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Construction of Rapid Prototyping Testbeds Using Meccano

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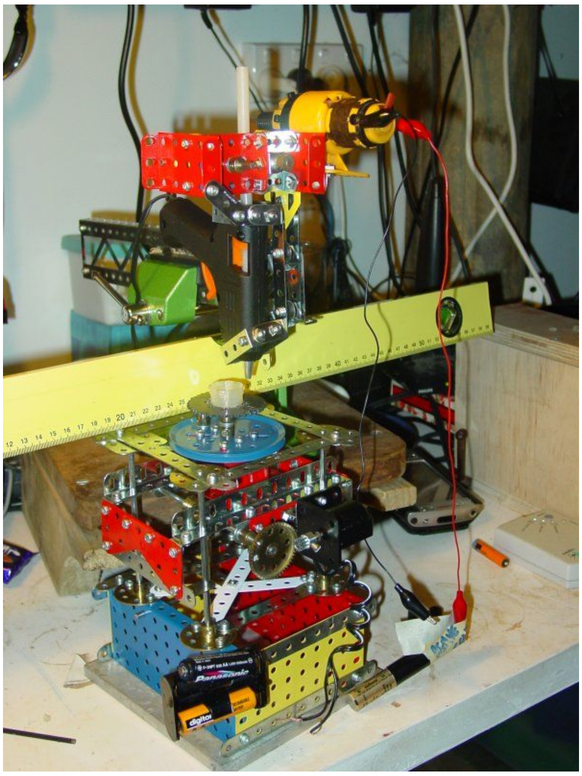

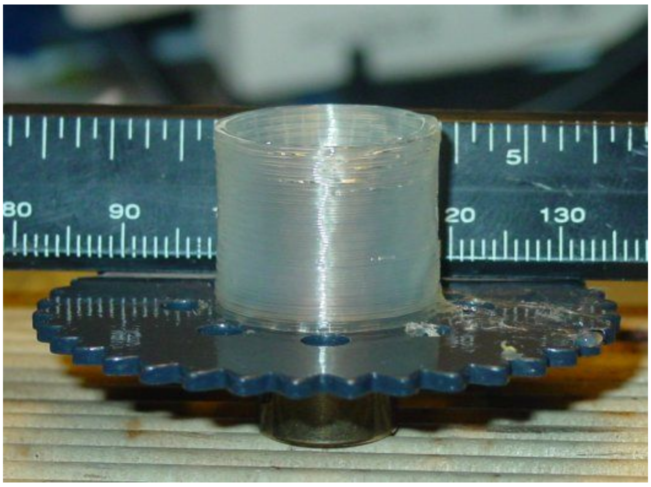

Acknowledgements are due to my long-suffering family, without the patient support of whom I would not get half as close to subjects such as this.

1. Report Summary

This report is the result of an ongoing investigation into the suitability of recycled High Density Polyethylene (HDPE – used for 'milk bottles') as a feedstock for a Rapid-Prototyping (RP) device. This itself required the Rapid Development (RD) of a testbed, which became a prime example of how relatively simple technologies can be used to pursue the goal of a self-replicating RP machine. It is incomplete, in as much as it is only a portion of the original goals, but is being shared under the spirit of the GNU Public Licence (GPL).

Unmodified commercial Meccano components, long recognised as a rapid prototyping system before the advent of computers, were used to construct a turntable which automatically lowered itself as it rotated. As pointed out by Dr. Adrian Bowyer (2004) in his introduction to The RepRap Project, turntable-based systems are inherently more simple than X-Y plotters, and the turntable design allowed the effect of changing the speed of deposited material to be examined using only one motor.

The extrusion head was implemented from an inexpensive "glue gun" which was fed conventional rods of hot-melt glue through a geared pinch-roller and sprocket assembly. To simplify construction, the entire extrusion head and feed mechanism remained fixed in position.

The original intent was, and still is, to extrude HDPE but as the method of preparing HDPE stock from recycled material has not yet been developed, glue sticks were used as a substitute for the development stage.

By regulating the rate of descent of the turntable with respect to its rotation speed, and controlling the feed rate of the glue sticks, intact and regular hollow cylinders of plastic were fabricated while some basic design methodologies and constraints were determined.

The investigations into HDPE will be continued, starting with the creation of well-formed HDPE stock and modifications to the extrusion head to enable it to melt the more robust material. Computer controlled motion of the turntable and extrusion head will also be added. The order in which these developments will take place is unknown and subject to budgetary constraints.

"We don’t have the money, so we have to think." - Ernest Rutherford

1.1 GPL Summary

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2.Glossary

This section defines some terms which are commonly used throughout the report:

Contrate Gear	A gearwheel whose teeth extend perpendicularly to the face of the gearwheel.
EVA	Ethylene Vinyl Acetate. A relatively soft, insoluble copolymer with a melting point of around 85°C used in hot melt glue.
FDM	Fused Deposition Method: a specific RP technique.
HDPE	High Density Poly-Ethylene, or polyethylene, which is very dense due to low molecular branching. "Society of the Plastics Industry (SPI) Type 2" plastic milk bottles are made from this material.
PET	Poly-ethylene terephthalate. "Society of the Plastics Industry (SPI) Type 1" plastic soft drink bottles are made from this material.
Infill	The RP process of filling the volume between critical surfaces of components with structural material.
Meccano	Metal construction toy common in the UK and mainland Europe. The Meccano marks and logos seen here are exclusive property of MECCANO S.N. For details see: http://www.meccano.com
Rapid prototyping (RP)	A technology which can create parts using fused deposition modelling. Components are designed using 3D solid modelling software package (e.g. SolidEdge or ArtOfIllusion) and then sent to the RP machine which will then automatically manufacture the component.
RPEC	Rapid Prototyped Electronic Circuits. The name of the technology whereby electrical circuit inclusion is possible with rapid prototyped components.
Wood's metal	Low melting point (70 °C) alloy. Also know as bend alloy.

3.Introduction

In April 2005, The RepRap project headed by Dr. Adrian Bowyer of the UK's Bath University suggested the concept of creating a fabrication device capable of manufacturing the majority of its components using its own capabilities. By releasing this under the GPL, the project is on its way to producing such a device. Raw materials should be durable, recyclable, and relatively plentiful. The author (Vik Olliver) reasoned that the wide availability of HDPE and PET would make a reasonable choice, thanks to the widespread use the material in recyclable plastic milk and oil containers.

A series of basic experiments was performed by the author to determine basic working temperatures for the two materials, and HDPE was chosen primarily because of the lower working temperature of approximately 150°C. Due to the very limited funding available, 10W glue guns from the *$2 Store* and parts of a childhood *Meccano* brand metal construction toy were pressed into service.

The glue guns reached only 110°C, and were unable to melt the HDPE samples. Rather than modify the gun, the easier route of using 7mm hot-melt glue sticks for pre-prototyping work was chosen, and the glue guns would be modified at the end of the project, with 7mm HDPE stock preparation to continue as an ongoing task during periods when testbed development was not possible.

Over a 6-day period in early April 2005, a testbed capable of creating well-formed, regular, hollow cylinders by FDM over 40mm in diameter and 18mm tall, with wall widths as fine as 0.85mm had been prepared.

After an e-mail conversation with Dr. Bowyer, it was decided that the experiences to date should be published to demonstrate how useful work can be carried out in this area by an amateur with very basic equipment.

Summary Of Work

A motley collection of Meccano was used to construct a slowly-rotating, descending turntable powered by a stock Meccano 3V motor. A suspended glue gun was added over the turntable, cleaned up, and tested manually. A mechanism to automatically advance the glue stick using a pinch-wheel and sprocket driven by a geared motor was added.

Adjustments were made to the feed rate of the glue stick, and rotation and descent of the turntable, with periodic test cylinders being made.

Finally, the feed mechanism was stressed to its limit to determine the maximum relative feed rate – and hence the deposition rate - possible with this equipment.

Design Principles

The intention was to create a device suitable for use as a testbed, rather than a fully-functional fabrication system. Turntables are fundamentally simpler to manufacture than X-Y tables, and allow the deposition speed to be varied by moving the extrusion head between the centre and perimeter of the turntable.

The turntable is supported at four points that slide vertically for stability. To cause the turntable to descend, the axle supporting the turntable proper is used to drive a threaded shaft. This screws itself into a threaded brass bushing as the turntable rotates, driving the entire turntable downwards.

The extrusion head uses a very high gearing ratio and a pinch-roller to gradually feed 7mm plastic glue sticks into a low-cost 10W 240V glue gun. An arm supports the glue gun and feed mechanism, and the whole is supported in a multi-position vice to allow the extrusion head to overhang the turntable.

No computer control was used in the system, though this can be added at a later date and the extrusion head is easily repositioned under manual control by moving the turntable assembly on the bench. Movement of the turntable is preferred to moving the extrusion head since the turntable has to be constructed solidly to provide even rotation.

Construction

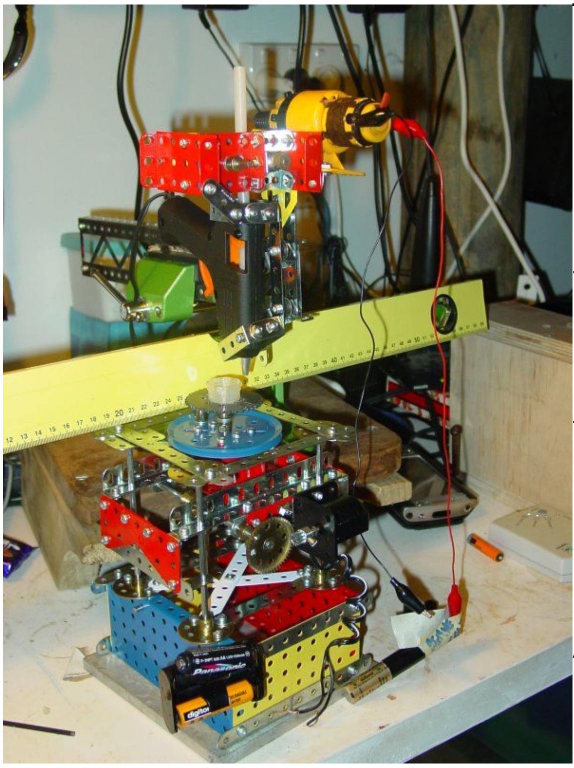

Figure 1The assembled Meccano fabricator with a yellow builder's level marked in cm units for scale. Photo taken just after the first successful cylinder was formed.

The mechanisms (Figure 1) were all constructed from the combined content of several Meccano construction kits without modifying any of the parts. Dimensions of Meccano parts given here without units refer to the number of holes, set at a ½ inch (12.5mm) pitch, found in the larger face of the part. The exact parts are not essential, so no attempt is made to provide a complete component listing. However, it should be possible to reconstruct the device from the images and descriptions given.

It was important to construct rigidly, in order to avoid potential play in the structure which would affect the accuracy of the final extrusion. All static parts were braced.

All axles were held at their ends by brass collars rather than spring clips, and where possible at least 2 washers were used. Care was taken to select undamaged parts. All nuts were thoroughly tightened with a spanner, and light lubrication with WD40 was used.

Turntable

A 7x5 baseplate with flanges on the 5-hole side was used as the base for the turntable (Figure 2). Two 3x3 flanged baseplates were stood vertically, toward one unflanged edge. This was necessary to allow clearance for a worm drive mechanism suspended from 5-hole strips attached to the flanges, which overhung the edge of the main baseplate by 1 hole.

A large pulley wheel was attached to the top of the two 3x3 baseplates, providing a stable bearing for the turntable wheel itself, which was a powder-coated 50mm chain gear. The axle descended through the pulley into the baseplate, where washers, a 38mm gear wheel and a 12.5mm pinion gear were attached.

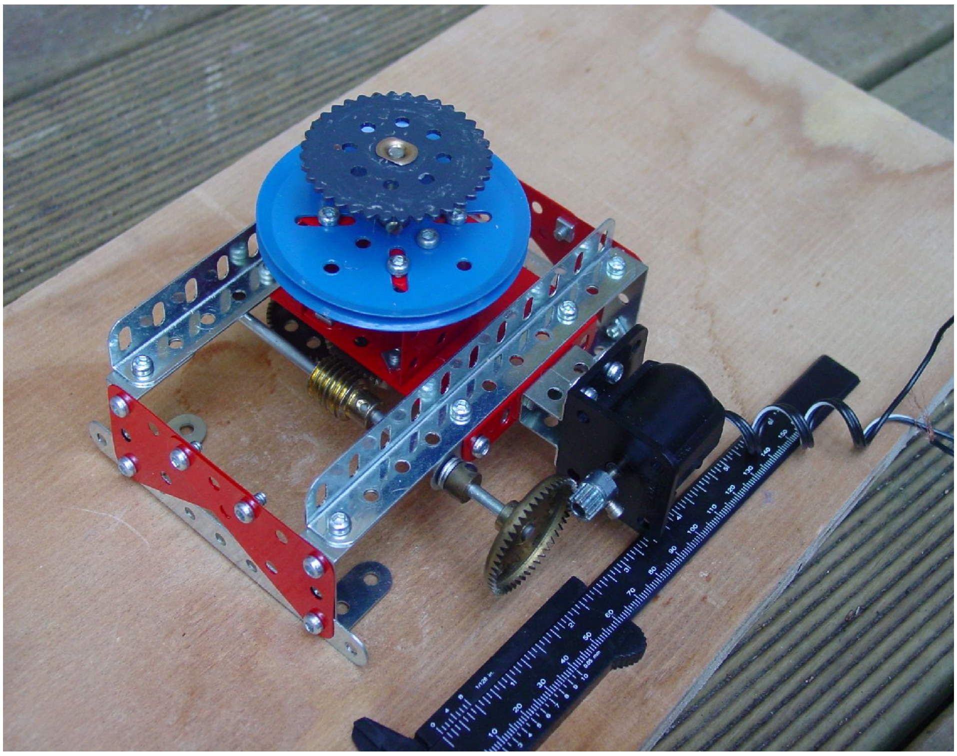

Figure 2Top view of turntable.

The larger gear engaged with the worm gear, and the pinion gear was latter used for a 3:1 reduction gear mounted towards the edge of the baseplate to drive the descent screw .

The axle bearing the worm gear was extended to one side, and a contrate gear attached. This was then driven by an 8mm pinion gear, attached to the shaft of a 3V ungeared motor (part no. 700). By sliding the contrate gear on the axle, it was possible to accommodate a variety of pinion gears on the motor shaft. This was fortunate as the smallest available gear turned out to give the right speed.

11 Hole lengths of angle iron were used to provide support for the turntable so that it could move on 4 vertical shafts within its supporting framework. Extended double angle strips were attached to the ends of the angle iron as guides.

Once completed, the turntable rotated at a reasonably steady 12 RPM.

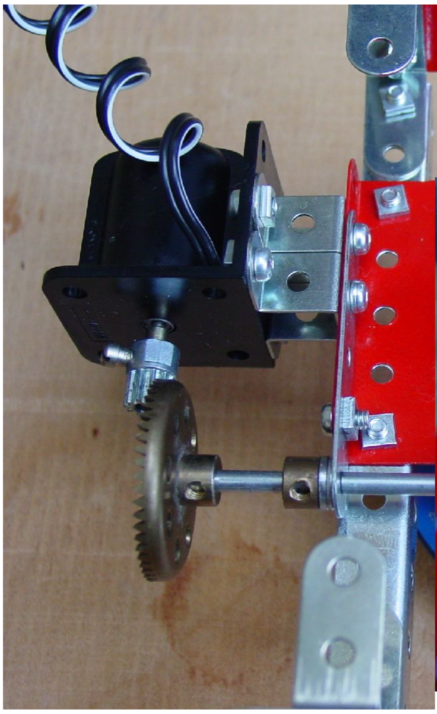

Figure 3 Gearing on underside of turnta

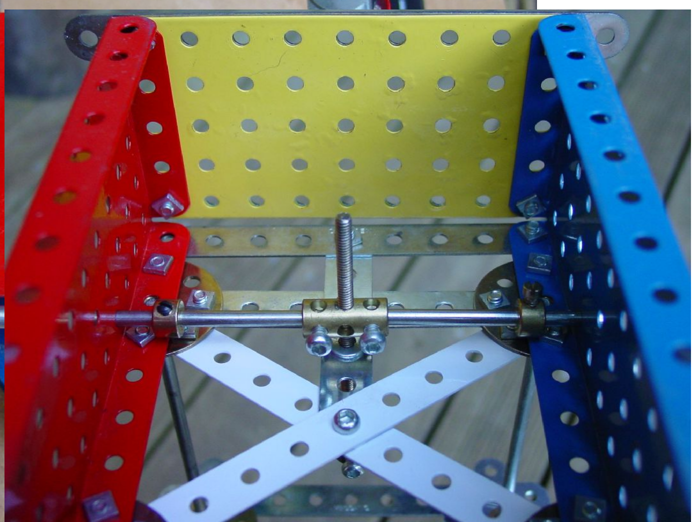

Figure 4 Underside of base, showing the vertical threaded drive rod securely mounted in a large cylindrical brass collar.

Turntable Support

The turntable slides vertically along four 110mm axles, anchored firmly in four pierced wheels fitted with collars. These were braced and held in an assembly of two flanged 5x12 baseplates, capped with 9x5 flat plates. The flat plates were reinforced with 11-hole strips (Figure 5).

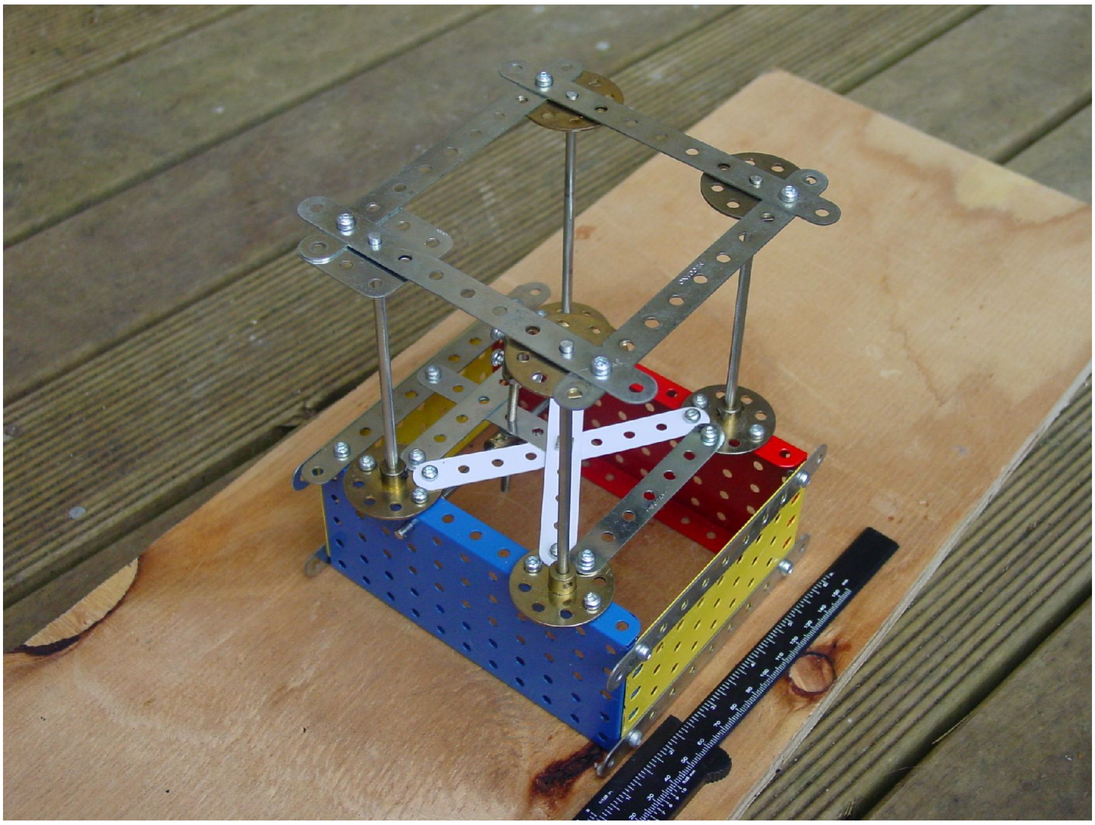

Figure 5 Turntable support. Vertical threaded drive rod is just to the left of the centre of the bracing.

A removable top brace was fitted, made from the remaining 3 pierced wheels, a handy 3x3 flat plate and a collar.

As Figure 4 illustrates, a large brass collar with three rows of threaded holes was used to provide an anchor point for the traction created by a threaded drive rod. This rod is securely anchored by a similar collar on its top end, to the bottom of the shaft that can be seen protruding to the right side of Figure 3. When the turntable has completed 3 turns, the large gear completes one turn. As this is connected to the rod on top of the drive rod, the entire turntable assembly slides downward. The rate of descent is one thread width – 0.25mm – for every complete revolution of the turntable.

An additional 5-hole strip was added from the centre of the white cross-braces to add additional support to the drive rod.

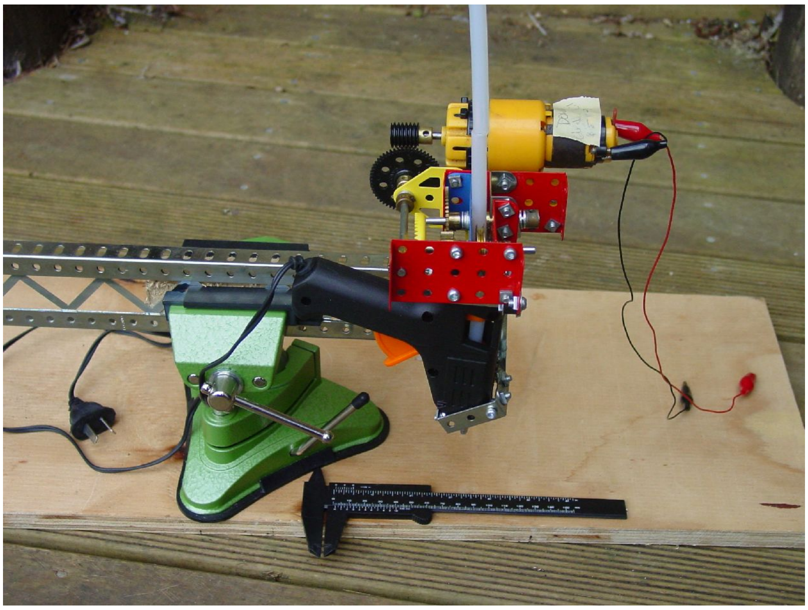

Figure 6 The assembled extrusion head clamped in a multi-position vice, showing glue gun and geared Meccano motor.

Figure 7 The NZ$2 glue gun used for these experiments. It takes 7mm glue sticks, consumes 10W 110/240VAC. Max. tip temp. ≈110 °C, 1mm nozzle exit.

Extrusion Head and Support

After some consideration of screw mechanisms, it became apparent that more volume was going to be required than could be supplied by one stick. So a gear feed and pinch-wheel mechanism was designed, and a very low ratio reduction gearbox was made. The yellow motor visible in these illustrations is a 20 year-old Meccano design that provides selectable 3:1, 6:1, 12:1, 16:1, 32:1 and 60:1 gearing. Worm gears are the preferred method, as shown in the gearbox detail in Figure 8. The remaining gears were all that were left in the set.

The glue gun (Figure 7), purchased for NZ$2 with NZ$2 of glue sticks, was restrained to the gearbox in an improvised, braced cradle. Rubber grommets held in place only with tight-fitting bolts proved effective in padding out the slack. The whole was attached to a braced girder, that was packed with a wooden block and securely held in a multi-position lockable vice (Figure 6) from Dick Smith Electronics – a present from my daughter, Tamara.

Feedstock

The feedstock was constructed from 7mm diameter sticks of EVA. The free end of the stick in the mechanism was heated with a micro-blowtorch to melting point, and brought square-on to a similarly melted end of the new stick. A little twisting melded the sticks, and slight tension reduced the bulge at the join. Bad joins caused jams against the manual feed mechanism.

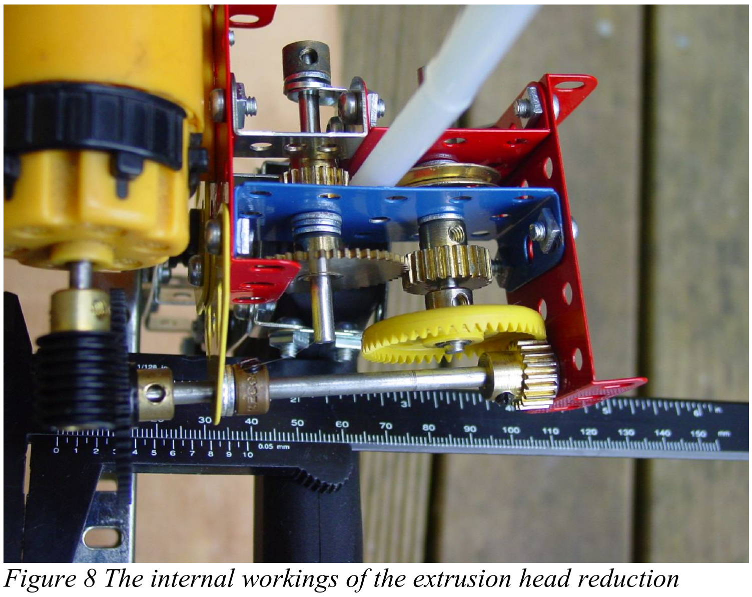

Figure 8 The internal workings of the extrusion head reduction gearbox. The worm gear on the left does in fact engage sufficiently.

4.Experimentation

Summary

Extrusion head, turntable and support were assembled and given a few dry runs. Any part exhibiting excessive bending was braced. Aluminium blocks and a keyboard rest were used to bring the turntable and nozzle into light contact, and the mechanisms rotated in useful directions.

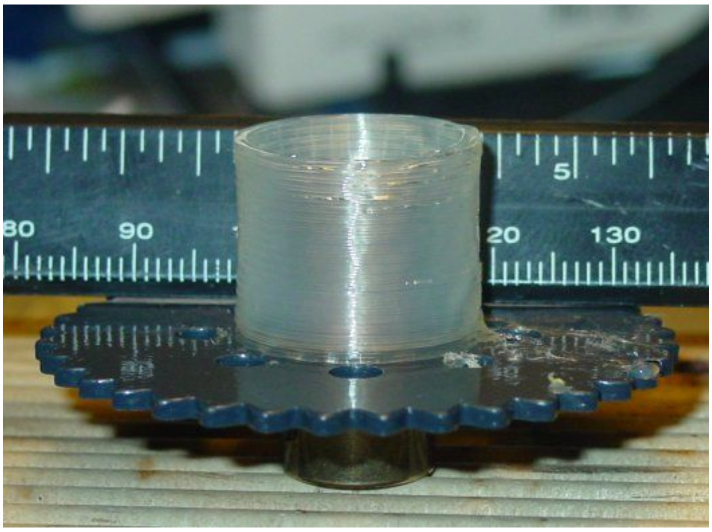

Figure 9 Turntable wheel removed from machine to allow photographing against a millimetre and inch scale. The cylinder has 0.85mm thick walls, 19.5mm in diameter and is 18mm high.

The structure was then bent, aimed, tightened and gently abused until the correct mixture of battery voltage, ambient temperature, flow rate of the day presented itself. Attempts are still being made to establish controlled ambient conditions of any kind, but a 70W domestic fan 1.2 metres away on 60% or more power seemed to make the plastic cool in a well-formed way. The results can be seen in Figure 9 and .

Figure 10 Various deposited EVA cylinders, arranged approximately chronologically.

Apparatus

As pictured in Figure 11, the turntable, support and extrusion head assembly were wired to battery packs and a fan aimed for cooling. Note deployment of precision counterweight. The 50cm 70W fixed fan is situated immediately behind the camera user.

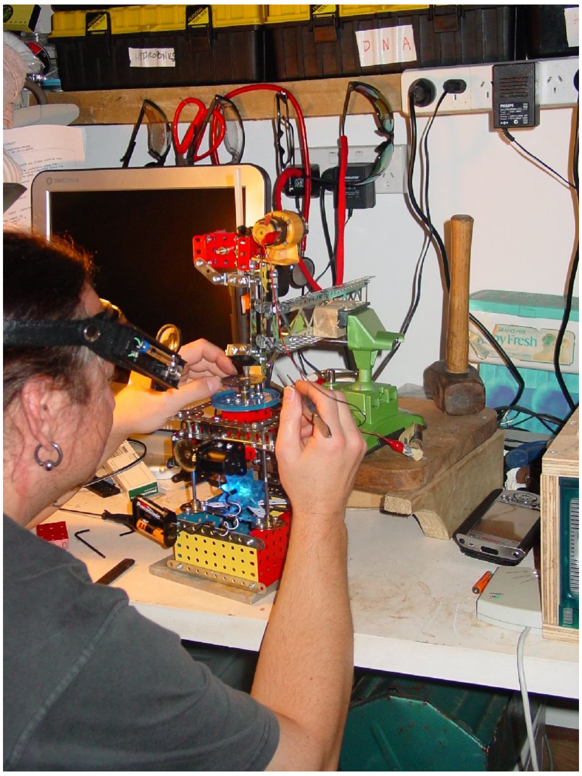

Figure 11 The author adjusts the blocked feed. Flashing blue light is a reminder to reconnect the drive shaft after tinkering.

Method

Strategic screws were undone on the gears to allow the turntable to freely rotate, and the feed mechanism to be manually operated. A chain of 3 glue sticks was fed into the head, which was initially kept clear of the turntable.

The glue gun was set to pre-heat, and battery polarity was checked to ensure all mechanisms rotated in useful directions. EVA was extruded under power until bubbles ceased appearing in the stream. The power was then shut off, the glue gun nozzle cleaned with a large craft knife and tissue, the turntable raised to a level where it just contacted the nozzle of the glue gun and the screws were re-tightened.

The fan was then turned on, and power (3V DC) applied to the feed mechanism. As EVA bulged out around the nozzle, the power was turned on to the turntable mechanism.

With a thread pitch of 0.75mm and a 3:1 gearing ratio on the drive rod, each time the turntable rotated it had moved down by 0.25mm . Consequently, the gearing and voltage on the feed head motor had to be adjusted to suit the diameter of the hollow cylinder being deposited on the turntable. It was not possible to test other ratios as no more gears were available.

Too much EVA resulted in thick walls being laid down. Too little would cause regular skips in the cylinder wall, resulting to a sawtooth pattern and fine filaments of EVA being draped around the workpiece.

Between each attempt, the nozzle was cleaned with a tissue, and the turntable cleaned with boiling water and a scrubbing brush – a remarkably effective method for removing excess EVA.

5.Discussion

The extruded EVA is not simply laid down in a coil, but is flattened by the nozzle onto previous layers. Thermal conductivity by this thin layer partially melts the underlying material causing the layers to fuse.

One key point to successful extrusion is the ambient temperature. Because the layers of EVA need to be fused, significant heat is transferred into the workpiece on the turntable. Unless this is removed by a fan or similar, the heat builds up and melts the workpiece into a shapeless blob, as with the early samples in Figure 10. If the extrusion speed is too high, the problem is exacerbated.

6.Conclusions

If nothing else, the experiment shows what can be accomplished by a newcomer to FDM in a relatively short time using commonly available materials. This in itself bodes well for the outcome of the RepRap project.

It does appear that hot-melt glue guns are suitable for use in a RepRap. Examining the final cylinders reveals that EVA itself is not suited to structural components, but it may well have an application in producing moulds, where its flexibility can be an advantage. It may be possible to replace it with ABS or a low melting point polymer called 'Polymorph' and further experimentation is required.

If improvements to the efficiency of the fan design are not possible, it may be necessary to extrude more complex shapes in paths, rather than a raster-style deposition to avoid unwanted heat build-up.

Though the apparatus was not originally intended as the basis for a fabricator, it is interesting to note the work that needs to be done to convert it into one:

- Independent control of drive screw.
- Mechanism to stop and restart extrusion/deposition.
- Improved cooling.
- Control of either extrusion head or turntable in an axis perpendicular to the turntable's rotation.
- Precise control of turntable rotation.
- Larger turntable.
- Controlling the tracking speed of the head across the turntable.
- Addition of another head to apply conductive material.

This illustrates the need for a standardised approach to the RepRap project, so that different technologies can provide useful data. Ultimately, entirely different systems should be able to independently model RepRap components.

Calculating the deposition speed

Given the rotation speed of 12RPM, or once every 0.2s, and the diameter of a typical good-quality tube at 20mm, it follows that the head is moving at (0.02m/0.2s) 0.1m/s

Calculating The Maximum Deposition Rate

Each layer in a good-quality cylinder is 0.25mm thick and 0.85mm wide, so in 1 second 100mm x 0.25mm x 0.85mm = 21.25mm^3 as the production rate for a gear-fed mechanism.

7.Acknowledgements

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9.Appendix

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END OF TERMS AND CONDITIONS

10. Author's Footnote - Further Research

I intend to continue this research in the hope that it may be of use to other people who wish to explore the implications of self-fabricating devices in a world where, I believe, they will ultimately exist.

[25-May-2005 – A document you might consider for further reading is the "Construction of PCBs Using Sliver Paint and EVA Hot-Melt Glue" by this author. The device described here now has 3-axis movement.]

Vik :v)

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