DIY 3D Printing: Open source 3D printer development by students of engineering product design

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Abstract

This paper documents a project undertaken by undergraduate students of Engineering Product Design at the author's institution. Five small groups were each provided with a kit of components for a RepRapPro Huxley 3D printer, and tasked with assembling, testing, and then redesigning it to improve or adapt its function. They were asked to document the process, and encouraged to share their learning experiences and innovations online through the 'Instructables' website.

The objectives of the project were to emulate the self directed educational nature of the Maker Movement in an academic setting, to foster a level of craftsmanship in students' use of 3D printing as a tool for design and to explore their attitudes towards open intellectual property.

The results are presented through descriptions of the redesigned printers, observations from the tutor throughout the process, and feedback from the students themselves. Two of the five groups chose to publish their designs online; these were highly positive about the feedback they received from the community. It is concluded that the project provided a highly beneficial, contemporary and relevant project based learning experience, deepening students' practical understanding of 3D printing technologies and extending the capacity for independent learning.

Keywords: *3D printing, open source, self-regulated learning.*

Context

3D printing is currently enjoying a frenzy of media attention; digital fabrication, coupled with a global marketplace through the Internet, has been recognised for some years as harbouring the potential for the consumer of tomorrow to 'design, order, and receive a product without leaving their home' (Hague et al., 2003, p.27). A decade later, the global 3D printing market reached $2.5billion, with growth forecast to be worth $16.2 billion by 2018 (Canalys, 2014). In 2014, consumer 3D printing reached the 'peak of inflated expectations' on the Gartner Hype Cycle (Gartner, 2014). This was fuelled largely by the expiry in 2009 of the patents on the FDM 3D printing process (Benchoff, 2013). There is now a multitude of affordable machines targeted at consumer use, which raise intriguing questions for the design profession about the future role that consumers will play in the design and manufacture of their objects.

Domestic 3D printers, however, are not necessarily the utopian home fabrication panacea that the media would have us believe. They require considerable technical skills to assemble and operate, and on-going maintenance and adjustment to both hardware and software in order to keep them working effectively. The organic nature of the open source 3D printer movement has meant that the hardware often outgrows the accompanying literature and learning resources that are available, making the assembly process a complex and sometimes frustrating task for the new user. For the patient and technically minded user it can also be a delightful, rewarding, educational, and even profitable activity to build and operate such a machine.

There is growing evidence in literature and practice of users participating in processes of design and innovation without the involvement of a production bureau or a design professional. The Maker Movement has been described as a revolution by a number of authors (Hatch, 2014). The term 'Makers' is used to describe the participants, characterized by an increasingly broad demographic of people who participate in creative and design tasks, using digital manufacturing and CAD technologies to make products for themselves. Chris Anderson defined three characteristics of the Maker Movement:

1. People using digital desktop tools to create designs for new products and prototype them ('digital DIY').
2. A cultural norm to share those designs and collaborate with others in online communities.

3. The use of common design file standards that allow anyone, if they desire, to send their designs to commercial manufacturing services to be produced in any number, just as easily as they can fabricate them on their desktop. (Anderson, 2012)

The first two of the statements listed above formed the inspiration for the project described in this paper.

Objectives

There is a strong self-directed educational foundation to the Maker Movement, as participants teach themselves to use the technologies to fabricate new objects, learning from, and reciprocally sharing with, the global community via the Internet. This project was established to explore the value of the learning experience that, following a self directed assembly and design project with 3D printers, can offer to students of design, and by extension, to other user groups and makers as well.

The project was conducted with a group of 17, 2nd year students of BSc Engineering Product Design. The philosophy of this degree course lays a heavy emphasis on design through making, particularly in the production of functional prototypes. Students have access to a well-equipped design workshop that hosts a number of industrial-grade 3D printers. Through observation, it became apparent that to the students, these machines represent something of a 'black box' in the cybernetic sense (Glanville, 1997), in that they learn to feed files into the software, and to receive the finished model when the print is complete, with little understanding of what happens in between. A technician performs the technical setup of the build; students are taught the principles of how the machines operate through layer-wise addition of material, but have no experience of how they function on an operational level. Thus the second objective of this project was to engender a level of craftsmanship in students' use of 3D printers, through fostering that intimate understanding of the tools of their trade, which is fundamental to craft practice.

Following Anderson's, 'cultural norm to share those designs and collaborate with others in online communities', the third objective of the project was to explore the attitudes of this generation towards sharing their ideas with the maker community. Students were encouraged to communicate the results of their learning experience, and their own innovations, to the wider 3D Printing community, through the medium of an 'Instructable' – an open, online instruction guide for future students or others to follow in building similar machines.

Project Design

In the early planning stages, the option to purchase each printer kit from a different manufacturer was considered. This would have provided an insight into the differences between machines that have all forked and evolved from one original concept. This idea was discounted for practical reasons: after the project, the maintenance and operation of the machines would be considerably easier for the technical support staff with only one model to learn to use. A number of manufacturers were considered, and although cheaper options were available, the RapRapPro Huxley was eventually selected for a number of reasons: the RepRap brand carries 3D printing heritage, being the first of the commonly available open source machines; the company are UK based, and relatively local to the institution, so it would be beneficial in the longer term to forge a positive relationship with them; and finally, the Huxley model is one of the most compact printers available, making it more suitable for students to move it around and store it.

In order to emulate the self-directed and self-regulated nature of the Maker Movement, it was intended that the students would operate and learn as autonomously as possible (within their individual groups) throughout the project. Self-regulated learning is defined by Vermunt and Rijswijk (1988) as 'performing educational activities oneself, taking over educational tasks from teachers, educating oneself. Fully self-regulated learning, or fully teacher-regulated learning is, however, less common in higher education than one or another intermediate form'. There is evidence to suggest that the interplay between self-regulation and external (teacher-) regulation of learning can give rise to either congruence or friction between learning and teaching strategies (Vermunt and Verloop, 1999). Congruence occurs if the learning strategies of the students are compatible with the teaching strategies of the tutor; clearly this is beneficial to the student learning experience. Friction occurs when this is not the case, but this is not necessarily detrimental to learning. Constructive friction can encourage students to employ learning and thinking strategies that they have not used before, improving their learning skills. Destructive friction, however, can occur if the teacher over-rides learning strategies that students have employed of their own accord (Vermunt and Verloop, 1998). The intention, in this case, was to stimulate constructive friction by giving the students more autonomy over their learning than they had previously experienced on the course; it was hoped that this would not only increase the depth of their learning and personal development as they encountered and addressed problems themselves, but also that it would highlight the problems that others will face in following a similar project. Teaching was planned to be more reactive than proactive, following a constructivist approach in which the students discovered, and attempted to solve problems for themselves as they arose. In order to avoid destructive friction however, the tutor would be on hand in classes to provide targeted tutorial support when needed.

The budget for the project dictated that the students must be divided into groups. Group allocation is a perennial difficulty in higher education; allocation by the tutor provides a closer simulation of real-life working environments, but invariably results in complaints from students when individual team members do not make a fair contribution to the work. Allowing students to self-select their groups, however, results in friendship groups sticking together, which can limit the value of the peer learning that might arise from working with unfamiliar group members. This issue were decided through reference to the Maker Movement paradigm, in which like minded individuals tend to self-select groups in which to operate: thus the students were allowed to choose their own groups of three or four members for this project.

Delivery

Each group was provided with a kit of components for a RepRapPro Huxley printer and the necessary tools for its assembly. They were briefed to conduct their own research into the assembly procedure through the official instructions, and any other resources they could find, in order to assemble, calibrate, and test the machine. When this was complete, they were to propose and implement derivative designs that improved or adapted the function of their printers, the inspiration for which was expected to arise from the experiential learning process that they had undergone in assembling it. Students would be formally assessed on their grasp of the technical factors required to build the printer, their clear communication of these through the 'Instructable', and innovative thinking in their proposals for derivatives of the original printer model. They were offered a choice of whether or not to publish the 'Instructable' online or simply submit the unpublished document to the tutor for their assessment.

Students were timetabled to four hours of lecturer contact per week in a teaching lab, throughout the six weeks of the project. During the first session, an open-ended discussion was held, chaired by the tutor, in which the students were encouraged to share and discuss their knowledge of 3D printing. This highlighted a number of gaps and misconceptions in their understanding of the range and capabilities of the technology. They were also shown a demonstration of another open source self-assembly printer, which had been adapted by colleagues to extrude a syringe full of food paste. They were encouraged to identify key physical and operational elements of the printer, and to speculate on the potential problems they might encounter. During subsequent sessions the students worked in their groups to assemble their printers, with no formal taught content in lecture form. The tutor endeavoured to provide guidance in response to specific questions from the students during these periods.

The printer kits, in boxes, were made available for the students to sign out in order work on in the university labs outside of class time. Following impassioned requests, this permission was later extended to allow them to take the machines home or elsewhere to work on them outside of university hours. Four of the five groups took advantage of this immediately, which led to a marked increase in the pace of their assembly work, and the first machine was printing parts by the end of that week, following 'several all nighters'. In contrast, the fifth group were the only ones not to take advantage of this until the fifth week of the project; these were also the last group to achieve an operational printer.

Project Outcomes: Tutor observations

Due to an administrative issue, the start of the project was delayed by a week until the kits were delivered. This served to build the level of anticipation amongst the students, which was reflected in the tangible atmosphere of excitement when the kits were eventually distributed. One student had to be warned not to rip at the tape in such a way in case he damaged the contents of the box! This level of enthusiasm persisted throughout the classes: without exception, all students were fully engaged by the task, with no requirement for prompting or encouragement from the lecturer. There was generally an excited buzz of conversation throughout, as groups discussed the instructions and their next steps in the build process.

Early issues that became apparent were in identification of the components. Students were encouraged to check their kit contents against the packing list, and several requested help in distinguishing between such components as microswitches, thermistors, and more obscure names such as 'Bowden tubes'.

Various approaches were used to document their process. One group mounted a 'GoPro' helmet camera on the ledge above their workbench and filmed their entire process. Another designated one member as a videographer whilst the others conducted the assembly. The remaining groups used still-shot photographs at key milestones during the process.

One spare kit of parts was kept available for use as spares, which proved invaluable. Despite their checking the packing lists at the start of the project, there were a few small components that were either missing from the pack, or lost or broken by the students. In the worst case, students managed to short-circuit one of the Melzi control boards. This happened during a class workshop, although not under the direct supervision of the tutor. The students were somewhat vague in their explanations of exactly how it had happened but subsequent consultation with the manufacturer suggested that one of them had touched the circuit board whilst the machine was operating, short circuiting something. This served to highlight a flaw in the original design, which that group later addressed in their redesigned model. During the assembly process, students were observed to become more critical of the original components. Spotting the potential for improvement in a marketed product developed their faith in their own abilities to contribute to the design of it.

A number of the groups used the AutoDesk Inventor CAD package to model their assemblies in order to redesign their machines. This built on skills developed in an introductory CAD module taken during the previous academic year, but despite this, one student observed that 'when we're doing it for ourselves, it's a lot more complex that the classroom exercises that you gave us'.

The first group achieved a functional machine within two weeks of the start of the project, with three of the others following in the next two weeks after that. By week five, one group had already rebuilt their frame, replacing a number of the studded bars with laser cut MDF panels. They claimed that this had an immediate positive effect on the build quality. The same group observed that the machine would still operate when lying on its side at 90 degrees; they were also discovered wearing it on their heads in order to 'hear the noises it makes through the vibrations'. This suggests an interesting *designerly* approach to the project, in looking at the issue from, quite literally, a different angle.

The project had been scheduled to run for a six week teaching period. By week five, although all of the printers would be operational, the students had not yet had sufficient time to design and implement their modifications. This was not through lack of engagement with the project, as most were contributing well over the expected self-managed hours. They were therefore offered a choice of two options: to submit on the deadline, but with a reduced submission requirement of just the working machine, the 'Instructable', and the test components, or to extend the deadline by an further three term time weeks (a total of six weeks due to the Easter holiday period), in which to complete their project to the original deliverables.

Submission requirements for test components were also discussed and negotiated with the students, as they began printing with their machines and understanding their capabilities. *The Make 3D printing Guide 2014* used a number of components downloaded from the *Thingiverse* website in order to test the capabilities of a range of consumer level 3D printers. These were agreed in class as appropriate test pieces that could be compared against each other as a reflection of the quality of the build process and/or the improvements. In addition to this, students were asked to submit a 'showstopper' component, that would best demonstrate the capabilities of the machine following their design improvements.

Project Outcomes: The printers

The primary design concern of group one was the 'birds nest' of electrical cables running around the support structure, which not only reduced the visual appeal of the printer (particularly to the less technically minded user), but also increased the risk of them accidentally becoming caught and disconnected from the control board, which was mounted on the top of the frame structure. They designed and manufactured a control box that would nest between the table and the print bed, housing and protecting the control board inside it. They then protected all of the electrical cables inside expandable sheathes to leave a clean, tidy finish. A colour coding scheme was devised, both to enhance the high-tech aesthetic, and also to improve the ergonomics of the machine by visually indicating the operational components. Black and orange were chosen as the colour scheme, with all metallic parts anodised black, and all remaining plastic parts sanded, primed, and sprayed either black or orange. When questioned on why they did not simply reprint the plastic components using a coloured filament, they indicated that they were unhappy with the layered surface finish that is a result of the FDM process, and wanted parts that appeared as though they had been injection moulded.

Group two increased the Z height build capability of the printer, using extended lengths of the 6mm silver steel and M6 threaded bars that comprise the primary structure of the machine. They were also concerned with the messy aesthetics of the wiring, and so redesigned the frame to be encased entirely in laser cut acrylic, moving away from the triangulated structure of the original. The original design provided no mounting point for the filament spool; when left loose on a table, this could cause problems with the feed. The group extended two of the vertical rods even further above the assembly and hung the filament spool from these on a cross-bar, such that it could rotate freely as required.

Group three observed that the structural stiffness of the frame was affecting the quality of the printed parts. The PLA plastic components of the machine tended to distort slightly under the compression of the M6 nuts, affecting the overall tolerances of the frame. They redesigned the frame to be comprised of two rectangular support plates, laser cut from 8mm MDF. These not only changed the visual aesthetic but stiffened the structure to improve the precision of the build quality. They had also observed that cooling was

Image 1

Image 1.
The group one printer
Photo: © Amar Shah.

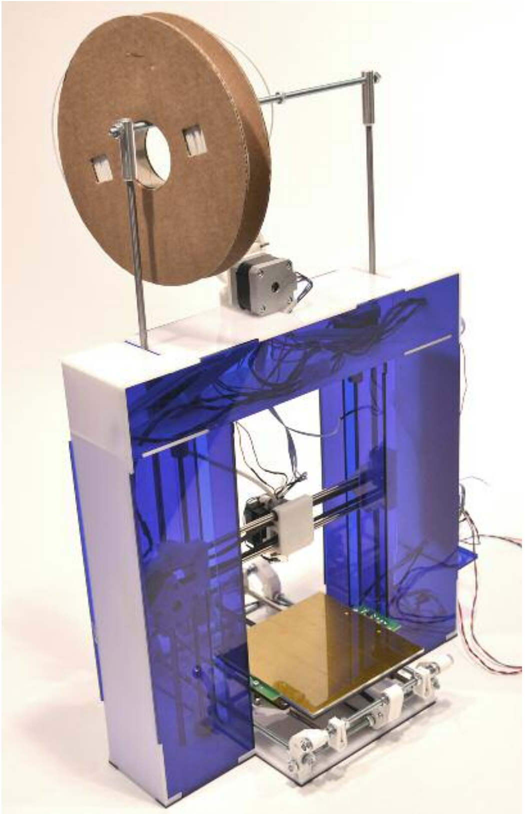

Image 2

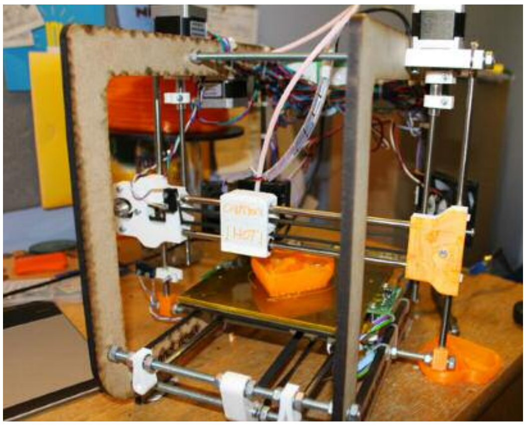

Image 3

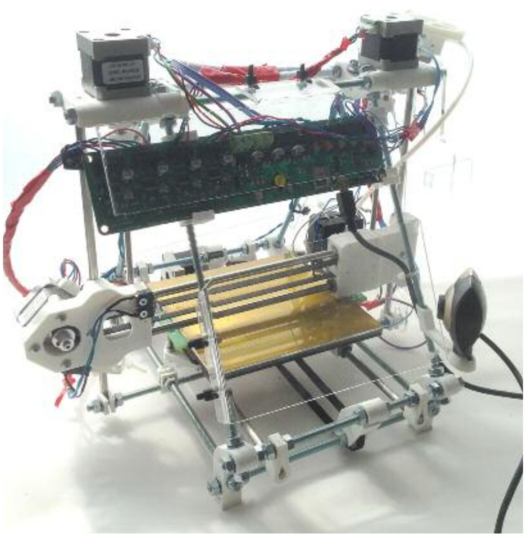

Image 4

Image 2.
The group two printer
Photo: © Adam Shacklady.

Image 3.
The group three 'Huxley FU' printer.
Photo: © Matt Wegner.

Image 4.
The group four printer.

an issue, particularly in a machine that built parts in an open chamber that was dependent upon the atmospheric conditions of the room. They mounted two additional large computer fans to significantly increase the airflow over the part as it was built. They named their printer the 'Huxley FU', standing for 'Fanned Up'.

Group four took an interesting approach to the occasionally unreliable nature of the printer. After having experienced several builds that failed, they concluded that the machine should not be left unsupervised, but that it was also inconvenient for a user to have to watch it throughout the build. They designed a mount for a webcam at the base of the build plate. Using a simple piece of freeware, this video feed could be accessed from any web-enabled device, enabling them to leave their machine operating, but to check on it regularly whilst working on other tasks elsewhere. They also added some hinged guards made from clear acrylic, to prevent access to the working parts during the build process. They too addressed the issue of messy wires, although with somewhat less finesse than some of the other teams, by wrapping the bundled cables with red electrical tape.

The final group struggled with the assembly process, and so made less progress than the others. This was possibly due to the fact that of the three members, one withdrew from the course for personal reasons early on in the project; neither of the other two was a native English speaker, and so they found more difficulty than most groups in following the technical terminology in the literature. This was also evidenced by their being more dependent upon guidance from the tutor throughout the process. By the final submission date, their original machine had been assembled and operated successfully, but they had not had time to implement any improvements. The did however submit proposals for these; they wanted to make the machine more attractive to a younger generation of users, following Anderson's description of giving a 3D printer to his children (Anderson, 2012), by redesigning the plastic components of the machine into zoomorphic shapes, giving it a character, and reducing the technical and machine-like aesthetic.

Project Outcomes: Student feedback

The students were surveyed at a number of points throughout the project, and at the end through a written questionnaire. This consisted of open ended questions in order to discourage prompt specific replies as much as to elicit personal and genuine feedback. The following section presents some of the key feedback points from the students, grouped into common themes, with some discussion of the implications:

Components

- *'Alignment and accuracy of the print was difficult, but guides and tools were used to fix the issue'.*
- *'Quality of printed parts were bad and often needed sanding / adjusting'.*
- *'The extruder needed to be reprinted'.*

Many components for the RepRap printers are themselves 3D printed on the same machines. The students expressed surprise in finding difficulty when assembling these with engineered components such as silver steel rods. This highlighted an important learning point in the tolerances that the machines are capable of achieving, and gave students a benchmark understanding of what their own machines should be aiming to improve on. A number of the groups expressed dissatisfaction with the design of the extruder assembly, although in all cases they did not attempt to redesign this themselves, but sourced improvements through the open online communities.

Resources

- *'The Reprap Wiki page combined with the knowledge of our lecturer.'*
- *'The rep-rap wiki online; the lecturer's knowledge; sharing with other groups.'*
- *'Taking the printer home / out of uni. Spare parts already available.'*
- *'The paperwork provided did not provide enough detail as to put together complex parts. Youtube and other videos found to be the most resourceful forums closely behind it.'*

All groups used the RepRap instructions extensively, but many also found these to be not detailed enough, or confusing at points, and explored other sources from YouTube and Online forums, and also from other groups within the class. Despite the teaching strategy of reacting rather than leading, several also clearly valued having an experienced lecturer to call on when necessary. The ability to take the kit home, and having a spare kit of replacement parts available was also cited as beneficial.

Assembly

- *'The breakdown in stages and lack of a comparative model often meant moving back a step to fix something which went wrong earlier.'*
- *'How a 3d printer works, what material is used, importance of accurate building.'*
- *'Fitting parts together. I solved it by a great deal of sanding and hammering.'*
- *'Labelling the wires to keep track of them.'*

The sequential nature of the operations in the build process involved a lengthy period of work on the machine before any testing could be done which would show that all of the steps had been followed correctly. In a couple of cases, testing highlighted a mistake that had been made at the early stages of the process. This required another prolonged period of work disassembling the machine to repair the error. This had the positive benefit of encouraging students to develop strategies to assist them in this process, such as labelling the wires for easy identification.

Operation

- *'How much the environment affects the build quality.'*
- *'Software. [the tutor] helped us.'*
- *'Changing the print settings to find the best.'*

Students were surprised to discover the susceptibility of the build quality, in particular the adherence of the part to the bed, and to variations in local environmental conditions. Another hurdle that was problematic for some, was in installing and operating the software, which is a Python based program that proved difficult to install on some of their laptops.

Grouping

- *'Groups of four may be too much (at best two students at a time can work on the printer).'*
- *'Too many people in a group. Not much space to move around the machine because of this.'*
- *'If the group is smaller it will take less time to complete the project.'*

Several of the students pointed out that no more than two people can feasible participate in the assembly process at any one time, so suggested that smaller groups would enhance the learning experience for all. This of course is constrained by the budget for the project; it also, however, encouraged the students to develop strategies for distributing the workload between them.

Decision Making

- *'A clear direction is needed for the redesign, this should be decided early.'*
- *'The worst: leaving the redesign build to the last minute. The best: Taking time building the frame to make sure it is calibrated properly.'*
- *'The worst thing was taking a long time to figure out the improvements we were going to make on the printer. The best thing was reverse engineering the printer to make a frame for it.'*
- *'We decided to anodise the metal components for the build – looked aesthetically pleasing but cost us a small fortune.'*
- *'The best decision was to go down the route of designing our own parts. It was a very good experience and some of feedbacks from people which have downloaded our parts is great. The worst decision would be leaving the designing of the parts so late, which left little time for further developing them.'*
- *'Best: Reading through before building; Redesign: CAD assembly on computer followed by MOD1 MDF model. Worst: timekeeping, rushing at the end.'*

A recurring theme throughout the comments on decision-making was timekeeping. During the scheduled six weeks, the students contributed well over the expected hours, knowing that they would see the tutor each week and be expected to show progress. It seems that when the deadline was extended, many of them shelved the project for a while in order to catch up with other work and then found themselves pressured to complete the redesign at the end. The result was that whilst all but one team submitted a redesigned, and operational printer, none of them had left time enough to print out the full set of test components that were intended to be compared for build quality.

Learning experiences

- *'Hands on! Being able to feel and set up every part was the best part of learning. How the axes work, wiring up, programs'.*
- *'Practical, learning to solve problems as they come about from electrical problems to simple mechanical problems'.*
- *'With this project it was very much a case of learn as you go along, things which we could not predict happening which required on the spot fixes, helped gain a lot of resourcefulness'.*
- *'Having hands on experience of making a 3d printer is something that cannot be taught in a lecture'.*
- *'In terms of improvements to the design you could only really get ideas from your own experiences, which influence the direction you go in'.*

The students were generally highly satisfied by the practical and project-based nature of the work, and began to recognise the value of self-directed learning in developing deeper understandings of the work that they were conducting.

Sharing

- *'Sharing my work and getting a positive response from the online community is an addictive feeling. It has influenced me to build my own printer and keep putting new / improved designs up'.*
- *'I think it is a very useful tool if everyone shares their ideas and tips, it improves everyone's work'.*
- *'Happy to share it; this is what brings the project forward and this is what helped us create our design. Sharing is caring'.*
- *'Really good 'cos you get feedback and comments which happened a day after it was uploaded showing the community was interested in kit 3d prints'.*
- *'As there are numerous Instructables online we thought it was a bit pointless. But making an Instructable is a good learning curve as we could advise people on problems we encountered during the build'.*
- *'Better not'.*

Only two of the five groups decided to share their designs online. These immediately found followers amongst the community; at time of writing, these designs have had 1029 views and 21 *favourites*, and 840 views and six *favourites* respectively. These two groups were delighted with the feedback they received from the community. Of the groups who didn't share the work online, interestingly, most did not provide any explanation as to their reasoning for this. Almost all of them left this question field blank; in total there were only two responses that provided any negative feeling towards openly sharing their ideas. The first of these recognised that the act of creating the instructional material was a useful learning experience in itself; the final one however, was more blunt, in simply stating 'Better not'.

Discussion

The observations of, and feedback from, students on this project, have served to highlight some key distinctions between theory and practice in a learning experience of this nature. Students of design and engineering are typically taught about the reliability and precision of digital manufacturing processes. This contrasts with the need for careful and continuous maintenance, without which, the parts produced can be highly variable in their surface finish and tolerances. Optimising the settings of the control software for an accurate build is a process that can only be learned through experience. The theory behind the electronic circuits that control it is far removed from the technical skills of precise soldering and wiring that are needed to make the machine operate effectively. The published instructions carry an authority that suggests completeness; a good build derives from tacit skills in technical assembly that must be developed through practice.

The project aimed to provide as little formal structure to the learning process as possible. This was problematic when balanced against the formal requirements for academic assessment; students did not complete all of the required elements in the printed components for testing. The deadline needed to be extended, although to some extent this was also due to the experimental nature of the project: it was difficult to forecast in advance exactly what rate of progress was realistic to expect. In four out of five cases, the friction caused by giving the students a highly self-regulated learning experience appears to have been constructive in that the students successfully achieved their objectives and expanded their capacity for independent learning. In the fifth case, it is possible that the students' self-regulatory learning skills were to some extent mismatched with the expectations of the tutor and the requirements of the project, resulting in an incomplete submission.

Of the two groups who published their designs online, both used the Creative Commons Attribution Non-commercial Share Alike licence. The students from these groups were vocal and unanimously positive about the experience of sharing, and the feedback comments from the community were also positive. The groups who chose not to share their designs did not generally attempt to explain their reasons for this. A class discussion had been held in the early stages of the project about the implications of either protecting or opening intellectual property, but it might be beneficial in future to cover these issues more deeply in classes prior to the project.

Looking forward, it should be considered how this project might best be integrated into the course on an annual basis. It was expensive to run: approximately £2000 between 17 students. This can be offset against adding the operational machines to the departmental 3D printing capability, but the expense makes the project unfeasible to run annually, notwithstanding the fact that the department would soon end up with a surplus of 3D printers that would never be used. One option would be for successive cohorts to begin by learning to operate the previous year's project submissions, and then dismantling them before rebuilding and redesigning. Another would be to dismantle the machines and repurpose the key components such as stepper motors to other electro-mechanical tasks. A further option might be to offer the students the option to purchase their machines at cost price from the University after the project.

As a learning experience, the students were generally highly positive in their feedback on this project, even those from the group that did not fully complete it. They clearly felt that it was relevant to their careers and enjoyed the self-directed and practice-based nature of it. From a craft perspective, they have deepened their understanding of a tool that will be central to their careers in product design, and the tacit skills required to get the best possible results from the technology.

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