Project-based Learning of Systems Engineering V Model with the Support of 3D Printing

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CONTEXT
Systems engineering is a branch of engineering integrating interdisciplinary engineering teams to design and manage complex engineering design projects. The principles can be described with the V Model representing different phases of a systems engineering project development lifecycle. Due to the complexity in delivering multi-disciplinary outcomes, students often find the subject difficult to comprehend when it is put into practice. By its nature, systems engineering knowledge could best be delivered by incorporating the activities in the systems engineering V development lifecycle in the learning process. However, normal systems engineering practices are applied to large scale systems development. A different approach that can be practised effectively in a classroom environment is required where only small scale projects are possible to complete the development lifecycle.

PURPOSE
Systems engineering concepts are abstract and hard to form a solid identifiable personal experience even for professional engineers. This article discusses the project design and assessment structure in a systems engineering course to facilitate the learning process at different stages of the systems engineering V Model. The 3D printing process is organised as a learning resource for the students to verify their system design in a demonstrable format.

APPROACH
Project based learning methodology has been successfully applied to teaching conventional subjects involving design. A project based learning environment in which students are required to go through stages of the systems engineering V Model lifecycle while designing and developing a hurdle robot as the engineering design outcome has been established. 3D (three-dimensional) printing is recognized as an emerging technology breakthrough, and plays a key role in future product design and manufacturing. To ensure the students work within the constraint of the semester, the learning environment is designed with the support of 3D printing facilities and extra learning resources in the learning management system. Access to these resources is unrestricted except in case where there are conflicting classes in the same space.

RESULTS
Students are allocated into groups. Different designs of the hurdle robot are produced and tried. The student groups that follow closely the systems engineering V Model lifecycle seem to settle down with the final version of their designs quickly. This proves that the environment has facilitated learning of the systems engineering V development lifecycle process.

CONCLUSIONS
A project based learning environment has been developed for learning and teaching in systems engineering. With the support of 3D printing technology, students are able to test and verify what they have designed according to the complete V model so that they can experience the systems engineering core activities.

KEYWORDS
Systems engineering, 3D printing, project-based learning.

Introduction

Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the sustainability of the system after commissioning (Blanchard & Fabrycky, 2010). However, teaching systems engineering is difficult, due to the highly conceptualized nature of the engineering process.

The essence of this branch of engineering is well represented by the V system development cycle (INCOSE, 2011). Except at the very early stage of feasibility study and concept exploration, at each stage of system development, there is a corresponding plan to demonstrate successful achievement of that stage. V system development cycle is commonly used in large scale system development in which many stakeholders are affected or where new technologies will potentially have significant social impact. However, developing new systems inevitably deal with innovation and creativity within an infinite solution space (Lardeur & Longueville, 2004). The fundamental learning outcome expected from a product design subject is the ability to be innovative so that not only the students' engineering knowledge is applied, but also their creativity is stimulated and exploited freely. Research in the improvement of product development processes has been conducted for over 30 years (Chang & Chen, 2014). The activities of design specification and review have been systemized but help to the learning of ideas generation and fermentation.

Most research has been focused on the improvement of capturing system requirements (Flint, 2002) and the corresponding manufacturing system design (Hao & Helo, 2014). However, most of the students learn the product development techniques but not the systems engineering process. To succeed in developing a user acceptable and cost effective engineering system, the system engineer is also required to have fundamental knowledge of the whole systems engineering design process. Unfortunately, typical systems engineering courses use large scale engineering systems as the learning entity which in itself is a challenge for any engineer due to the fact that it is a costly system implementation stage in between.

Nowadays, 3D printing or additive manufacturing process has been recognized as the fourth industrial revolution. The advancement in data driven manufacturing accelerates application of this technology to many areas including small batch manufacture, remote location support and maintenance (Eisenberg, 2013). The additive manufacturing process allows intelligent factories, machines and products communicating with each other, driving production cooperatively. Additive manufacturing process education primarily has occurred at the level of higher education (Scott et al, 2012). Yet, few educational institutions have developed or even have access to books, instructional guides, and other educational materials needed for courses and lab activities in additive manufacturing (Huang & Leu, 2012). Recent advances in additive manufacturing have developed a reasonably open solution environment. The process produces 3D objects directly from a digital model by the successive addition of materials. This allows rapid development of products with low materials consumption and low costs.

Recently, project-based learning (PjBL) is a team-based teaching and learning approach that uses "real life" projects to help students gain technical knowledge and develop important skill sets in problem-solving, collaborative engagements, effective communication and research (Stojcevski et al, 2015). This paper is not about learning of product design skills. The 3D printing facility allows the students to explore innovative ideas and design functions of the system that often require sophisticated manufacturing machine tools. This paper explores the opportunity to combine PjBL approach with additive manufacturing process to create an enabling learning environment for students to learn both sides of a complete systems engineering V development lifecycle.

Literature Review

The miniaturization of products in the study of mechatronics using microprocessors and micro-devices has provided a good opportunity to develop problem-based learning platforms for many engineering curricula involving design activities. This solution space for the problem is much easier to testify with low cost mechatronic devices based on generally well defined standalone functions (Simic & Mo, 2008). Mo et al (2009) applied an industry developed education system in mechatronic courses and proved the advantage of open specification in learning. These problem-based learning researches suggest that an innovative approach should be adopted for different subjects.

Project-based learning (PjBL) approach is commonly applied in science subjects. Ergül and Kargın (2014) analysed the effect of the PjBL method on degree of success and motivation of students. The results showed that the problem based learning method made a positive contribution to the students' success. De los Ríos et al (2010) presented an educational methodology of cooperative problem based learning in the final years of the undergraduate programme. The results show that the methodology provides three main advantages in facilitating training in technical, personal, and contextual competences, collaborative learning and problem solving ability.

In a PjBL environment, rather than providing students with theory and other materials in an abstract manner, students are requested to work on one or more projects for the whole learning period using prepared learning materials on the learning management system to analyse and/or propose solutions or courses of action (Woodfield et al, 2015). The research showed that PjBL is particularly useful to motivate students to learn specific knowledge within the course.

PjBL offers a range of educational advantages over a traditional content-driven curriculum, providing opportunities for students to develop skills in solving problems, teamwork, articulation of ideas, forming, presenting and defending arguments, critical thinking, and relating theory to practice (Taylor et al, 2015). In the real world, the solution space can be infinite but in a problem-based learning environment, it is necessary to recognize the limited knowledge that a student or a group of students has (Gallagher, 1997). The systems engineering V development cycle should be supported as a facility that encourages innovative yet viable solutions to be implemented within the timeframe of the educational environment. Problems arising from product design are good topics that motivate innovation.

Literature reviews show that two critical support structures are required to be created to enable PjBL to be effective. First, the environment supporting PjBL activities should be established properly to allow a student-paced learning process. Second, resources and to a large extent, learning activities have been carefully planned to focus students' learning to what the system aims to achieve. This paper explores the requirements for these two support structures and outlines a pilot study for knowledge in systems engineering using the latest student friendly 3D printing facility.

Methodology and Supporting Structures

We have designed a project in which students are required to create a hurdle robot that can jump over an obstacle. A laboratory manual and learning resources were provided to guide students to explore the solutions in a systematic manner. A pilot study has been conducted for the year 2 students studying BEng (Hons) Sustainable Systems Engineering. There were 6 groups involved in the test and 4 students for each group. A representative group was selected as our case study and feedback from the students was collected in our study.

Laboratory Support

In this pilot study, an additive manufacturing facility is made available to students. The laboratory is an open laboratory such that so long as the students are trained to use the equipment on the bench, they can come to the laboratory to do it any time they like. This open laboratory concept has been experimented before and has proved to be particularly useful for the engineering education environment (Feisel & Rosa, 2005).

To ensure the solution for this open-ended problem can be found by the students within the constraint of the curriculum, a systematic process has been developed in the form of an example laboratory manual and is made available to the students.

A laboratory manual is designed to guide student to create the robotic car components through a series of additive manufacturing process (Advanced Manufacturing Precinct, 2015). The laboratory manual contains information of transforming the design of the hurdle robot to a data format that is acceptable to the additive manufacturing equipment. The students are required to complete the design of the robot as well as build the robot and manage the manufacturing process. In the manual, robotic car components such as “integrated chassis”, “robot arm”, etc. will be manufactured using 3D printing system. Standard components include two motor gearboxes, wheels and shafts will be provided in our problem so that students can think of the solution based on the existing resources.

Once the hurdle robot “product” is designed in the CAD, the students are instructed to import the CAD file into the 3D printing system, which is the control system for the additive machine. On the additive manufacturing system, the students are instructed to add an object by clicking the “Add” icon from the upper side of the interface and select base part of the robotic car “base.stl”. Choose “Move to Platform” to put the object on the printing platform.

Next, the students are asked to orientate the object in the manufacturing process in an optimized way. The 3D printing system allows the user to select the object and move the object to anywhere on the platform. Manipulation functions such as “Turn” and “Move” will position and orientate the object as if it has been built. The parts can be made individually as a batch of objects made in one manufacturing run.

Knowledge Support

The learning resources of the course are consolidated in a folder within the learning management system so that the students are able to learn these materials at a time of their choice. These learning resources include lecture notes and slide presentations on the principles of systems engineering, the V development lifecycle, tools and models that can be used in systems design, analyses and decision criteria.

Students are also encouraged to find additional information anywhere in the world, for example, projects that are governed by systems engineering management process to success.

Lifecycle Based Assessment Process

A project in which students are required to create a hurdle robot that can jump over an obstacle is defined in the first meeting with the students.

To start with this learning process, the problem statement is given to the students and explained in class. They are required to build a hurdle robot to the specification described above within 4 weeks’ time. The robot is controlled manually and must stay at upright position at all times. Then, the students will learn the additive manufacturing process by following the instructions of the laboratory manual to create the hurdle robot.

User Requirements

The user specification is typically a very generic statement of use and contains hardly any direct implication to the look-and-feel of the final product or system. Table 1 lists a design and build project for a “robot”.

Table 1: User requirements for the design and build project

No.	Description
1	Travel 1000 mm, jump over the obstacle, jump down the other side, and travel another 1000 mm, within one minute.
2	Control manually (not by a computer).
3	Use supplied 2 motors only to minimise cos.
4	“Cock pit”, where the driver will sit, must stay upright at all times.

Students are then required to deliver the system in 4 stages (assignments):

Stage 1 (A1) – Concept exploration and concepts of operations

In this stage students will work individually to produce a system design document containing the following information:

- System objectives, user needs and application scenarios
- Exploration of different options
- Selected concepts of operations with rationale
- System acceptance criteria

Stage 2 (A2) – Functional design

Students are required to form groups of 3 to 4. The individual concept of operations document in assignment 1 can be used as the basis to unify to one design in the group. This process is similar to one of the engineering challenges in a work environment, i.e. networking and team building. There are many ways to achieve the outcome. Typically, the first step in the Systems Engineering approach is to develop the functional block diagram. The system functional designs are assessed in a presentation by the group.

Stage 3 (A3) – Detail design

In this stage students are required to produce detail engineering design (computational) information to prove that your design has the ability to perform at or above the user requirements in Table 1. One report for all functions is required to describe the system design. For each function, the detail functional decomposition that lead to parts drawings, dimensions and test plans for the decompositions are required including assembly drawings. In the design of parts, students have to consider several manufacturing capabilities of the 3D printers. Some important manufacturing considerations include materials, size, accuracy and cost.

Staged 4 (A4) – Build the system

Students use the 3D printing facilities to build the components and finally the machine. A final system verification test is conducted on a narrow testing platform.

Results

There are many ways to achieve the outcome. Student groups can exercise their innovative thinking as much as possible.

Functional design and system verification

The system is then decomposed into functions that can be individually designed and manufactured as shown in Figure 1. Interpretation of the functions depends on the imagination and knowledge of the students. It is normal that the students will search the Internet to find any similar solutions.

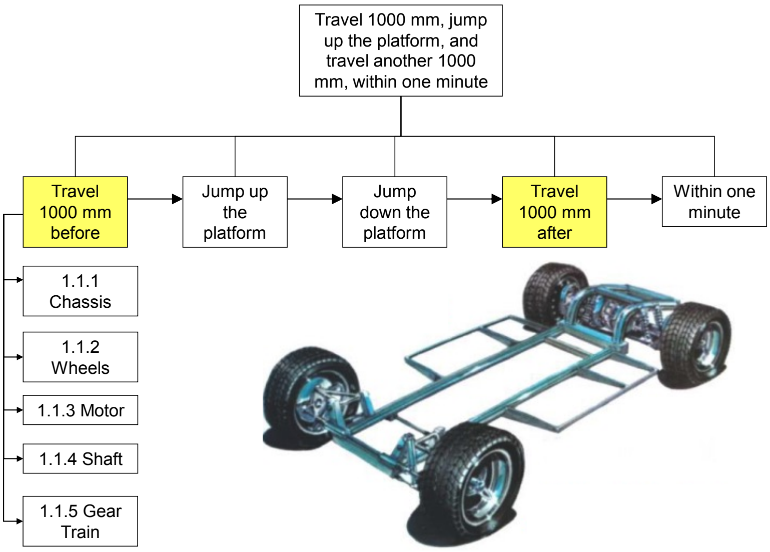

Figure 1: Functional design

Detail design and component testing

The hurdle robot is created by 3D computer-aided design (CAD) package. Figure 2 shows the assembly drawing of the robot.

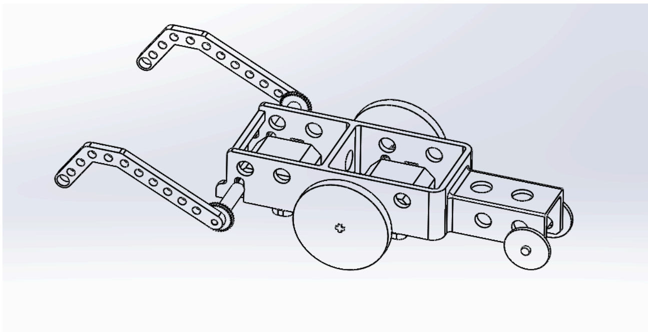

Figure 2: Assembly drawing of the designed robot created by CAD package

System development

In order to demonstrate the achievements in learning process with our approach, a group of students with their designed robotic car was selected as a case study. Based on their submitted group report, the students have successfully demonstrated the use of systems engineering approach such as functional block diagram and v systems development cycle in solving the open-ended problem. Figure 3 illustrates the hurdle robot designed and built by the students.

Student feedback

The pilot study was a preliminary run based on the new support structures. Initial responses from the students were very positive. Some comments are quoted here.

> *Project work, small class size and relevance to systems engineering.*

> *The project is engaging and allows us to practice the key principles of systems engineering*

The same pattern, with minor modifications, will be run again in the future with different types of systems to be designed and demonstrated. Besides, a negative comment is quoted below:

> *I think that the course content was not taught or explained very well therefore it made it difficult to do the assignments*

Further improvement and investigation will be conducted to address the problem in the next delivery in 2017.

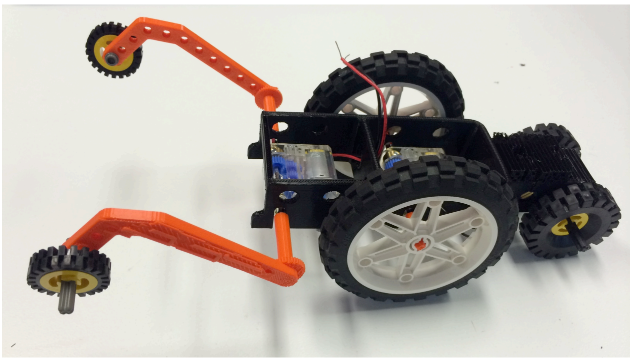

Figure 3: The assessment hurdle robot

Conclusion

A new project based learning process has been developed using additive manufacturing facility to stimulate the imagination and innovation of the students. In this approach, students are required to apply their innovative ideas and knowledge to formulate a robot design solution. The designed hurdle robot should able to jump over an obstacle within specified requirements. To enable this process, two support structures are setup: (1) A 3D printing facility is organised with open-access to the students so they can decide their best time of learning using system design tools available from the learning management system. A laboratory manual is designed to assist the students to learn the additive manufacturing process and create the hurdle robot. (2) A structured series of assignments are set representing stages of a typical systems engineering V development lifecycle. Students are guided to produce necessary engineering computational data to substantiate their design. A system verification stage forms part of the assessment requirements that complete the standard systems engineering V development lifecycle. Through the project based learning process supported by the two support structures, preliminary results based on students' feedback found that the course is much more stimulating and relevant to systems engineering.

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