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Development of a Ball and Plate System

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Development of a Ball-and-Plate System

Abstract

This paper presents the development of a dynamic ball-and-plate system successfully completed for a one-semester Senior Capstone Design project. A group of five undergraduate students developed the project concept and constructed a prototype within a semester, integrating major mechatronics engineering concepts learned in classes. The three-degree-of-freedom system consists of sensors, actuators, and controls to keep a free rolling ball in a desired position on a flat plate, accounting for any possible external disturbances. Due to its complexity, multiple steps were taken to solve the design challenges and develop the system. The major works were mathematical modeling, kinematic constraints and dimensional analysis, simulations, and construction of the system. The control system required an effective control strategy and a thorough analysis of system parameters. The system's feasibility and optimal operation were fully considered in the design phase. The design was then validated by simulations using Simulink/MATLAB™ and experimental testing. The completion of the system development provided the understanding of analyzing different control designs on various system parameters based on multidisciplinary mechatronics design principles. Lastly, the class outcomes confirmed the effectiveness of students' learning on multidisciplinary mechatronics engineering through this hands-on project as an assessment of the design project presented.

I. Introduction

A ball-and-beam system is one of the challenging control bench-marking systems integrated into many practices and techniques [1]. This project will resolve in taking the ball-and-beam concept and develop a ball-and-plate balancing system. The system will utilize sensors, actuators, and control law to manipulate the servos in a feedback stabilization using three-degree-of-freedom compensation. This is essentially implementing two ball-and-beam experiments in parallel to constructing a ball-and-plate prototype.

The concept of the ball-and-beam system is a simple system that is an unstable open-loop. Without an active feedback control system, the horizontal beam will tilt to either side, and the ball will roll off the end of the beam. In order to stabilize the ball, a control system is applied to measure the position of the ball and adjusts the beam accordingly.

The objective of this project is to keep a ball on a platform within a predetermined boundary. The sensor's function is to monitor a ball's position. When the ball moves outside the boundary, the sensor will send signals to the controller to determine the coordinates needed to stabilize the ball to its designated location. The controller and the servos will simultaneously control the plate's pitch and roll to center the ball within the boundary. The platform consists of a touch panel and a base to house the components.

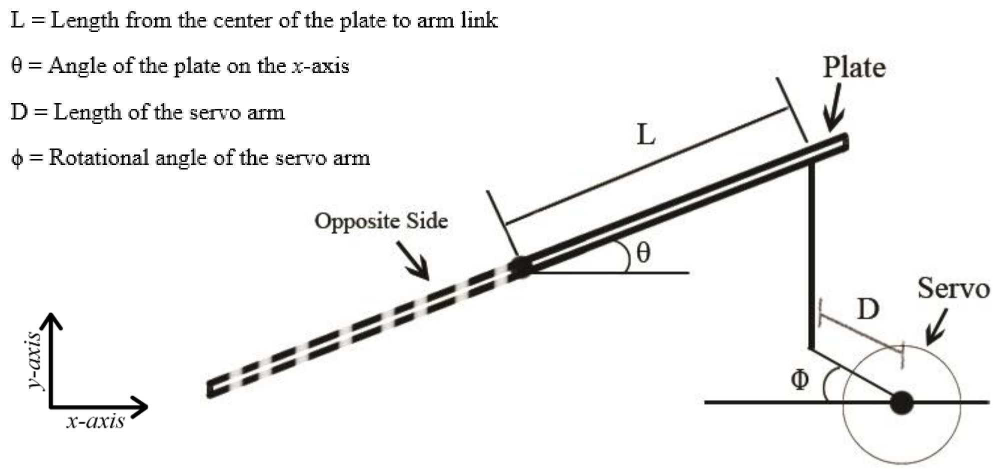

Figure 1: Ball-and-plate model in two-dimension

In Figure 1, the simple system shows a ball-and-plate control system broken into two parts; each part controls a single axis whose angle is adjusted by two other angles. The beam is mounted on an electric servo that is tilted when the position of the ball object is determined by sensors, bringing the ball to the center. However, since the ball object accelerates proportionally to the tilt, the feedback of the control system must simultaneously position the ball on the beam by altering the beam's angle. This concept is implemented into the ball-and-plate system, where a ball rolls on top of a plate whose inclination can be adjusted by tilting it on the *x* and *y* axes.

The major developments are the structural design and analysis, control system design and analysis, actuators, sensors, prototype assembly, circuitry and programming. The overall structural development was based on CAD using Solidworks™ and then tested for overall functionality. Major components of the system are four servos, an Arduino MEGA™, battery, touch panel and ball-and-socket joints.

The ball-and-plate system is designed with the purpose to have key functionalities in mind. The first is automatic stabilization of the ball's location. The system should also provide feedback on where the ball is located on the sensor, have three-degree-of-freedom, and be able to have variable predestination of the desired ball location. So the ball's desired position can be changed at any time from user input.

The development of the system is to bring and retain a ball object on a plate to a preset boundary. The system integrates sensors, actuators, and a computer system to control motors to stabilize the system using three-degree-of-freedom. The system configuration is given by the block diagram in Figure 2. The ball's location will be obtained from the resistive touch panel in terms of voltage. A controller that came with the touch sensor will translate the sensor readings into coordinates. The coordinates of the ball will be sent to the MEGA that will be used to program the data. This will determine how much current each servo should receive to manipulate the plate to be at the appropriate angle. The controller takes the signal from the sensors and determines the roll and pitch needed to stabilize the ball into the desired location. With the signal from the controller, the motors will simultaneously control the plate's pitch and roll to center the ball within the boundary. Essentially the sensors, controller, and the motors are a feedback system.

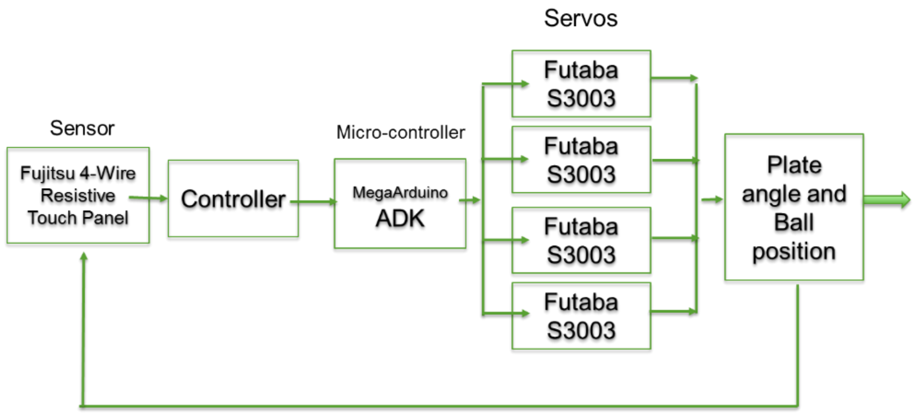

Figure 2: The block diagram of the ball-and-plate system

The design for the prototype system had an in-depth structural design and analysis, control system analysis, actuators, sensors, prototype assembly, circuitry and programming. Similar projects in the past would use a web camera to sense the ball's location [2]. Research showed an alternate option to use a touch sensor. Continuation of research would eventually lead to the consideration of using a resistive touch screen. Resistive touch screens use two layers of material that enclose a circuit. The top layer is flexible which causes the surface to deform when a force is applied. The deformation changes the resistance that the circuit experiences which can be read as a change in voltage. Each corner of the sensor detects the voltage change and the microcontroller will take in the voltage changes from each corner and translate it into a coordinate. Due to how the resistive touch screen works, any material can be used on it. The resistive touch screen was decided to be used as opposed to a camera due to the increased accuracy and smaller size requirements of the touch sensor. The camera would have to be suspended a few feet above the ball and make the system much bulkier.

II. Development of the Ball-and-Plate System

Touch panel platform

The sensor mount is fabricated for the touch panel to fit within the platform to eliminate any sliding, and allows joints and arms to be attached to the platform itself. This would greatly lower any risk of damaging the sensor. Ball-and-socket joints were then selected for the mount. Arms-and-elbow joints are assembled and attached to four simulated servos to observe the possible motions of the entire system. The platform for the touch panel was 3D printed as shown in Figure 3.

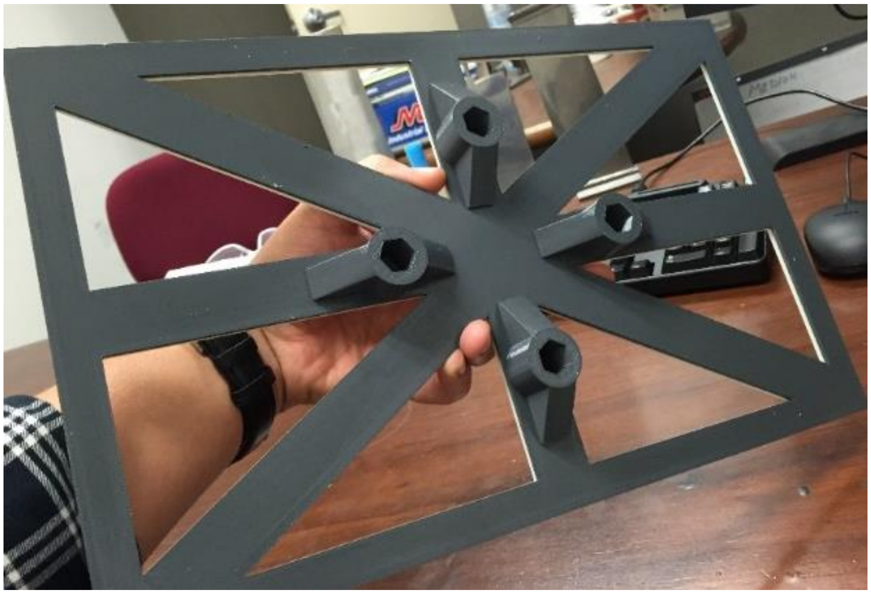

Figure 3: Touch panel platform

Touch panel

The system is implemented with a 4-wire resistive feather touch panel from Fujitsu to obtain the location of the ball. The touch panel is composed of two layers that incase an electric current. As shown in Figure 4, the top layer was flexible which causes the surface to deform when a force is applied. The operation force range is 0.02-0.3N. The deformation changes the resistance that the circuit experiences which can be read as a change in voltage. Each corner of the sensor detects the voltage change and the microcontroller will take in the voltage changes from each corner and translate it into a coordinate. Due to how the resistive touch screen works, any material can be used on it. The resistive touch screen was decided as opposed to a camera due to the increase in accuracy and smaller size requirements of the touch sensor.

Figure 4: Touch screen

Servo

The servos provide the capability of positional feedback through simple programming. The preferred Futaba S3003 servo offers the desirable 180˚ degrees of rotational angle, with 56.9 oz-in of torque, and 0.19 sec/60˚ degrees of speed at the system operating voltage of 6.0 for stabilization of the ball.

Electronics

The electronics consist of three modules: 4-Wire touch screen, Futaba actuators, and Arduino MEGA™ microcontroller which is powered by 6 V battery. The microcontroller receives and processes coordinates from the touch screen, then delegates via P8 and P10 I/O ports for the y-axis, and P9 and P11 I/O ports for the x-axis to the servos correcting the ball's position.

This project uses Arduino™ integrated development environment software. Being open source, there are various examples of working Arduino™ code as well as libraries of modules and functions that it utilizes. This open source programming language is a link to communicate and control the sensors and actuators. The touch screen came with a controller to convert the raw data from the touch screen to useable formatted values.

The Arduino Mega ADK™ is based on the ATmega 2560™, it has 54 I/O pins, 16 analog inputs, a USB host shield interface, USB connection, USB macro connection for pc, power jack and a reset button for easy troubleshooting. The mega ADK can be powered either by a USB or an external power supply. The Mega ADK™ has 256 Kbytes of flash memory used for storing code (8KB for the boot loader), 8 KB SRAM and 4 KB EEPROM.

Control system

When programming the ball-and-plate system, it was decided to have each opposing servo in order to rotate the exact same angle, but in different directions. So if *Servo A* rotates 15°, then the opposite servo will rotate -15°. The entire system will prevent the plate from translating side to side, so a pivot point is assumed to be at the center of the entire system. This allows each axis to be controlled with its own control system which simplifies the process.

The control system utilizes Euler-Lagrange equations to derive a function that can be implemented into a Simulink™ model [3]. The equations of motion were found using energy principles.

The Lagrangian of a system is a quantity which is defined as

$$L = K - U \qquad \textbf{(1)}$$

where K is the kinetic energy and U is the potential energy of the system. The kinetic energy of the beam is

$$K_1 = \frac{1}{2} J \dot{\theta}^2 \qquad \textbf{(2)}$$

where J is the moment of inertia of the beam and $\dot{\theta}$ is the angular velocity of the beam. The kinetic energy of the ball is

$$K_2 = \frac{1}{2} J_b \dot{\theta_b}^2 + \frac{1}{2} m v_b^2 \quad \textbf{(3)}$$

where $\dot{\theta}_b$is the angular velocity of the ball, v_b is the linear velocity of the ball, J_b is the moment of inertia of the ball, and m is the mass of the ball. The angular velocity of the ball $\dot{\theta}_b$ is given by

$$\dot{\theta}_b = \frac{p}{r} \quad \textbf{(4)}$$

where r is the radius of the ball and p is the position of the ball on the beam. Also, v_b is expressed as

$$v_b{}^2 = \dot{x}^2 + \dot{y}^2 \quad \textbf{(5)}$$

where the terms are given as

$$x = pcos\theta\ ,\ \ y = psin\theta \quad \textbf{(6)}$$

Substituting (4) and (5) into (3), the expression for the kinetic energy of the ball is obtained in terms of

$$K_2 = \frac{1}{2}(J_b + m)\,\dot{p}^2 + \frac{1}{2} m p^2 \dot{\theta}^2 \quad \textbf{(7)}$$

The potential energy of the system is given by,

$$U = mgpsin\theta \quad \textbf{(8)}$$

Substituting (2) and (3) into (1), results of the Langrangian for this system

$$L = \frac{1}{2}(J_b + m)\,\dot{p}^2 + \frac{1}{2}(mp^2 + J)\dot{\theta}^2 - \ mgpsin\theta \quad \textbf{(9)}$$

Then, the equation of motion for the ball-and-beam becomes

$$(mp^2 + J)\ddot{\theta} + 2mp\dot{p}\dot{\theta} + mpgcos\theta = \tau \quad \textbf{(10)}$$

where the $2mp\dot{p}\dot{\theta}$ is the effect of the rotating axis for nonlinear simulations of the system, and τ is the external applied torque.

The equation of motion derived from Langranigan

$$\ddot{r} = \left(-\frac{1}{\frac{J}{R^2} + m}\right)\left(mg\sin(\alpha) - mr(\dot{\alpha}^2)\right)$$

where α is the beam angle and r is the ball position coordinate for the state function $\ddot{r}$. This translates to the following when implementing into the general function block and substituting u[3] = α , u[1]= r, and u[4]^2 = $\ddot{\alpha}$ resulting in:

$$\left(-\frac{1}{\frac{J}{R^2}+m}\right)\left(mg\sin(u[3]) - mu[1](u[4]^2)\right)$$

By taking the function block, the block diagram represented in Figure 5 is constructed with two feedback loops. These loops act as the changes in the balls position and the plate angle and the two inputs are the initial position of the ball and initial angle of the plate.

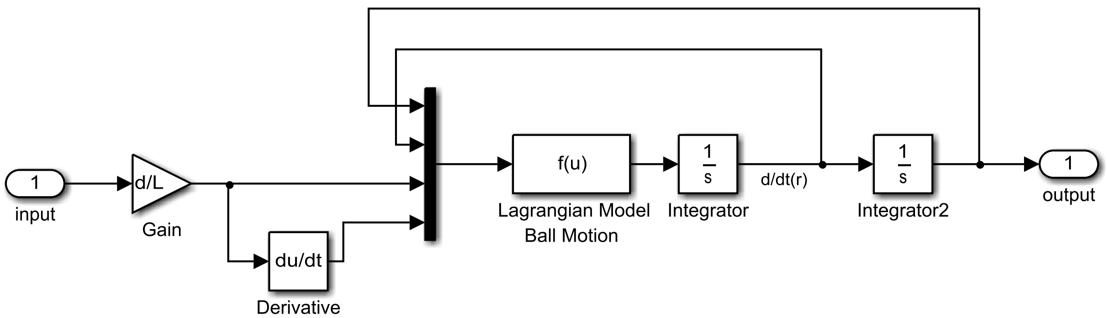

Figure 5: Block diagram with feedback loops for plate angle and two input position

Prototype

Figure 6 shows the developed prototype. The movement of the prototype operates the same as the generated model; in such the resistive touch panel detects and sends data to the controller and microcontroller, commanding the four servos to produce torque to move the arm links and panel. There are few alterations made to the dimensions of the arm links and mounts for the servos. Inclusively, the ball-and-plate system is created in relation to the model simulation.

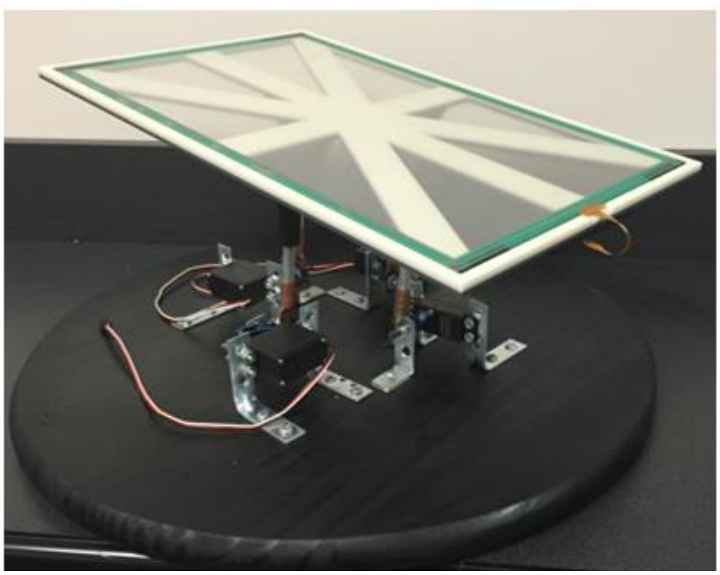

Figure 6: Ball-and-Plate prototype

III. Analysis, simulation, and test

Using the acquired parts and designs of the prototype, a structural model of the system was developed on SolidWorks™ and was put through a stress analysis to observe the forces the system would experience. The structure, shown in Figure 7, displays the integrity of the structure as the forces are applied as the system moves. When the parallel servos apply rotational torque to adjust the object on the panel, it translates the forces on the arm links. This causes displacement on the ball joint connected to the arm links in the y-axis. This displacement has a direct relation to the arm link joint to the servo, causing shear stress as the forces on the ball joint increases.

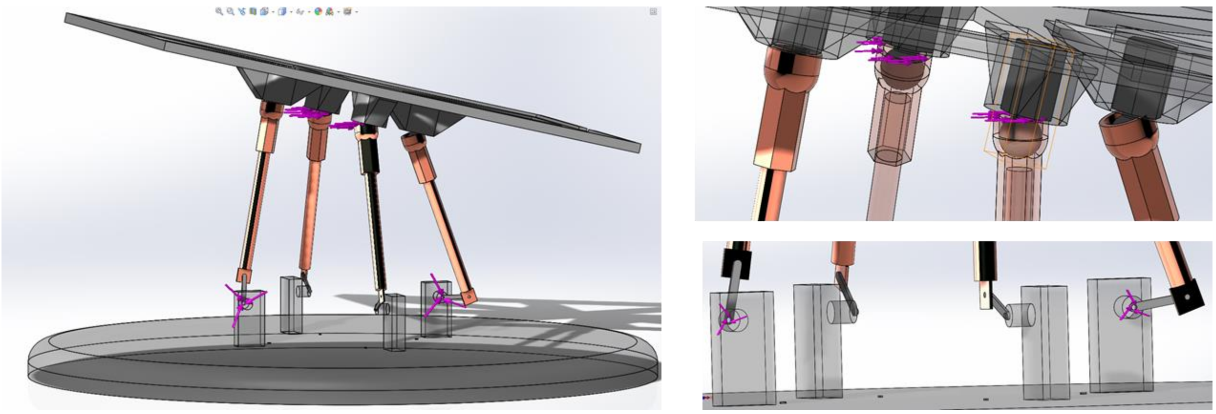

Figure 7: Stress analysis on arms joints to test the integrity

The displacement in the arm link, shown in Figure 8 simulation, has a direct relation to the arm link joint connected to the servo gear, by which it causes shear stress. Stress analysis results are shown in Figure 8. As the displacement increases in ball joint from the forces, the copper connection feels the stress.

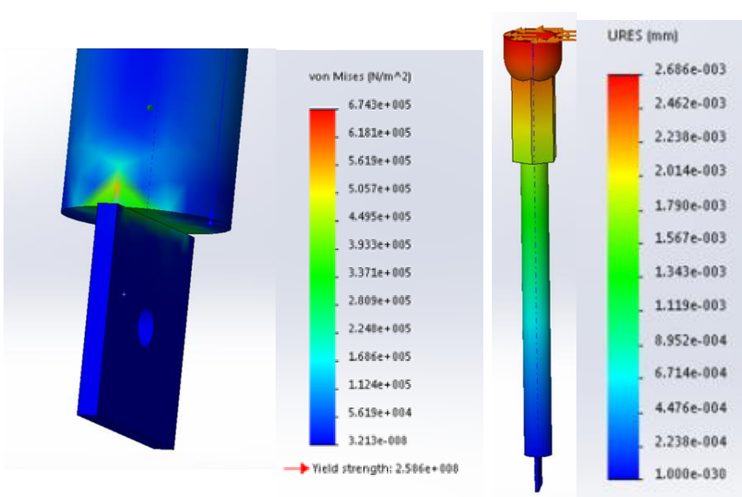

Figure 8 Stress analyses on links

MATLAB™ was used to simulate the control system. A block diagram was constructed using Simulink to describe the motion of the ball. The block diagram would act as foundation for simulating the step response of the system.

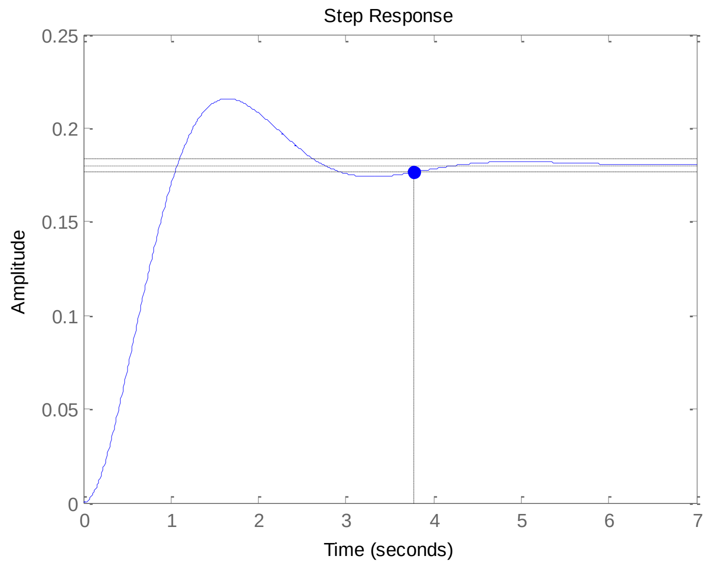

Figure 9: Settling time of set response estimated at 3.8 seconds

It is important to note the effects of a lead compensator [4]. A root locus is used to find the effects of multiple lead compensators so that a proper one can be implemented to induce stability within the system. The step response would demonstrate how far the ball needs to travel to reach the desired location. Without a lead compensator, the step response would be unstable and would translate into the ball rolling off the sensor entirely. A lead compensator forces the motor to change angles and adjust the plate angle so that the step response would be stable.

This control system simulation was first done on one side as a two dimension beam [5]. The step response showed that the ball eventually settled at the desired location after approximately 3.8 seconds. The same process was done for the shorter side, meaning the maximum distance from the center must be smaller with the ball at a maximum of 0.1125 meters away from the center. The step response with the appropriate gain and lead compensator is shown in Figure 9.

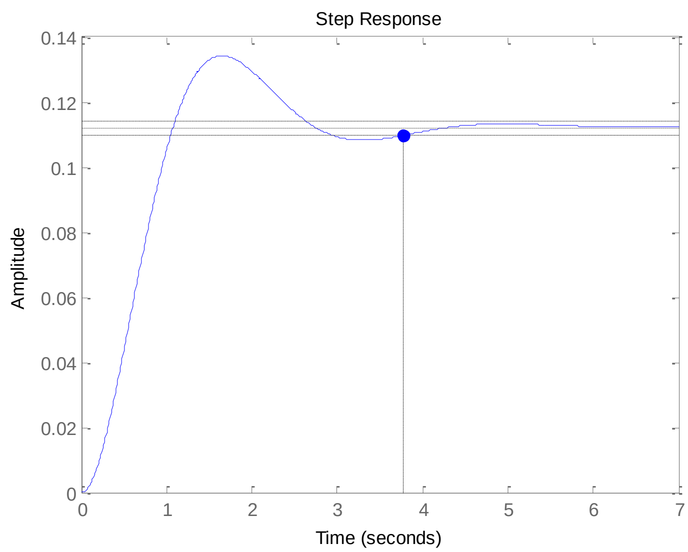

Figure 10: Settling time of the entire system is under 4 seconds

Figure 10 shows the simulation result, if the ball was 0.18 meters from the center from one side and 0.112 meters from the center on the other side, the entire system would have a settling time just under 4 seconds.

The main control objective is to place ball within a 2 inch radius of the center of the plate and to stabilize in less than 5 seconds. Experimental results validated the system concept and operational capability. However, the control system should be improved since a stability issue is found during the test. An irregularity of the system performance may result from the sensitivity of the touch screen and control algorithm.

IV. Assessment of Outcome and Impact on Students

At the beginning of the semester, the design project proposal was presented in the first week. Based upon their expression of interest, all five senior year mechatronics students were assigned to the project team. The approval of the design project was based upon the technical content, equipment and software availability, and the specific background of the student group. The design should be carried throughout the conceptual and detailed design phases, and build and test a prototype according to the design specifications selected. At the end of the semester, a final project report was required that detailed the team's work. Completion of the prototype was also required which covered the building, testing, and evaluation of the prototype. Additionally, each student was required to maintain an engineering logbook of the efforts on the project, keeping track of the time spent, the tasks being worked on, etc. The project required planning, proposal presentation, scheduling, engineering, implementation, and written and oral presentations of project results.

The assessment of the course was twofold: 1) learning of a design process and 2) developing a prototype by utilizing concepts and technical skills learned from courses throughout the mechatronics curriculum. Based on the course objective, the following items were used to assess students' learning outcomes.

1. System Concept Review (SCR) & System Requirements Review (SRR) Presentation, *may be held together*	10%
2. Preliminary Design Review (PDR) Presentation & Written Report	10%
3. Critical Design Review (CDR) Presentation & Written Report / Final Presentation and Written Report	20%
4. Completion and Demo of a Prototype	30%
5. Logbook, Weekly Progress Report, and other Presentations/Exams.	20%
6. Performance Evaluation by Peer	10%

The five students were graded on their teamwork based on the first four criteria. As a group they received full percentage, if not extra points, in each of the outcomes. On criteria 5 and 6, they were graded individually on how each member contributed to group and what he/she understood in this learning process.

Proper project management was also an important focus of this project; advanced planning was used to decide on the tasks that needed to be completed before approaching deadlines. This also provided the students an understanding that nothing works perfectly and the opportunity to use troubleshooting and debugging processes to find alternative methods or components whose specifications meet the design performance. Delegation of tasks was used to divide the work load and use the strength of each individual to accomplish key tasks. Throughout the entirety of the project, presentations and technical journals for which each member could write down their contributions were used to check progress of the system development. The technical journals acted as documentation so that the work of each individual could be observed and be replicated. Proper management enables the group to submit all necessary work on time and illustrates the necessity of maintaining professional work ethic. This further ensured that the group would remain focused and on schedule to finish the ball-and-plate system.

This project requires major technical disciplines of mechatronics engineering: structure and mechanism, sensors and data acquisition, actuators and controller, and computer hardware and software. Through the project, students also learned fundamental multidisciplinary principles in order to achieve a compact, portable, and an affordable system while taking consideration of cost, performance, and functionality.

The final class grade confirmed effective learning outcomes of the project team. All five students of the team received class grade A or B while the course success was defined a grade C or higher. In addition, a class survey administered to the team students showed the students' full satisfaction with the course on how their learning of multidisciplinary mechatronics engineering improved for their professional career development in the future. As a result, students learned clear lessons on how a multidisciplinary engineering design project is implemented. In addition, the framework established in this project provides a valuable reference system for Mechatronics students and classes. Future students can optimize this type of system by designing a more compact and responsive system. This can be accomplished by upgrading the ball and socket joints for a good connection point, using stronger servos and battery for longer and more fluid performance, and having a better feedback sensor for a faster response time.

V. Conclusion

As a one-semester senior Capstone Design project, a dynamic ball-and-pate system was successfully developed. Though the system concept is well known, this is a newer and optimal design approach integrated with Mechatronics principles and discipline, resulting in overall enhancement, such as in size reeducation and quick response time, to the system. This project covered major technical disciplines of mechatronics engineering. It also provided a real-world engineering design practice for students. The successful completion of the project confirmed the effectiveness of the Mechatronics curriculum for students’ multidisciplinary learning and practical competence. Moreover, the ground work established in this project provides a valuable bench-marking system for Mechatronics students and classes in which various control designs are empirically evaluated.

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