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RepRap: The Replicating Rapid Prototyper
Maximizing Customizability by Breeding the Means of Production

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Introduction

Consider the wolves that you see being led down the street every day. Their appearance ranges from the whimsical to the grotesque, and their adult body size covers a span unmatched by any other species. This virtuoso and antic variety was created by one of humanity's oldest and grandest technologies: genetic engineering. We have been customizing life since the invention of agriculture in Mesopotamia around 9500 BCE (Wikipedia, 2007).

Nowadays much of that customisation is done industrially, though the techniques still retain an important characteristic that they have had over the millennia: they can be done by a single person possessing equipment no more advanced than a breeding pen or a potting shed. Even the latest twist of the helix ─ direct manipulation of DNA ─ requires modest wherewithal well within the resources of an individual (Dyson, 2006).

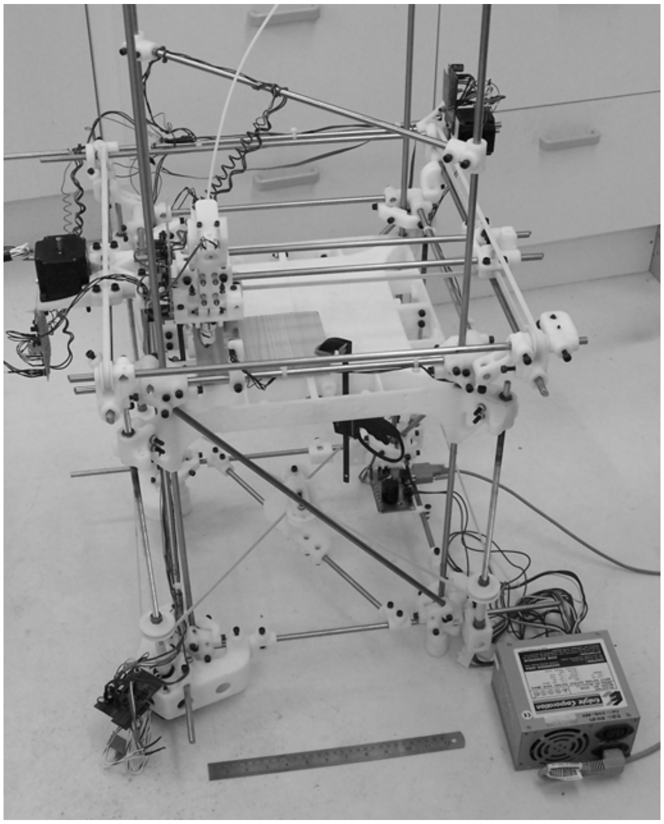

Figure 1. A working prototype RepRap machine fabricated using polymer parts from a commercial 3D printer. There is a 300 mm rule in the foreground for scale. Note the use of the 12v line out of an old PC supply for power. In remote or impoverished regions a car battery would work just as well.

The exuberant variation that we have achieved in the customization of our domesticated plants, animals and microbes is completely reliant upon one phenomenon: the fact that they can copy themselves. How may we extend that phenomenon, and hence that degree of customization, to the products of engineering?

One way would be to design a general purpose manufacturing engine that could also make copies of itself. This is not a new idea ─ Samuel Butler put self-replicating machines into his novel *Erewhon* in the nineteenth century (Butler, 1872), and John von Neumann did extensive theoretical studies in the middle of the twentieth (von Neumann, 1966). For a comprehensive review of the history and technology of self-replicating machines, see the book by Freitas and Merkle (2004).

However, nobody has yet made a self-replicating machine with the intention of using it as an everyday piece of production technology. That is what this paper is about.

The RepRap Machine

RepRap is short for ***rep***licating ***rap***id-prototyper. It is intended to be a practical self-replicating 3D printer. Specifically, it is a filament deposition rapid prototyping machine that has been designed to be able to make most of its own parts. Figure 1 shows a working prototype RepRap machine constructed by the authors.

Method and design

As can be seen in Figure 1, the bulk of the machine is a conventional Cartesian robot. This moves heads that extrude the build materials.

Right from its instigation (Bowyer, 2004) the RepRap project has deliberately subjugated theoretical perfection to the requirements of practicality. In particular, the following principles were adopted:

1. Self-replication is distinct from self-assembly. The fact that all organisms (except viruses) do both is not a reason to conflate these ideas. Machines are much better at making accurate parts than are people; people are much better at putting parts together than are machines. It therefore makes sense to have a collaborative division of labour. Indeed, the proposed collaboration is more than that ─ it is a symbiosis between two replicators. People will help RepRap machines to reproduce by assembling them in return for the other goods that they produce. There is an exact analogy between this and the symbiosis between ─ for example ─ flowers and insects: insects help flowers to reproduce in return for nectar. Because of this the RepRap design (at least initially) will concentrate on making the parts; its owner will assemble it.
2. Use some bought-in parts. Labouring extravagantly to have the machine make parts that are already ubiquitously available and cheap would waste better-directed effort. For example, it would doubtless be possible to have the machine make its own fasteners that could be used in place of conventional nuts and bolts. But nuts and bolts are available at insignificant cost even in the poorest and most deprived places, so there is no immediate practical advantage in making replacements. (For the benefits that this technology might bring to developing nations, see the section on Implications below.) Thus the machine will make all the parts that are specific to itself, but things like fasteners, steel rods, stepper motors, and microcontroller chips will be added. This means that while RepRap may not be a philosophically perfect self-replicating machine, it will be a practical one.

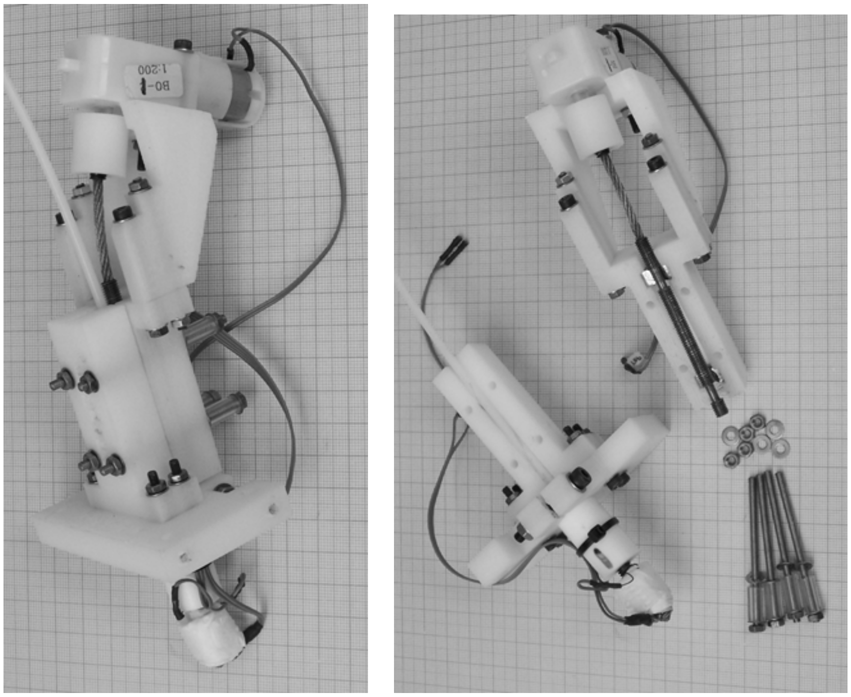

Figure 2. The RepRap polymer extruder assembled (left) and its internals (right). In addition to a US$4 geared motor it only has one moving part ─ a threaded drive rod mounted on two half-bearings and rotated by a flexible coupling (a length of steel cable) to allow the motor to be offset. This threaded rod bears against the 3mm diameter polymer supply (which can be seen coming in from the left in both pictures) and drives it down into a melt chamber heated using nichrome wire. The chamber is just another threaded rod that has been drilled down the middle and that ends in a 0.5mm extrusion nozzle. The offsetting is to allow the polymer to run straight down the drive thread. This is not necessary for the polymer used, which is flexible, but will be useful for other materials. The large grid squares are 10 mm.

3. Distribute the control logic. As one of the purposes of the machine is to allow the maximum customization ─ not just of the products that it makes, but also of itself ─ it was decided that each component would have its own microcontroller (a PIC16F628) connected in a token ring along with the controlling computer. This allows the addition of, for example, extra extruder heads very simply. The distribution is taken to the lowest level, with a separate controller for each axis-drive stepper. The Bresenham DDA that generates movement paths for the extruder heads works round the ring with one extra synchronization line between the three axes. Other than that one wire, there are only four other wires that connect everything in the machine (ground, +12v, and two serial data lines).

4. Open source the project. This sounds like a political choice rather than a design principle. And indeed the initial decision to open-source RepRap was taken because it is potentially a powerful technology, and a good way to make bad things happen with a powerful technology is to put it at the disposal of some people and not of others. But it was almost immediately also realised that it is not practical to attempt exclusive sales of a machine that can copy itself (sales figures would total one), nor was it practical to attempt to protect any “Intellectual Property” in the machine (as it can copy itself, this would just be a recipe for

spending lengthy periods in courts of law attempting to prevent people from doing with it the very thing that it was designed to do).

Here are the RepRap machine's specifications:

Working volume: adjustable, but nominally a 300 mm cube
Working materials: Polycaprolactone and a polyethylene glycol/sugar mix
Material handling: Two material deposition extruders, user exchangeable
Configuration: 3-axis Cartesian drive using stepper motors
Line and space: 0.5mm and about 0.2mm
Feature size: about 2mm
Positioning accuracy: 0.1mm
Layer thickness: adjustable, but nominally 0.5mm
Computer interface: RS232 (or USB -> RS232) at 19200 baud
Power supply needed: 8A max, 3A continuous at 12V DC
Driving computer and operating system needed: Microsoft Windows, Linux, Unix, or Mac.

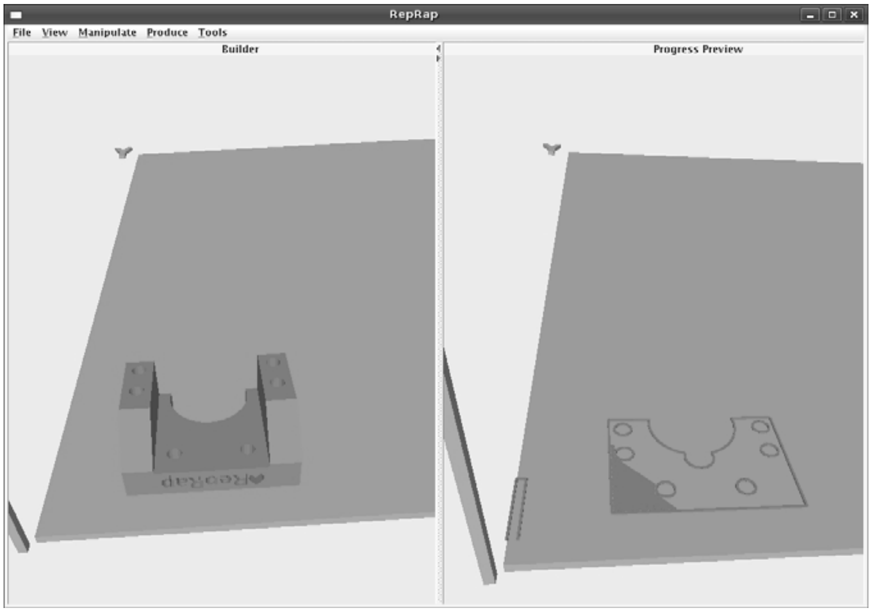

Figure 3. The RepRap GUI on the host computer. The user loads STL files of parts to be made into the left hand window and uses the mouse to place them in the position and orientation where they are to be built on the build base. Starting the build both sends instructions to the RepRap machine and runs a simulation showing progress in the right-hand window (the little inverted U shape is the extruder clearing itself at the start). The host software is written in Java.

Considerable thought, trial, and error went into the design of the polymer extruder head. Figure 2 shows the release design of one of these (left), and a dismantled view (right).

Initially the polymer that is being used as a build material is polycaprolactone. This is a very tough nylon-like polymer that has the added advantage of melting at about 60 ^{o}C. This low melting point makes it very easy to work with in the machine.

Figure 3 shows the GUI that the user of the machine sees when building objects with it. The only actions required are loading STL files, positioning and orienting them on the build base, and instructing the machine to start.

Results

Figure 4 shows a close-up of another prototype RepRap machine with the extruder head described above (made in ABS by a commercial FDM RP machine) on the right, and on the left an identical head made by that first head in polycaprolactone. The new head that the machine has made for itself is shown starting to extrude polycaprolactone.

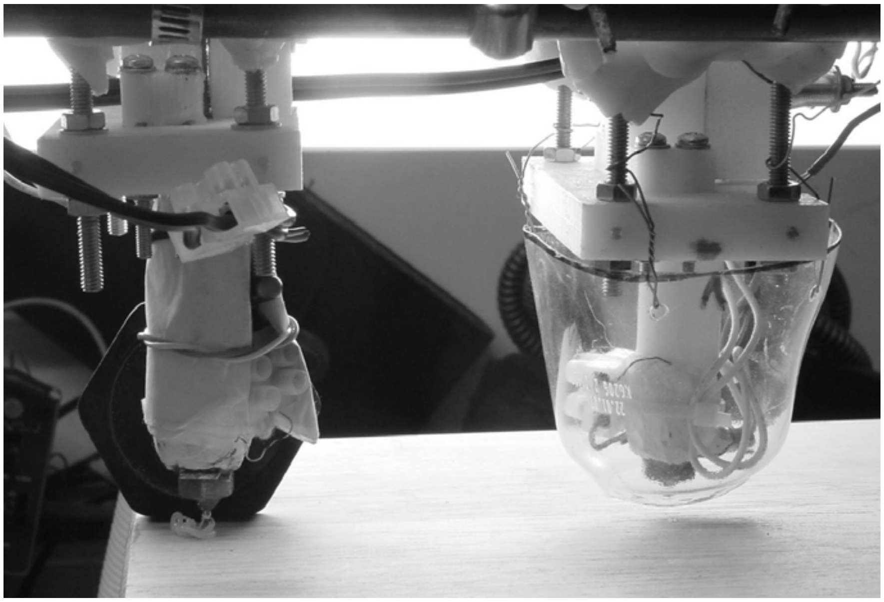

Figure 4. An extruded extruder extrudes. The RepRap extruder head on the right was made in a commercial FDM rapid prototyper (the transparent plastic shroud is to reduce cooling by air currents). That right-hand extruder then made the extruder on the left, which is shown starting its first test extrusion for itself. Both heads are mounted in a prototype RepRap machine.

Experimentally other polymers have been tried through the head. Running at higher temperatures it has successfully extruded HPP, HDPE and ABS. Even though these are less costly than polycaprolactone the project will continue to use that to start with because it is so easy to handle.

Extensive and detailed reporting of all the many experiments being conducted with the machine and its components (which are too numerous to include in this paper) can be found on the project blog at http://blog.reprap.org/.

Future developments

The next step of the project will be to add a support material extruder. Overhangs of 45^o and steeper can be built without support, but shallower angles require it. We propose to rapid-prototype a motorized syringe similar to the one used in the Fab@Home project (Malone and Lipson, 2006), but to add a heater. It will deposit a mixture of polyethylene glycol and icing sugar. This has the consistency of candle wax at room temperature, but melts at about 65 ^oC to an extrudable paste that holds its form well. It is both friable and water soluble, and so makes an ideal support material.

As described below, future developments of RepRap after its first release will depend much more on its user community than on its original creators. However, some work has already been done on a second release of the machine to incorporate a low-melting-point metal alloy in the structures the machine builds for use as an electrical conductor (Sells and Bowyer, 2006). This would allow the machine to make electrical circuits (including things like IC holders) in three dimensions in the body of otherwise mechanical parts.

Though initially the project will be using polycaprolactone as its main working material, it is intended to switch this to polylactic acid in the future. This has a rather higher melting point, but has the advantage that it can be synthesised by fermentation from starch (corn/maize or potatoes, for example). The RepRap machine would make the fermenter, of course. This would mean that anyone with a RepRap machine and a few tens of square metres of land would not only have a self-replicating manufacturing machine, they would also have a self-replicating source of build material.

Polylactic acid is (like polycaprolactone) fully biodegradable. This gives the user of such a machine a local route to recycling involving no transport or processing. Old or broken products would simply be thrown on a compost heap to prepare for the next corn planting.

The first release of RepRap is planned for 2008 after achievement of self-replication. However all its designs, software and documentation are put on the web as they become available, and so most are already there at the time of writing.

Implications

Almost all current manufacturing systems (for example CNC lathes or injection moulding machines or chip fab lines) are geared towards the mass production of identical parts, and all such machines make goods in an arithmetic progression. But a machine that can copy itself can grow its numbers in geometric progression, and the goods it produces can also grow in geometric progression. Any geometric progression, no matter how slow, eventually overtakes every arithmetic progression, no matter how fast.

But having goods produced in a geometric progression is something that humanity has experienced for a long time. As was mentioned in the Introduction, agriculture goes back twelve millennia, and is exclusively concerned with entities that copy themselves and thus grow in number geometrically. Self-replicating manufacturing technology makes engineering much more like agriculture. But whereas agriculture (traditionally) takes generations to customize its products by selective breeding (and quite a while to do it by recombinant DNA techniques), a self-replicating manufacturing machine can have a new part designed, then made, then fitted, in an afternoon. Its owner can also customize the products that the machine makes with equal facility.

The open-source nature of the RepRap project means that many design improvements will be posted back on the web. Owners of old-version machines will be able to use those machines themselves to upgrade to the latest design. RepRap will evolve, like the wolves of the Introduction, by artificial selection. This evolution will almost certainly be taken in many different directions. Some possibilities are: reducing the number of bought-in parts, increasing the size of objects that can be made, making the machine simpler to assemble, refining its resolution, and increasing the number of materials that can be processed. The authors see one of the advantages of creating a self-replicating machine as being that, once the first design has been released, they can sit back and let Charles Darwin (in the guise of hundreds of thousands of highly-motivated tinkerers) take over the job.

The target cost for the bought-in parts and materials for one RepRap machine is US$400, which is well within the resources of a single individual in a developed country. And at this level small communities of people even in the most deprived parts of the world should be able to afford a machine. This should allow them to place one foot on the manufacturing ladder that has made the rest of humanity rich. And their labour costs allow them to undercut everyone else when they make products using the technology, so this should give an economic boost where it is most needed. Such low labour costs often fail to give the advantage that they should because of the high capital cost of starting a manufacturing venture. With RepRap that limitation should not arise.

RepRap will put individual cottage industry on a closer footing with conventional big manufacturers. This will be a general phenomenon with consequences for manufacturers with large production runs. These effects will be even more significant in small and niche markets, which currently generate more expensive goods due to lower output and the lack of economies of scale. For example, there are people in both the developed and undeveloped world who cannot afford Braille typewriters, sophisticated limb prostheses, and page-turning machines. Inexpensive 3D printing will make these objects more widely available.

The open-source nature of RepRap means that anyone who owns one is free to use it to copy itself and to give those copies to friends. Indeed RepRap etiquette asks owners of machines to do this at cost at least twice. It also means that a company with a machine can double its production rate simply by having their machine copy itself. This strategy can, of course, be repeated.

With self copying, self-repair comes free. When someone acquires a RepRap machine one of the first things that they will be instructed to do is to make one each of all its component parts and to put them on a shelf in a cardboard box in a cool dry place. Then, when a part breaks, it can simply be replaced. Another such part would then be made and put back in the box for next time. Alternatively two machines have the ability to self-repair reciprocally.

Conclusions

An ear of wheat is almost unrecognizable when compared with the seeds of the ancient grasses from which people customized it. It is also more intricate than any machine ever made. And yet it is virtually free. The reason for this is that it can copy itself. Self replication leads to an exponential growth in numbers, and large numbers mean that the replicator becomes very inexpensive. At US$400 the RepRap machine starts off inexpensive (when compared to commercial rapid prototyping machines), and that cost can only go down.

In addition, self-replication allows RepRap to go beyond the customisation of products: it allows the creator of those products not just to customize them, but also to customize the machine that produces them.

And it allows that creator and the machine's user to be the same person.

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