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[DesktopLabs] Desktop Laboratories: Web Share and Additive Manufacture of Engineering Educational Models

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Abstract

Physical models are desirable in engineering education as they enhance visual literacy, provide insight into critical design failure modes and design attributes, and can be implemented in a classroom scenario in concert with multimedia displays and lecture slides. Despite the advantage, such physical models are often: not commercially available; are excessively costly; are not tailored to the intended learning outcomes; or are difficult to share across multiple geographic locations.

In this work, the authors have developed an approach to address these shortcomings by exploiting the emerging capabilities of additive manufacturing equipment, increasingly present within educational institutions. The [DesktopLabs] project engages students to develop and additively manufacture physical models, to allow in-class demonstration of complex systems that would not be otherwise possible. By engaging with physical models of technical systems, students enhance their capacity to engage with emerging engineering technologies, and to solve new and complex problems. Combined with access to online sharing facilities, [DesktopLabs] allow web share of the developed model files, thereby allowing ready dissemination amongst other educators for additive manufacture in other geographic locations. Although applied in an engineering context, the benefit of [DesktopLabs] are directly transferrable to teaching areas to aid in the education of successive generations of undergraduate and postgraduate students.

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1. Introduction

Professional engineers are responsible for the design and maintenance of a variety of technical systems. It is typically impractical to bring these technical systems to the classroom environment, and physical models are used as a convenient proxy for real-world technical systems. The benefit of 3D educational models to aid in technology transfer and education is well documented, for example [1]. Physical models are particularly desirable as they enhance visual literacy [2, 3], provide insight into critical design failure modes and design attributes, and can be implemented in a classroom scenario in concert with multimedia displays and lecture slides. Despite the advantage, such physical models are often not commercially available, are excessively costly, or, are simply not tailored to the intended learning outcomes. To overcome these limitations, recourse is made to custom made technical models. This allows the development of models that accommodate specific details of interest, however this can involve substantial time and cost commitments. Furthermore, once a specific design has been developed and implemented, the design effort is typically not shared, or made available to other educators due to communication and logistical barriers.

Additive manufacturing (AM) is an emerging manufacturing approach in which material layers are successively joined to produce objects from 3D model data [4]. A range of polymer based additive manufacturing processes have been developed which are capable of rapidly producing prototypes and functional components. A common polymer AM process is Fused Deposition Modelling (FDM) in which a thermoplastic filament is extruded through a planarly actuated heated nozzle, and subsequently deposited onto a vertically actuated platform to build 3D parts layer by layer [5]. FDM can accommodate the manufacture of complex part geometries in a broad range of plastics, and has recently seen increased popularity through the growing availability of many low-cost, consumer level FDM machines [6]. The attractive capabilities and reducing costs have resulted in AM systems becoming commonplace within educational institutions, which is enabling innovative ways to engage with undergraduate students [7].

The availability of AM technologies provides an opportunity to manufacture custom physical models of technical systems “on demand” that are low cost and customized for specific educational outcomes. For example, technical models can be developed in computer aided design (CAD) design tools and additively manufactured with reduced need for labor, tooling and traditional machining equipment, thereby reducing time and costs commitments associated with custom made technical models. Furthermore, additive manufacturing allows for the ability to manufacture models and components as required, to accommodate changing demand for model units, or spare components for maintenance. Model design effort can also be reduced by the ability to re-use component designs common across multiple technical models (such as gear elements in gear based mechanical power transmission models). Additionally, as AM systems typically work with standardized digital file formats (such as Stereolithography (STL) files [8]) the developed technical model designs can be rapidly shared electronically and made available to other educators to allow manufacture of models with local AM equipment. Similar approaches have been successfully implemented in projects which leverage internet connectivity to share resources across multiple teaching campuses [9]. Furthermore, AM systems such as FDM require a relatively low level of operator training, allowing for student accessibility and direct engagement in the design, manufacture and assembly of technical models as part of relevant engineering courses (such as CAD, machine component design and design for manufacture subjects).

To take advantage of the identified opportunities enabled by AM for the rapid manufacture of technical models, the authors have developed and implemented an education approach which aims to allow students to engage with technical equipment within the machine design domain. This aim is achieved through the project: [DesktopLabs] Desktop Laboratories: Web Share and Additive Manufacture of Engineering Educational Models.

2. DesktopLabs

2.1. Methodology

[DesktopLabs] Desktop Laboratories: Web Share and Additive Manufacture of Engineering Educational Models aims to allow students to engage with technical equipment within the machine design domain, through the application of digital design and additive manufacturing tools available within educational institutions, to the manufacture of physical models demonstrating the operating principles of various mechanical systems. Combined
with access to web sharing facilities, [DesktopLabs] allows the ready dissemination of digital plans for educational models, to other educators in geographic locations featuring additive manufacturing equipment.

The [DesktopLabs] approach was developed in a second year mechanical engineering design course, where a series of physical models were designed and manufactured to allow in-class demonstration of specific properties of mechanical systems, which are difficult to show without physical aids. This was realized by engaging a select group of motivated students enrolled in the course, to contribute to the design, additive manufacture, assembly and testing of physical models of mechanical devices (Fig 1.). Formal notice was given to all students about the opportunity, and a number of students expressed interest and attended a collaborative meeting. Within this meeting, students identified preferred team members, and relevant designs of interest to them and the selected course. Recruited students comprised of approximately 6% (16 student) of the class population. The model design and build projects identified by the student teams are detailed in Section 2.2.

Students were provided with regular access to CAD labs, and presented with several design for additive manufacture case studies based on prior work. Students were then given a bill of allowable materials, including consumables, additive manufacture polymers, laser cut sheet and low-cost ball bearings to use in their design. Initial concepts were presented to the group, and based on feedback (primarily from peers), the student teams refined their design and developed detailed CAD models (Fig 1. (i)).

Models were manufactured and assembled within an engineering laboratory facility featuring additive manufacturing equipment as well as basic workshop tools (Fig 1. (ii)). Students were responsible for all details of additive manufacture of models using FDM equipment, such as minimizing build time by identifying efficient part packing layouts on the build platform. The [DesktopLab] models were manufactured from Acrylonitrile Butadine Styrene (ABS) polymer using professional FDM equipment as available at the teaching facility. The models were also trialed successfully on low cost (<$5k) desktop FDM machines from polylactide (PLA) polymer.

Fig. 1. (i) Students engaged in [DesktopLabs] physical model design. (ii) Student manufacture of physical models. (iii) Students engaging with manufactured physical models (including demonstration on overhead data projector).

Students were responsible for all design decisions, and were expected to act as professional engineers with accountability for the project outcomes, group work and timely delivery. Through this responsibility, the contributing students were given the opportunity to develop deeper understanding of CAD design, and the manufacturing capabilities and limitations of additive manufacturing technologies. The students’ ability and experience varied significantly, with some students able to generate concepts and CAD with very little assistance, where others required active advice and assistance. However, the common attribute of the student designers appeared to be enthusiasm for creative design, rather than experience or existing capabilities.
Once manufactured, the models were used by all students within the course during in-class demonstrations to familiarize themselves with the model operation and observe underlying operating principles (Fig. 1 (iii)). The models were specifically sized to enable demonstration using overhead digital projectors to facilitate discussion and concurrent demonstration by the instructor.

An electronic, shared database of educational models was established through a Google Docs repository, which included the following files:

- Native CAD model – to allow manipulation of original data
- Stereolithography (STL) model files – to allow additive manufacture by external teams
- Digital images of components and assemblies – to aid in assembly and selection of [DesktopLabs] models

This outcome allows sharing of models electronically, enabling other educators and students access to the source code required for them to manufacture the models locally with their AM equipment. This is especially valuable for universities that teach at multiple geographic locations, as physical models that can be shared electronically and built as required.

2.2. Models

The models developed by students as part of the [DesktopLabs] project were chosen based on topics covered in the associated mechanical design course, which focused on the functionality of geared devices and mechanical joints. The models are detailed in Table 1, Figure 2 and Figure 3.

| Model                          | Figure | Intended demonstration                                                                 |
|--------------------------------|--------|----------------------------------------------------------------------------------------|
| Gear Design: Backlash          | 2 (i)  | Importance of backlash as a design variable requiring correct definition to achieve   |
|                                |        | robust gear function.                                                                  |
| Gear Design: Hunting tooth     | 2 (ii) | Concept of Hunting Tooth gear behaviors and its significant influence on the durability |
|                                |        | of a gear design, as well as that minor changes in gear ratio result in significant   |
|                                |        | changes in function.                                                                  |
| Gear Design: Undercut          | 2 (iii)| Concept of tooth undercut; its significance in achieving robust gear function, and    |
|                                |        | also its effect on tooth bending stresses.                                            |
| Differential gear              | 2 (iv) | Complex mechanical outcomes enabled by combination of machine elements (bearing,      |
|                                |        | shaft, bevel gear). In this case that the differential gear, allows input power to    |
|                                |        | be transferred from an input shaft to two independent output shafts.                  |
| Hooke’s constant velocity joint| 2 (v)  | Limitations and capabilities of a Hooke’s joint to transfer rotary power while        |
|                                |        | changing shaft orientation.                                                          |
| Gear box assembly 1            | 3 (i)  | Function of a two-stage reduction gearbox.                                             |
| Gear box assembly 2            | 3 (ii) | The highly sophisticated mechanical function achieved by the combination of simple    |
| Four stroke Internal Combustion Engine | 3 (iii)|                                                                                      |
|                                |        | elements.                                                                             |
2.3. Student reception and outcomes

In evaluating this work, a series of qualitative questions were asked of the students regarding the use of physical models:

1. “Has the use of physical models contributed to your understanding of the fundamental machine elements developed in this course?”
2. “Has the use of physical models aided in your visual and spatial understanding?”
3. “Would the use of additional physical models contribute further to your understanding of the fundamental machine elements developed in this course?”

These responses to questions were strongly positive and confirmed that the models developed through [DesktopLabs] enhanced the student experience. Additionally, it was observed that when [DesktopLab] models were presented in tutorials, students typically congregated around the models, and without prompting began to dissect and interact with them. This encouraged interaction between teaching staff and students and led to a less formal, more collaborative, environment. The combination of physical model and data projector allowed interested students to interact physically with a specific model, while all in the room could watch the interaction on the data projector. Unlike computer generated models that are subject to a simulation of the real world, working physical models demonstrate the function of a real-world concept, with real word functional requirements. Consequently, students were able to observe the intended sub-component and assembly function (e.g. differential action), but also, often asked additional relevant questions regarding not only the intended function, but also, secondary physical phenomena and potential failure modes. The lecturers and tutors have not observed this higher-level inquisitiveness in prior years (where only sub-components were available as physical models, and systems were presented as CAD simulations and video).
Furthermore, the student that participated in the model design and manufacture component, were found to be capable of design, manufacture and commissioning of the models with a high degree of autonomy and self-direction. This opportunity allowed high-performing students to engage deeply with the fundamental engineering problems, as well as developing a capability to apply advanced manufacturing processes, i.e. additive manufacture. The positive response validated the [DesktopLabs] approach as a useful tool for aiding in the education of undergraduate students.

3. Conclusion

Engineering degrees intend to equip students with the capability to conceive, design, implement and operate technical systems and equipment. Physical models are an invaluable tool for enhancing visual literacy and aiding in technology transfer. The current generation of additive manufacturing equipment allows robust, low cost manufacture of custom components and assemblies, such as physical models for engineering education. [DesktopLabs] demonstrates the many benefits of developing additively manufactured physical models for student education:

- The creativity and enthusiasm of the students associated with the course is utilized to develop the physical models, thereby increasing educational impact.
- Students are responsible for all design decisions, and act as a professional engineer accountable for the project outcomes, which aids in the development of understanding of the capabilities and limitations of additive manufacture.
- Students are able to readily engage with the models to examine the intended functionality, as well as additional physical principles of relevance (an outcome not possible with computer generated models or multimedia presentations).
- The project outcomes are compatible with the capabilities of low cost (sub $5000 AUD) FDM additive manufacturing equipment.
- Associated model data can be shared online to allow model manufacture at other geographic locations. This outcome is especially valuable for engineering universities that teach at multiple campuses.
- The project outcomes were validated with positive student response.
- Although applied in an engineering context, the benefit of [DesktopLabs] are directly transferrable to other research and teaching areas where relevant model may be developed as appropriate for the associated course.

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