Practicum of Systems Integration in Engineering Education

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Abstract

This project asked engineering students to develop a multi-subsystem design that would produce electricity. Students over the duration of this project learned how to simulate and design systems theoretically using computer tools. Furthermore, students were expected to produce a prototype of their model, thereby self-analyzing the practicality levels and enhancing learning.

With the technology available to students advancing, systems integration techniques become more efficient learning experiences to the students. The benefits of systems integration can also be expanded to the professional world these students will soon step into. Therefore, teaching these techniques now will give students a better further insight on real world experience in a classroom setting. When students make the expected leap into the job market, it is important for them to have a solid understanding of system integration and multi-system design. It is this understanding that will make students more desirable to top end employers and set them apart form their peers.

Key Words:

Stirling Engine, Thermal Fluid design, Electricity Generation, System Programing, System Integration, new product development (NPD)

1. Frame of Reference

Due to the developments of advanced technology, a system-of-systems approach plays an important role in designing and developing new products. A system-of-systems is composed of several individual systems and their subsystems. Thus, multidisciplinary collaboration and efficient system integration are necessary to deliver a desired product. Systems integration (SI) facilitates efficient delivery for the overarching functionality in the product. This SI technique has been widely used in many companies, even though this discipline has not yet fully developed in engineering education. Engineering students often learn how to develop individual systems without ever examining how their designs or products would work with other systems in the real world. Oftentimes, engineers are expected to learn hands-on skills in the job environment, leading to the vast and ever-growing skills gap in STEM fields.

Engineering students at UT Tyler are not just taught about system dynamics theory, but are expected to deliver a design project to model and analyze a working dynamic and control system by applying the New Product Development (NPD) process. Students are asked to develop full scale Computer-Aided Design (CAD) models and simulations of their final product before physically establishing the synergized subsystems into a working prototype. This class, senior and graduate level, succeeds in combining multiple professional disciplines into one involved project. Topics such as system integration and feasibility analysis suddenly become much more critical to the students than previously experienced. Furthermore, students can alter their designs not only toward optimal performance, but also toward synergizing a product effectively. Lastly, students also experienced the power of practicality and quickly learned not to over-engineer certain aspects of their project. In summary, the practicality of the SI in the NPD can ensure the ideal active, experiential and collaborative learning experience for higher-level engineering students.

Engineers of today, not only develop computer models of individual parts, mechanism, and machines, but also develop entire virtual systems before advance any idea further. This method is especially attractive to the energy industry, and an example is shown in Figure 1.

This is done to save money and time and to potentially improve an idea before even building a prototype. Therefore, it is of utmost importance, that engineering students get exposed to SI along with new product development during their college years. To deliver a more thorough learning experience, engineering students at UT Tyler are expected to put their class knowledge to the test by delivering an involved class project. This project is intended to force students to use their knowledge of system dynamics theory to develop a new product. This new product should be thoroughly designed in some computer simulation first, and a prototype is then to be built, and address critical subject areas, such as systems integration and feasibility analysis.

The rest of the paper is organized as follows: Section 2 is the outline of design approach and model description. In Section 2, we describe the subsystems of the Stirling engine, including generator, combustion heat source system and thermal fluid heat exchanger. In Section 3, we introduce some lessons we learned and discussed interesting findings. In Section 4 we offer some closing remarks.

2. Design Considerations

2.1 Overview

Systems integration [2] is a process that integrates several components into a cohesive system to work together in a logical, cost effective way. SI is one of the important stages of the lifecycle of any complex system [3]. In this paper, the virtual design and manufacturing of a Stirling engine system is introduced as an example of the practicality of SI in engineering education.

As required by project guidelines, students developed a MATLAB/Simulink model of their theoretical design using Simscape blocks. Simscape [4] is one of MATLAB/Simulink's toolboxes that allow users to develop physical models with desired attributes using model blocks. This allowed for immediate optimization and quick adjustments. Five subsystems were developed: the Stirling engine, the thermal fluid heat exchanger, the combustion heat source, the electric generator, and the processor unit.

The heart of the system is the Stirling engine it converts the temperature difference in its power pistons to torque. This torque will be converted into electricity using the electric generator, which is driven by a belt directly connected to the Stirling engine. To create an optimal temperature difference, the cold power piston of the Stirling engine needs to be maintained at a low temperature. To achieve this goal, the thermal fluid heat exchanger was modeled as a subsystem that pumps cold water to reduce the temperature of the cold piston only as needed. To keep the hot piston hot, a reactive combustion heat source system was implemented. The reactivity is to conserve energy and reduce carbon emissions as much as possible while still ensuring that the hot power piston is maintained at a hot temperature. The reactivity of all other subsystems is calculated and implemented by the processor unit. The processing subsystem is responsible for sensing the data of all other subsystems and running calculations as needed to ensure enough electricity is generated at a steady state without wasting resources.

2.2 Stirling Engine

The first Stirling engine patent was made in 1816 by Robert Stirling [5]. More powerful steam engines already existed, but were still considered dangerous. Steam engines often had material failure and the hot steam burned, injured and killed operators far too often. Therefore, Robert Stirling made efforts to produce an engine that worked with far less gas pressure. The first Stirling engines are remarkable in the fact that they operated 40 years before the documented understanding of thermodynamics and the works of Sadi Carnot. However, once the development of steam engines further progressed, the Stirling engines became obsolete. The Nazi regime, however, further improved the sterling engine, but still not enough to be used in a practical, everyday use. Recently, NASA has decided to produce a nuclear-powered

Stirling engine to serve a power source in space exploration.

The Stirling engine is an external combustion engine, meaning that the heat source is not directly inside the piston cylinder assembly [6]. The movement of the pistons is created by a working fluid that stays within the piston cylinder assembly at all times. There are three distinct categories of Stirling engines: alpha, beta, and gamma. In this project, an alpha type Stirling engine was used. An alpha type Stirling engine is distinct because it uses two separate power pistons such as the example, which is shown in Figure 2, which are a hot piston and a cold piston. The piston cylinder assembly of the Stirling engine was chosen to be reusable glass syringes. Glass syringes are very heat resistant and are manufactured precisely enough to be air tight. Therefore, glass syringes are more cost-efficient and reliable than student-manufactured steal or aluminum alternative. The various other mechanical components of the Stirling engine were 3D printed to allow for a custom fit to the glass syringes. Additional metal shafts and ball bearings were purchased to ensure quality function of the mechanical subsystem.

2.3 Thermal Fluid Heat Exchanger

Heat exchangers are devices that facilitate the exchange of heat between two or more fluids that are at different temperatures, while keeping them from mixing with each other. These devices are commonly used in practice in a wide range of applications, from heating and air conditioning systems in a house hold, to industrial applications in large power plants. Heat transfer in heat exchanger involves convection in each fluid and conduction through the separating wall between the two fluids.

2.3.1 TYPES OF HEAT EXCHANGER

Heat transfer applications differ in practice. Thus, different components and configurations are required for the heat transfer equipment. In an attempt to determine the right components and configurations for the heat transfer requirements within specified constraints, numerous innovative designs evolved.

The double-pipe heat exchanger is the simplest of all exchangers. It is made of two concentric pipes at different diameters as shown in Figure 3. A fluid flows through one pipe (smallest pipe) while the other fluid flows through the annular space between the two pipes. The flow in this type of heat exchanger could be either parallel or counter-flow.

The compact heat exchanger is another type of heat exchanger characterized with large heat transfer surface area per unit volume. A heat exchanger with area density greater than 200ft^2/ft^3 is considered as being compact. Application of the compact heat exchanger is found in car radiators, glass ceramic gas turbines, regenerators of Stirling engine, and human lungs. For industrial applications, the shell and tube type heat exchanger are commonly used. It consists of large number of tubes arranged in a shell with the tube axis parallel to that of the shell.

In determining the specifications required of a heat exchanger, two methods are extensively used to carry out analysis of the exchanger: the Logarithmic Mean Temperatures Difference (LMTD) method and the Number of Transfer Units (NTU) method. The log mean temperature difference method is easy to use when the temperatures of the inlet and outlet fluid are known. However, when the type and size of heat exchangers are known, to determine the heat transfer rate and the outlet temperatures of the hot and cold fluids for specified fluid mass flow rates and inlet temperatures, the NTU method is used. This method is suitable for our analysis. The heat transfer performance of the heat exchanger is to be determined. The LMTD method can also be used for this problem, but it will require tedious iterative process.

2.3.2 OUR DESIGN AND INTEGRATION CHALLENGES

We employ the simple case of a counter flow heat exchanger [8], where the dimensionless heat transfer effectiveness is defined as

$$\varepsilon = \frac{Q}{\dot{Q}_{max}} \tag{1}$$

where Q and Q_{max} represent actual heat transfer rate and maximum possible heat transfer rate, respectively.

The actual heat transfer rate is determined from an energy balance on the cold fluid as

$$Q = C_c(T_{c,out} - T_{c,in}) \tag{2}$$

where C_c is heat capacity rate for the cold fluid, and $T_{c,in}$ and $T_{c,out}$ represent the inlet and outlet temperatures of the cold stream, respectively.

The maximum temperature difference in the heat exchanger is the difference between the inlet temperatures of the hot and cold fluids [9], which is,

$$\Delta T_{max} = T_{h,in} - T_{c,in} \tag{3}$$

where $T_{h,in}$ and $T_{c,in}$ are the inlet temperature of the hot and cold fluids.

The heat transfer reaches maximum value when the cold fluid is heated to the inlet temperature of the hot fluid or when the hot fluid is cooled to the inlet temperature of the cold fluid. These two conditions can only be reached simultaneously when the heat capacity rates of both fluids are the same. The maximum possible heat transfer rate is given by

$$Q_{max} = C_{min}(T_{h,in} - T_{c,in}) \tag{4}$$

where C_{min} is the heat capacity rate smaller of C_h and C_c.

2.4 Combustion Heat Source System

Stirling engines work on temperature differences between the two power pistons. This means that the higher the temperature of the hot piston, the larger the rpm output of the Stirling engine. By being able to regulate the temperature of the hot piston, one can directly influence the rpm output of the sterling engine. Students chose an isopropanol lamp as their designated heat source. Isopropanol was the fuel choice because it has a relatively hot flame and burs very clean. In addition, isopropanol as a fuel is readily available and isopropanol lamps are relatively safe to use also. In this subsystem, students decided to place the heat source on a mechanism that would allow for the isopropanol lamp to move away from the hot piston. With this mechanism, student can control the rpm output of the engine by directly maneuvering the heat source to and away from the hot piston.

Considering that the glass syringe has a specific heat and can hold on to heat fairly well, experiments needed to be done to find the response time for cooling hot power piston. Likewise, the heating response time also needed to be experimentally derived to allow for proper programing later. Furthermore, the response time and measurement locations of the thermistors also played a factor in the optimization of the heating subsystem. Engineering students, through designing this combustion heat source learned about the vast uncertainty engineers must face and deal with in all products. For example, their theoretical designed and mathematical capabilities vary vastly form their actual production capabilities. One factor is the uncertainty of measurement tools, such as thermistors, and various environmental factors that cannot be accounted for in all situations. By understanding the limitation of measurement accuracy, engineering students had to start implementing error propagation into their external combustion heat source subsystem. Lastly, students had to seriously consider how the addition of one subsystem could affect the entire project, and if adding a subsystem is really going to make a significant change in their final product.

2.5 Electric Generator

Electricity is defined as the physical flow of electrons known as electrical current. Electricity is an energy carrier that can be generated by several methods. In all of these methods, one form of energy is converted to another to generate electricity. For this project, the pressure difference between the operating fluids creates a rotational motion on the flywheel which turns a small DC motor to produce electricity. The small DC motor (red box in the figure) is connected via belt to the rotating flywheel; this can be seen in Figure 4. The voltage generation directly correlates to the rpm of the Stirling engine. This means that the produced voltage is an energy transfer from the Power pistons of the Stirling engine to the DC motor.

2.6 Processor Unit: System Programming

If the Stirling engine is the heart of the project, then the programming is naturally the brain. In the MATLAB/Simulink model, the theoretical design was automatically programmed, by nature of Simulink. This was easily done by requiting mathematical operation blocks and making the right connections in the system design. However, the final product, a physical prototype, needed a microcontroller to operate all five subsystems. To accomplish this task, an Arduino Uno microcontroller was implemented to actuate the individual subsystems. Thermistors at each power piston provided valuable temperature data to the microcontroller. In return, the microcontroller will decide whether to add heat to the hot piston, or to pump more cold water to cool the cold piston. The choice to add more heat to the hot piston, will be directly related to the rpm of the Stirling engine. Since the rpms of the Stirling engine also directly relate to voltage output, the desired voltage production of the electric generator can be directly correlated to the rpms of the Stirling engine likewise. As one can imagine, there will be a lag in the system. For this reason, the programming of the Arduino must also include a PID controller to reduce the maximum overshoot and to help maintain an acceptable steady state range. Proper programming and tuning was one of the most vital parts of this entire project and this is why the programming is considered the brain of all five subsystems.

3. Results and Discussion

3.1 Model Description

The MATLAB/Simulink model was created by students at first. This allowed students to theoretically test if it was possible for them to develop their final product. For example, the Simulink model would give them the exact amount of fire heat they would need to create 3 voltages of electricity. If, however, students need more heat than a candle could provide they could adjust their design accordingly.

The final MATLAB/Simulink model can be seen in Figure 5. All black model blocks are Signal Processing and represent the Processor Unit. The PID look in this case is the Arduino Uno. All model blocks in dark and bright green are part of the sterling engine. Everything in orange is the Combustion Heat Source counteracted by everything in purple, which is the Thermal Fluid Cooling System. Lastly, all blocks in blue, are representing the Electric Generator.

The Desired Voltage will be inserted by the user, in the very most left block, and the PID controller will adjust the amount of heat to be extracted from the heat source (in orange). This Heat is directly inserted into the Piston assembly (dark green) and the translational motion is converted to rotational torque (bright green). The rotational energy is converted to electric voltage in the green and blue interface. Finally, the final voltage signal is send back into the PID loop for further processing.

3.1.1 STUDENT INVOLVEMENT

Student groups were formed by students themselves, a few days after the task was assigned. To give students more freedom for creativity, the task assigned was very vague and read as the following: “Using computer programming and simulations, create the interaction of multiple subsystems. Create a prototype of your model.” This was done to place responsibility of team work and communication into the student’s hands and allow them to make the assigned project as in depth as they wish. However, the students were asked to keep the cost of their project under $150.00

3.2 Key Results

3.2.1 RESULTS

Students acquired promising results through their theoretical Simulink modeling. Their theoretical design was able to produce 0.3 voltages of electricity in about 50 seconds. Graph 1 in Figure 6 shows the voltage profile of a simulation run. It can be noted that within the 50 seconds the voltage production reaches within 5% of the desired value. This is accepted as a good result.

Graph 2 in Figure 6 shows the amount of heat that was required from the heat source to achieve 0.3 volts in 50 seconds. It is important to understand that the simulation would import any value of heat. However, the candle students used in the physical model only had a maximum capability of 80 J/s. Therefore, it became important that the computer simulation would never ask for a heat value over 80 J/s. It is shown that the maximum amount of heat needed to reach 0.3 volts is less than 60 J/s in Graph 2.

Lastly, the rpm output of the Stirling engine is shown in graph 3 of Figure 6. It is important to note that the rpm of the Stirling engine is a direct multiple of the voltage production. This multiplication factor turned out to be 0.01V/rad/sec and this value is realistic and achievable with a small DC motor.

3.2.2 LEARNING OBJECTIVES ACHIEVED BY THE PROJECT

For students various traditional and none traditional learning outcomes were expected. In the case of this project, the range includes multiple disciplines and different areas of engineering.

The first and main learning objective is the mastery of MATLAB/Simulink to develop idealized subsystem integration. The next Learning objectives varied amongst teams, but for this project the following learning objectives were mastered by students: the ability to understand, design, and build small external heat engines. This includes thermodynamic topics such as the Carnot cycle and Carnot efficiency, in addition to mechanic system design. Lastly, the production of the prototype was limited to 3D printing and small manufacturing processes which also count as hand on experience.

For the electrical section, students learned about DC motors and the basics in linear circuit analysis. This became essential not only for the electricity production, but also for the system communication.

In terms of system integration, Students were expected to master and use efficient programing to integrate the communication about all subsystems.

Lastly, to provide energy to the engine, students had to understand the dynamics of convective heat transfer. Heat transfer in this case is essential to transfer heat energy into the Sterling engine.

In addition to the hard skill learning objectives, more valuable soft skill learning was also done through this project. Students learned to work effectively in interdisciplinary teams, since the project consisted of multiple subsystems of multiple disciplines. More so, student gained valuable experience in applying system integration to a design problem. Finally, students learned to relate the application of system integration to real-world problems in a case study.

3.2.3 IMPACTS OF THE MULTI-SUBSYSTEM DESIGN PROJECT

To further analyses the impact of a multi-subsystem design project in a more tangible manor, students were asked to answer some survey questions about their experience. Out of all the participants, 5% were sophomores, 10% of participants were juniors, 60% were seniors and 25% were graduate students; figure 7 shows this data as well. Students have participated in a diverse variety of projects, including competitions, independent study courses, research and others. The percentage of participation in each area can be seen in Figure 8. Only 75% of students reported having participated in projects with 3 or more subsystems, while 25% reported having participated in projects with either two or less subsystems. The participation pie chart can be seen in Figure 9. Lastly, Students were asked about their learning experience with the multisystem design projects. All participants reported that multisystem design projects helped them better understand system dynamics and system integration. In addition, students reported having an overall better learning experience with the projects, compared to the traditional classroom learning. These Results can be seen in Figure 10.

3.3 Discussion

Overall, it can be said that the students were successful in developing their product. Once the students used MATLAB/Simulink to develop their design and implement system integration, they had to use more techniques of new product development to turn their theoretical design into a physical working prototype. Through the transition from theoretical to physical model, students were expected to reflect back to their theoretical design and better understand the purpose of computer-aided simulation. This should have given students a better appreciation of how companies save time and money by developing computer models to verify and discuss new products and especially the interaction of subsystems. In addition, this project gave students a chance to experience system design and system optimization. Such an experience is almost impossible to provide to a student through the traditional classroom experience. Lastly, students were expected to reflect on to their expectations and understand that not all theoretical designs will work as intended in a real model.

4. Concluding Remarks

Students successfully managed to design an electrical power producing system made of five subsystems: Stirling Engine, Thermal Fluid Heat Exchanger, Combustion Heat Source, Electric Generator, and Processor Unit for System Programing. These five subsystems were integrated virtually in MATLAB/Simulink and tuned by implementing a PID controller. Computer simulation results were optimal in a sense that all values were realistic and achievable with the physical prototype.

In summary, the practicality of the SI in the independent study at UT Tyler can facilitate the ideal active, experiential, and collaborative learning experience for higher-level engineering students.

For the future, work data on the physical model needs to be collected to compare the physical model results to that of the computer design to see any inefficiency's or any unaccounted factors exist.

Acknowledgement

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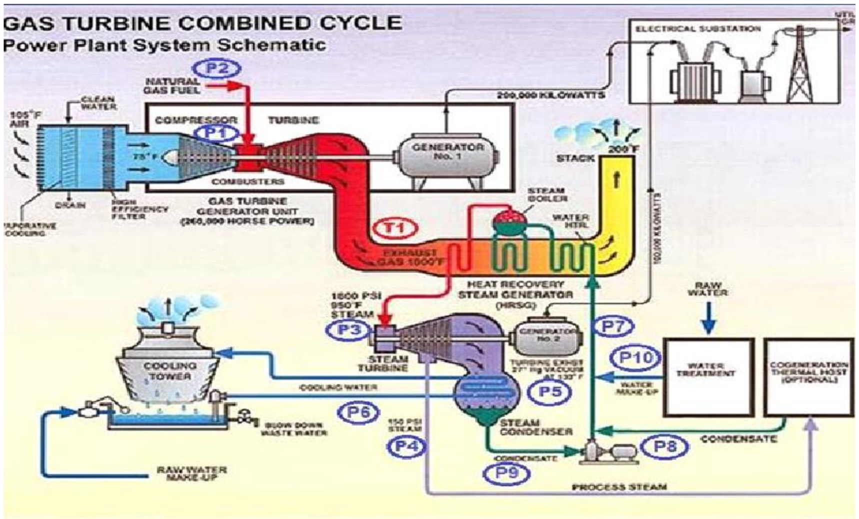


Figure 1. Power plant system [1]

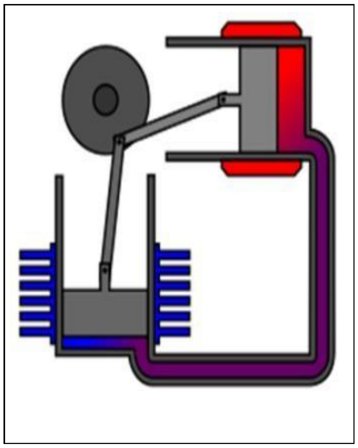


Figure 2. Alpha Stirling engine

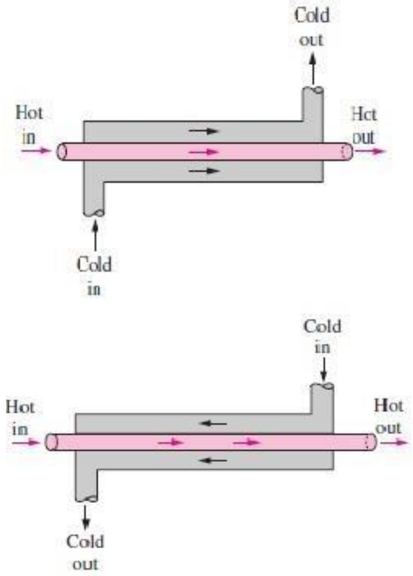


Figure 3. Configuration of Double-pipe heat exchanger: (a) parallel flow and (b) counter flow [8]

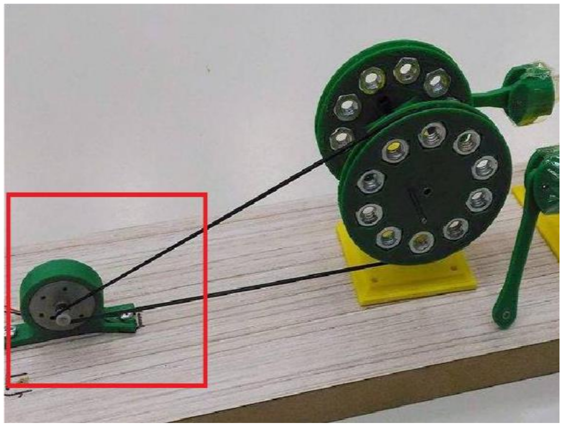


Figure 4. Electric generator

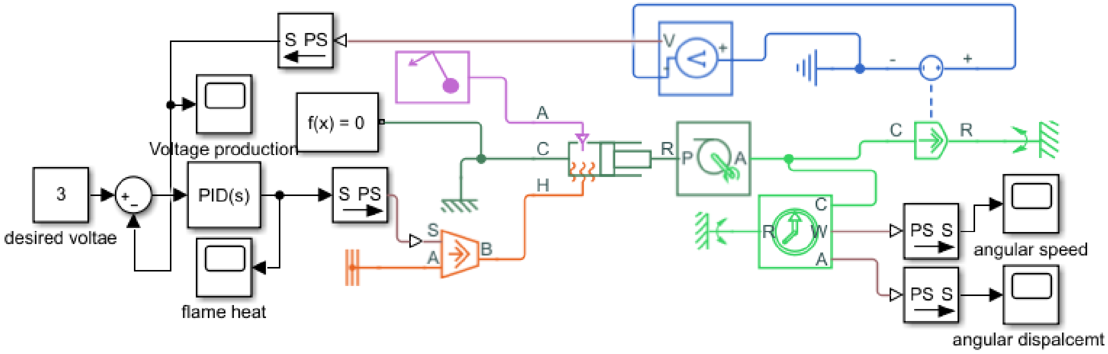
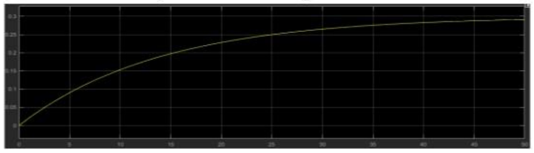
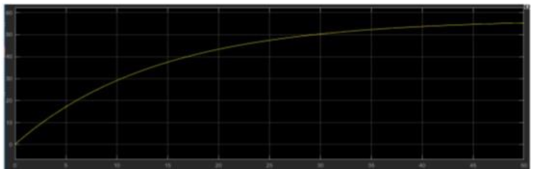


Figure 5. MATLAB/Simulink model of multi-subsystem

Graph 1. Voltage vs Time



Graph 2. Jouls vs Time



Graph 3. RPM vs Time

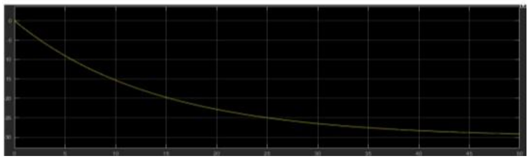


Figure 6. Output results in MATLAB/Simulink model

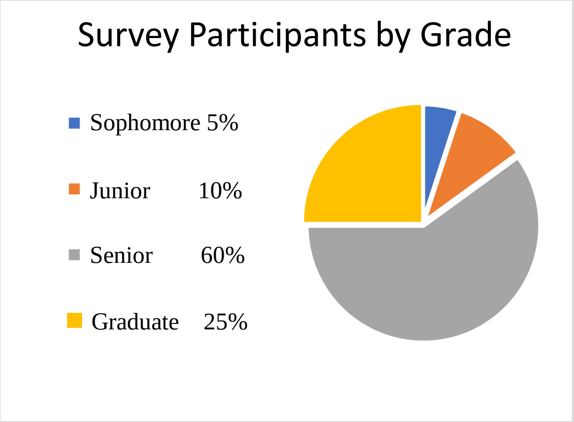


Figure 7. Survey participants demographic

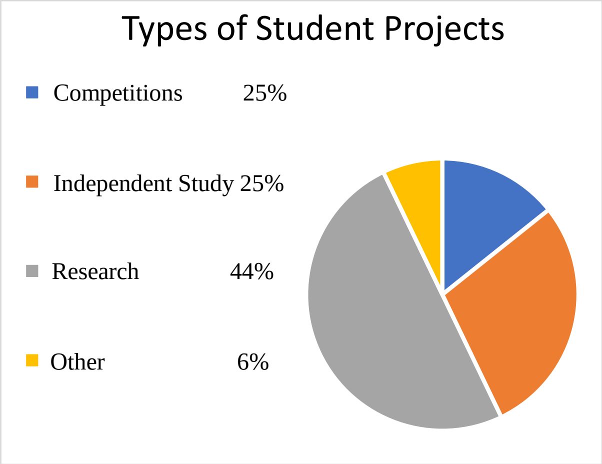


Figure 8. Types of student projects

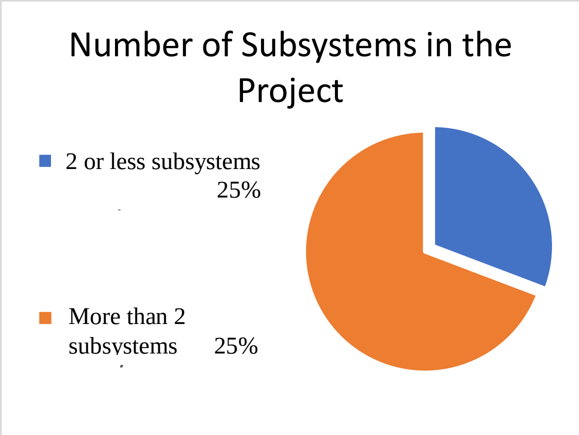


Figure 9. Number of subsystems in student projects

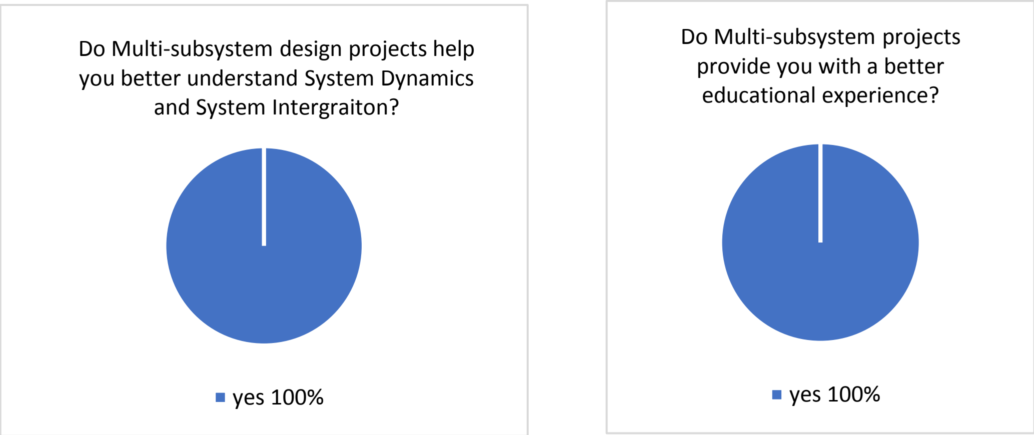


Figure 10. Student opinion about the multi-subsystem design project educational experience