracy and finish, office OK	Accuracy, materials,	Office OK, price, size	Office OK price, materials	Accuracy, finish, office OK	Speed, office OK, price, colour
Weaknesses	Post processing, messy liquids	Size and weight, post processing	Size and weight, system price, surface finish	Limited materials, finish and accuracy	Speed	Speed, limited materials, part size	Limited materials, fragile parts, finish
System Price	$75K-800K	$60K-85K	$300K	$15K	$19K-300K	$70K-80K	$20K-70K
Plastics	$165-242	$132-$440	$66-132	$40	$253-407	$220	
Metal			$55-66				
Other			$11 (sand)				

13.3   Analysis of the motion systems available to the RepRap Printer

Table 18: Analysis of motion systems available to the RepRap Printer

System	Pros	Cons
Polar	• Excellent for producing cylindrical or rotationally symmetric objects	• Minimum 3 motors • Software is complex to deal with helical plotting path (as opposed to planar) • Very non-linear distances between "steps". This also implies non-linear speed or very slow speed. • Object moves (possibly a problem if the material takes some time to set or platform changes direction quickly) • Resolution decreases with distance from centre.
Cartesian	• Linear distances between "steps" (and consistent speed) • Software is simple. Planar cuts through a geometry are simpler to calculate. • No platform stability issues (object can remain in a fixed position with only heads moving), though this is dependant on the Cartesian configuration.	• Minimum 3 motors • Harder to produce smooth cylindrical or rotationally symmetric objects.

13.4   Z-bed movement concepts evaluation

Table 19: Z-bed movement concepts estimated evaluation

Consideration	Screw drive	Cable drive
Drive complexity	Standard	Experimental
Design efficiency	Average/poor	Excellent (uses X/Y pillars as a resource for the idler bearings)
Stability	Excellent	Might be a problem with securing the position of the pulley bearings
Jam risk	Medium	Medium/High
Design effort	Low	High
Motion resistance due to debris	Poor – debris likely to collect in thread	Good – debris brushed away on plain bushes

13.5   Wire wrap riding constraints for cable transmission

This section continues from Section 6.4.1, page 68.

13.5.1   Wire wrap: full constraint

A drive wheel was designed to allow a full wrap of the wire. Shelves were added to the profile in attempt to prevent the warp from moving axially (Figure 98). This was considered important to maintain the accuracy of the drive system. This failed – the wrap ended up knotting itself on the constraint.
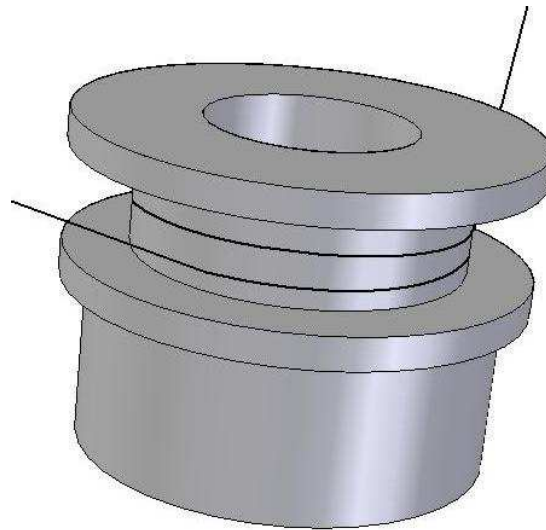
Figure 98: Single wrap wheel including full constraint

13.5.2   Wire wrap: Coaxing constraint

It was thought that perhaps a less exaggerated constraint would solve the problem. Therefore a drive wheel with a bowl profile was designed in the hope that it would coax the wrap into the centre of the wheel (Figure 99). This did not prevent the wrap from riding up and down the length of the wheel.

Figure 99: Drive wheel with a concave section acting as a constraint to keep the wrap in the centre of the wheel

13.5.3   Wire wrap spreader bar

A spreader bar was designed (Figure 100) to constrain the inward and outward wire in an attempt to fix the position of the wrap. This failed to overcome the axial friction in the wire wrap.
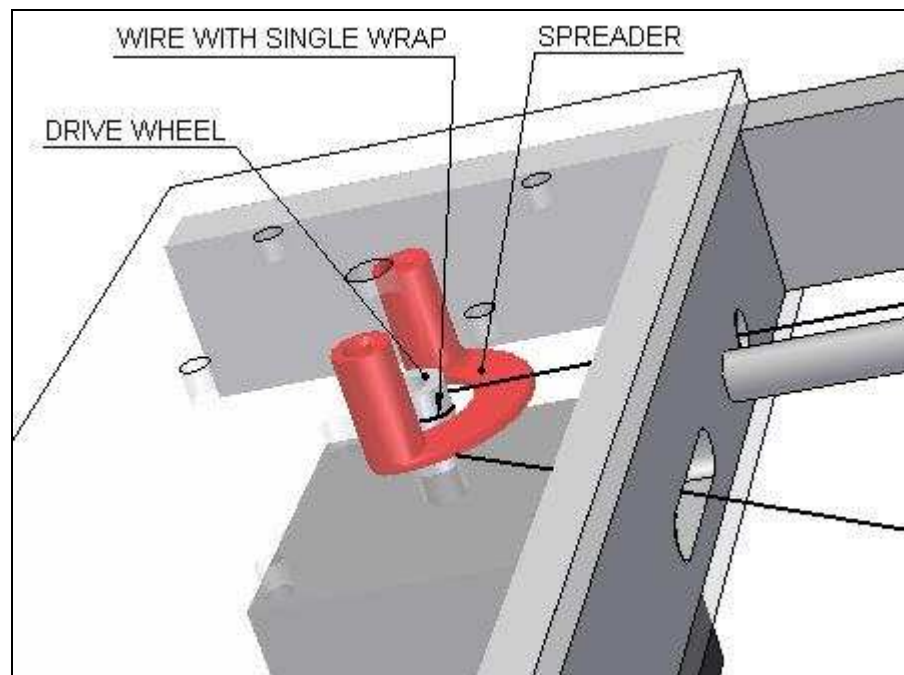
Figure 100: Spreader assembly to constrain the height of the input and output wires, in an attempt to fix the position of the wrap.

13.6 Bill of materials for Darwin design and Part count analysis raw data

Table 20: Raw data for the part count analysis of the RepRap printer. The analysis identifies the types of components in the printer's design and how they might change during the evolution towards pure a self-manufacturing machine over the coming years. Changes between years are identified in bold text. Justifications for these changes have been discussed in Section 9.2, page 142.

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
				Current design			**Post 1 year development**			**Post 2 year development**		
1	Jigs	1	Rod 355 (X/Y frame spacer)	1	1	Rod/Stud	1	1	Rod/Stud	1	1	**RP**
2	Jigs		Foot spacer	1	1	RP	1	1	RP	1	1	RP
3	Jigs		Belt splicer (male and female)	1	1	RP	1	1	RP	1	1	RP
4	Jigs		X axis square jig	1	1	RP	1	1	RP	1	1	RP
5	Z toothed pulley moulding	1	M8 nut	2	2	Fastener	0	0	**Eliminated**	0	0	Eliminated

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
6	Z toothed pulley moulding		M8 washer	2	2	Fastener	0	0	**Eliminated**	0	0	Eliminated
7	Z toothed pulley moulding		M5 nuts	4	4	Fastener	0	0	**Eliminated**	0	0	Eliminated
8	Z toothed pulley moulding		M5 x 8 grub	4	4	Fastener	0	0	**Eliminated**	0	0	Eliminated
9	Z toothed pulley moulding		Stud 100	1	1	Rod/Stud	0	0	**Eliminated**	0	0	Eliminated
10	Z toothed pulley moulding		Plastic bag (moulding release)	1	1	Other	0	0	**Eliminated**	0	0	Eliminated
11	Z toothed pulley moulding		~160mm of belt (Length 950, pitch 2.5, width 6, thick ~1.3)	1	1	Other	0	0	**Eliminated**	0	0	Eliminated

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
12	Z toothed pulley moulding		PCL	1	1	Other	0	0	**Eliminated**	0	0	Eliminated
13	Z toothed pulley moulding		Z toothed pulley mould male	1	1	RP	0	0	**Eliminated**	0	0	Eliminated
14	Z toothed pulley moulding		Z toothed pulley mould female	1	1	RP	0	0	**Eliminated**	0	0	Eliminated
15	Y toothed pulley moulding	1	Rod 100	1	1	Rod/Stud	0	0	**Eliminated**	0	0	Eliminated
16	Y toothed pulley moulding		Belt scrap from remainder of Z moulding process	0	0	Other	0	0	**Eliminated**	0	0	Eliminated
17	Y toothed pulley moulding		PCL	1	1	Other	0	0	**Eliminated**	0	0	Eliminated

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
18	Y toothed pulley moulding		Pot	1	1	RP	0	0	**Eliminated**	0	0	Eliminated
19	Y toothed pulley moulding		Belt collar	1	1	RP	0	0	**Eliminated**	0	0	Eliminated
20	Y toothed pulley moulding		Y blade	1	1	RP	0	0	**Eliminated**	0	0	Eliminated
21	X toothed pulley moulding	1	PCL	1	1	Other	0	0	**Eliminated**	0	0	Eliminated
22	X toothed pulley moulding		Stepper motor ST5709M1208-B (borrowed from X axis SA)	0	0	Eliminated	0	0	Eliminated	0	0	Eliminated
23	X toothed pulley moulding		X blade	1	1	RP	0	0	**Eliminated**	0	0	Eliminated

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
24	X idler and constraint bracket	1	M5 x 15 cap	8	8	Fastener	8	8	Fastener	8	8	**RP**
25	X idler and constraint bracket		M5 washer	9	9	Fastener	9	9	Fastener	9	9	**RP**
26	X idler and constraint bracket		M5 nut	10	10	Fastener	10	10	Fastener	10	10	**RP**
27	X idler and constraint bracket		M5 x 8 grub	2	2	Fastener	2	2	Fastener	2	2	**RP**
28	X idler and constraint bracket		Rod 40 (X idler)	1	1	Rod/Stud	1	1	Rod/Stud	1	1	**RP**
29	X idler and constraint bracket		X idler bracket	1	1	RP	1	1	RP	1	1	RP
30	X idler and constraint bracket		X constraint bracket	1	1	RP	1	1	RP	1	1	RP

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
31	X idler and constraint bracket		Bearing insert 180 X	1	1	RP	1	1	RP	1	1	RP
32	X idler and constraint bracket		Y belt clamp	2	2	RP	2	2	RP	2	2	RP
33	X idler and constraint bracket		X/Y pulley idler	1	2	RP	1	2	RP	1	2	RP
34	X carriage	1	M5 cap x 15	8	8	Fastener	8	8	Fastener	8	8	**RP**
35	X carriage		M5 nut	8	8	Fastener	8	8	Fastener	8	8	**RP**
36	X carriage		M5 washer	10	10	Fastener	10	10	Fastener	10	10	**RP**
37	X carriage		X carriage	1	1	RP	1	1	RP	1	1	RP
38	X carriage		X belt clamp	3	3	RP	3	3	RP	3	3	RP
39	X carriage		Bearing insert 360 run	2	2	RP	2	2	RP	2	2	RP
40	X motor bracket	1	M5 washer	11	11	Fastener	11	11	Fastener	11	11	**RP**

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
41	X motor bracket		M5 x 15 cap	12	12	Fastener	12	12	Fastener	12	12	**RP**
42	X motor bracket		M5 nut	14	14	Fastener	14	14	Fastener	14	14	**RP**
43	X motor bracket		M5 x 8 grub	2	2	Fastener	2	2	Fastener	2	2	**RP**
44	X motor bracket		Rod 520	2	2	Rod/Stud	2	2	Rod/Stud	2	2	**RP**
45	X motor bracket		Stepper motor ST5709M1208-B	1	1	Other	1	1	Other	1	1	Other
46	X motor bracket		X belt (Length 950, pitch 2.5, width 6, thick ~1.3)	1	1	Other	1	1	Other	1	1	**RP**
47	X motor bracket		X toothed pulley	1	1	Moulded	1	1	**RP**	1	1	RP
48	X motor bracket		X motor bracket	1	1	RP	1	1	RP	1	1	RP
49	X motor bracket		X belt clamp	2	2	RP	2	2	RP	2	2	RP
50	X motor bracket		Y belt clamp	2	2	RP	2	2	RP	2	2	RP

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
51	X/Y frame	2	M5 nut	8	16	Fastener	8	16	Fastener	8	16	**RP**
52	X/Y frame		M5 x 8 grub	8	16	Fastener	8	16	Fastener	8	16	**RP**
53	X/Y frame		Rod 500 (X/Y frame rod)	4	8	Rod/Stud	4	8	Rod/Stud	4	8	**RP**
54	X/Y frame		Corner bracket	4	8	RP	4	8	RP	4	8	RP
55	Studding idler	3	M8 nut	12	36	Fastener	12	36	Fastener	12	36	**RP**
56	Studding idler		M8 washer	6	18	Fastener	6	18	Fastener	6	18	**RP**
57	Studding idler		M5 nut	3	9	Fastener	3	9	Fastener	3	9	**RP**
58	Studding idler		M5 x 20 cap	1	3	Fastener	1	3	Fastener	1	3	**RP**
59	Studding idler		M5 x 25 cap	1	3	Fastener	1	3	Fastener	1	3	**RP**
60	Studding idler		M5 washer	2	6	Fastener	2	6	Fastener	2	6	**RP**
61	Studding idler		Stud 384	1	3	Rod/Stud	1	3	Rod/Stud	1	3	**RP**

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
62	Studding idler		Spring	1	3	Other	1	3	**RP**	1	3	RP
63	Studding idler		Grease	1	3	Other	1	3	Other	0	0	Eliminated
64	Studding idler		Z toothed pulley	1	3	Moulded	1	3	**RP**	1	3	RP
65	Studding idler		Studding tie bracket	1	3	RP	1	3	RP	1	3	RP
66	Studding idler		Bed corner	1	3	RP	1	3	RP	1	3	RP
67	Studding idler		Z pulley rim	1	3	RP	1	3	RP	1	3	RP
68	Studding drive	1	M5 x 40 cap	1	1	Fastener	1	1	Fastener	1	1	**RP**
69	Studding drive		M5 nut	8	8	Fastener	8	8	Fastener	8	8	**RP**
70	Studding drive		M5 washer	7	7	Fastener	7	7	Fastener	7	7	**RP**
71	Studding drive		M5 x 50	1	1	Fastener	1	1	Fastener	1	1	**RP**
72	Studding drive		M5 x 15 cap	4	4	Fastener	4	4	Fastener	4	4	**RP**
73	Studding drive		M8 nut	2	2	Fastener	2	2	Fastener	2	2	**RP**

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
74	Studding drive		M5 x 8 grub	2	2	Fastener	2	2	Fastener	2	2	**RP**
75	Studding drive		Stud 260	1	1	Rod/Stud	1	1	Rod/Stud	1	1	**RP**
76	Studding drive		Stepper motor ST5709M1208-B	1	1	Other	1	1	Other	1	1	Other
77	Studding drive		Spring	1	1	Other	1	1	**RP**	1	1	RP
78	Studding drive		Grease	1	1	Other	1	1	Other	0	0	Eliminated
79	Studding drive		Belt (Length 1750mm, pitch 2.5, width 6, thick ~1.3)	1	1	Other	1	1	Other	1	1	**RP**
80	Studding drive		Z toothed pulley	1	1	Moulded	1	1	**RP**	1	1	RP
81	Studding drive		Z pulley rim	1	1	RP	1	1	RP	1	1	RP
82	Studding drive		Z motor bracket	1	1	RP	1	1	RP	1	1	RP
83	Studding drive		Z motor coupling	1	1	RP	1	1	RP	1	1	RP

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
84	Studding drive		Vertical hole plug	1	1	RP	1	1	RP	1	1	RP
85	Studding drive		Bed corner	1	1	RP	1	1	RP	1	1	RP
86	Vertical (Z) posts	1	M5 nut	4	4	Fastener	4	4	Fastener	4	4	**RP**
87	Vertical (Z) posts		M5 x 8 grub	4	4	Fastener	4	4	Fastener	4	4	**RP**
88	Vertical (Z) posts		Rod 500	3	3	Rod/Stud	3	3	Rod/Stud	3	3	**RP**
89	Vertical (Z) posts		Rod 465	1	1	Rod/Stud	1	1	Rod/Stud	1	1	**RP**
90	Bed constraint	2	M5 x 20 cap	2	4	Fastener	2	4	Fastener	2	4	**RP**
91	Bed constraint		M5 washer	4	8	Fastener	4	8	Fastener	4	8	**RP**
92	Bed constraint		M5 nut	4	8	Fastener	4	8	Fastener	4	8	**RP**
93	Bed constraint		Bed constraint bracket	1	2	RP	1	2	RP	1	2	RP
94	Bed constraint		Bearing insert (1* '360 run', 1 * '180 Z')	1	2	RP	1	2	RP	1	2	RP

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
95	Bed assembly	1	M5 x 30	12	12	Fastener	12	12	Fastener	12	12	**RP**
96	Bed assembly		M5 nut	12	12	Fastener	12	12	Fastener	12	12	**RP**
97	Bed assembly		M5 washer	24	24	Fastener	24	24	Fastener	24	24	**RP**
98	Bed assembly		Bed	1	1	Other	4	4	**RP**	4	4	RP
99	Bed assembly		Bed clamp bracket	4	4	RP	4	4	RP	4	4	RP
100	Top X/Y frame mounting	1	M5 nut	4	4	Fastener	4	4	Fastener	4	4	**RP**
101	Top X/Y frame mounting		M5 x 8 grub	4	4	Fastener	4	4	Fastener	4	4	**RP**
102	Base diagonals	2	M5 nut	2	4	Fastener	2	4	Fastener	2	4	**RP**
103	Base diagonals		M5 x 8 grub	2	4	Fastener	2	4	Fastener	2	4	**RP**
104	Base diagonals		Stud 660	1	2	Rod/Stud	1	2	Rod/Stud	1	2	**RP**
105	Base diagonals		Diagonal tie bracket	2	4	RP	2	4	RP	2	4	RP

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
106	Y bearing housings	3	M5 nut	3	9	Fastener	3	9	Fastener	3	9	**RP**
107	Y bearing housings		M5 x 8 grub	2	6	Fastener	2	6	Fastener	2	6	**RP**
108	Y bearing housings		M5 x15 cap	1	3	Fastener	1	3	Fastener	1	3	**RP**
109	Y bearing housings		M5 washer	2	6	Fastener	2	6	Fastener	2	6	**RP**
110	Y bearing housings		Rod 70	1	3	Rod/Stud	1	3	Rod/Stud	1	3	**RP**
111	Y bearing housings		Y bearing housing	1	3	RP	1	3	RP	1	3	RP

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
112	Y bearing housings		Bearing insert (2 * '360 jam', 1 * '360 run')	1	3	RP	1	3	RP	1	3	RP
113	Y Idler rod	1	Rod 472	1	1	Rod/Stud	1	1	Rod/Stud	1	1	**RP**
114	Y Idler rod		X/Y pulley idler	2	2	RP	2	2	RP	2	2	RP
115	Y drive rod	1	M5 x15 cap	4	4	Fastener	4	4	Fastener	4	4	**RP**
116	Y drive rod		M5 nut	8	8	Fastener	8	8	Fastener	8	8	**RP**
117	Y drive rod		M5 x 8 grub	2	2	Fastener	2	2	Fastener	2	2	**RP**
118	Y drive rod		M5 washer	2	2	Fastener	2	2	Fastener	2	2	**RP**
119	Y drive rod		Rod 452	1	1	Rod/Stud	1	1	Rod/Stud	1	1	**RP**
120	Y drive rod		Stepper motor ST5709M1208-B	1	1	Other	1	1	Other	1	1	Other

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
121	Y drive rod		Y belt (Length 950, pitch 2.5, width 6, thick ~1.3)	2	2	Other	2	2	Other	2	2	**RP**
122	Y drive rod		Y toothed pulley	2	2	Moulded	2	2	**RP**	2	2	RP
123	Y drive rod		Y motor bracket	1	1	RP	1	1	RP	1	1	RP
124	Y drive rod		Y coupling (short)	1	1	RP	1	1	RP	1	1	RP
125	Y drive rod		Corner bracket vertical hole plug	2	2	RP	2	2	RP	2	2	RP
126	Y drive rod		Circlip	2	2	RP	2	2	RP	2	2	RP
127	Side diagonals	8	M8 nut	4	32	Fastener	4	32	Fastener	4	32	**RP**
128	Side diagonals		M8 washer	4	32	Fastener	4	32	Fastener	4	32	**RP**
129	Side diagonals		M5 x 8 grub	2	16	Fastener	2	16	Fastener	2	16	**RP**
130	Side diagonals		Stud 610	1	8	Rod/Stud	1	8	Rod/Stud	1	8	**RP**

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
131	Side diagonals		Diagonal tie bracket	2	16	RP	2	16	RP	2	16	RP
132	Opto switch bracket	3	M5 nut	1	3	Fastener	1	3	Fastener	1	3	**RP**
133	Opto switch bracket		M5 washer	2	6	Fastener	2	6	Fastener	2	6	**RP**
134	Opto switch bracket		M5 x 20 cap	1	3	Fastener	1	3	Fastener	1	3	**RP**
135	Opto switch bracket		Optoswitch bracket	1	3	RP	1	3	RP	1	3	RP
136	Opto switch bracket		Optoswitch	1	3	Electronics	1	3	Electronics	1	3	Electronics
137	Opto flag X	1	M5 x 30 cap	2	2	Fastener	2	2	Fastener	2	2	**RP**
138	Opto flag X		M5 nut	2	2	Fastener	2	2	Fastener	2	2	**RP**

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
139	Opto flag X		M5 washer	4	4	Fastener	4	4	Fastener	4	4	**RP**
140	Opto flag X		X PCB bracket	1	1	Electronics	1	1	Electronics	1	1	Electronics
141	Opto flag X		Y belt clamp	1	1	RP	1	1	RP	1	1	RP
142	Opto flag X		X opto flag	1	1	RP	1	1	RP	1	1	RP
143	Opto flag X		Foil	1	1	Other	1	1	Other	1	1	Other
144	Opto flag X		Adhesive	1	1	Other	0	0	**Eliminated**	0	0	Eliminated
145	Opto flag Y	1	M5 x 15 cap	1	1	Fastener	1	1	Fastener	1	1	**RP**
146	Opto flag Y		M5 nut	1	1	Fastener	1	1	Fastener	1	1	**RP**
147	Opto flag Y		M5 washer	2	2	Fastener	2	2	Fastener	2	2	**RP**
148	Opto flag Y		Y opto flag	1	1	RP	1	1	RP	1	1	RP
149	Opto flag Y		Foil	1	1	Other	1	1	Other	1	1	Other
150	Opto flag Y		Adhesive	1	1	Other	0	0	**Eliminated**	0	0	Eliminated

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
151	Opto flag Z	1	M5 x 15 cap	1	1	Fastener	1	1	Fastener	1	1	**RP**
152	Opto flag Z		M5 x 20 cap	1	1	Fastener	1	1	Fastener	1	1	**RP**
153	Opto flag Z		M5 nut	2	2	Fastener	2	2	Fastener	2	2	**RP**
154	Opto flag Z		M5 washer	4	4	Fastener	4	4	Fastener	4	4	**RP**
155	Opto flag Z		Z opto flag	1	1	RP	1	1	RP	1	1	RP
156	Opto flag Z		Z opto flag base	1	1	RP	1	1	RP	1	1	RP
157	Opto flag Z		Foil	1	1	Other	1	1	Other	1	1	Other
158	Opto flag Z		Adhesive	1	1	Other	0	0	**Eliminated**	0	0	Eliminated
159	Extruder PCB	1	M3 x 15 cap	2	2	Fastener	2	2	Fastener	2	2	**RP**
160	Extruder PCB		M3 nut	2	2	Fastener	2	2	Fastener	2	2	**RP**
161	Extruder PCB		M3 washer	4	4	Fastener	4	4	Fastener	4	4	**RP**
162	Extruder PCB		Extruder PCB	1	1	Electronics	1	1	Electronics	1	1	**RP**

				Current design			Post 1 year development			Post 2 year development		
Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
163	X stepper PCB	1	M3 x 15 cap	2	2	Fastener	2	2	Fastener	2	2	**RP**
164	X stepper PCB		M3 nut	2	2	Fastener	2	2	Fastener	2	2	**RP**
165	X stepper PCB		M3 washer	4	4	Fastener	4	4	Fastener	4	4	**RP**
166	X stepper PCB		Stepper PCB	1	1	Electronics	1	1	Electronics	1	1	**RP**
167	Y/Z/Comms board	3	M3 x 25 cap	2	6	Fastener	2	6	Fastener	2	6	**RP**
168	Y/Z/Comms board		M3 nut	2	6	Fastener	2	6	Fastener	2	6	**RP**
169	Y/Z/Comms board		M3 washer	4	12	Fastener	4	12	Fastener	4	12	**RP**
170	Y/Z/Comms board		Stepper/Comms PCB	1	3	Electronics	1	3	Electronics	1	3	**RP**
171	Y/Z/Comms board		PCB mount	2	6	RP	2	6	RP	2	6	RP
172	Fan	1	M5 nut	1	1	Fastener	1	1	Fastener	1	1	**RP**
173	Fan		M5 washer	1	1	Fastener	1	1	Fastener	1	1	**RP**
174	Fan		M5 x 20 cap	1	1	Fastener	1	1	Fastener	1	1	**RP**

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
175	Fan		M3 nut	1	1	Fastener	1	1	Fastener	1	1	**RP**
176	Fan		M3 washer	2	2	Fastener	2	2	Fastener	2	2	**RP**
177	Fan		M3 x 30 cap	1	1	Fastener	1	1	Fastener	1	1	**RP**
178	Fan		Fan	1	1	Other	1	1	Other	1	1	Other
179	Fan		Fan leg	1	1	RP	1	1	RP	1	1	RP
180	Fan		Fan base	1	1	RP	1	1	RP	1	1	RP
181	Extruder fastening	1	M5 x 20 cap	2	2	Fastener	2	2	Fastener	2	2	**RP**
182	Extruder fastening		M5 x 30 cap	1	1	Fastener	1	1	Fastener	1	1	**RP**
183	Extruder fastening		M5 washer	6	6	Fastener	6	6	Fastener	6	6	**RP**
184	Extruder fastening		M5 nut	3	3	Fastener	3	3	Fastener	3	3	**RP**
185	Extruder	1	Clamp	1	1	RP	1	1	RP	1	1	RP
186	Extruder		Motor holder	1	1	RP	1	1	RP	1	1	RP

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
187	Extruder		Hex drive	1	1	RP	1	1	RP	1	1	RP
188	Extruder		Polymer holder	1	1	RP	1	1	RP	1	1	RP
189	Extruder		Screw holder	1	1	RP	1	1	RP	1	1	RP
190	Extruder		PTFE barrel holder, 16mm PTFE rod	1	1	Other	1	1	Other	1	1	**RP**
191	Extruder		Extruder PCB	1	1	Electronics	1	1	Electronics	1	1	**RP**
192	Extruder		200:1 geared motor	1	1	Other	1	1	Other	1	1	Other
193	Extruder		Heater barrel: M6 brass/steel/Al studding	1	1	Rod/Stud	1	1	Rod/Stud	1	1	**RP**
194	Extruder		200mm Heater wire, 0.2mm nichrome	1	1	Other	1	1	Other	1	1	Other
195	Extruder		M6 dome nut	1	1	Fastener	1	1	Fastener	1	1	**RP**

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
196	Extruder		Thermistor, glass bead type	1	1	Other	1	1	Other	1	1	Other
197	Extruder		Screw drive, M5 steel studding	1	1	Rod/Stud	1	1	Rod/Stud	1	1	**RP**
198	Extruder		Flexible coupling, 3mm steel wire	1	1	Other	0	0	**Eliminated**	0	0	Eliminated
199	Extruder		Solder	1	1	Other	0	0	**Eliminated**	0	0	Eliminated
200	Extruder		M5 Drive nut	1	1	Fastener	1	1	Fastener	1	1	**RP**
201	Extruder		PCB screw, M3 15mm cap screw	1	1	Fastener	1	1	Fastener	1	1	**RP**
202	Extruder		M3 x 25 cap	4	4	Fastener	4	4	Fastener	4	4	**RP**
203	Extruder		M3 x 35 cap	7	7	Fastener	7	7	Fastener	7	7	**RP**

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
204	Extruder		Guide screws, 55mm M3 studding	4	4	Fastener	4	4	Fastener	4	4	**RP**
205	Extruder		M4 x 30 cap	1	1	Fastener	1	1	Fastener	1	1	**RP**
206	Extruder		M4 washer	2	2	Fastener	2	2	Fastener	2	2	**RP**
207	Extruder		M4 nut	2	2	Fastener	2	2	Fastener	2	2	**RP**
208	Extruder		M3 nut	20	20	Fastener	20	20	Fastener	20	20	**RP**
209	Extruder		M3 washers	34	34	Fastener	34	34	Fastener	34	34	**RP**
210	Extruder		Spring	1	1	Other	1	1	**RP**	1	1	RP
211	Extruder		Grease	1	1	Other	1	1	Other	0	0	**Eliminated**
212	Extruder		High-temp epoxy, JB Weld	1	1	Other	1	1	Other	1	1	Other
213	Extruder		Plumber's thread seal tape, 100mm, PTFE	1	1	Other	1	1	Other	1	1	Other

Ref	Sub-Assembly (S.A.)	S.A. qty	Part	Current design			Post 1 year development			Post 2 year development		
				Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type	Qty per S.A.	Total qty	Type
214	Wiring	1	Wire	1	1	Electronics	1	1	Electronics	1	1	Electronics
215	Wiring		Power supply	1	1	Electronics	1	1	Electronics	1	1	Electronics
216	Wiring		Cable ties	25	25	Other	25	25	**RP**	25	25	RP

13.7   Suppliers

For extruder servo motors (specifically the GM3 version):

Solarbotics Ltd,
201 35th Ave NE,
Calgary,
AB T2E2K5,
Canada
http://www.solarbotics.com/

For general electronic components:

RS,
Electrocomponents plc,
International Management Centre,
8050 Oxford Business Park North,
Oxford OX4 2HW,
United Kingdom
http://uk.rs-online.com/web/

Farnell,
Canal Road,
Leeds,
LS12 2TU,
http://uk.farnell.com/

The RepRap Research Foundation
111 E 14th St
PMB #166
New York, NY 10003

13.8   Core RepRap project team members

Adrian Bowyer (author's supervisor): Founder and leader of the RepRap project.

Vik Olliver: programmer/developer with workshops in the Waitakere rainforest.

Ed Sells (author): postgraduate in the Mechanical Engineering Department at Bath.

Simon McAuliffe: software and electronics developer from New Zealand.

Chris Palmer: software developer and electronics designer in the North West of England.

Seb Baillard: physics grad student located in the wilds of Canada.

Ian Adkins: mechatronics engineer.

Forrest Higgs: a former professor and research scientist in building science, California central coast.

Johnathon Marsden: Java host software and C firmware specialist.

Michael Hart: founder of the Project Gutenberg and is interested in RepRap for its potential as a disruptive technology.

Zach Smith: computer programmer and electronics developer, New York.

Steve DeGroof: computer programmer and electronics developer, North Carolina.

13.9 RepRap software parameters

Table 21 defines the parameters needed in the RepRap software. Definitions have been taken from Bowyer's documentation on the project wiki. Those parameters critical to print quality have been identified in the second column.

Table 21: Parameters for the RepRap software (at the time of writing)

Parameter for RepRap software: <Parameter name>=<Default value>	Critical to print quality?	Definition
AxisCount=3		The number of Cartesian axes in the machine.
BackColourB(0..1)=0.9, BackColourG(0..1)=0.9, BackColourR(0..1)=0.9		The RGB values of the background in the graphics window.
BackFactor=2.0		A viewcone parameter needed for Java 3D.
BaudRate=19200		The communications speed between the host computer and the RepRap microcontroller.
BoundFactor=3.0		A viewcone parameter needed for Java 3D.
CommsDebug=false		Setting this true will cause each message to and from the RepRap machine also to be written to System.out.
Debug=false		Setting this true will cause each action the host makes the RepRap do to be written to System.out.
DisplaySimulation=false		Setting this true will cause a new window to be opened in which each segment laid down by the RepRap machine is represented as a long thin box of the right dimensions, so you can see the

Parameter for RepRap software: <Parameter name>=<Default value>	Critical to print quality?	Definition
		build happening on the computer's screen as well as in the machine itself. To stop instructions being sent to the RepRap machine and just do a simulation, see RepRap_Machine below.
FastSpeed(0..255)=240		Legacy. The fastest rate that the PIC X/Y steppers can be stepped.
FoundationLayers=4	✓	The number of layers of material to put down under the object being built before building proper starts. Set this to -1 to suppress the laying down of foundations.
FrontFactor=0.001		A viewcone parameter needed for Java 3D.
GCodeUseSerial=false		Setting this true causes the code to send G-codes direct to the RepRap machine (as opposed to writing them to a file) from communications port Port (see below).
IdleZAxis=true		Legacy. Causes the PIC to turn off the current to the Z-axis stepper when there is no vertical movement.
InterLayerCooling=true	✓	Setting this true causes RepRap to turn on the cooling fan between layers to freeze/set the build material being used. See Extruder0_CoolingPeriod(s) below.
MachineColourB(0..1)=0.3, MachineColourG(0..1)=0.4, MachineColourR(0..1)=0.3		The colour of the RepRap build bed in the graphics window.
MaximumFeedrateX(mm/minute)=1600	✓	The fastest speed that the X axis can be driven at without stalling or missing steps.

Parameter for RepRap software: <Parameter name>=<Default value>	Critical to print quality?	Definition
MaximumFeedrateY(mm/minute)=1600	✓	The fastest speed that the Y axis can be driven at without stalling or missing steps.
MaximumFeedrateZ(mm/minute)=50	✓	The fastest speed that the Z axis can be driven at without stalling or missing steps.
MouseTranslationFactor=50		A scaling factor for mouse movements in 3D in the graphics window.
MouseZoomFactor=50		A scaling factor for mouse movements in 3D in the graphics window.
MovementSpeedZ(0..255)=240		Legacy. The speed to move the Z axis on the PIC controlled machine.
NumberOfExtruders=1		How many extruders are in use. Note that you can use the same extruder more than once. That is to say you can copy all the parameters of Extruder0 (say), call them Extruder1, and edit them to get different behavior (leaving the address the same - see below). Then you can flip between the two when you load objects to build.
Port(name)=/dev/ttyUSB0		The port on the host computer that is connected to the RepRap machine.
RadiusFactor=0.7		Another Java 3D parameter. This sets the size of the world that you're looking at.
RememberWindowPosition=false		When set true, forces the system to put the RepRap back where it was and the same size after you've folded it away.
RepRap_Machine=GCodeRepRap		The type of RepRap machine attached to the host computer. This decides the encoding of the information sent from the host. Valid types are: GCodeRepRap, SNAPRepRap, and Simulator.

Parameter for RepRap software: \<Parameter name>=\<Default value>	Critical to print quality?	Definition
SelectedColourB(0..1)=0.2, SelectedColourG(0..1)=0.2, SelectedColourR(0..1)=0.6		When you load an object to be printed onto the picture of the RepRap build area, then select it with the mouse so you can slide it about, this decides what colour it will change to to indicate that you have selected it.
Subtractive=false		Set this true if you have a cutting head, rather than an extruder, in your RepRap. Experimental...
UnselectedColourB(0..1)=0.3, UnselectedColourG(0..1)=0.3, UnselectedColourR(0..1)=0.3		The default colour of an object to be built when it's not selected. This is overridden by Extruder0_ColourB/G/R (see below).
WorkingLocation=reprap-wv.stl		The file containing the stl for the model of the RepRap build base that appears in the graphics window.
WorkingOffsetX(mm)=-17.3, WorkingOffsetY(mm)=-24.85, WorkingOffsetZ(mm)=-2		The position of the bottom left hand corner of WorkingLocation (see above) relative to (0, 0, 0).
WorkingX(mm)=300, WorkingY(mm)=300, WorkingZ(mm)=300		The lengths of movement in the three directions. There is a bug in the code that handles these, so they are set to a nominal 300mm each at the moment.
WorldName=RepRap-World		An internal label that is used as the root of the Java 3D graphics object tree.
XAxisAddress=2		The address of the X-axis stepper controller. These addresses are used by the Arduino to decide what physical device the host is talking to.

Parameter for RepRap software: <Parameter name>=<Default value>	Critical to print quality?	Definition
XAxisScale(steps/mm)=7.99735	✓	The number of X stepper-motor steps needed to move 1 mm. A good way to set this is to get the machine to build a long thin brick 100 mm long and a few mm deep and high. Then measure the object with accurate vernier calipers (giving length L, say) and change this value accordingly: $XAxisScale_{new} = XAxisScale_{old}.L/100$.
XAxisTorque(%)=100		Legacy. The power to sent to the X-stepper coils. This is now controlled by a potentiometer on the stepper controller board.
X/YReZeroInterval(mm)=-1	✓	Repeatedly stop building and re-zero the X and Y axes against the opto endstops after this distance of movement. Set this negative to suppress this behaviour. The axes are re-zeroed between each layer anyway.
YAxisAddress=3		The address of the Y-axis stepper controller. These addresses are used by the Arduino to decide what physical device the host is talking to.
YAxisScale(steps/mm)=7.99735	✓	The number of Y stepper-motor steps needed to move 1 mm. See XAxisScale above for how to set this.
YAxisTorque(%)=100		Legacy. The power to sent to the Y-stepper coils. This is now controlled by a potentiometer on the stepper controller board.
ZAxisAddress=4		The address of the Z-axis stepper controller. These addresses are used by the Arduino to decide what physical device the host is talking to.

Parameter for RepRap software: <Parameter name>=<Default value>	Critical to print quality?	Definition
ZAxisScale(steps/mm)=320	✓	The number of Z stepper-motor steps needed to move 1 mm.
ZAxisTorque(%)=100		Legacy. The power to sent to the Z-stepper coils. This is now controlled by a potentiometer on the stepper controller board.
Extruder0_Address=8		The address of the extruder. These addresses are used by the Arduino to decide what physical device the host is talking to.
Extruder0_AngleSpeedFactor(0..1)=0.5		Legacy. Go faster round angles/changes of direction in the path according to this: relative speed = 1 - 0.5*(1 + cos(angle))*AngleSpeedFactor. See also X/YFeedrate (below).
Extruder0_AngleSpeedLength(mm)=-1		Legacy. The distance either side of a change of direction to speed up for. Set this negative to suppress this behaviour.
Extruder0_ArcCompensationFactor(0..)=10	✓	When the extruder moves in an arc, too much material is laid down on the inside, and not enough on the outside. This factor extends the radius of the toolpath depending on how tight the original radius is.
Extruder0_ArcShortSides(0..)=1	✓	To detect and arc from an STL file (which describes shapes in triangular facets) in order to effect the above parameter, a maximum segment length for an arc must be defined.
Extruder0_Beta(K)=550.0		The beta value of the thermistor used to measure the temperature of the extruder.
Extruder0_Capacitor(F)=0.000003		The capacitor value in the PIC controller used to time the resistance of the thermistor.

Parameter for RepRap software: <Parameter name>=<Default value>	Critical to print quality?	Definition
Extruder0_ColourB(0..1)=0.6, Extruder0_ColourG(0..1)=0.3, Extruder0_ColourR(0..1)=0.3		The colour of objects made by the material in this extruder in the graphics window.
Extruder0_CoolingPeriod(s)=1	✓	The time to turn the cooling fan on between layers. Set this negative to suppress cooling between layers.
Extruder0_ExtrusionBroadWidth(mm)=2.0	✓	The gap between the infill zig-zag pattern used to fill the interior of an object when coarse infill is being used. Set this negative to suppress coarse infill.
Extruder0_ExtrusionDelayForLayer(ms)=1000	✓	For the first use of the extruder in a layer the time delay between turning on the extruder motor and starting to move the extruder to lay down material. See also ValveDelayForLayer (below).
Extruder0_ExtrusionDelayForPolygon(ms)=200	✓	For the second and all subsequent use of the extruder in a layer the time delay between turning on the extruder motor and starting to move the extruder to lay down material. See also ValveDelayForPolygon (below).
Extruder0_ExtrusionFoundationWidth(mm)=2	✓	The gap between the infill zig-zag pattern used to fill the interior of the foundations (if any).
Extruder0_ExtrusionHeight(mm)=0.4	✓	The depth of each layer.
Extruder0_ExtrusionInfillWidth(mm)=0.8	✓	The gap between the infill zig-zag pattern used to fill the interior of an object when fine infill is being used.

Parameter for RepRap software: \<Parameter name>=\<Default value>	Critical to print quality?	Definition
Extruder0_ExtrusionLastFoundationWidth(mm)=1	✓	The gap between the infill zig-zag pattern used to fill the interior of the last layer of the foundations (if any).
Extruder0_ExtrusionOverRun(mm)=3	✓	The distance before the end of a sequence of infill or outline depositions to turn off the extruder motor. See also ValveOverRun (below).
Extruder0_ExtrusionSize(mm)=0.66	✓	The width of the filament laid down by the extruder.
Extruder0_ExtrusionSpeed(0..255)=215	✓	The PWM signal to send the extruder motor, as a fraction of 255. If there is no motor in use, set this negative. See also Extruder0_t0 (below).
Extruder0_ExtrusionTemp(C)=240	✓	The temperature to run the extruder at.
Extruder0_IncrementedStart=true	✓	When plotting a layer, start each polygon one edge further round on successive layers. This stops all the start points lining up for a vertically-sided object and can improve quality. See also RandomStart below.
Extruder0_InfillOverlap(mm)=0.2	✓	The amount to make the infill and outline overlap. This causes the two to weld together. You can set it negative and make a gap instead.
Extruder0_InfillSpeed(0..1)=0.45	✓	The fraction of the fastest extruder X/Y speed to do the infill at. See also X/YFeedrate (below).
Extruder0_LowerFineLayers(0...)=2	✓	Give this many layers at the bottom of the object fine infill.

Parameter for RepRap software: <Parameter name>=<Default value>	Critical to print quality?	Definition
Extruder0_MaterialType(name)=ABS	✓	The name of the material in use.
Extruder0_MaxSpeed(0..255)=255	✓	The maximum value of Extruder0_ExtrusionSpeed (see above). If you have an extruder motor with a rated voltage below 12v this allows you to protect it. For 12v motors, just set this to 255.
Extruder0_MinimumZClearance(mm)=0.5	✓	When moving over the build bed while not laying down material, don't move below this height. If you set this negative, then the head stays at the same level all the time for each layer. That's to say it doesn't lift for fast no-print moves. For some materials (ABS, for example) this can give a quicker and better result. For others (polycaprolactone, for example) it makes a mess...
Extruder0_NozzleClearTime(s)=10	✓	When nozzle wiping, run the extruder for this time between layers to get it working again.
Extruder0_NozzleWaitTime(s)=0	✓	After clearing, wait for this time before doing anything else.
Extruder0_NozzleWipeDatumX(mm)=26		The X coordinate to move to at the start of the nozzle-wipe sequence.
Extruder0_NozzleWipeDatumY(mm)=0.5		The Y coordinate to move to at the start of the nozzle-wipe sequence.
Extruder0_NozzleWipeEnabled=true	✓	Set false to suppress nozzle wiping.
Extruder0_NozzleWipeFreq=1	✓	How many times to wipe the nozzle.
Extruder0_NozzleWipeStrokeX(mm)=0	✓	How far to move in X to wipe the nozzle.

Parameter for RepRap software: \<Parameter name\>=\<Default value\>	Critical to print quality?	Definition
Extruder0_NozzleWipeStrokeY(mm)=21.5	✓	How far to move in Y to wipe the nozzle.
Extruder0_NumberOfShells(0..N)=1	✓	Normally (when this is 1) RepRap puts one outline round each layer before infilling it. You can create multiple outlines (or none) by changing this value.
Extruder0_OffsetX(mm)=0, Extruder0_OffsetY(mm)=0, Extruder0_OffsetZ(mm)=0		The offset of the extruder from (0, 0, 0) when the extruder is parked in X and Y. This is used to get multiple extruders in registration.
Extruder0_OutlineSpeed(0..1)=0.25	✓	The fraction of the fastest extruder X/Y speed to do the outline at. See also X/YFeedrate (below).
Extruder0_PauseBetweenSegments=false	✓	If true, wait for the user to mouse-click between each straight line segment being laid down.
Extruder0_RandomStart=false	✓	When plotting a layer, start each polygon at a random vertex on successive layers. This stops all the start points lining up for a vertically-sided object and can improve quality. See also IncrementedStart above.
Extruder0_Reverse(ms)=0	✓	The time to reverse the extruder motor when it is turned off, drawing the extrudate back into it.
Extruder0_Rz(ohms)=4837		The resistance of the thermistor used to measure the temperature of the extruder at 0°C. For an Arduino controller set this to 4837 *regardless of what thermistor you actually use*.
Extruder0_SeparationFraction(0..1)=0.5	✓	When building foundations, make the level of the last foundation layer this fraction of a layer

Parameter for RepRap software: <Parameter name>=<Default value>	Critical to print quality?	Definition
		thickness above the previous one. This leaves a slightly bigger gap under the part being built, making it easier to separate the two.
Extruder0_SeparationInfillSpeed(0..1)=0.45	✓	The fraction of the fastest extruder X/Y speed to do the infill at for the first layer after the foundations. See also X/YFeedrate (below).
Extruder0_SeparationOutlineSpeed(0..1)=0.25	✓	The fraction of the fastest extruder X/Y speed to do the outline at for the first layer after the foundations. See also X/YFeedrate (below).
Extruder0_ShortLength(mm)=-1		Legacy. For line segments this long or shorter speed up according to ShortSpeed (below).
Extruder0_ShortSpeed(0..1)=0.35		Legacy. For line segments under ShortLength (above) lay down at this fraction of the fastest extruder X/Y speed.
Extruder0_UpperFineLayers(0...)=2	✓	Give this many layers at the top of the object fine infill.
Extruder0_ValveDelayForLayer(ms)=200	✓	For the first use of the extruder in a layer the time delay between opening the extruder valve and starting to move the extruder to lay down material. See also ExtrusionDelayForLayer (above).
Extruder0_ValveDelayForPolygon(ms)=200	✓	For the second and all subsequent use of the extruder in a layer the time delay between opening the extruder valve and starting to move the extruder to lay down material. See also ExtrusionDelayForPolygon (above).
Extruder0_ValveOverRun(mm)=2	✓	The distance before the end of a sequence of infill or outline depositions to close the extruder valve. See also ExtrusionOverRun (above).

Parameter for RepRap software: \<Parameter name>=\<Default value>	Critical to print quality?	Definition
Extruder0_ValvePulseTime(ms)=-1	✓	The time to pulse the valve to open or close it. Set this negative if no valve is in use.
Extruder0_X/YFeedrate(mm/minute)=420	✓	The fastest movements in the X/Y directions that this extruder can move at. This is used as the basis for all other movements, which are expressed as a fraction (which can be 1) of this. When the extruder is being moved in-air and is not laying down material, this speed is used.
Extruder0_hb(C)=20		Legacy. The base temperature for PIC extruder heater power settings. This is usually room temperature. This is not used in the Arduino.
Extruder0_hm(C/pwr)=0.86		Legacy. The equilibrium temperature of the extruder for one PWM increment (out of 255) driving the heater. This is not used in the Arduino.
Extruder0_t0(0..255)=0	✓	The PWM value below which the extruder motor will not turn. See ExtrusionSpeed (above).

13.10 Mechanical illustrations

This section illustrates Darwin's design with a focus on the parts specifically designed for self-manufacture using the FFF process. Documentation begins with a general assembly of the machine (Figure 101, on the following page). Subassemblies are then illustrated to identify the positions of the self-manufactured parts. After the subassembly diagrams the self-manufactured parts are illustrated individually. All illustrations are isometric.

Digital descriptions have been included in the DVD which accompanies this thesis:

- STL files of the self-manufactured parts. This data can be used to automatically make the self- manufactured components using the FFF process, or any other RP process.

- SolidEdge (version 19) and STEP files: both define a parametric model of the assembly for development.

13.10.1 Sub-assemblies

The following subassemblies have been included to illustrate the functions of the components in the Darwin's general assembly. Illustrations of the assemblies are not to scale.

Note: Sub-assembly references will either refer to a further sub-assembly (in which case a section and page number will be given), or to an illustration of the self-manufactured part (SMP). In the latter case the SMP number will be given, along with the page number for the identification table. As this thesis is focussed on the self-manufacturing aspect, individual illustrations of imported parts will not be given in this section. However, these imported parts are listed in the bill of materials in Section 13.6, page 196, and digital part descriptions have been included on the DVD which accompanies this thesis.

All any references to measurements are made in millimetres.
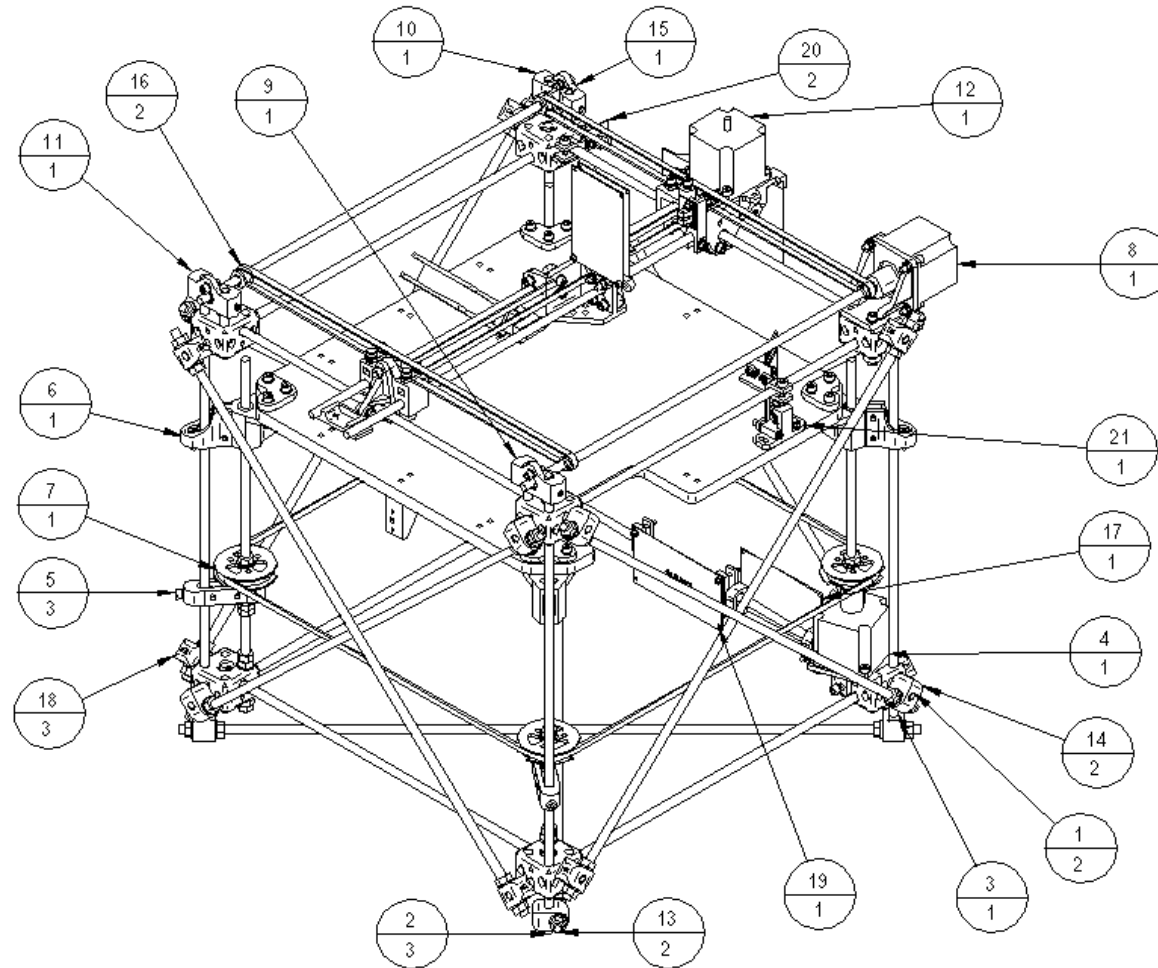
Figure 101: General Assembly for Darwin

Table 22: Parts list for Darwin's general assembly

Item Number	Part/SA for G.A.	Quantity	Detail Section	Page
1	X/Y frame SA	2	13.10.1.1	238
2	Z bar long	3	-	-
3	Z bar short	1	-	-
4	Z motor SA	1	13.10.1.2	239
5	Z stud idler SA	3	13.10.1.3	240
6	Bed SA	1	13.10.1.4	241
7	Z belt	1	-	-
8	Y motor SA	1	13.10.1.5	242
9	Y bearing assembly running fit SA	1	13.10.1.6	244
10	Y bearing assembly jam SA (left hand)	1	0	244
11	Y bearing assembly jam SA (right hand)	1	13.10.1.8	244
12	X axis SA	1	13.10.1.9	245
13	Diagonal base SA	2	13.10.1.10	246
14	Diagonal vertical SA	2	13.10.1.11	246
15	Y idler SA	1	13.10.1.12	247
16	Y belt	2	-	-
17	Universal PCB SA	1	13.10.1.13	248
18	Side diagonal SA	3	13.10.1.11	246
19	Comms-Power PCB SA	1	13.10.1.13	248
20	Optoswitch SA	2	13.10.1.14	249
21	Z flag SA	1	13.10.1.15	250

13.10.1.1   *X/Y frame SA*
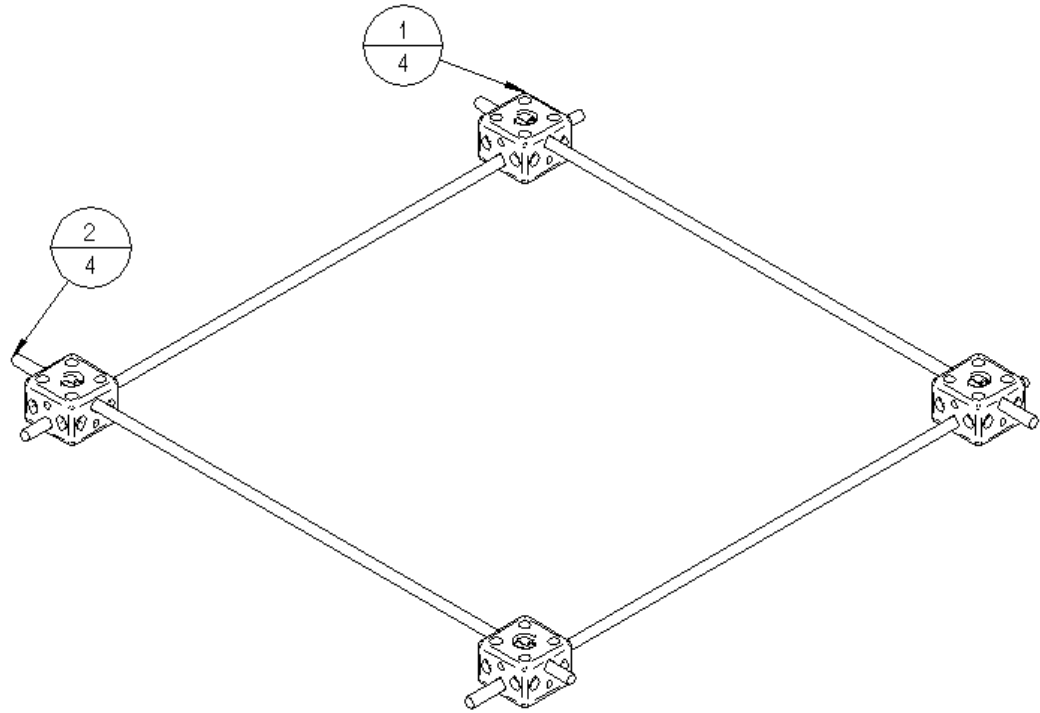
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	Corner bracket	4	13.10.2	Page 261 SMP #: 8
2	X/Y frame bar	4	-	-

13.10.1.2   Z motor SA
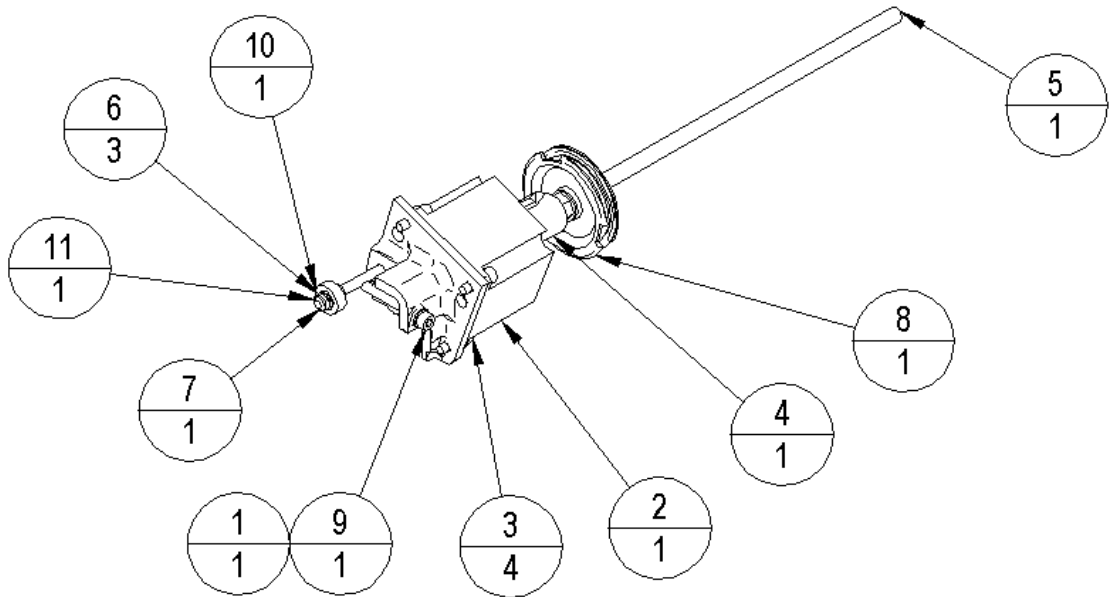
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	Z motor bracket	1	13.10.2	Page 261 SMP #: 31
2	Motor, stepper ST5709S1208-B plain shaft	1		
3	M5 socket bolt x 15	4		
4	Z motor coupling	1	13.10.2	Page 261 SMP #: 32
5	Z studding drive	1		
6	M5 washer	3		
7	M5 socket bolt x 50	1		
8	Z pulley toothed SA	1	13.10.1.16	Page 252
9	M5 socket bolt x 40	1		
10	Corner bracket vertical plug	1	13.10.2	Page 261 SMP #: 9
11	M5 nut	1		

13.10.1.3   *Z stud idler SA*
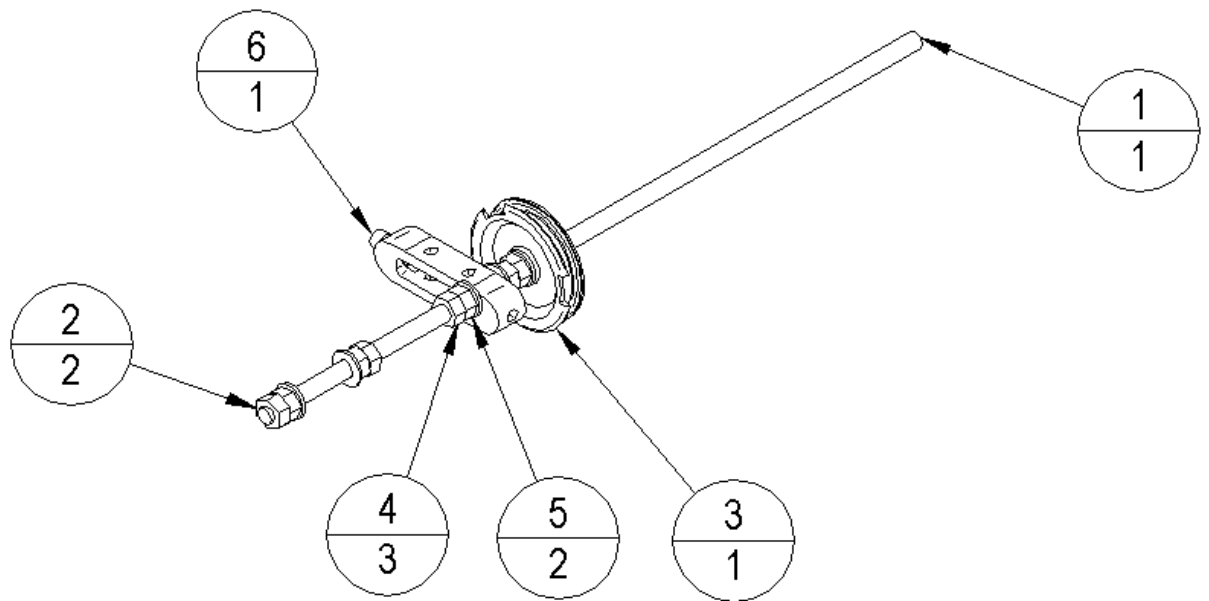
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	Z studding idler	1		
2	M8 double locked nuts and washer	2		
3	Z pulley toothed SA	1	13.10.1.16	Page 252
4	M8 nut	3		
5	M8 washer	2		
6	Z studding tie SA	1	13.10.1.17	Page 253

13.10.1.4   Bed SA
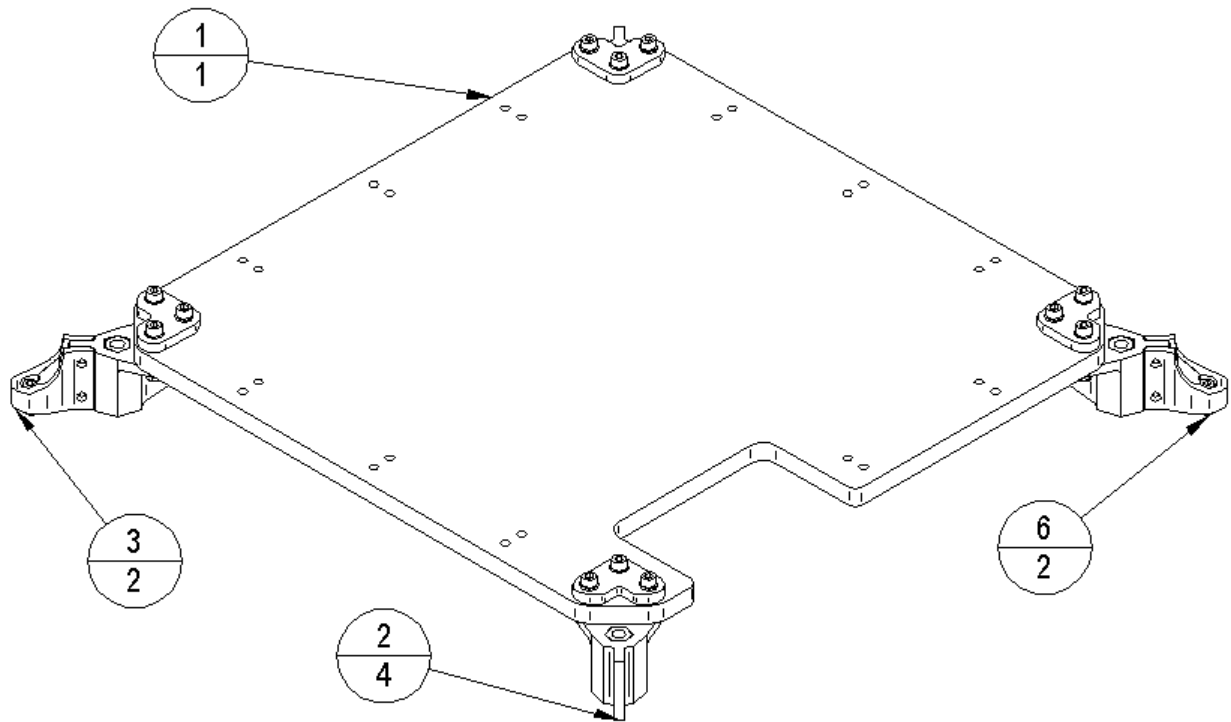
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	Bed	1		
2	Bed corner SA	4	13.10.1.18	Page 254
3	Bed constraint bracket	2	13.10.2	Page 261 SMP #: 6
4*	Bearing insert 180 Z	1	13.10.2	Page 261 SMP #: 2
5*	Bearing insert 360 run	1	13.10.2	Page 261 SMP #: 4
6	M5 x 15 plus washer	2		
7*	M5 washer	2		
8*	M5 nut	2		

* 4 & 5 rest in 3, constrained by 7 & 8

13.10.1.5   Y motor SA
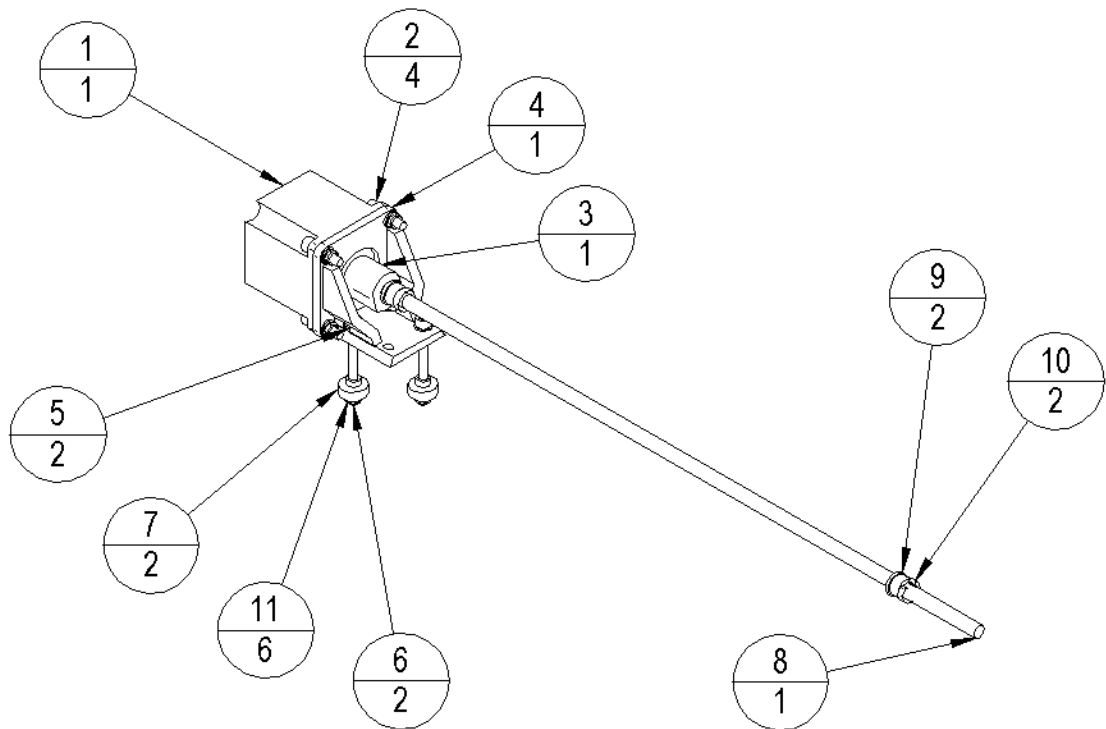
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	Motor stepper ST5709S1208-B plain shaft short	1		
2	M5 socket bolt x 20	4		
3	Y motor coupling	1	13.10.2	Page 261 SMP #: 26
4	Y motor bracket	1	13.10.2	Page 261 SMP #: 25
5	M5 washer	2		
6	M5 socket bolt x 50	2		
7	Corner bracket vertical bolt plug	2	13.10.2	Page 261 SMP #: 9
8	Y bar drive	1		
9	Y pulley toothed	2		

10	Circlip M8	2		
11	M5 nut and washer	6		

13.10.1.6 *Y bearing assembly running fit SA*
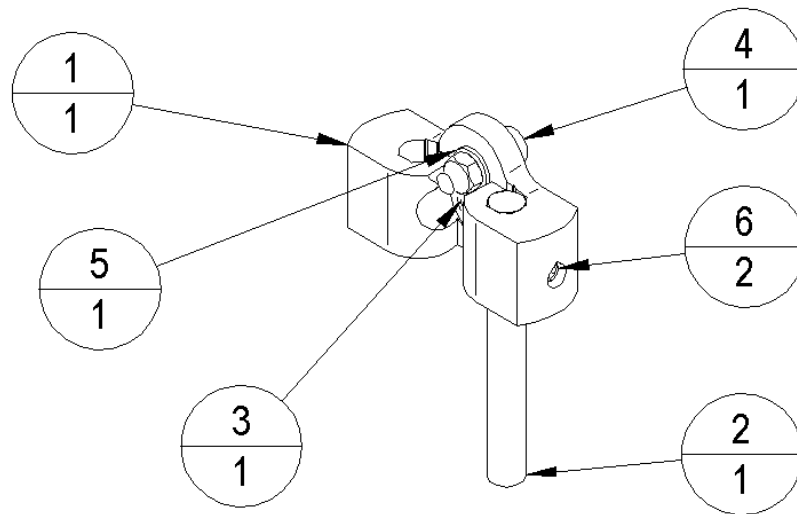
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	Y bearing housing	1	13.10.2	Page 261 SMP #: 23
2	Y post	1		
3	Bearing insert 360 run	1	13.10.2	Page 261 SMP #: 4
4	M5 x 15 plus washer	1		
5	M5 nut and washer	1		
6	M5 nut and grub	2		

13.10.1.7 *Y bearing assembly jam fit SA (left hand)*

Same assembly as SA in Section 13.10.1.6, but 'Bearing insert 360 run' is replaced with 'Bearing insert 360 jam'.

13.10.1.8 *Y bearing assembly jam fit SA (right hand)*

Same assembly as SA in Section 13.10.1.7, but 'Y post' is mounted in opposite housing hole.

13.10.1.9   X axis SA
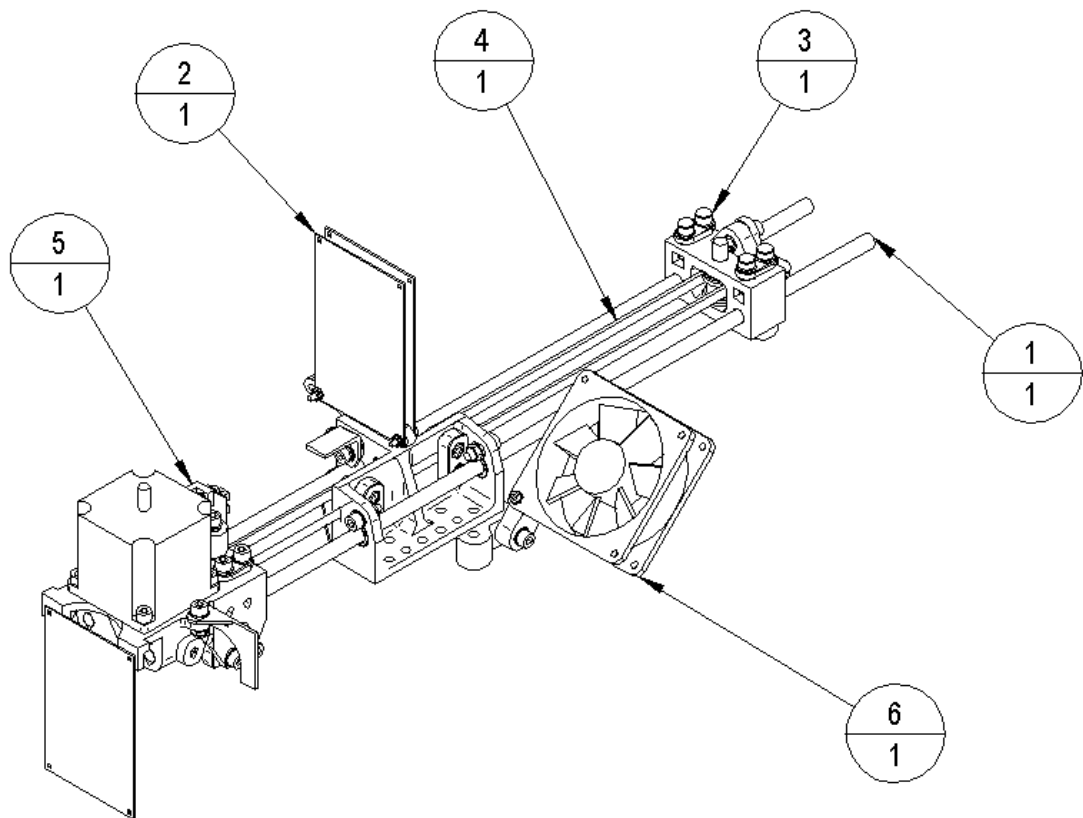
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	X motor bracket SA	1	13.10.1.19	Page 255
2	X carriage SA	1	13.10.1.20	Page 257
3	X idler end SA	1	13.10.1.21	Page 259
4	X belt	1		
5	Optoswitch SA	1	13.10.1.14	Page 249
6	Fan SA	1		

13.10.1.10   Side diagonal SA
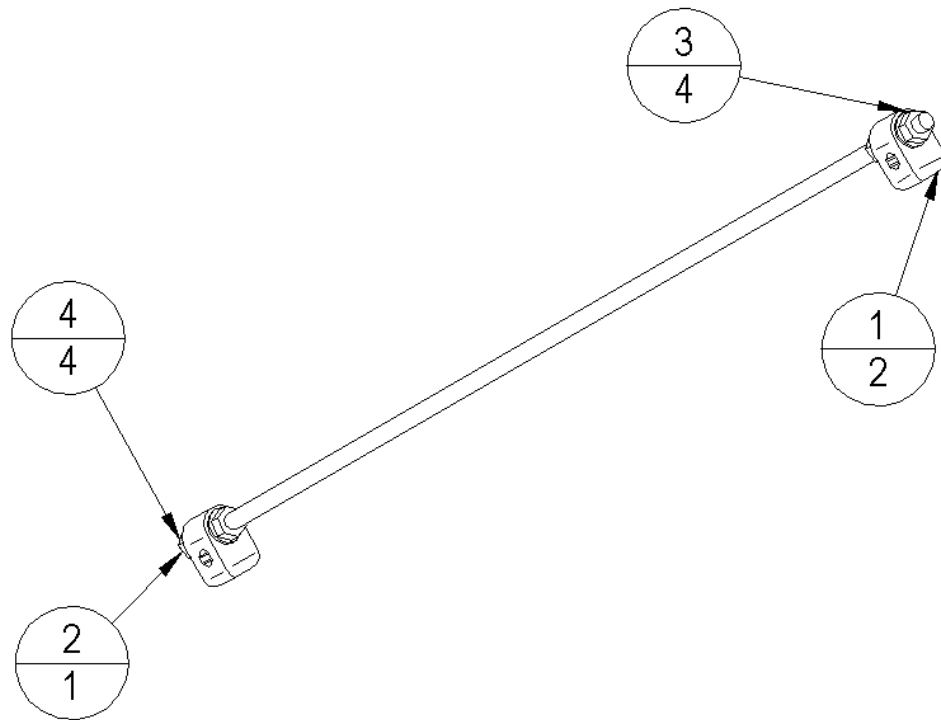
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	Diagonal tie bracket	2	13.10.2	Page 261 SMP #: 10
2	M8 Studding x 660	1		
3	M8 washer	4		
4	M8 nut	4		

13.10.1.11   Diagonal vertical SA

Same assembly as SA in Section 13.10.1.10, but 'M8 Studding x 660' is replaced with 610 length.

13.10.1.12   Y idler SA
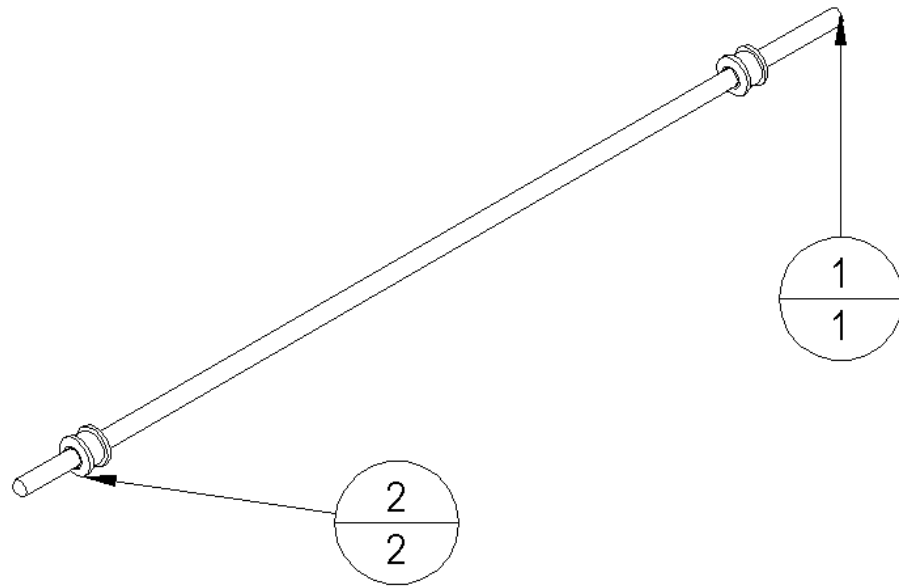
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	Y bar idler	1		
2	X/Y pulley idler	2	13.10.2	Page 261 SMP #: 22

13.10.1.13   PCB bracket SA
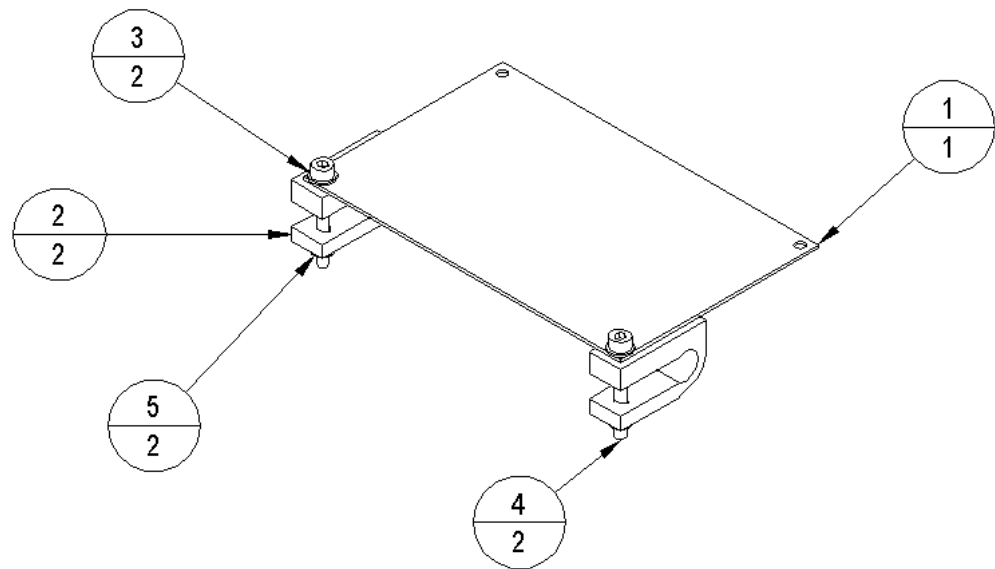
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	Universal PCB	1		
2	PCB clamp	2	13.10.2	Page 261 SMP #: 14
3	M3 washer	2		
4	M3 cap x 25	2		
5	M3 nut and washer	2		

13.10.1.14   Optoswitch SA
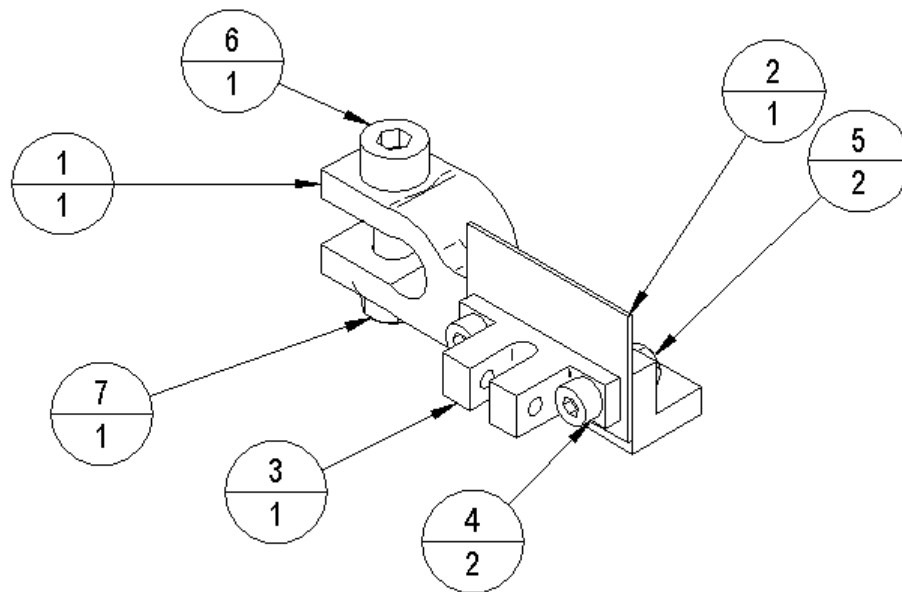
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	Optoswitch bracket	1	13.10.2	Page 261 SMP #: 13
2	Opto PCB	1		
3	Optoswitch RS304560	1		
4	M3 cap x 10	2		
5	M3 nut and washer	2		
6	M5 socket bolt x 20	1		

13.10.1.15　　Z flag SA
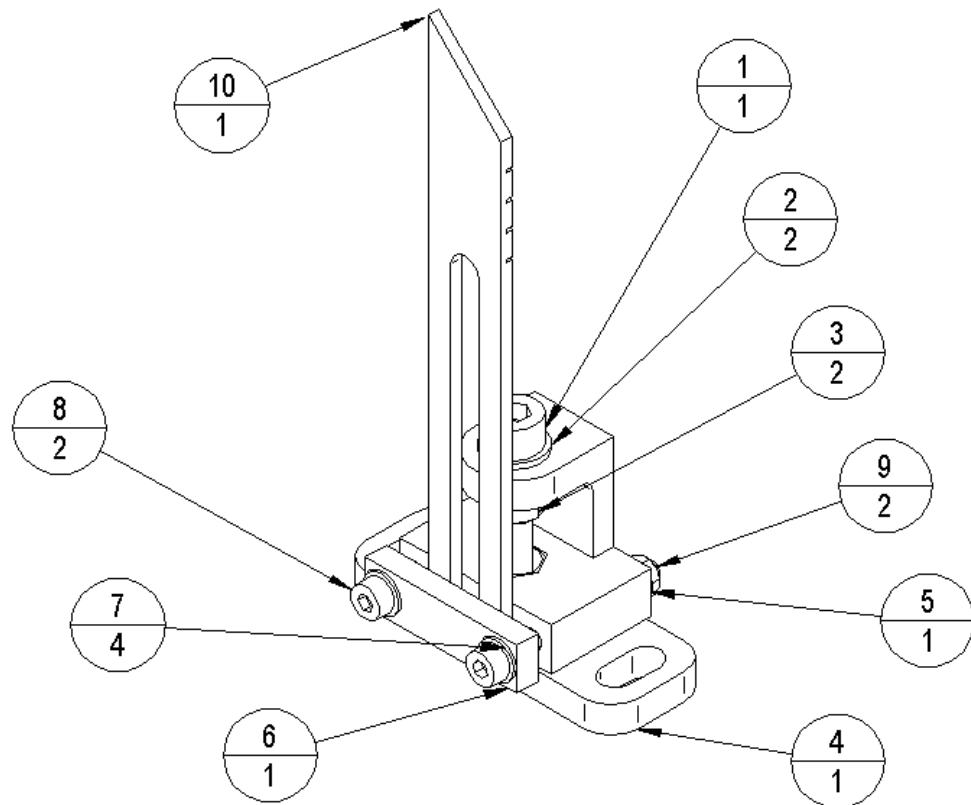
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	M5 socket bolt x 30	1		
2	M5 washer	2		
3	M5 nut	2		
4	Z flag adjuster housing	1	13.10.2	Page 261 SMP #: 28
5	Z flag slider	1	13.10.2	Page 261 SMP #: 30
6	Z flag clamp	1	13.10.2	Page 261 SMP #: 29
7	M3 washer	4		
8	M3 cap x 30	2		
9	M3 nut	2		

10	Z opto flag	1	13.10.2	Page 261 SMP #: 33

13.10.1.16   *Z toothed pulley SA*
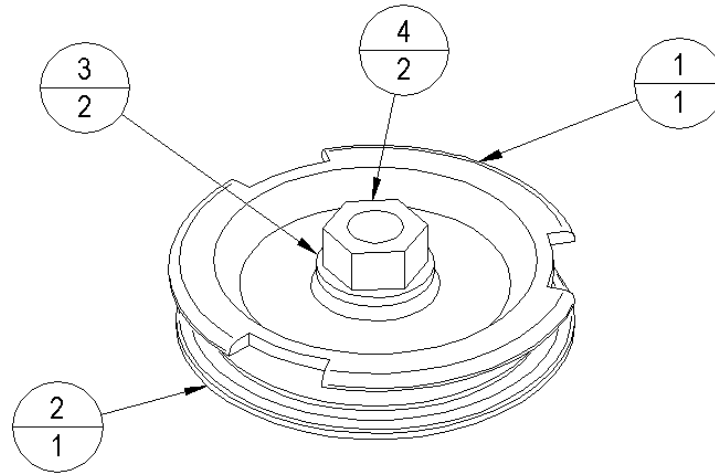
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	Z toothed pulley	1		
2	Z toothed pulley rim	1	13.10.2	Page 261 SMP #: 35
3	M8 washer	2		
4	M8 nut	2		

13.10.1.17   *Z studding tie SA*
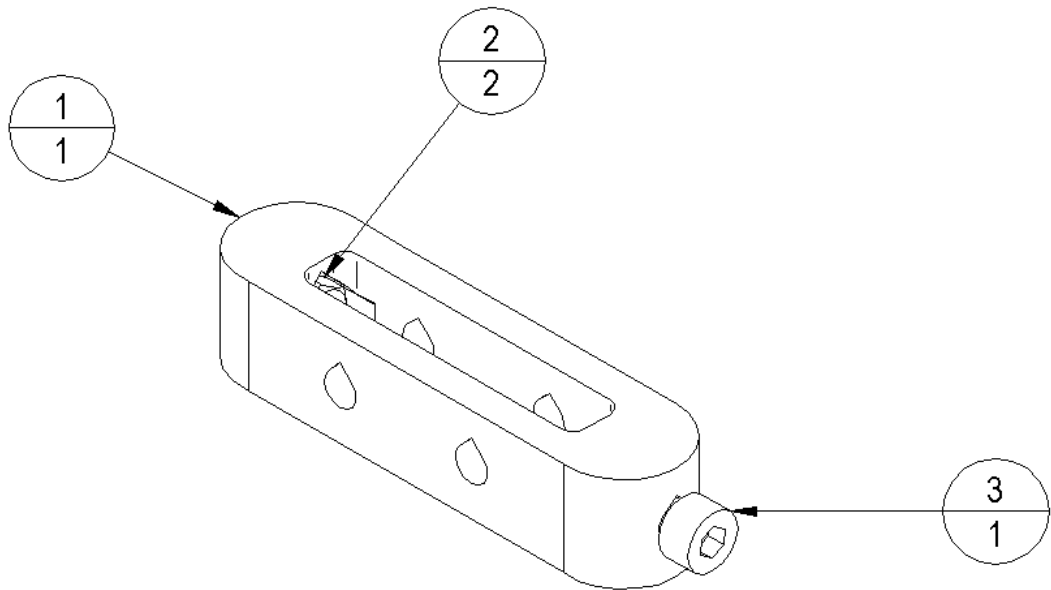
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	Z studding tie	1	13.10.2	Page 261 SMP #: 34
2	M5 nut	2		
3	M5 socket bolt x 15	1		

13.10.1.18   Bed corner SA
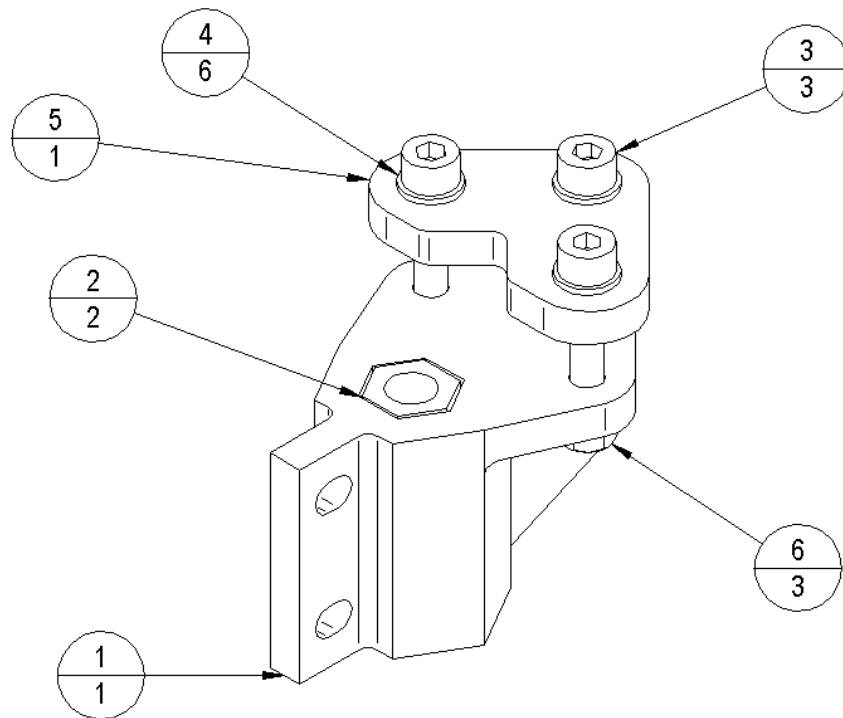
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	Bed corner	1	13.10.2	Page 261 SMP #: 7
2	M8 nut	2		
3	M5 socket bolt x 30	3		
4	M5 washer	6		
5	Bed clamp	1	13.10.2	Page 261 SMP #: 5
6	M5 nut	3		

13.10.1.19   X motor bracket SA
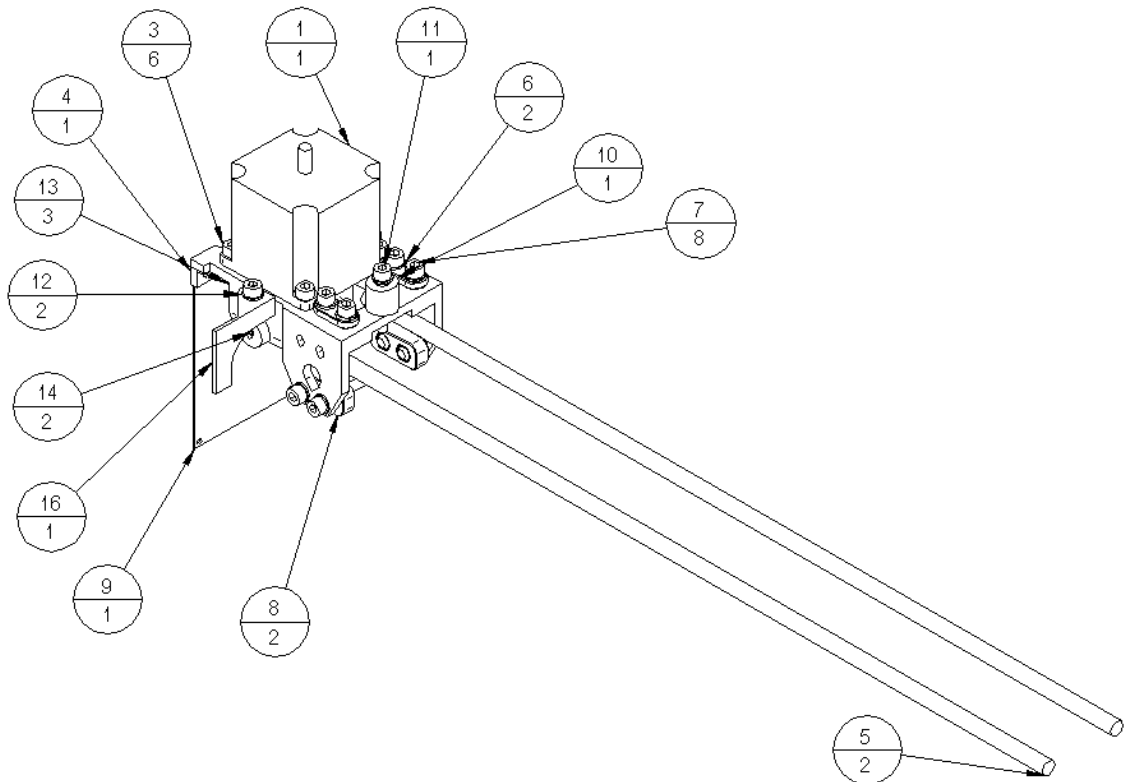
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	Motor stepper ST5709S1208-B plain shaft	1		
2*	X pulley toothed	1		
3	M5 socket bolt x 15	6		
4	X motor bracket	1	13.10.2	Page 261 SMP #: 19
5	X bar slide	2		
6	Y belt clamp	2	13.10.2	Page 261 SMP #: 24

Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
7	M5 x 15 plus washer	8		
8	X belt clamp with nuts	2	13.10.2	Page 261 SMP #: 15
9	Universal PCB	1		
10	X calliper mount	1		
11	M5 socket bolt x 30	1		
12	M5 washer	2		
13	M5 nut and washer	3		
14	M5 nut and grub	2		
15*	M5 nut	6		
16	Y opto flag	1	13.10.2	Page 261 SMP #: 27

* 2 fitted to lower motor shaft. 15 used to fasten belt clamps and 6, 11 and 12.

13.10.1.20　　X carriage SA
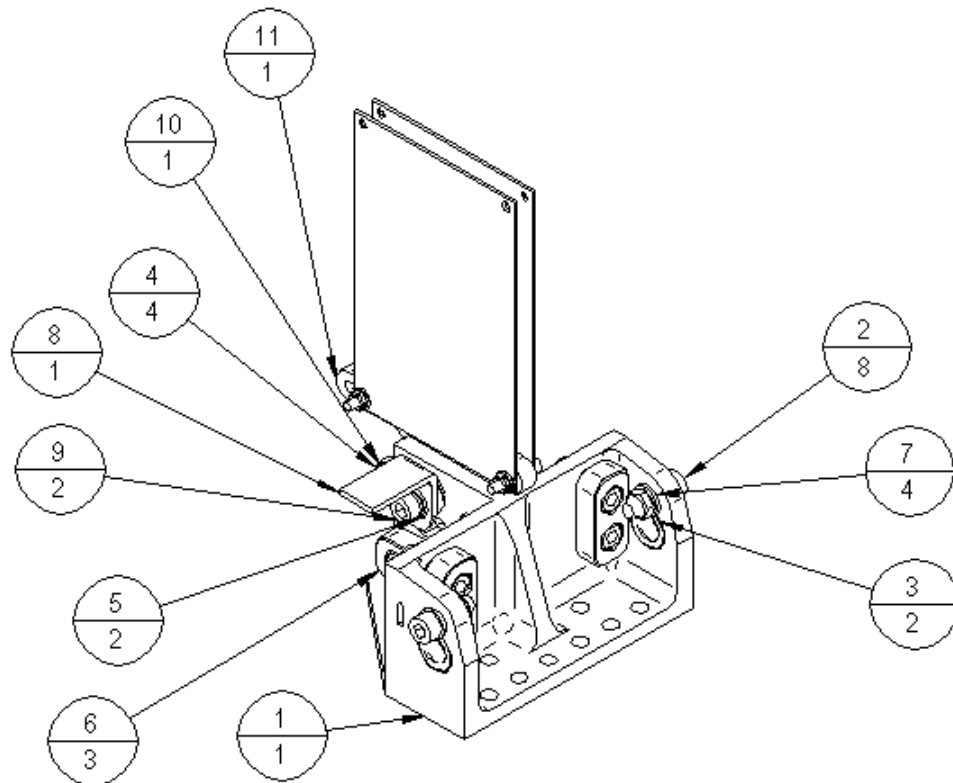
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	X carriage	1	13.10.2	Page 261 SMP #: 16
2	M5 x 15 plus washer	8		
3	Bearing insert 360 run	2	13.10.2	Page 261 SMP #: 4
4	M5 washer	4		
5	M5 socket bolt x 20	2		
6	X belt clamp with nuts	3	13.10.2	Page 261 SMP #: 15
7	M5 nut and washer	4		
8	X opto flag	1	13.10.2	Page 261 SMP #: 20

9	M5 socket bolt x 30	2		
10	Y belt clamp	1	13.10.2	Page 261 SMP #: 24
11	X PCB	1		

13.10.1.21   X idler end SA
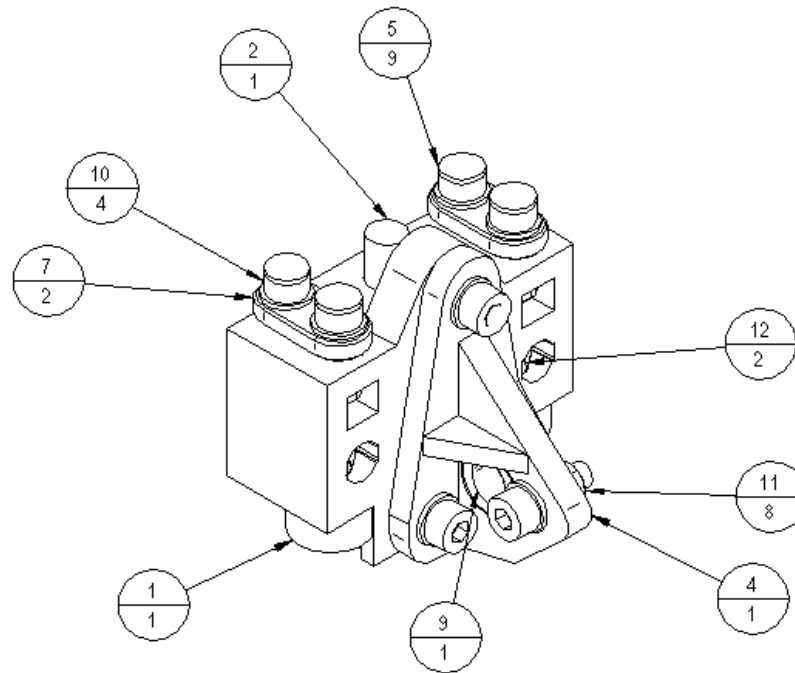
Item Number	Part/SA	Quantity	Detail Section	Page/SMP ref #
1	X idler bracket	1	13.10.2	Page 261 SMP #: 18
2	X bar idler	1		
3*	X/Y pulley idler	1	13.10.2	Page 261 SMP #: 22
4	X constraint bracket	1	13.10.2	Page 261 SMP #: 17
5	M5 x 15 plus washer	9		
6*	M5 washer	1		
7	Y belt clamp	2	13.10.2	Page 261 SMP #: 24
8*	M8 washer	2		
9	Bearing insert 180 X	1	13.10.2	Page 261 SMP #: 1
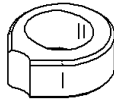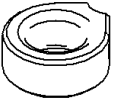
10	M5 socket bolt x 15	4		
11	M5 nut	8		
12	M5 nut and grub	2		
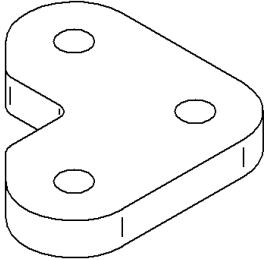
* 3 rotates about 2 in major cavity of 1, 8 either side of 3 to buffer rotation. 6 is for 11.
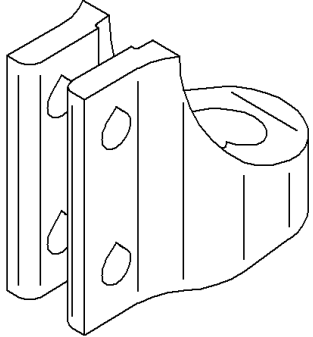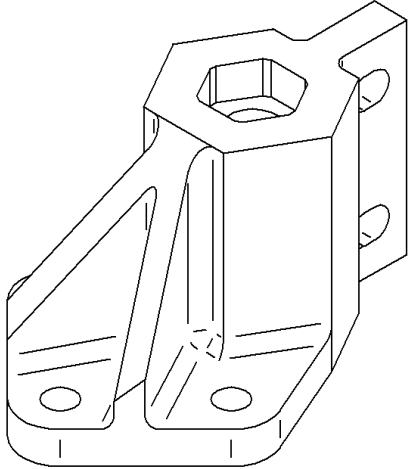
13.10.2　Self-manufactured parts (SMPs)
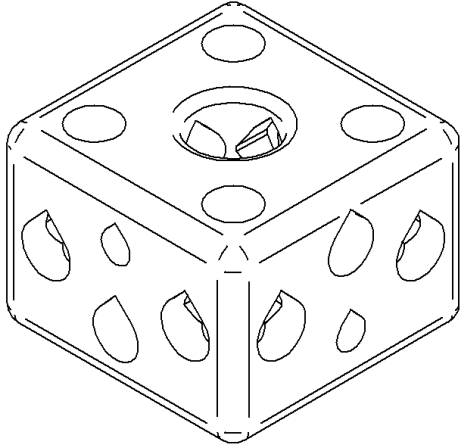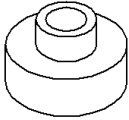
The isometric illustrations of individual SMPs in the Darwin assembly are to a scale of 1:1.
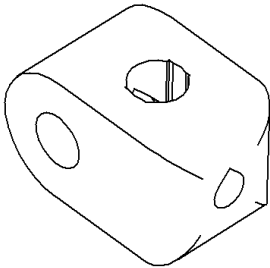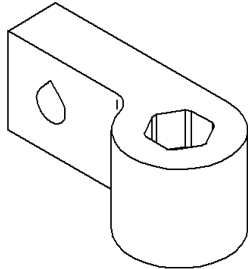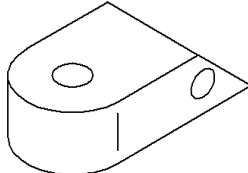
Table 23: Isometric illustrations of self-manufactured parts for Darwin
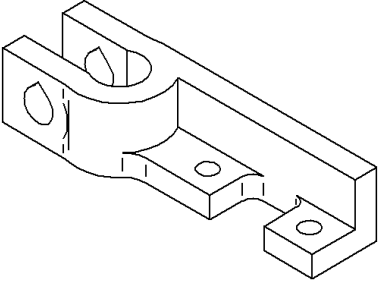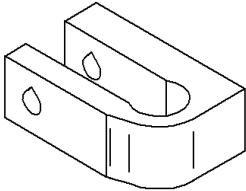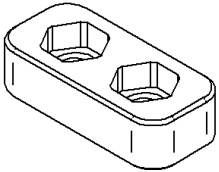
SMP #	Part name	Isometric drawing of part, scale 1:1 unless otherwise stated
1	Bearing insert 180 X	
2	Bearing insert 180 Z	
3	Bearing insert 360 jam	

4	Bearing insert 360 run	
5	Bed clamp	

| 6 | Bed constraint bracket | |
| 7 | Bed corner | |

8	Corner bracket	
9	Corner bracket vertical bolt plug	

10	Diagonal studding tie	
11	Fan base	
12	Fan leg	
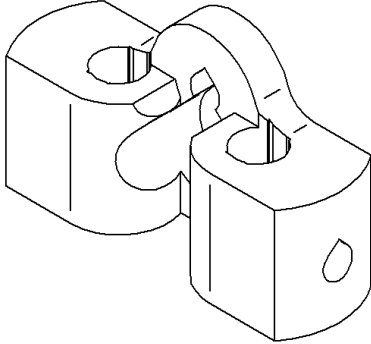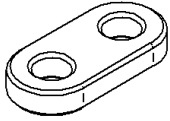
13	Optoswitch bracket	
14	PCB clamp	
15	X belt clamp	

| 16 | X carriage | |

17	X constraint bracket	
18	X idler bracket	

| 19 | X motor bracket | |
| 20 | X opto flag | |

21	X PCB bracket	
22	X/Y pulley idler	

| 23 | Y bearing housing | |
| 24 | Y belt clamp | |

25	Y motor bracket	
26	Y motor coupling	

27	Y opto flag	
28	Z flag adjuster housing	
29	Z flag clamp	

| 30 | Z flag slider | |
| 31 | Z motor bracket | |

| 32 | Z motor coupling | |
| 33 | Z opto flag | |

34	Z studding tie	
35	Z toothed pulley rim	

13.11   Achieving parallel plane motion using linkages

Figure 102 and Figure 103 illustrate the use of linkages to achieve parallel plane motion, thus avoiding the need for slideways. It should be noted, however, that these designs rely on robust hinges for them to work accurately.
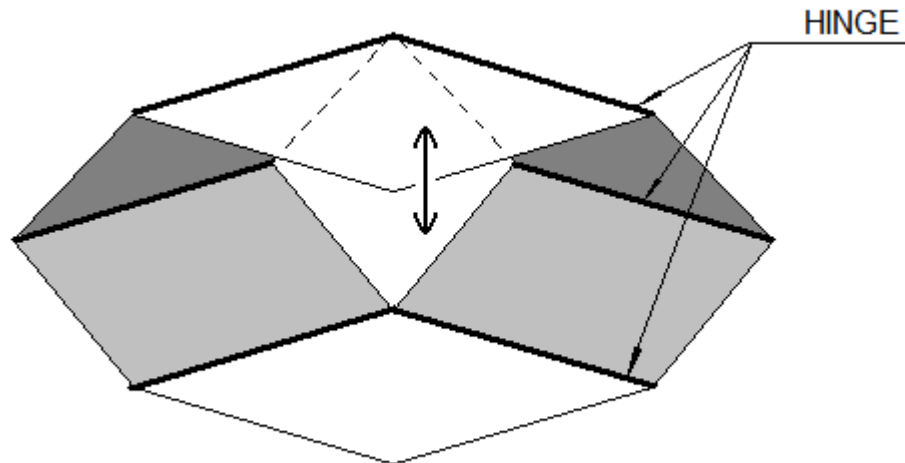
Figure 102: Perpendicular hinge constraint

Figure 103: Mechanical lifting jack

13.12   Syringe extruders

Figure 104 shows the author's design to use a non-captive stepper motor (left) and a servo motor (right) to drive a syringe extruder. The idea of using a non-captive stepper motor is credited to Evan Malone from the Fab@Home project.
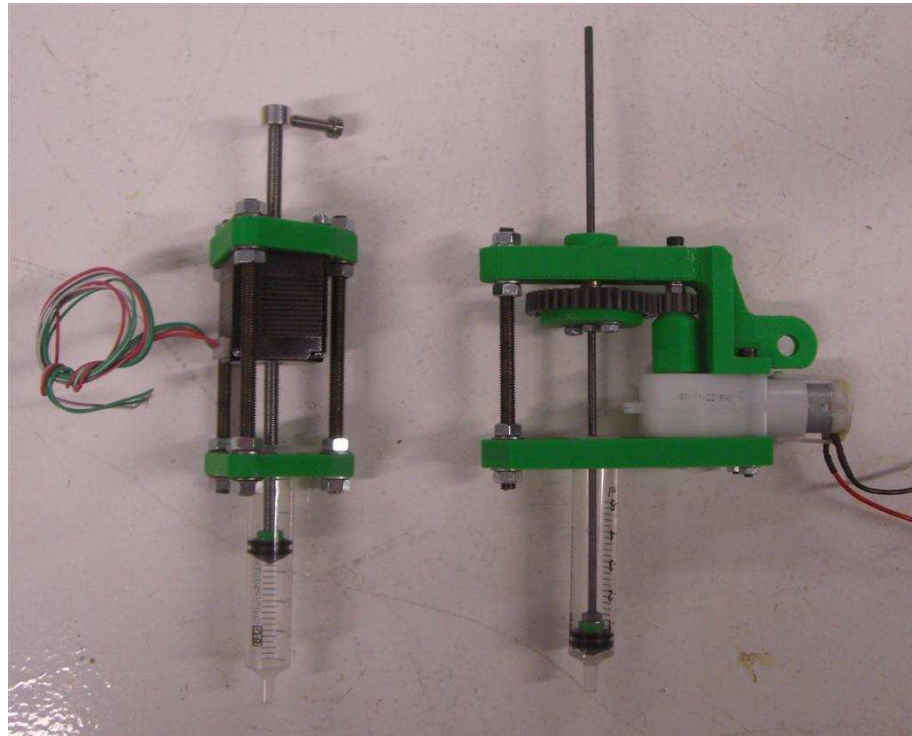
Figure 104: Syringe extruders designed by the author. Designs use a non-captive stepper motor (left) and a servo motor (right).

13.13   Alloy extruder

Figure 105 shows Bowyer's prototype for an alloy extruder which uses Nichrome wire as a heating element and a brass nozzle. Deposition relies on the gravity feed of the molten alloy, and is restricted with a solenoid.
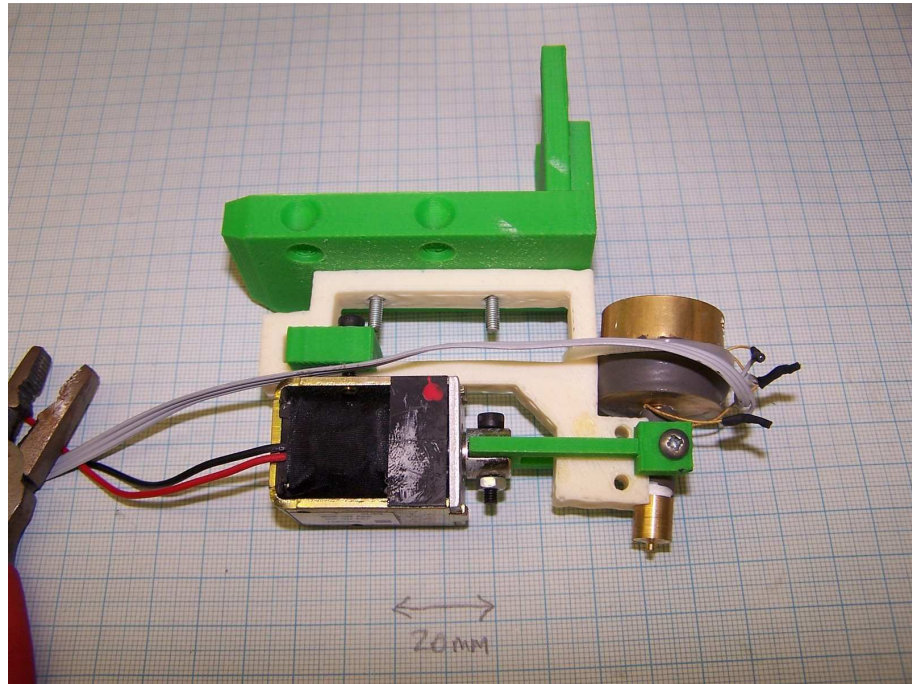
Figure 105: Prototype alloy extruder designed by Bowyer.

13.14   General Public Licence

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Finally, any free program is threatened constantly by software

patents. We wish to avoid the danger that companies distributing free software will individually obtain patent licenses, thus in effect transforming the program into proprietary software. To prevent this, we have made it clear that any patent must be licensed for everyone's free use or not licensed at all.

Most GNU software, including some libraries, is covered by the ordinary GNU General Public License, which was designed for utility programs. This license, the GNU Library General Public License, applies to certain designated libraries. This license is quite different from the ordinary one; be sure to read it in full, and don't assume that anything in it is the same as in the ordinary license.

The reason we have a separate public license for some libraries is that they blur the distinction we usually make between modifying or adding to a program and simply using it. Linking a program with a library, without changing the library, is in some sense simply using the library, and is analogous to running a utility program or application program. However, in a textual and legal sense, the linked executable is a combined work, a derivative of the original library, and the ordinary General Public License treats it as such.

Because of this blurred distinction, using the ordinary General Public License for libraries did not effectively promote software sharing, because most developers did not use the libraries. We concluded that weaker conditions might promote sharing better.

However, unrestricted linking of non-free programs would deprive the users of those programs of all benefit from the free status of the libraries themselves. This Library General Public License is intended to permit developers of non-free programs to use free libraries, while preserving your freedom as a user of such programs to change the free libraries that are incorporated in them. (We have not seen how to achieve this as regards changes in header files, but we have achieved it as regards changes in the actual functions of the Library.) The hope is that this will lead to faster development of free libraries.

The precise terms and conditions for copying, distribution and modification follow. Pay close attention to the difference between a "work based on the library" and a "work that uses the library". The former contains code derived from the library, while the latter only works together with the library.

Note that it is possible for a library to be covered by the ordinary General Public License rather than by this special one.

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A "library" means a collection of software functions and/or data prepared so as to be conveniently linked with application programs (which use some of those functions and data) to form executables.

The "Library", below, refers to any such software library or work which has been distributed under these terms. A "work based on the Library" means either the Library or any derivative work under copyright law: that is to say, a work containing the Library or a portion of it, either verbatim or with modifications and/or translated straightforwardly into another language. (Hereinafter, translation is included without limitation in the term "modification".)

"Source code" for a work means the preferred form of the work for making modifications to it. For a library, complete source code means all the source code for all modules it contains, plus any associated interface definition files, plus the scripts used to control compilation and installation of the library.

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2. You may modify your copy or copies of the Library or any portion of it, thus forming a work based on the Library, and copy and distribute such modifications or work under the terms of Section 1 above, provided that you also meet all of these conditions:

a) The modified work must itself be a software library.

b) You must cause the files modified to carry prominent notices stating that you changed the files and the date of any change.

c) You must cause the whole of the work to be licensed at no charge to all third parties under the terms of this License.

d) If a facility in the modified Library refers to a function or a table of data to be supplied by an application program that uses the facility, other than as an argument passed when the facility is invoked, then you must make a good faith effort to ensure that, in the event an application does not supply such function or table, the facility still operates, and performs whatever part of its purpose remains meaningful.

(For example, a function in a library to compute square roots has a purpose that is entirely well-defined independent of the application. Therefore, Subsection 2d requires that any application-supplied function or table used by this function must be optional: if the application does not supply it, the square root function must still compute square roots.)

These requirements apply to the modified work as a whole. If identifiable sections of that work are not derived from the Library, and can be reasonably considered independent and separate works in themselves, then this License, and its terms, do not apply to those sections when you distribute them as separate works. But when you distribute the same sections as part of a whole which is a work based on the Library, the distribution of the whole must be on the terms of this License, whose permissions for other licensees extend to the entire whole, and thus to each and every part regardless of who wrote it.

Thus, it is not the intent of this section to claim rights or contest your rights to work written entirely by you; rather, the intent is to exercise the right to control the distribution of derivative or collective works based on the Library.

In addition, mere aggregation of another work not based on the Library with the Library (or with a work based on the Library) on a volume of a storage or distribution medium does not bring the other work under the scope of this License.

3. You may opt to apply the terms of the ordinary GNU General Public License instead of this License to a given copy of the Library. To do this, you must alter all the notices that refer to this License, so that they refer to the ordinary GNU General Public License, version 2, instead of to this License. (If a newer version than version 2 of the ordinary GNU General Public License has appeared, then you can specify that version instead if you wish.) Do not make any other change in these notices.

Once this change is made in a given copy, it is irreversible for that copy, so the ordinary GNU General Public License applies to all subsequent copies and derivative works made from that copy.

This option is useful when you wish to copy part of the code of the Library into a program that is not a library.

4. You may copy and distribute the Library (or a portion or derivative of it, under Section 2) in object code or executable form under the terms of Sections 1 and 2 above provided that you accompany it with the complete corresponding machine-readable source code, which must be distributed under the terms of Sections 1 and 2 above on a medium customarily used for software interchange.

If distribution of object code is made by offering access to copy

from a designated place, then offering equivalent access to copy the source code from the same place satisfies the requirement to distribute the source code, even though third parties are not compelled to copy the source along with the object code.

5. A program that contains no derivative of any portion of the Library, but is designed to work with the Library by being compiled or linked with it, is called a "work that uses the Library". Such a work, in isolation, is not a derivative work of the Library, and therefore falls outside the scope of this License.

However, linking a "work that uses the Library" with the Library creates an executable that is a derivative of the Library (because it contains portions of the Library), rather than a "work that uses the library". The executable is therefore covered by this License. Section 6 states terms for distribution of such executables.

When a "work that uses the Library" uses material from a header file that is part of the Library, the object code for the work may be a derivative work of the Library even though the source code is not. Whether this is true is especially significant if the work can be linked without the Library, or if the work is itself a library. The threshold for this to be true is not precisely defined by law.

If such an object file uses only numerical parameters, data structure layouts and accessors, and small macros and small inline functions (ten lines or less in length), then the use of the object file is unrestricted, regardless of whether it is legally a derivative work. (Executables containing this object code plus portions of the Library will still fall under Section 6.)

Otherwise, if the work is a derivative of the Library, you may distribute the object code for the work under the terms of Section 6. Any executables containing that work also fall under Section 6, whether or not they are linked directly with the Library itself.

6. As an exception to the Sections above, you may also compile or link a "work that uses the Library" with the Library to produce a work containing portions of the Library, and distribute that work under terms of your choice, provided that the terms permit modification of the work for the customer's own use and reverse engineering for debugging such modifications.

You must give prominent notice with each copy of the work that the Library is used in it and that the Library and its use are covered by this License. You must supply a copy of this License. If the work during execution displays copyright notices, you must include the copyright notice for the Library among them, as well as a reference directing the user to the copy of this License. Also, you must do one of these things:

a) Accompany the work with the complete corresponding machine-readable source code for the Library including whatever changes were used in the work (which must be distributed under Sections 1 and 2 above); and, if the work is an executable linked with the Library, with the complete machine-readable "work that uses the Library", as object code and/or source code, so that the user can modify the Library and then relink to produce a modified executable containing the modified Library. (It is understood that the user who changes the contents of definitions files in the

Library will not necessarily be able to recompile the application
to use the modified definitions.)

b) Accompany the work with a written offer, valid for at
least three years, to give the same user the materials
specified in Subsection 6a, above, for a charge no more
than the cost of performing this distribution.

c) If distribution of the work is made by offering access to copy
from a designated place, offer equivalent access to copy the above
specified materials from the same place.

d) Verify that the user has already received a copy of these
materials or that you have already sent this user a copy.

For an executable, the required form of the "work that uses the
Library" must include any data and utility programs needed for
reproducing the executable from it. However, as a special exception,
the source code distributed need not include anything that is normally
distributed (in either source or binary form) with the major
parts (compiler, kernel, and so on) of the operating system on
which the executable runs, unless that part itself accompanies
the executable.

It may happen that this requirement contradicts the license
restrictions of other proprietary libraries that do not normally
accompany the operating system. Such a contradiction means you cannot
use both them and the Library together in an executable that you
distribute.

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facilities not covered by this License, and distribute such a combined
library, provided that the separate distribution of the work based on
the Library and of the other library facilities is otherwise
permitted, and provided that you do these two things:

a) Accompany the combined library with a copy of the same work
based on the Library, uncombined with any other library
facilities. This must be distributed under the terms of the
Sections above.

b) Give prominent notice with the combined library of the fact
that part of it is a work based on the Library, and explaining
where to find the accompanying uncombined form of the same work.

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END OF TERMS AND CONDITIONS

Appendix: How to Apply These Terms to Your New Libraries

If you develop a new library, and you want it to be of the greatest possible use to the public, we recommend making it free software that everyone can redistribute and change. You can do so by permitting redistribution under these terms (or, alternatively, under the terms of the ordinary General Public License).

To apply these terms, attach the following notices to the library. It is safest to attach them to the start of each source file to most effectively convey the exclusion of warranty; and each file should have at least the "copyright" line and a pointer to where the full notice is found.

<one line to give the library's name and a brief idea of what it does.>
Copyright (C) <year> <name of author>

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Also add information on how to contact you by electronic and paper mail.

You should also get your employer (if you work as a programmer) or your school, if any, to sign a "copyright disclaimer" for the library, if necessary. Here is a sample; alter the names:

Yoyodyne, Inc., hereby disclaims all copyright interest in the library `Frob' (a library for tweaking knobs) written by James Random Hacker.

<signature of Ty Coon>, 1 April 1990
Ty Coon, President of Vice

That's all there is to it!

13.15 Publication

The final section of this thesis is a paper co-written by the author. The paper was for the "Mass Customisation and Personalisation Conference 2007" which was international and peer-reviewed. This paper was then selected for publication in an edited book of conference proceedings.

The book will be published by World Scientific Press, however, at the time of writing this publication has not yet been completed. A temporary citation has been included below:

SELLS, E., Z. SMITH, S. BAILLARD, A. BOWYER, and V. OLLIVER, 2007. RepRap: The Replicating Rapid Prototyper - Maximising Customizability by Breeding the Means of Production. *In: Mass Customisation and Personalisation Conference 2007*, F. Piller and M. Tseng, eds. October 7th-10th MIT, Boston. World Scientific Press.