OPEN DESIGN AND THE REPRAP PROJECT

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ABSTRACT

This paper details the investigation of an emerging trend within technology development: 'open design'. Improvements in communications and computing technology have made collaboration over geographically vast distances possible. This technology has already had a major impact on the field of engineering, from the development of CAD/CAE/CAM practices to the emergence of concurrent engineering. Taking the lead from open source software, open design is an approach to technology development in which technical design information is licensed in such a manner that it can be accessed, utilised, modified and redistributed by anyone. The potential implications of this concept can be inferred from the impact of open source software. A review of the existing literature on the subject was conducted. A practical demonstration of the process was undertaken, via an attempt to contribute to an existing open design technology: the RepRap. This is a low cost rapid prototyper capable of manufacturing the parts required to make a copy of itself. The ability to use resin as a construction material was identified as a requirement of the device. An approach to integrating resin extrusion within the device was selected, a suitable material identified, and an experimental rig designed and assembled. Initial test results indicated that resin extrusion is viable for the RepRap.

KEYWORDS: Open Design, Rapid Prototyping, Engineering Design

1. INTRODUCTION

Conventional rapid prototypers utilise one of a variety of proprietary methods, e.g. the Fused Deposition Modelling (FDM) technique trademarked by Stratasys Inc. Consumables, like print cartridges, are specific to the machine, often containing integrated computer chips which require that the user purchase supplies only from the machine manufacturer. Repairs and modifications to a device can often only be carried out by the manufacturer or a licensed third party. The processes and technologies used are protected by patents: technology developers who wish to incorporate these techniques into a new device or process must pay a license fee or buy the original patent.

The RepRap (or replicating rapid-prototyper) is a low-cost desktop rapid prototyper capable of producing the parts required to build a copy of itself. Detailed information on the technical design and operation of the device is publicly available on the internet. Any person with the necessary skills and resources is free to download this information and build their own machine, incurring no costs except those involved in obtaining the required parts (less than €500) from any source they choose. Developers are free to adapt and redesign the technology in any way they require, and can then redistribute the adapted design. Any person with a working RepRap can produce another RepRap and sell it, or give it away, without paying any fees to or seeking the permission of the original designer. The only legal restriction on the device is that any derivative technology must be licensed in the same way, i.e. information on the new design must also be made freely available. [1]

1.1 Open Design

The RepRap is an example of what has been termed an ‘open design’ process, which inverts the conventional logic of technology development by requiring that the information required to implement a technology be publicly available for free. Traditionally patents are provided to innovators for a finite period of time during which the innovator can profit by licensing the technology to others for a fee. When the patent expires, the innovation becomes part of the public domain and any individual or organization is free to use it, although often the technology must be reverse engineered due to a lack of documentation [2]. In contrast, open design projects focus on maintaining a public repository of design information, and use licenses to guarantee this information remains open to all.

A large number of technologies have been developed in a loosely open, collaborative manner including steam engines (after Watt's patent expired) [3] [4], blast furnaces [5], aircraft [6] and personal computers [4]. The most significant precursor of open design is open source software (OSS) which is software whose source code is made freely available. During the 1990s OSS products such as the Linux operating system and the Apache web server became serious competitors to closed source products such as Microsoft Windows [8].

In 1998, Dr. Sepehr Kiani, a mechanical engineer at MIT, realized that mechanical design could benefit from the concepts gaining ground within software engineering [9]. Along with two colleagues, he founded the Open Design Foundation as an organization to promote and support the concept, and evaluate licenses under the Open Design Definition [9]. Vallance et al [2] identified the following general terms specified under an open design license:

- ‘documentation of a design is available for free,
- anyone is free to use or modify the design by changing the design documentation,
- anyone is free to distribute the original or modified designs (for fee or for free), and
- modifications to the design must be returned to the community (if redistributed).’

1.2 Advantages of Open Design

1.2.1 Advancement of technology

Pooling information resources allows engineers to attain a better understanding of a technology being investigated, and the field of engineering as a whole benefits. Engineers in academia regularly publish the results of their experiments in keeping with the scientific method. However, when the same engineers use the results of their experiments to design or improve a technology, the result is often protected by a patent. In effect, the open design approach amounts to treating engineering design as a science, and design information as scientific data. According to Vallance et al. [2], scientific investigation in cutting-edge fields such as nanofabrication is in some cases limited by proprietary machines. Those authors further assert that useful designs are often lost because of the demise of a company, the termination of a project or the completion of a product life cycle. By placing design information in a public repository, designers have access to an archive of design knowledge and wheels do not require reinvention.

1.2.2 Rapid evolution of design

An open design process permits what Sells [10] terms ‘accelerated artificial selection’. Proprietary designs conventionally develop through discrete generations. Designs are slow to evolve and improve. In an open design project every individual instance of the device can potentially be a new design generation, incorporating the latest feedback and experimenting with new approaches. A developer/user (in existing projects most community members are both to some extent) is free to build or reconfigure their device in any way they see fit, and contribute their findings back into the public repository of design information. Thus, the technology evolves at an accelerated pace, which explains the speed with which Linux developed into a highly sophisticated technology [11].

1.2.3 Efficient debugging

As alluded to above, there is no meaningful distinction between users (or customers) and developers of open source/open design products, and this is one of the most important features of the process. Weber [11] identifies as a 'key element' of an OSS project the fact that the user base can and does propose and implement modifications, bug fixes and new features. A maxim of the OSS movement, referred to as Linus's Law after the initiator of the Linux project, is that 'given enough eyeballs, all bugs are shallow' [12]. For any complex system, there are a large number of parameters which can be varied, and only a tiny proportion of the potential permutations of these parameters will be used by any given user or tester. However given a large base of user-developers, the probability of detecting any given bug increases. Once a problem is identified it can potentially be tackled by a number of individuals or teams, resulting in a number of possible solutions. The community is then free to select the solution it deems most efficient.

1.2.4 Technological uncertainty

Meyer asserts that when a new technology emerges its future is often uncertain, and in these situations 'collective invention' does a better job at advancing the technology than a patenting environment [4]. His argument draws on examples already mentioned, including the development of personal computers. These situations are examples of what Meyer terms 'technological uncertainty', in which engineers were optimistic about the future of a technology, but could not predict how it would develop. Lacking data on which to judge the merits of one approach or the other, developers found it better to pool resources. The security afforded by sharing information and results allows individuals to adopt a trial and error approach, without fear of losing ground to a competitor. A greater number of experimenters allows a wider range of approaches to be investigated.

2. THE REPRAP PROJECT

The RepRap project was initiated by the Biomimetics Research Group at Bath University [13]. It is an attempt to design a rapid-prototyper capable of manufacturing the parts required to construct a copy of itself, i.e. a self-replicating machine. The theory of self-reproducing machines has its origins in von Neumann [14]. Dr. Adrian Bowyer, of Bath University, reasoned that the range of parts which could be manufactured by rapid-prototyping machines made the technology viable for self-replication [10]. In order to develop the machine rapidly (as well as to lower the barriers to self-replication), Bowyer licensed the project under the open source Gnu Public License [13]. All source code, mechanical design information and circuit schematics were released, and all derivatives are bound by the terms of the license to be released in the same manner.

The RepRap uses an FDM-style process to manufacture parts composed of thermoplastics (most commonly acrylonitrile butadiene styrene, ABS). The electronic hardware is based around the open source Arduino platform, and solid model files for parts to be manufactured are created using an open source software package (Art of Illusion). A community quickly built up around the project, and experimentation began on designing components for the device. The first completed design was the Darwin, shown in Figure 1.

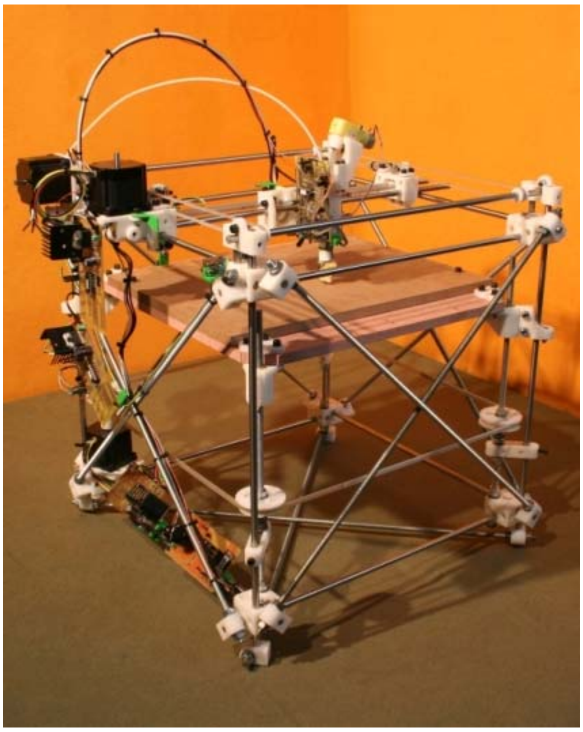

Figure 1 *RepRap I: Darwin*

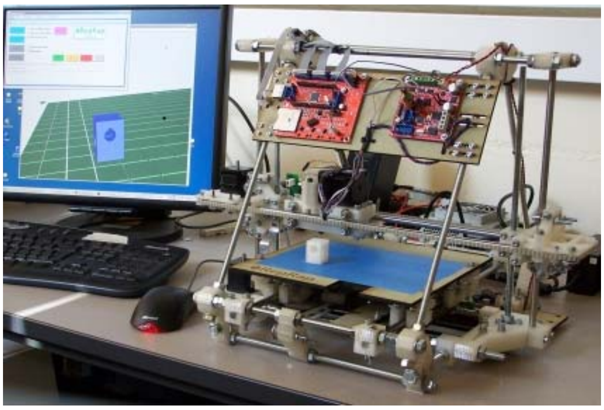

Figure 2: *RepRap II: Mendel*

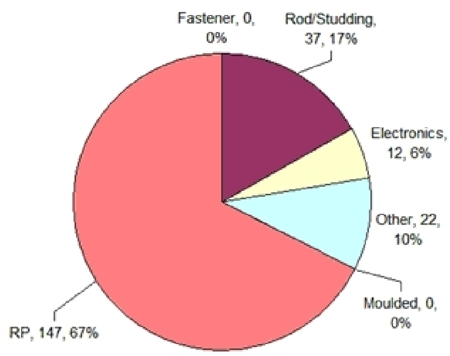

Figure 3: *Estimate of part count excluding fasteners [10]*

As of January 2009, Bowyer estimated that in excess of 2000 RepRaps had been constructed globally [13]. The project documentation is published via a wiki-based website, and community forums contain discussions and technical support information for and by users. A core development team releases the official designs, while users publish their modifications and fixes via the project website and personal weblogs. A second generation of the official design, Mendel, was recently released (Figure 2).

Sells [10] estimates that, excluding fasteners, the RepRap is currently capable of manufacturing between 48% and 67% of the parts required to make a copy of itself (Figure 3). He estimates that the ability to use resins, pastes and flexible polymers as construction materials would bring the self-manufacture ratio to 94%. It was therefore decided that the most worthwhile contribution that could be made to the RepRap project would be to investigate the viability of incorporating resin use into the device.

3. MATERIALS AND EXPERIMENTS

3.1 Experimental rig

The success of an open design project depends upon its modularity, i.e. the extent to which the system being designed is composed of subsystems which may be considered independent. In the case of the RepRap, there are four main subsystems of the device: software, electronic hardware, Cartesian robot, and the extruder which was the focus of this project. It was therefore possible to conduct experiments using a combination of hardware and software different to that used in the RepRap in the knowledge that the results would still be useful for that device. The experimental rig used consisted of a syringe-based extruder (see Figure 4) attached to a commercial 3-axis desktop CNC machine, the KOSY3.

3.2 Resin

Thermosetting plastics are synthetic compounds which can be hardened permanently ('cured') when treated, generally through a chemical reaction or the addition of heat. When selecting a suitable material for testing, a number of curing methods were considered.

- Two-part epoxies, which cure through the addition of a catalyst, are commonly used as heavy duty adhesives, coatings and industrial tooling. The strength obtainable with these materials makes them an attractive option; however the requirement to handle two materials which must be mixed in a specific ratio immediately before application presents a challenge to automating the curing process.
- Heat activated resins, in which cross-linking of polymer chains is stimulated by energy supplied as heat, typically react to high temperatures (above 200˚C) which would require the use of expensive equipment. Furthermore, the RepRap prints with (and is largely constructed from) thermoplastics, which would be damaged by such temperatures.
- Light activated resins contain photosensitive polymers that cause cross-linking when exposed to light of a specific wavelength, and are commonly used as adhesives due to their short curing times. It was the decided that the wide range of UV-curable resins available made them an ideal candidate for testing.

After considering a number of commercially available UV-curable adhesives, Evo-Comp UV-L – a bio-based resin containing 96% linseed oil and 4% photoinitiators – was selected. The resin was cured using a handheld UV flood lamp which emitted light with wavelengths above 315nm.

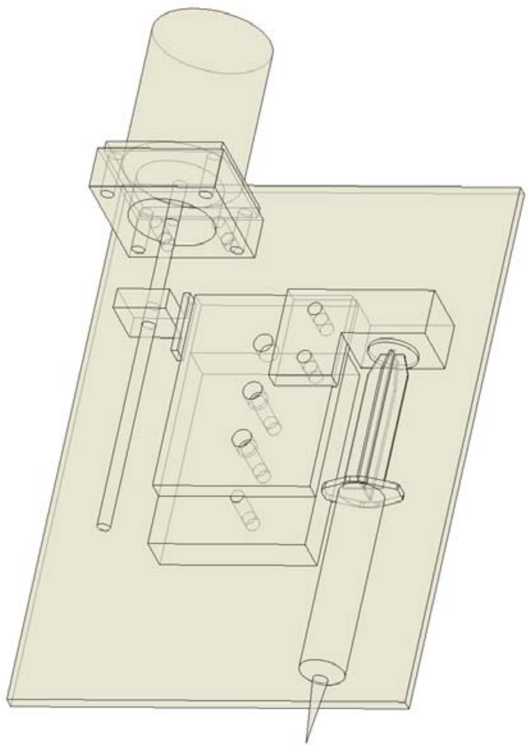

Figure 4: *Syringe-based, stepper motor driven extruder*

3.3 Experiments

Under investigation in these experiments were:

- The feasibility of “printing” parts: emulating an FDM-style process using a resin instead of a thermoplastic may not be possible on a low-cost, small-scale device such as the RepRap, and the primary objective of these experiments was to investigate this.
- The curing times achievable: as each layer must be cured in order to support further layers without deforming, the times associated with this process have a large effect on the overall production time.
- The effect of mixing the resin with other substances: a major advantage of being able to produce pieces using resins or pastes is the potential to vary the material properties of the substance by combining it with powders or liquids. This is not practically feasible with materials such as ABS which are obtained as solids and are melted immediately prior to extrusion. In these experiments, fumed silica powder was used to vary the viscosity of the

resin, and this presented an opportunity to observe the effects of mixing on print quality and curing times.

- The feasibility of producing parts made from both ABS and resin: the RepRap currently uses thermoplastics and if the development of a resin print head were successful it would be possible to produce parts containing both ABS and resin, e.g. an ABS component with a resin shield to act as a thermal barrier and prevent melting. For this to be useful, the resin and the ABS must not have a detrimental effect on each other, and the UV light used in curing the resin must not affect the ABS.
- The feasibility of using ABS as a support material for resin: when prototyping components which contain overhangs it is often necessary to print supports or scaffolds. In some situations these supports are made from the same material as the component and must be removed by force when construction is complete. The use of dissolvable support materials is more convenient as it permits the production of delicate parts and the removal of supports from inaccessible areas. ABS dissolves completely in acetone, and therefore may be useful as a dissolvable support material for the resin.

The tests conducted fall under two categories: printing unsupported resin and printing resin into ABS supports produced on a commercial FDM machine (but which could also be produced by a RepRap). In both cases the objective was to produce a simple cuboid. Tests consisted of varying the feed rate, extrusion rate and resin viscosity, and observing the resulting print quality.

4. RESULTS AND DISCUSSION

4.1 Cure times

The minimum time required to cure a layer of resin was ten seconds. This was sufficient to allow curing to occur between print cycles while maintaining reasonable printing times. In future tests the authors hope to replace the UV flood lamp with an array of UV LEDs, as this would provide a less expensive, more compact method of curing. However these advantages would be offset by an increase in curing times which may make the approach infeasible.

4.2 Print quality

Attempts to print simple shapes using the resin as shipped by the manufacturer were not successful as the viscosity was too low to prevent deformation before curing, regardless of the extrusion and feed rates used (see Figure 5). By increasing the resin viscosity it was possible to construct a simple cuboid (see Figures 6 and 7). The equipment used to control the extrusion and feed rates was found to be insufficiently sensitive to allow a high print resolution, but the experiments showed that it is feasible to produce parts through the successive layering of high-viscosity resin.

4.3 Combination of resin and ABS

When printing resin into ABS supports, a low viscosity was desirable to allow the resin to flow into any sharp corners, so resin containing no fumed silica was used. The white ABS support containing the cured resin can be seen in Figure 8. The materials did not have any noticeable detrimental effect on each other, and the UV lamp did not damage the ABS. Once the resin was cured, an attempt was made to remove the cast from the mould by mechanical means; however the stiffness of both materials made this impossible. The mould and cast were then submerged in acetone. Within two minutes, the acetone had turned a milky colour due to the ABS dissolving, as can be seen in Figure 9**.** Within an hour the ABS was almost completely dissolved and most of the acetone had evaporated, leaving behind a thin residue of ABS powder. The resin part remained intact (Figure 10), demonstrating that it is possible to use ABS as a dissolvable support material. This is a positive result, as support material which can be removed without the need for the application of force is extremely useful, for example in avoiding damage to small or fragile parts, or removing support material from areas that cannot be accessed by hand. The primary disadvantage of this approach is the cost associated with producing ABS supports which are then destroyed. However the RepRap core team is currently attempting to design a granular ABS extruder which, if successful, would allow the dissolved ABS to be re-used, thereby significantly reducing the material costs associated with the method [13].

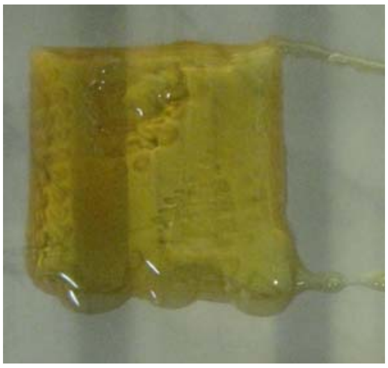

Figure 5: *Deformation of low-viscosity resin*

Figure 6: *Resin with increased viscosity*

Figure 7: *First successful cuboid*

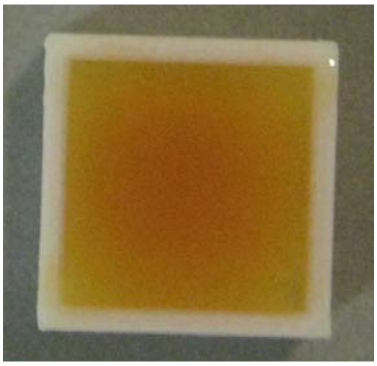

Figure 8: *ABS support (white) containing cured resin*

Figure 9: *ABS dissolving in acetone*

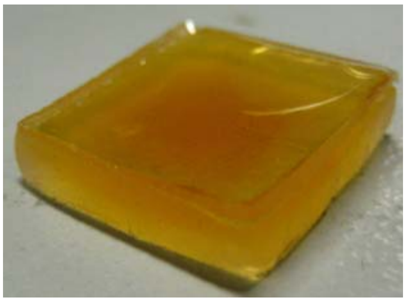

Figure 10: *Resin remaining after ABS has dissolved*

5. CONCLUSIONS

The project presented here was intended as a basis for further research into a topic that has received attention primarily from non-engineers despite having originated from, and being directly related to, the field of mechanical and manufacturing engineering. Open design represents a new approach to the production and dissemination of design information which, combined with advances in small-scale flexible manufacturing technology, could radically change the manufacturing industry. The open design concept exists in the context of a general trend towards the open exchange of information in many fields, most notably software development. The benefits of open design for engineers and industry include increased efficiency in testing and debugging, rapid evolution of designs, and more effective development of new and novel technology. For open design to be as successful as its software counterpart there exist a number of prerequisites including: improved interoperability of CAD and CAE software packages; robust online repositories for data exchange and storage; and accessible prototyping and manufacturing equipment. A number of open design and open source projects, including that of the RepRap, aim to provide these resources.

This paper presented a practical demonstration of the open design process by contributing to the development of the RepRap. The open design process was demonstrated in a number of ways. For example, the selection of materials and the design of a prototype extruder benefited from the information available on the RepRap project archive. The approach to resin deposition and curing was developed for implementation on the RepRap and the concept was tested despite not having access to a RepRap device. This was possible due to the modularity which is central to open design projects. The results of the experiments will be shared with the RepRap community, providing information regarding materials and machine calibration that will allow others to either further develop the technology without having to begin from scratch, or avoid the approach taken if they feel the results do not merit further efforts. For the authors, it is this constant cycle of feedback between experimenters and users that defines an open design process.

6. REFERENCES

[1] A. Bowyer, Distributing and copying RepRap [internet] (2006) Available at: http://reprap.org/bin/view/Main/RepRapGPLLicence [Accessed 19 January 2010]

[2] Vallance, Kiani and Nayfeh, Open Design of Manufacturing Equipment, *CIRP 1st Int. Conference on Agile, Reconfigurable Manufacturing* (2001)

[3] A. Nuvolari, Collective invention during the British Industrial Revolution: the case of the Cornish pumping engine, *Cambridge Journal of Economics* 28:347-363 (2004)

[4] P. B. Meyer, Episodes of Collective Invention, U.S. Bureau of Labor Statistics Working Paper 368 (2003)

[5] R.C. Allen, Collective Invention, *Journal of Economic Behaviour and Organization* 4: 1-24 (1983)

[6] P. B. Meyer, Network of Tinkerers: a model of open-source technology, U.S. Bureau of Labor Statistics Working Paper 413 (2007)

[7] D. Harhoff, J. Henkel, E. Von Hippel, Profiting from Voluntary Information Spillovers: how users benefit by freely revealing their innovations, *Research Policy* 32, 1753-1769 (2003)

[8] R. Casadesus-Masanell, P. Ghemawat, Dynamic Mixed Duopoly: A Model Motivated by Linux vs. Windows, *Management Science* Vol. 52, No. 7: 1072-1084 (2006)

[9] M. Koch, Y. I. Tumer, Towards Open Design: The Emergent Face of Engineering, *Proc. 17th International Conference on Engineering Design*, Vol. 3: 97-108 (2009)

[10] E. Sells, *Towards a Self-Manufacturing Rapid Prototyping Machine*, Doctoral dissertation, University of Bath (2009)

[11] S. Weber, The Political Economy of Open Source Software, *BRIE Working Paper Series* (2000)

[12] E. Raymond, *The Cathedral and the Bazaar*, O'Reilly, Sebastopol, CA (1999)

[13] R. Jones, *New RepRap Materials*, Master's thesis, University of Bath (2009)

[14] J. von Neumann, *Theory of Self-Reproducing Automata*, University of Illinois Press, Urbana (1966)