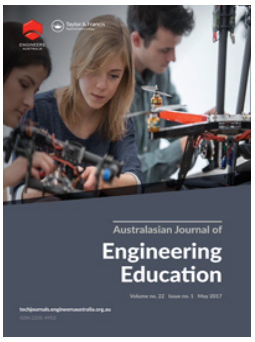

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Project-based learning of systems engineering V model with the support of 3D printing

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ABSTRACT

Systems engineering integrating interdisciplinary engineering team to design and manage complex engineering design projects. Systems engineering knowledge could best be delivered by incorporating the activities in the systems engineering V development lifecycle in the learning process. However, systems engineering concepts are 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. The 3D printing process is organised as a learning resource for students to verify their system design in a demonstrable format. Students are required to go through stages of the V development lifecycle while designing and developing a hurdle robot as the engineering design outcome. Students are allocated into groups tried to design and produce different hurdle robots with the support of extra learning resources in the learning management system. The student groups that follow closely the V model lifecycle seem to settle down with the final designs quickly. This proves that the environment has facilitated learning of the V development lifecycle process. With the support of 3D printing technology, students are able to test and verify what they have designed so that they can experience the systems engineering core activities.

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Systems engineering; 3D printing; project-based learning; V development lifecycle

1. Introduction

Systems engineering is an interdisciplinary approach and means to enable the realisation of successful systems. The principles of systems engineering can be described with different phases of a systems engineering project development lifecycle. The steps including 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 and Fabrycky 2010).

The main challenge of systems engineering is to design and manage complex engineering projects with an integrated interdisciplinary engineering team. The key process can be represented by the V system development cycle (INCOSE 2011) as shown in Figure 1. The lifecycle is divided into left and right-hand sides in a V-shaped form from high level to low level of a design process. The left-hand side of the V system development cycle consists of feasibility study, concept generation, product design and the corresponding manufacturing system design. The right-hand side represents the product testing and system validation processes. At each stage of system development, there is a corresponding plan to demonstrate successful achievement of that stage except at the very early stage of feasibility study and concept exploration. For instance, the concept of operations stage that generally forms the high level system performance specifications will require a system validation plan that defines a scenario or a series of scenarios that the future system is going to be tested and deliver outcomes that meet the expected performance. Likewise, more exact system requirements in terms of engineering specifications could have been extrapolated from the operational concepts (Bahill and Dean 2009). These engineering specifications are required to be tested in a controlled environment, sometimes specially designed test fields, to verify that the system can function in these extreme conditions. Similarly at the detailed design stage where components of the system is developed, a corresponding test plan of the components, usually in a laboratory scale, is required to be developed to prove that the components are functioning as they have been designed. In practice, system concept comes from user's expectations and operational needs. Using a range of modelling tools, a high level work process of the system can be formulated and some decisions will be made that influence the system design later in the V system development cycle. This process is commonly used in large-scale system development in which many stakeholders are affected

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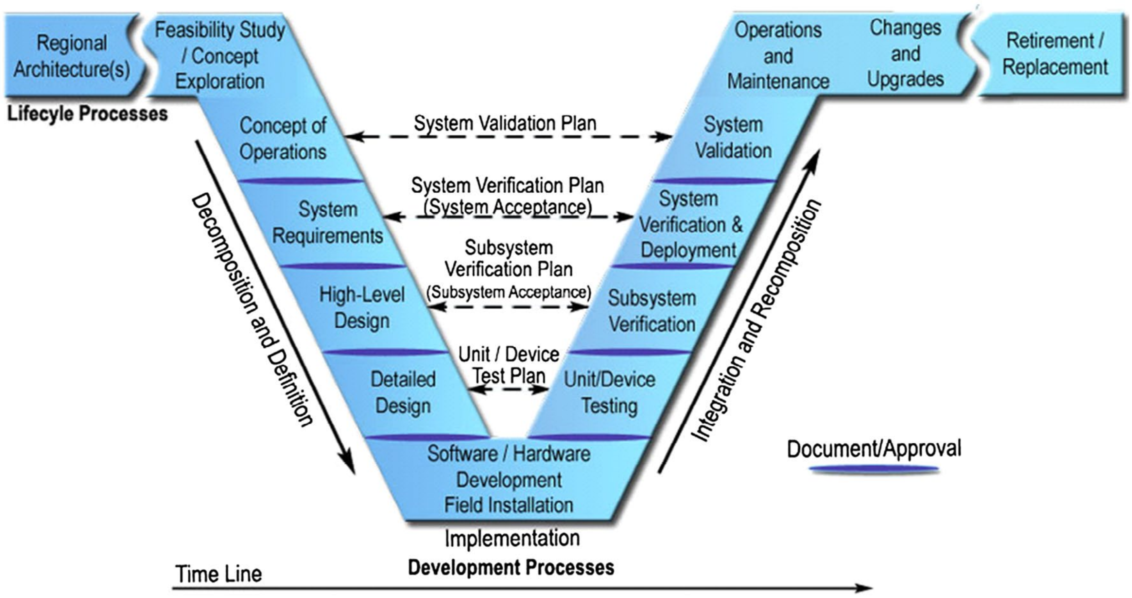

Figure 1. Systems engineering V system development cycle (International Council on Systems Engineering 2011).

or where new technologies will potentially have significant social impact.

Developing new design or systems inevitably deal with innovation and creativity within an infinite solution space (Lardeur and Longueville 2004). However, the learning outcome of a design subject is not only to find out solutions from numerous engineering problems. 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 and Chen 2014). Chang (2015) proposed an innovative dynamic product design method and found it effective in diversifying how designers think. The research showed that students with different learning styles, namely, the accommodators and convergers, performed almost identically under this method. To reduce time-to-market, Zhang et al. (2016) proposed a static design model within the framework of systems engineering to conciliate different requirements to produce innovative products. These researches aimed to streamline activities of design specification and help to the learning of ideas generation and fermentation.

Due to the highly conceptualised nature of the engineering process, teaching systems engineering is difficult because there is still no acceptable methods to impart and apply knowledge to managing complexity in multidisciplinary projects (Serna, Bachiller, and Serna 2017). On the other hand, students often find the subject difficult to comprehend when it is put into practice. Most researches have been focused on the improvement of capturing system requirements (Flint 2002) and the corresponding manufacturing system design (Hao and Helo 2014) representing the left-hand side of the V system development cycle. In an educational environment, exploration of the right-hand side activities and design of the corresponding system validation and test plan to demonstrate successful achievement of each product design stage is rare. That means students are learning 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 how the right-hand side activities. Unfortunately, typical systems engineering courses use large-scale engineering systems as the learning entity which is a challenge for any engineer.

This paper explores a new course design to learning and teaching systems engineering. Traditional method of teaching systems engineering is to talk through the systems engineering V system development cycle in Figure 1. However, without real-life experience, students find it difficult to grasp the concepts and processes. The major contribution of this article is to propose a new course design in an environment that simulates the V system development cycle so that students can experience the principles and rationale of various stages. The outcomes of this study can then form the basis of designing new teaching supports and resources, by assessing student feedback and suggestion for improvement from the students' perspective. The learning design is based on project-based learning (PjBL) approach and integrated with the support of an open laboratory infrastructure with 3D printing facilities. The new learning design includes a structured assessment scheme that provides learning experience resembling the systems engineering processes that are practised in industry so that students are able to get a feel of how engineers work in large-scale engineering design teams.

2. PjBL approach

PjBL is a team-based teaching and learning approach using 'real life' projects to help students in obtaining technical knowledge and developing important skill sets in problem-solving, collaborative engagements, effective communication and research (Stojcevski et al. 2015). In the past two decades, many researches have been done on applying and investigating the effect of PjBL (Levi 2011). 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 solution or course of actions (Woodfield, Hall, and Tansley 2015). The research showed that PjBL is particularly useful to motivate students to learn specific knowledge within the course. Experience showed that institutions often use projects as the learning mechanism to establish the framework for guiding students towards self-learning and research-oriented learning outcomes (Lawson, Hadgraft, and Jarman 2014). PjBL develops cognitive skills associated with problem-solving, group processing skills and reflective and evaluative skills as well as developing theoretical understanding. As students reflect on different solutions to the problem, they acquire transferable skills and knowledge which equip them with the ability to approach a range of novel situations likely to be encountered in their professional careers.

Hugerat (2016) compared two classes of science students. One class used PjBL strategies while the other class used traditional methods. The research found that the PjBL students were more satisfying and enjoying. Mo, Dawson, and Rahman (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. This teaching approach has also been applied in teaching mechatronic. The miniaturisation of products in the study of mechatronic using microprocessors and micro-devices has provided a good opportunity to develop problem-based learning platform 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 and Mo 2008). Likewise, Dzan et al. (2013) used PIPER (Preparation/Implementation/Presentation/Evaluation/Revision) model to the project activities including 3D boat design. This learning method provided students with a mix of experiences in design and construction, and elicited a positive attitude towards the engineering of boat-building.

Besides applying PjBL approach in the engineering subject, it is commonly applied in science subjects as well. Ergül and Kargın (2014) analysed the effect of the PjBL method in success degree and motivation of students. The results showed that the problem-based learning method made 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.

PjBL is therefore particularly suitable for teaching subjects that are open-ended, demand creativity and self-motivation. However, the learning environment has to be carefully designed to facilitate these characteristics to be exploited (O'Sullivan 2015). The learning environment in this sense not only included the design of the course materials and learning activities (structured approach), but also included a learning management system allowing instructors to share project specifications. Hung, Hwang, and Huang (2012) used a project-based digital storytelling approach for some elementary school students and found that the method could effectively enhance the students' science learning motivation, problem-solving competence and learning achievement. These researches suggested a flexible, action-oriented learning environment is essential for supporting PjBL.

3. Investigative environment for supporting PjBL of systems engineering

Several design features are clear from the foregoing literature review of PjBL approach to engineering. This research started by putting in place an investigative environment for supporting PjBL.

3.1. Teaching with 3D printing

Recently, 3D printing or additive manufacturing process has been recognised 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 and 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. (Tang and Mo 2015) proposed the problem-based learning of systems engineering using additive manufacturing processes. A lab manual was designed to guide the students learning 3D printing facilities with a case study.

3.2. Teaching supports and resources

For the PjBL, many learning models were designed to simulate an industry setting through laboratory facilities. Jeary et al. (1989) pioneered a revolutionary laboratory management system that integrated physics, chemistry and engineering laboratories into one large sharing resource. The integrated laboratory was open to staff and students during term periods. With the centralised management, all experimental equipments in the institution were accessible. Sense (2004) found that a successful PjBL environment should have five elements: (1) the learning relationships between participants in the project team; (2) the understanding of different cognitive styles in operation within the project team and how they impact situated learning; (3) the knowledge management approaches engaged within a project team; (4) the mandate for learning and the ongoing support provided by both the project and the organisational environments; and, the pyramid of authority (or accumulated political 'influence') that participants in the project team individually and collectively possess, that may be applied to their learning development during the course of the project. This study showed 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.

Nowadays, 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. PjBL offers a range of educational advantages over 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, relating theory to practise (Taylor, Harris, and Dargusch 2015). The challenge is to define an open-end question and a working environment that simultaneously maintains potential solutions for the students to explore. In the real world, the solution space can be infinite but in a problem-based learning environment, it is necessary to recognise the limited knowledge that a student or a group of students has (Gallagher 1997). The systems engineering V development cycle should be supported a facility that encourages innovative yet viable solution to be implemented within the timeframe of the educational environment. Problems arising from product design are good topics that motivate innovation.

This article is not about learning of product design skills. Hence, the learning focus is not on how to use the 3D printing system effectively. 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. This paper also explores the requirements for these two support structures and outlines a pilot study for knowledge in systems engineering using latest student friendly 3D printing facility.

3.3. Teaching with Lego Kits

Nowadays, Lego Kits are widely applied in the teaching and learning activities. (Mosley and Kline 2006) make use of the Mindstorms LEGO kits developing logical and creative solutions to problems. The class uses a PjBL environment and teaches robotics, computer programming concepts, and problem-solving skills to the students of all majors. Tang et al. (2016) teaches the university on using LEGO Mindstorm EV3 to provide service learning to the local secondary school students. The students are formed into groups (Figure 2). They have to prepare teaching materials related to science, technology, engineering and mathematics (STEM) to teach secondary school students. Lego kits are used to apply the STEM knowledge to complete a designed project for the students. They have to design a robotic car to achieve a specific task.

3.4. Teaching with 3D printing support

We have conducted a pilot study for students studying the systems engineering principles course. Students are required to form a group with four students for each group and six groups were involved in the test. We have designed a project in which students are required to create a hurdle robot that can jump over an obstacle. Based on the literature review results, we have designed two learning supports including laboratory manual and learning resources for the students. Details of the learning supports used in this project can be found in (Mo and Tang 2016). These learning supports provide guideline to the students to explore project solutions in a systematic manner.

In order to facilitate students to learn and study 3D printing, an additive manufacturing facility is made

Figure 2. Students are formed into groups to prepare teaching materials.

available to students. The laboratory is opened to the students any time they need. This open laboratory concept has been experimented before and has proved to be particularly useful for engineering education environment (Feisel and Rosa 2005). The laboratory manual was designed in a systematic manner under the constraint of the subject curriculum. Students can download the laboratory manual anytime online from our learning management system. The laboratory manual teaches the students how to create the components for a demo robotic car through a step by step manufacturing process (Advanced Manufacturing Precinct 2015). Figure 3 shows the figures on the lab manual used to teach students basic manipulation skills of the additive manufacturing facility.

4. Course design

We have designed a project that requires student to learn and apply techniques of the V systems development lifecycle. The project requires students to design and create a hurdle robot that can jump over an obstacle. Students not only need to form a solution in a systematic manner, they also need to apply the additive manufacturing techniques to create the components of the robotic car with additive manufacturing facilities by following the instructions of the laboratory manual. In this project, students have to apply the product design techniques that is on the left-hand side of the V systems development lifecycle as well as testing and validation plan (right-hand side of the V systems development lifecycle) corresponding to each stage of the design process.

The project is delivered to the students in the first meeting with the students. The problem statement is given to the students and explained in class so that they can start with the following learning process. Students are required to build a hurdle robot to the specification described in Section 4.1. About 4 weeks' time will be given to the students.

4.1. Knowledge support

The knowledge support includes lecture notes and slide presentations on the principles of systems engineering and the V development lifecycle. The materials also provide information on the tools and models that can be used in systems design, analyses and decision criteria. These materials and resources are consolidated in a course folder which is available to the students anytime through the online learning management system in the university.

Besides traditional teaching materials, some reference books and websites are provided in the learning system. Students are also encouraged to explore any other information such as systems engineering process and system analysis techniques in the world.

4.2. Project specification

The specification of the project includes a statement briefly describes the objective of the project, the problem statement and the requirement of the designed robot. The objective of this project is to design a robotic car that can jump over the obstacle and the problem of this project is described as follows:

(1) Travel along the pathway by 1000 mm.
(2) Jump over an obstacle with size.
(3) Jump down at the other side of the obstacle.
(4) Travel another 1000 mm along the pathway.

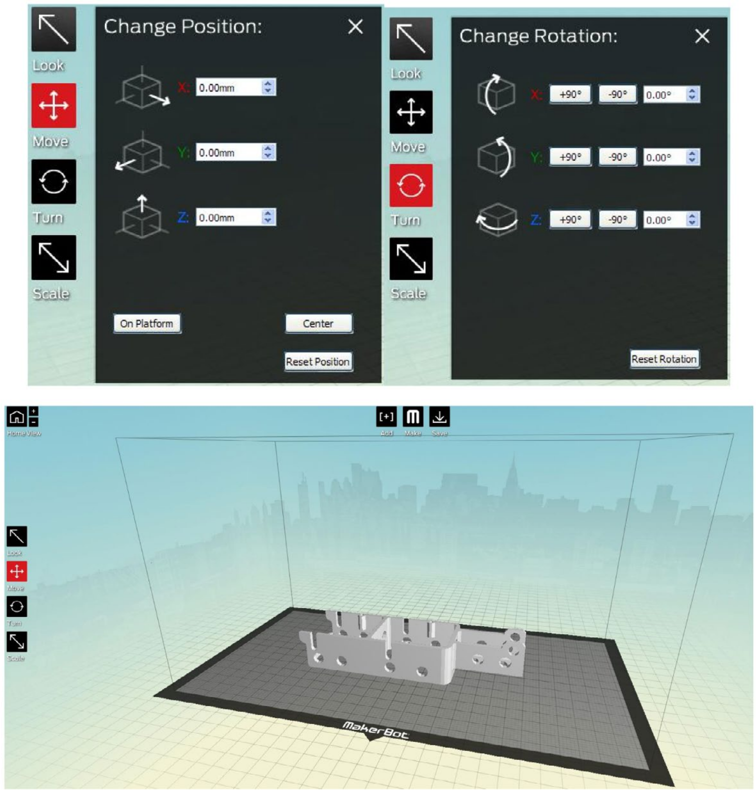

Figure 3. Snapshots of the lab manual used to teach basic operations of 3D printers.

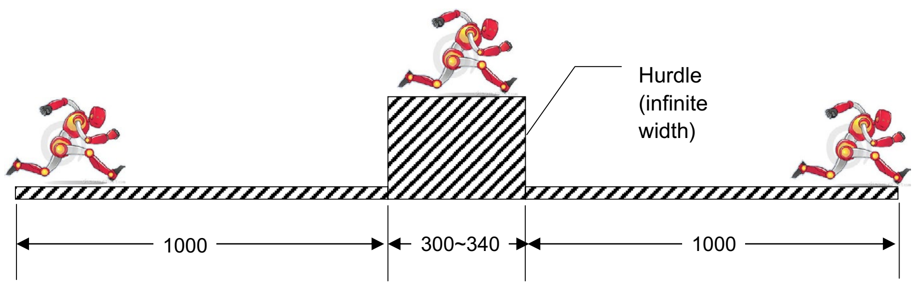

Figure 4. Diagrammatic conceptual representation of hurdle robot.

A diagram is also provided to represent the concept of the problem statement. Figure 4 shows the diagrammatic conceptual representation of hurdle robot. This project has several main requirements:

(1) The robot is controlled manually (not by a computer).
(2) The robot must provide a 'Cock pit', where the driver will sit and therefore need to stay at upright position at all times.
(3) The robot should arrive the destination within one minute.
(4) The robot can use maximum two motors.

4.3. V systems development lifecycle

As described in the Section 1, the V systems development lifecycle include product design and design of the corresponding validation plan. In order to assess the ability of the students in formulating solution in systems engineering, students are required to deliver the system in four stages and each stage will be assessed.

4.3.1. Stage 1 – concept exploration and concepts of operations

In this stage, students will work individually to produce a system design document. Each student will be assessed individually based on the report. The report should contain the following information:

- System objectives, user needs and application scenarios.
- Exploration of different options for their innovative robot design.
- Selected concepts of operations with rationale.
- Criteria of system and robot design selection process.

4.3.2. Stage 2 – functional design

In stage 2, students will be assigned into a group and each group consists of 3–4 team members. This stage requires students to build up then team work and relationship through networking and communication. There are many ways to achieve the outcome. The individual concept of operations document in stage 1 can be used as the basis to unify to one design in the group. In order to reach a conclusion of robot design solution, students will be asked to develop the functional block diagram and compare each of them. This stage will be assessed by a group presentation.

4.3.3. Stage 3 – detail design

In this stage, students are required to produce detail engineering design using available computer-aided design (CAD) packages such as CATIA. Students are also need to think about various validation plans to prove the ability of their design to perform at or above the user requirements described in Section 4.1. Students have to write a group report describing the system design and their plan for further validation. The system design includes detail information of each component such as part drawings, dimensions, assembly drawings and test plans. Besides the part design, students have to apply their knowledge on design for manufacturing (DFM) by considering several manufacturing capabilities of 3D printers such as the use of materials, dimension of each part, manufacturing tolerances, surface smoothness and cost. The quality of the group report will be assessed.

4.3.4. Staged 4 – build the system

Students have to make use of the 3D printing facilities in the laboratory to build the required components for their robot design. Then, they have to assemble the 3D printing parts and the existing components to build the robotic car. A testing platform will be provided for each group for final system verification test. Then, marks will be given according to the following criteria:

- Successful completion of the assigned task.
- Time required to complete the task.
- Design and innovation of the robotic car.

5. Results

Each project question has many solutions and ways to achieve the outcome. Through the project-based learning, student can practise and exercise their innovative thinking and ideas as much as possible, as well as learn through the design process.

5.1. Concept of operations and user requirements

In order to solve a problem, students need to formulate the requirements of the design based on the problem. After identified the requirements of the design, they need to generate different conceptual ideas. Students also need to develop the operational processes of the designed robot from their concept. In order to generate design concepts, it is very common for the students to find similar solutions from the internet and references and modify to suit their needs. They may also talk to each other to exchange ideas and compare results. These activities are common in industry. Figure 5 shows an example of the concept of operations produced by one of the students.

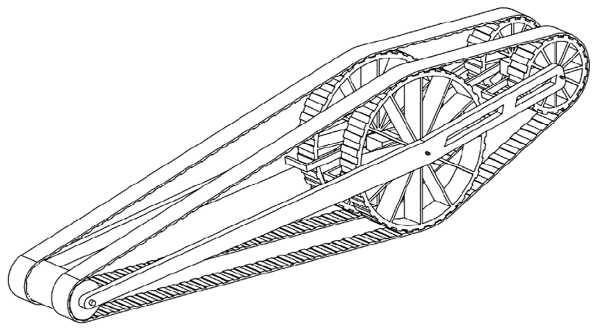

Figure 5. Concept of operations in the conceptual design stage.

5.2. Functional design and system verification

After completed the conceptual design stage, students are asked to form a group and unify to one design from the several ideas as concept. Students will be asked to develop the functional block diagram and compare each of them in order to reach a conclusion of robot design solution.

To develop the functional block diagram, the project question is decomposed into a series of steps and functions that can be individually designed and manufactured. Figure 6 illustrates an example of diagram which is divided into a number of functional designs. The diagram divided the project questions into a series of steps. For each step, the designer has to think about a solution that can perform functions to achieve the desired outcome. For instance the robot has to travel 1000 mm, the design team may decide to use four wheels. In this case, the team may also need to think about the components and other parts that are necessary to include forming the robotic car. Interpretation of the functions depends on the imagination and knowledge of the students. Again, students can search information from open sources.

5.3. Detail design and component testing

After deciding a design idea, the student team will design the hurdle robot in detail such as size and tolerance of each part. Students also need to consider manufacturing feasibility using 3D printers. The hurdle robot will be created by 3D CAD package. Such detail design activities require skills and knowledge learnt from the

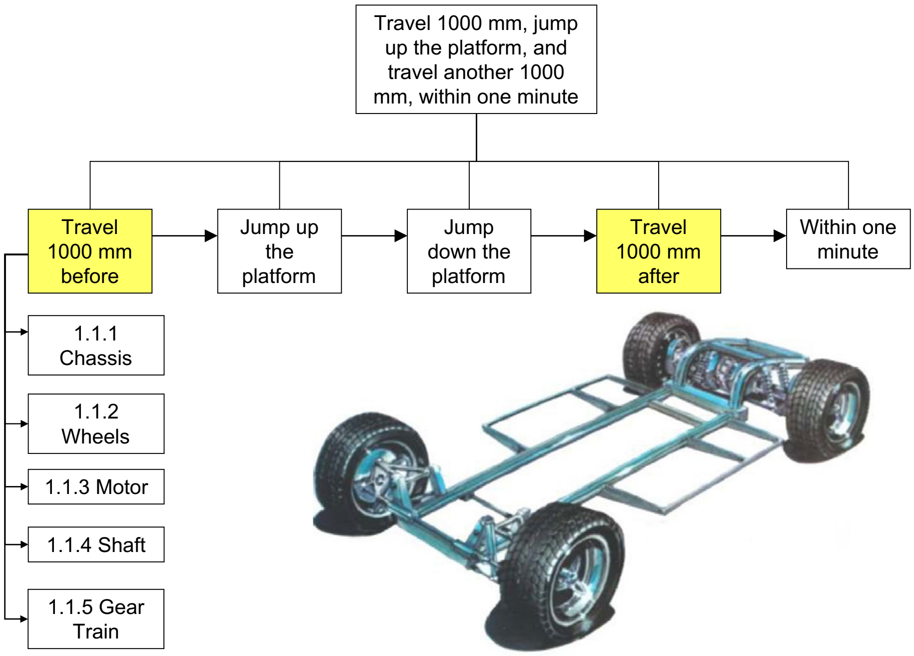

Figure 6. Functional design.

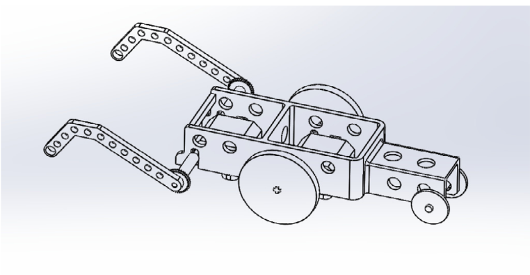

Figure 7. Assembly drawing of the designed robot created by CAD package.

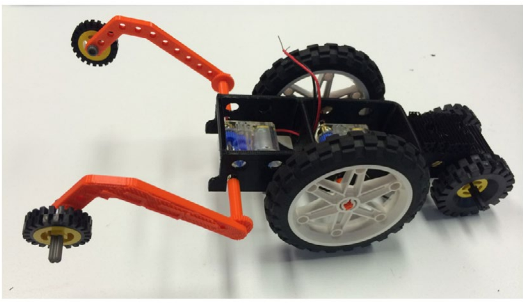

Figure 8. An example of the hurdle robot designed and built by the students.

other subjects such as CAD drawing techniques. The manufacturing feasibility may require students' hands on experience to operate the 3D printing facilities. For instance, if the accuracy of the 3D printers is not good enough to reach the tolerance requirement of the parts, students will need to consider re-designing the parts with features allowing higher tolerance. Figure 7 shows the assembly drawing of the designed robot.

5.4. System development

In this project, students have to submit group reports regarding to their robot design and the validation plan. Based on the submitted group reports, students have designed the hurdle robot and formulate validation plan for each system development process successfully. A testing platform is also provided for each group to conduct final system verification test. By conducting verification test of their designed robot, most of the students are able to demonstrate achievement of the project requirements satisfactorily. Figure 8 shows an example of the hurdle robot designed and built by the students.

6. Student feedback

The new course design has been run for one semester. 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. From the semester end survey, there is a general improvement of student satisfaction. In the previous course delivery (using the traditional teaching method), the general satisfaction index of the course was 50%, i.e. half of the students were not happy with the learning process and the learning environment. However, after new PjBL course design was implemented, the general score of the course was raised to between 60 and 70%. More specifically, the scores for the following survey questions are listed in Table 1.

Some students provided some good comments:

(1) Project work, small class size and relevance to systems engineering.

Table 1. Survey of students attending the new course design.

I found the assessment in this course challenging	78%
I learnt a lot through the process of drafting and resubmitting my assignments	67%
I understand the relevance of the assessment tasks to my professional and academic	67%
The teaching staff made it clear from the start what was expected in this course	56%
As a result of my course, I feel confident about tackling unfamiliar problems	67%
I found my studies intellectually stimulating	67%
The course included many real-life scenarios for discussion in class or online	67%
The course provided me with a broad overview of my field of knowledge	67%

(2) The project is engaging and allows us to practise 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:

(1) 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.

Preliminary results were obtained by collecting students' feedback from a selected subject. The subject has been implemented in several years. In the previous course delivery using the traditional teaching method, more than half of the students were not happy with the learning process and the learning environment. However, after the implementation of the new PjBL course design and learning supports, the student satisfaction was raised to over 60%. On the other hand, students' feedback was found that the course is much more stimulating and relevant to systems engineering. Further improvement and investigation will be conducted to collect more data and address the negative comment in the next delivery in 2017.

7. Conclusion

Teaching systems engineering is very difficult due to highly conceptualised nature of the engineering process. On the other hand, most of the existing education are focused on the achievement of product design stage. Exploration on the system validation and test plan for each product design stage is rare. This article proposes to use the project-based learning to stimulate the imagination and innovation of the students. A project-based learning process has been developed using additive manufacturing facility. In this approach, students not only required to apply their innovative ideas and knowledge to formulate a design solution, they also need to formulate the validation plan for each design process in order to learn through the systems engineering V development lifecycle.

The project requires students to design a hurdle robot to jump over an obstacle within specified requirements. Two teaching supports, laboratory manual and traditional teaching materials are designed and make available in the learning management systems to allow students to learn through the development process. The laboratory manual is designed to assist the students to learn the additive manufacturing process and create the hurdle robot. The traditional teaching materials include notes, reference books and a structured series of assignments. Students are guided to produce necessary engineering computational data to substantiate their design. The assignments are set representing stages of a typical systems engineering V development lifecycle and forms part of the assessment requirements in V development lifecycle. On the other hand, the 3D printing facilities are open to the students anytime so that they can decide and arrange their time for learning.

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Disclosure statement

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