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Simulation and Control of Space Mechanisms: An Undergraduate Controls Course for Mechanical Engineering Students

Dr. Brian James Slaboch, Milwaukee School of Engineering

Brian J. Slaboch holds a Ph.D. in Mechanical Engineering from Marquette University and is currently an Associate Professor at the Milwaukee School of Engineering. His research is in the general area of mechanism design, and he is currently investigating ways to utilize mechanisms with variable topology, as applied to manufacturing, healthcare, and space applications.

Dr. Luis Alberto Rodriguez, Milwaukee School of Engineering

Dr. Luis A. Rodriguez is currently an Associate Professor in the Mechanical Engineering Department at the Milwaukee School of Engineering (MSOE). He completed his doctoral training at the University of California-Irvine where he was a National Science Foundation Bridge to the Doctorate Fellow. He completed his master's degree at the University of Wisconsin-Madison where he was a GEM fellow and Graduate Engineering Research Scholar. He also holds a bachelor's degree from University of California San Diego. His interests include robot control, design of mechatronics systems, pneumatic actuation, motion planning and optimal control.

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Abstract

Students in a traditional undergraduate mechanical engineering program typically take a controls course during their junior or senior year. Often, these courses are highly theoretical and may or may not have a corresponding lab component. Students often struggle to connect the fundamentals of feedback control systems with practical hardware and software implementation. To address this crucial learning gap and to foster more engaging learning experiences, a new technical elective was developed at the Milwaukee School of Engineering titled "Simulation and Control of Space Mechanisms." The new course is a follow-on course to a traditional undergraduate mechanical engineering controls course that incorporates research with experiential learning. The ten-week course provides students an opportunity to use modern computer tools to aid in the simulation and control of space mechanisms. In particular, the course focuses on the mathematical modeling, simulation, and control of an innovative planar pick and place mechanism capable of dynamically changing its topology within its workspace. This immersive educational experience allows students to connect fundamental mathematical modeling of a physical system to the real-time control of physical hardware. This paper documents the structure of this new course, its learning objectives, and outlines the unique project and laboratory experiences that students engaged in to enrich their educational journey.

Introduction

Advances in robotics and automation have led to a significant increase in the number of controls engineers needed in industry [1]. Manufacturing is undergoing an important change in which the introduction of robots and automation leads to reduced costs, improved safety, and an increase in productivity [2]. Industries heavily reliant on robotics and automation include the automotive industry, food processing, e-commerce, and the pharmaceutical industry, to name a few. With the rise of artificial intelligence and machine learning, this trend is set to accelerate in the years to come.

To meet industry demand, it is essential that modern undergraduate mechanical engineering programs prepare students for careers in robotics and automation. In a traditional undergraduate mechanical engineering program, an introductory controls course is mandatory. A typical controls course covers topics such as mathematical models of systems, feedback control systems, and an introduction to frequency response methods, among other topics. This type of controls course may or may not have a lab component associated with the class. Lab topics often include system identification, dynamic response characteristics, and tuning a PID controller for a physical system such as a DC motor with an encoder [3] or a magnetic levitation system [4].

A traditional undergraduate controls course is often highly theoretical, and students sometimes struggle to connect the underlying mathematics to a physical system. Frequently, students will take a complete controls course and not fully understand what is meant by a feedback control system. Students are focused on the mathematics, but often do not connect how the mathematics relates to the physical system being controlled [5]. To bridge this gap, this paper presents a new controls course that is meant as a follow-on course to an introductory undergraduate controls course. The new course is titled "Simulation and Control of Space Mechanisms." While the course title emphasizes space mechanisms, the course format is intended to be general in nature such that others could follow a similar structure in another focus area. For instance, a similar course could be created called "Simulation and Control of Automotive Mechanisms," where the examples used throughout the course are more automotive related.

An important aspect of this new course is that it is vertically integrated, and the course uses one primary physical system throughout the course. For the "Simulation and Control of Space Mechanisms" course presented in this paper, the course is centered around the mathematical modeling, simulation, and control of an innovative, planar pick and place mechanism that can change its topology within its workspace [6]. By using one consistent physical system throughout the course, students have an opportunity to gradually build their system modeling and controls knowledge throughout the course and more fully understand each part of the process.

This results in an immersive educational experience that allows students to connect fundamental mathematical modeling of a physical system to the real-time control of physical hardware. This paper documents the structure of this new course, its learning objectives, and outlines the unique project and laboratory experiences that students engaged in to enrich their educational journey.

Course Overview

This course focuses on the use of modern computer tools to aid in the simulation and control of space mechanisms. The course topics include mathematical modeling of planar mechanisms, mechanism simulation using computer tools, control design for closed-loop mechanisms, and practical implementation of controller on hardware.

In this section, the course learning objectives, course organization, and grading policy is presented.

Course Learning Objectives:

Upon completion of the course, students should be able to:
1. solve the forward and inverse kinematics of a planar four-bar linkage and crank-slider mechanism.
2. solve the forward and inverse dynamics of planar, closed-loop mechanisms.
3. create mechanism simulations using Matlab's Simscape Multibody software.
4. implement both low-level and high-level control using Matlab's simulation software.
5. apply concepts of structured programming in the control of hardware.
6. formulate a Langrangian approach to model and control space mechanisms.

Course Organization:

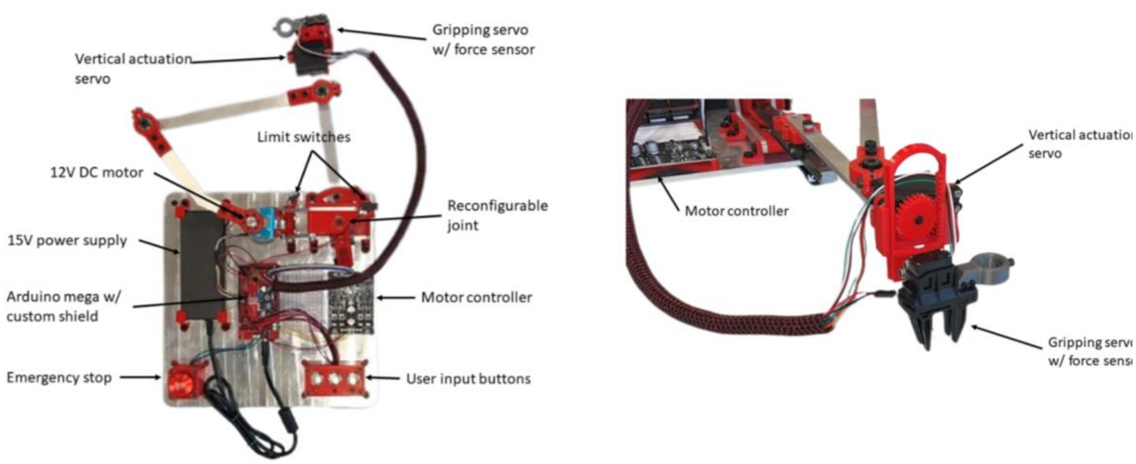
- The course is a senior level mechanical engineering technical elective.
- The course is a ten-week course that meets twice a week. There is one 50-minute session and one 110-minute session. The shorter session is used to introduce important concepts through a traditional lecture session, and the longer session is used for the laboratory portion of the course.
- The course consists of 6 laboratory sessions, a midterm project, and a final project.
- Homework assignments are used to reinforce lecture and laboratory topics.

Grading Policy:

Homework	30%
Laboratories	30%
Midterm Project	20%
Final Project	20%

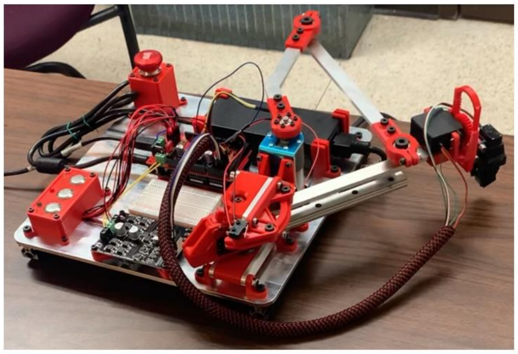
Pick and Place Mechanism

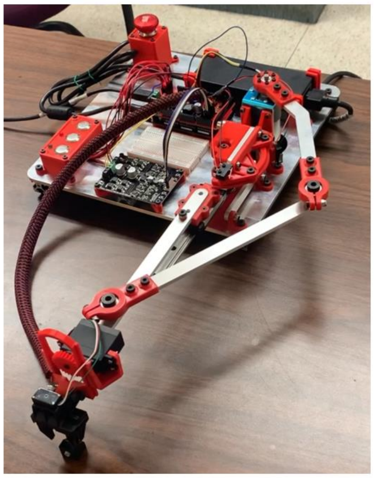
The course is based on a recently developed pick and place mechanism [6] that is shown in Figures 1 and 2. The mechanism is a one degree of freedom (i.e., one motor as an input) mechanism called an RRRR-RRRP mechanism which corresponds to the joint topology of the mechanism. In state 1, shown in Figures 1a and 2a, the mechanism is constrained to be a four-bar linkage with four revolute joints (RRRR configuration) connecting four links. As the input is turned clockwise, the mechanism reaches a transition configuration where a latching mechanism activates and changes the mechanism's topology from a four-bar linkage to a crank-slider mechanism that has three revolute joints and one sliding joint (RRRP configuration). This changes the output link motion of the mechanism from a rotational motion to a sliding (i.e., prismatic) motion as shown in Figures 1b and 2b. As shown in Figure 2, the mechanism is used



(a) (b)

Figure 1. (a) The RRRR-RRRP pick and place mechanism used throughout the course. (b) The gripper used for pick and place tasks.





(a) (b)

Figure 2. (a) The mechanism shown with a block picked up off the table in the four-bar linkage (RRRR) state. (b) The mechanism shown placing the block on the table in the crank-slider state (RRRP).

for pick and place operations. For example, a block can be pick up in one location and moved seamlessly to another location. The advantage of this mechanism is that it can perform a complex motion profile with a single DC motor. This reduces the weight of the mechanism, reduces the power consumption, and lowers its cost. These factors are highly desirable in space applications, and therefore this mechanism is considered a space mechanism in the context of this course.

Figure 1a shows the electrical and mechanical setup of the mechanism. An Arduino Mega is used as the main microcontroller. The motor controller drives a 12V DC motor. There are two limit switches that are used to ensure the mechanism does not exceed its travel limits. The mechanism is powered by a 15V power supply and has an emergency stop for safety purposes. The mechanism is controlled by three user input buttons. A gripping servo is included on the output link and is used to both grip objects and move them up and down in the vertical direction.

Throughout the course this mechanism is analyzed in depth. Students start the course by deriving mathematical models governing the mechanism's motion. From there, students simulated the mechanism using commercially available software and perform high-level control design in simulation. In the final phase of the course, students perform real-time control of the mechanism using the experimental setup.

Simulation Laboratory Content

The laboratory content is meant to build up students' knowledge and capabilities as the course progresses. The first half of the course covers the mathematical modeling and simulation of the mechanism, and the second half of the course covers the real-time control of physical hardware. Each lab builds upon the prior lab and connects directly to the lecture content students encounter during the most recent lab week. This section presents each of the labs created for this course including the purpose of the lab and the accompanying lab activities.

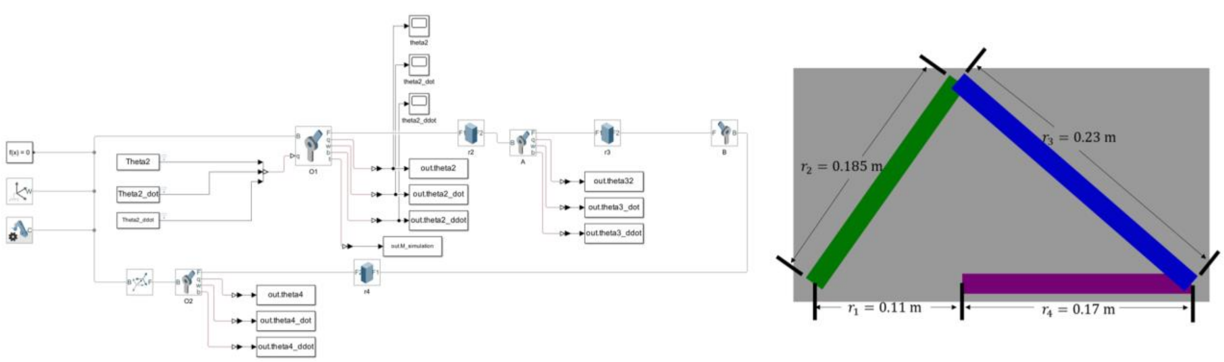
<u>Laboratory #1-Simscape Multibody Modeling</u>

The first lab in the course is centered on mathematical modeling and simulation of a physical system using commercial software. Specifically, the purpose of this lab is to (i) introduce students to commercial multibody simulation software through the simulation of a four-bar linkage, and (ii) to compare outputs from the simulation to previously derived mathematical models of the four-bar linkage.

For this laboratory, MathWorks's Simscape Multibody simulation software was used. Simscape Multibody software was chosen as it provides an easy to use, yet powerful environment to model mechanical systems. Further, once a mechanical system is developed, the model can be used for control system design and can be integrated with electrical, hydraulic, pneumatic, and other physical systems.

Prior to the lab, students had derived the forward and inverse position, velocity, and acceleration kinematics of a four-bar linkage. Upon completing the kinematic analysis, students used these results to derive the inverse dynamics of a four-bar linkage. That is, students calculated the required motor torque necessary for the four-bar linkage, given the motor's angular position, angular velocity, and angular acceleration profile as inputs.

Figures 3a and 3b show the resulting Simscape Multibody model and four-bar linkage simulation. Note that the four-bar linkage has identical dimensions to the RRRR-RRRP mechanism from Figures 1 and 2. Figure 3a shows that the four-bar linkage can be easily created using a series of links connected to joints. Simscape Multibody allows an engineer to easily sense information from the resulting physical system. For example, in this simulation the required motor torque can be sensed directly from the Simscape Multibody model. Figure 4 shows a plot of the resulting motor torque required versus time from both the Simscape



(a) (b)

Figure 3. (a) Simscape Multibody simulation of a four-bar linkage created by students during the first lab. (b) The four-bar linkage created in laboratory number 1 using Matlab's Simscape Multibody simulation tools. This corresponds to a simulation of the RRRR portion of the mechanism.

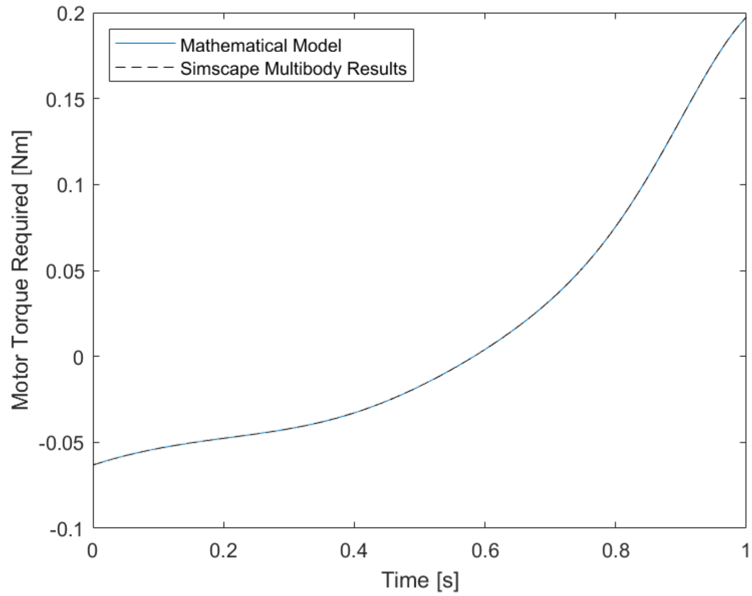


Figure 4. This figure compares the required motor torque for the RRRR-RRRP mechanism for both the hand derived mathematical model and the sensed value from the Simscape Multibody model. The results are identical.

Multibody model and the hand derived inverse dynamics calculations. As shown, the results of the mathematical model and Simscape Multibody model are identical. This comparison shows students both the value of the commercial software and the importance of mathematical modeling. With this lab, students were able to make strong connections between the physical hardware, the mathematical equations of the mechanism, and the resulting Simscape Multibody simulation.

<u>Laboratory #2-High-Level Control System Design and Simulation</u>

The second lab in the course builds on the first lab and is intended to improve student's control simulation capabilities. Specifically, the purpose of the lab is to (i) introduce students to MathWorks' Stateflow toolbox, and (ii) provide students an opportunity to simulate a real-world high-level control system. Students are tasked with developing a high-level control system in which the RRRR-RRRP mechanism performs a continuous pick and place operation upon command of the user. The user has the option to start, stop, or reset the machine at any time, and two limit switches are included for safety considerations.

Figure 5 shows the graphical code needed to produce the simulation. Students are provided with the "MSOE Reconfigurable Space Mechanism" subsystem, which includes a SimscapeMultibody model of the RRRR-RRRP mechanism, a motor model in Simulink, and a low-level PID speed controller. Students were then tasked with writing the Stateflow code for the "MRSM State Machine," as shown in Figure 5. Mathworks' Stateflow toolbox is a graphical programming language that allows the user to implement a state machine architecture where the user can develop supervisory control for a Simulink model. The resulting simulation for lab 2 is shown in Figure 6. As students press the start, stop, or reset button, they can see the simulated

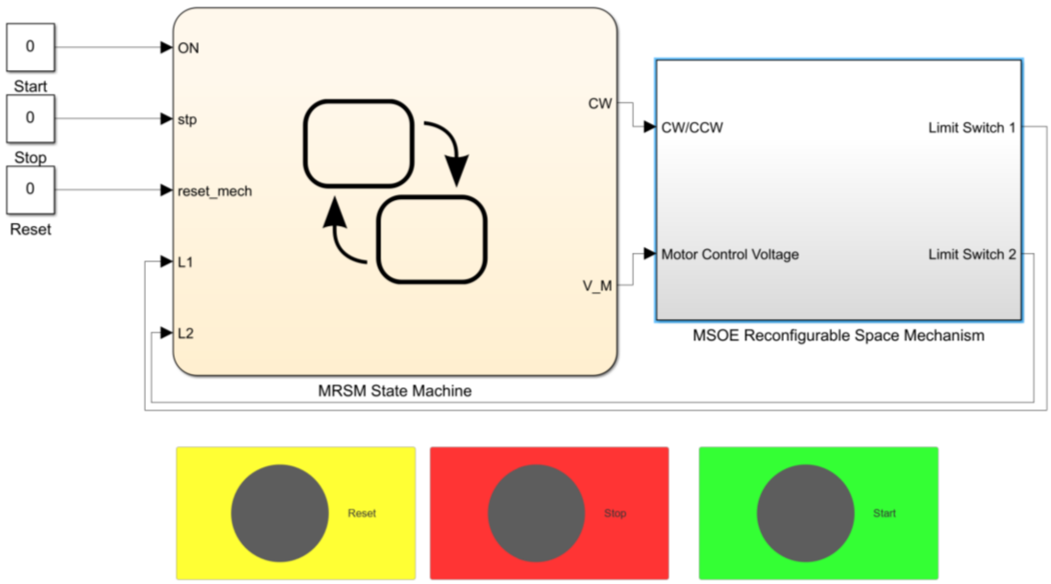


Figure 5. Simulation of the RRRR-RRRP mechanism using MathWorks' Simscape Multibody and Stateflow toolboxes. Students can test their high-level control algorithms in simulation prior to connecting to the physical hardware.

machine perform the corresponding motion that they programmed in the Stateflow chart. Thus, in this lab students can make mistakes and test their high-level control system to ensure it is working properly without connecting to physical hardware.

In completing this lab, students are also tasked with writing out test specifications to ensure that their high-level controller meets all requirements. Students are placed in groups of two in order to write test specifications and test each other's code for correctness. At the end of the lab students have a working simulation for a pick and place operation for the RRRR-RRRP mechanism. The code from the second lab will then be used for lab 3.

<u>Laboratory #3-Real-Time Hardware Control</u>
The third lab in the course continues to build on the first two labs. During this lab students have an opportunity to test their high-level control algorithm on physical hardware. The purpose of the

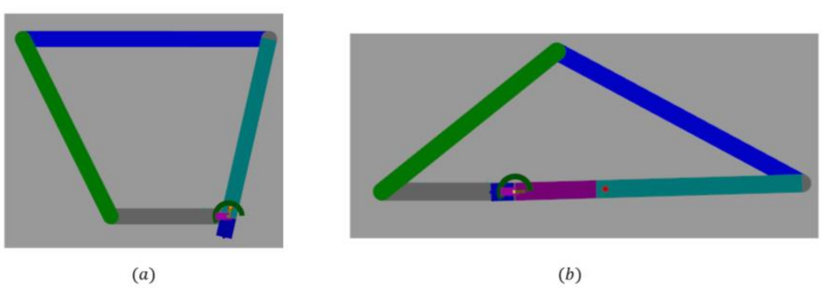


Figure 6. Simulation of the RRRR-RRRP mechanism using MathWorks' Simscape Multibody and Stateflow toolboxes. Students can test their high-level control algorithms in simulation prior to connecting to the hardware.

lab is to (i) provide students an opportunity to test their control algorithm on a physical system and (ii) show students the value of programming and testing control algorithms in simulation.

During this lab students are separated into pairs, and each pair has a physical RRRR-RRRP mechanism at their lab station, as shown in Figure 7. Students are then provided with a base code that contains the sensor inputs, and the low-level motor control for the mechanism (see Figure 8). Students then copy and paste their Stateflow code from Lab 2 into the code provided for Lab 3. That is, if everything is programmed correctly in simulation, students can replace the yellow Stateflow chart from their simulation into code that can run the hardware in real-time. One important aspect of this lab is that students do not need to worry about any embedded programming. MathWorks has a Simulink support package for Arduino hardware that allows students to deploy their code to the Arduino Mega through a single button press.

For this lab safety is of the utmost importance. Students are instructed to keep their hands away from any moving parts at all times, and an emergency stop is included to stop the machine at any time. Students are also instructed to only deploy the code with the instructor present to ensure that all safety procedures are being followed. Further, the machine is programmed to limit the motor speed in the event that the student's program is incorrect and would result in dangerous motor speeds.

The results of the lab during the initial pilot section of the course were that all but one of the teams successfully programmed the robot correctly on the first try. The one team that had a minor mistake was able to quickly adjust their code in simulation to ensure proper functioning on the hardware. This lab emphasized to the students the value of testing control algorithms in simulation, rather than only testing on hardware.

Mid-Course Project-Development and Simulation of 3-RPR Mechanism

The course has two projects used to help students master the fundamentals of the simulation and control of mechanisms. There is a mid-course project and a final course project. The mid-course

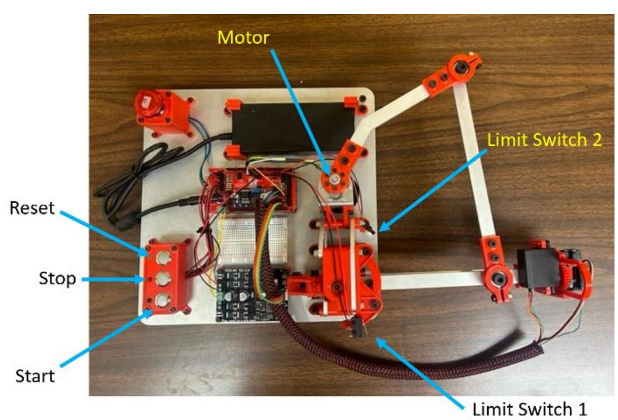


Figure 7. The physical setup for lab 3. Students work in pairs to test their control algorithm on physical hardware.

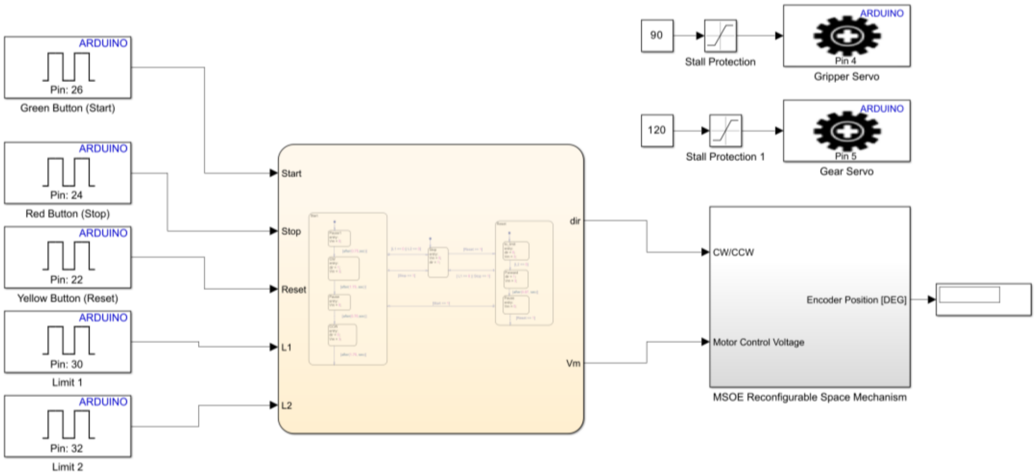


Figure 8. Simulation of the RRRR-RRRP mechanism using MathWorks' Simscape Multibody and Stateflow toolboxes. Students can test their high-level control algorithms in simulation prior to connecting to the hardware.

project focuses primarily on mechanism simulation, and the final project includes both a full simulation as well as control of real-time hardware.

The mid-course project is intended to bring together mathematical modeling of a physical system, simulation of a mechanical system using Simscape Multibody, and high-level control design using MathWorks' Stateflow toolbox. For this project, students are tasked with simulating a 3-RPR mechanism. The 3-RPR mechanism is shown in Figure 9. This type of robot has three legs with a revolute-prismatic-revolute structure where each leg is controlled by the prismatic joint.

For this project students must first develop the mechanical system of the 3-RPR by creating the model using Simscape Multibody. Upon completion of the mathematical model, students will

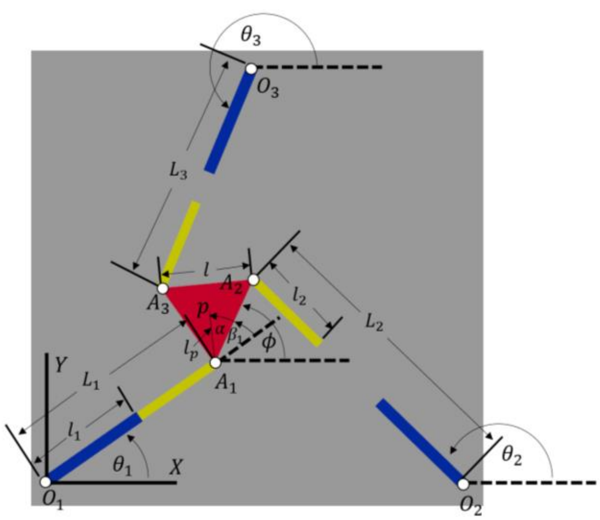


Figure 9. Schematic showing the 3-RPR mechanism simulated during the mid-course project. Each leg of the mechanism is actuated by the prismatic joint.

implement a low-level resolved rate controller that must be tuned by selecting appropriate PID gains. During the final phase of the project, students must implement a high-level control algorithm that includes both an autonomous mode and manual mode. Students program the 3-R$\underline{P}$R for a task of their choosing, and they must verify that their program works properly and meets required safety specifications. Figure 10 shows the resulting simulation that brings together a complete simulation including modeling the physical system and implementing both low-level and high-level control strategies. Even though students do not have an opportunity to test these control algorithms on physical hardware, this project provides meaningful insight into the simulation of physical systems, and because students do have experience implementing control algorithms on hardware, they understand the value and importance of a proper simulation.

Hardware Laboratory Content

The focus of the first half of the course was on the mathematical modeling and simulation of the mechanism, while the second half of the course involved the real-time control of the physical hardware. To accurately control the hardware deterministic models of the DC-Motor and the mechanism where first determined from collected experimental data. Then, the developed motor and mechanism models were used to implement PID and feedforward control for the mechanism. Once students were comfortable controlling the mechanism, students were tasked with completing a final project to demonstrate their understanding of the course materials. Subsequently, additional details will be provided on the covered topics and the developed labs.

Lab 4: DC-Motor and Gearbox Modeling and Data Collection

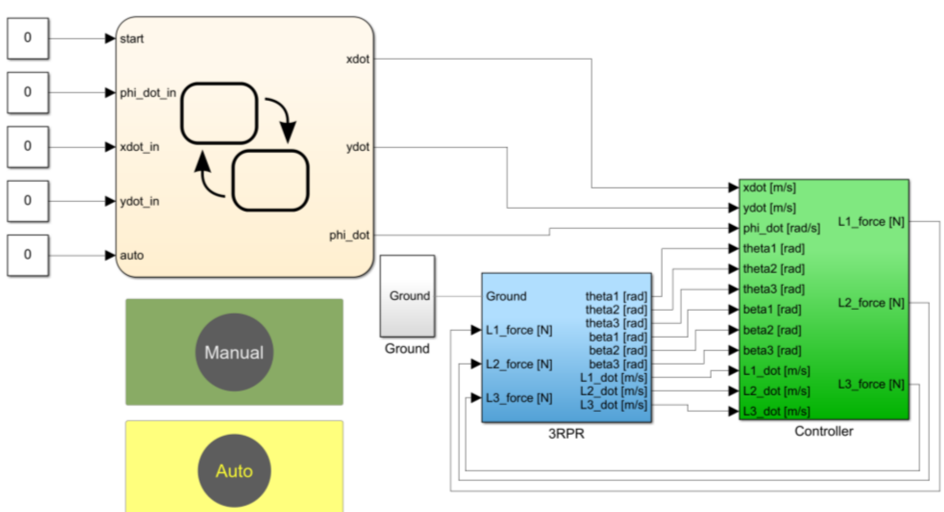


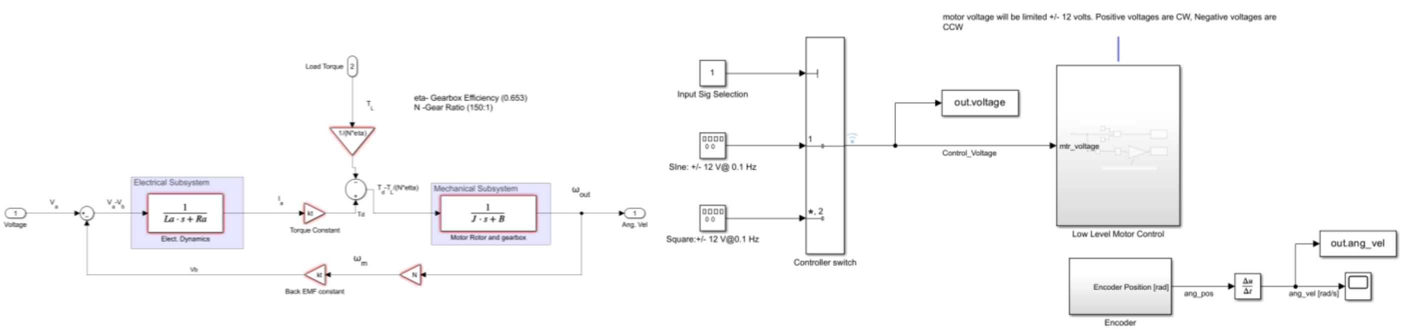
Figure 10. The resulting simulation from the mid-course project. Students create the 3-R$\underline{P}$R using Simscape Multibody, implement a closed loop resolved rate controller, and develop a high-level control for both a manual and autonomous motion of the machine.

The main objectives of this laboratory exercise were twofold. Firstly, it aimed to create a deterministic Simulink model for the motor and gearbox used in actuating the mechanism. Secondly, it sought to collect experimental motor data, which would be utilized on a later lab for the identification of motor parameters.

These objectives stemmed from the recognition that, despite manufacturers providing some estimates for certain motor parameters, these values may be rough or general approximations that may not capture the precision needed for accurate control. Moreover, certain quantities like motor friction characteristics are often omitted due to their challenging determination. Our plan was to precisely estimate these parameters for our model, ensuring it accurately represents the actual DC motor system. Additionally, since parameters can fluctuate over time due to wear and tear, and aging effects which impact performance, we wanted to implement a procedure for routine motor parameter identification. This approach ensures the maintenance of an accurate motor model.

To prepare students for the laboratory, they were given lectures covering the modeling of a DC motor and gearbox, characteristics of steady-state motor performance curves, and fundamental principles of encoder operation. Additionally, students were taught how to use the onboard motor driver and the custom Arduino shield for controlling the mechanism. Furthermore, prior to the lab students were asked to visit the motor manufacturer website and review any specifications, and performance curves that they could use to estimate the motor and encoder system parameters.

On the day of the lab students worked in pairs and developed the motor and gearbox Simulink model and created Simulink models to run the physical motor, measure the angular position and velocity of the motor using the motor encoder and collected motor step and sinusoidal voltage response data. Figure 11a shows a typical motor and gearbox Simulink model while Figure 11b demonstrates a sample Simulink model used to control the motor and collect input and output experimental data.



(a) *(b)*

Figure 11. a) Simulink model of motor and gearbox subsystem b) Simulink model used to command the motor and obtain step and sinusoidal experimental data

From this experience students familiarized themselves with the various subsystems in the mechanism, realized the importance of obtaining open-loop system response data, and appreciated the importance of modeling and using manufacturers specifications and information to construct useful models while at the same time appreciating the challenges that come with having to estimate system parameters when information is not available.

Lab 5: Estimate Motor Parameters from Experimental Data

After collecting step and sinusoidal experimental data for the motor system in Lab 4 and obtaining initial motor parameter estimates using information found in the manufacturer's website, students were prepared to refine and estimate the motor parameters using an optimization approach. Consequently, the objective of Lab 5 was to take the collected experimental test data along with the estimated motor parameters to obtain more accurate values for the motor parameters that better matched the experimental data.

To achieve this objective, the optimization process was conducted using the Simulink Design Optimization Parameter Estimator App. To find an optimal solution, the parameter estimation process consisted of the following steps:

1. Use the motor step response experimental data to perform the optimization. This will be the training data.
2. Specify the motor parameters to estimate from the motor Simulink model previously developed. Define the initial value guesses for the motor parameters from the formerly estimated values and set parameters bounds to prevent unrealistic solutions. For instance, it is unreasonable for any of the motor parameters to have negative values.
3. Perform the optimization by selecting an estimation algorithm and setting its properties. For the lab we used the default settings.
4. Once the optimization has ended and converged on a viable solution the estimated motor parameter values are validated using experimental data that has not been used to find the estimated values. In our case, the step response motor data was used to find the estimated values therefore we used the sinusoidal experimental data to validate the estimated motor parameters.
5. If the estimated motor values correlate well with the validation data, then the values can be used in the deterministic model otherwise the above steps need to be repeated to find a feasible solution.

Figure 12 showcases Simulink’s Parameter Estimator App and results obtained with the training (step response) data and the validation (sinusoidal) data. An aspect that students often find inadvertently frustrating is that the estimating algorithm may fail to converge or yield an unreasonable solution if it is not provided with reasonable initial estimates for the motor parameters. Therefore, students need to exercise caution in offering realistic guesses, ensuring an understanding of reasonable values to prevent the optimizer from converging onto an impractical solution.

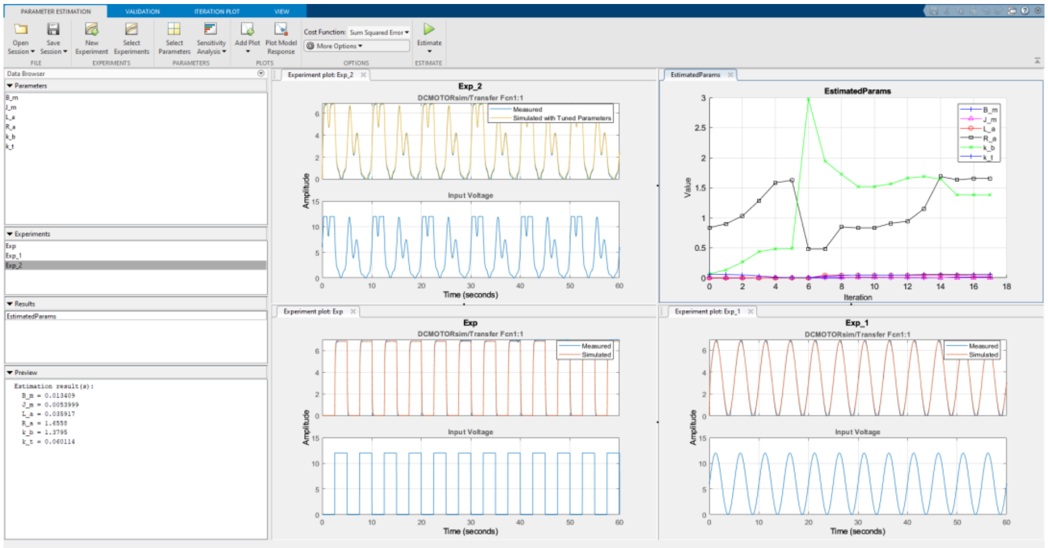


Figure 12. Simulink Design Optimization Parameter Estimator App used to estimate the motor parameters.

<u>Lab 6: Euler-Lagrange Formulation and Feedforward Control</u>

After estimating the motor parameters and developing a deterministic motor model, students were introduced to the application of the Euler-Lagrange Formulation for modeling the dynamics of the mechanism. In the development of the model, the links were treated as basic rectangular bars and frictional effects were omitted. This analysis was done to create a deterministic model of the dynamics to be used in the control of the mechanism. Furthermore, students were introduced to the use of feed-forward control to track time varying trajectories and reduce or minimize the effects of disturbances.

Hence, the key objectives for Lab 6 were for students to 1) utilize the derived Euler-Lagrange dynamics for the mechanism to obtain the inverse dynamics for the four-bar configuration of the mechanism that includes the motor and gearbox 2) implement a PID and feedforward control scheme to track a sinusoidal reference signal and compare its performance with a traditional PID implementation. For this particular lab students simulated the four-bar configuration of the mechanism and did not use the hardware due to time limitations and to reduce the risk of damaging the mechanism as students learn how to properly implement a feedforward control scheme.

Figure 13 demonstrates the feedforward and PID feedback control structure used. As can be seen both the inverse dynamics of the four-bar mechanism and the geared motor are part of the feedforward structure and are used to determine the feedforward motor voltage necessary to track the input while the PID controller is used to compensate for any errors and mitigate disturbances.

Through this lab experience, students gained insights into the value of employing deterministic models to enhance control performance and developed an appreciation for the integration of various components to form a cohesive and complete control system.

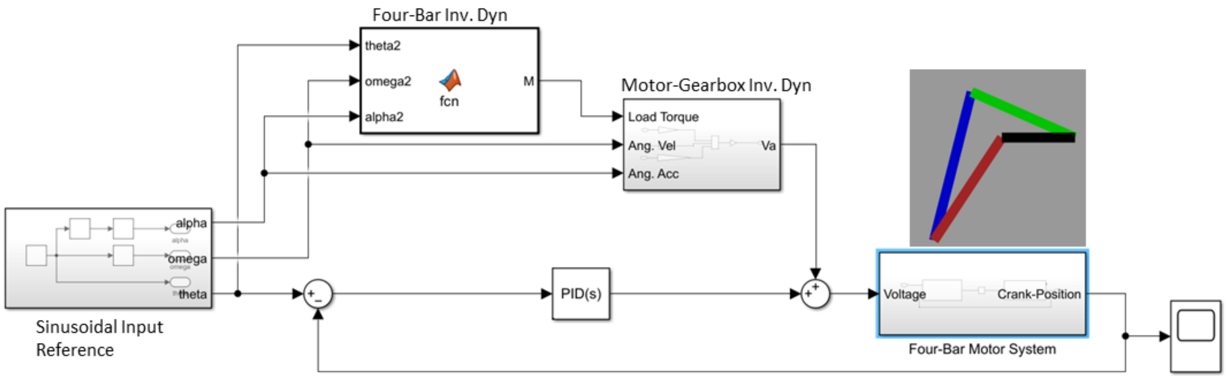


Figure 13. Simulink Design Optimization Parameter Estimator App used to estimate the motor parameters.

Final-Course Project – Space Exploration

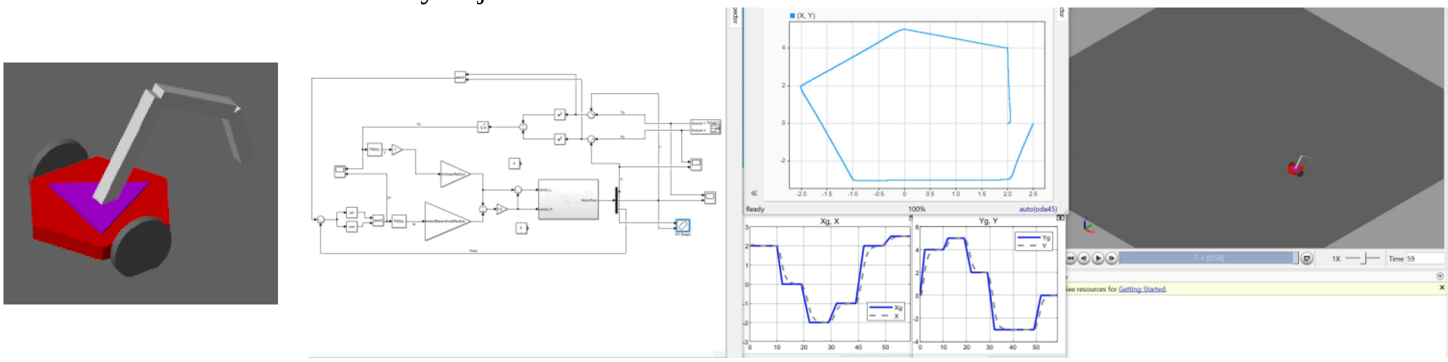
In preparation for the final project, students were given lectures on the kinematics of differential drive robots and provided with an introduction to image processing and computer vision. The fundamental topics covered encompassed the development of a differential drive kinematic model, the implementation of goal-to-goal behavior for a mobile robot, as well as key concepts in image representation, acquisition, filtering, and segmentation.

The primary objective of the final project was for students to creatively showcase their understanding of the course material by:

1. Developing a simulated multi-body differential drive platform capable of transporting a mockup four-bar space mechanism, and demonstrating Goal-to-Goal behavior to reach various locations.
2. Utilizing the space mechanism hardware for sorting, picking, and placing objects.
3. Employing a webcam and image processing techniques for acquiring images and determining object properties and features.
4. Collaboratively determining the application for space exploration as a team.

The project was to be completed in teams of two or three. The project allowed students to integrate the various aspects they learned, collaborate with their classmates, overcome challenges associated with system integration, and come up with creative solutions to develop a mobile robot for space exploration.

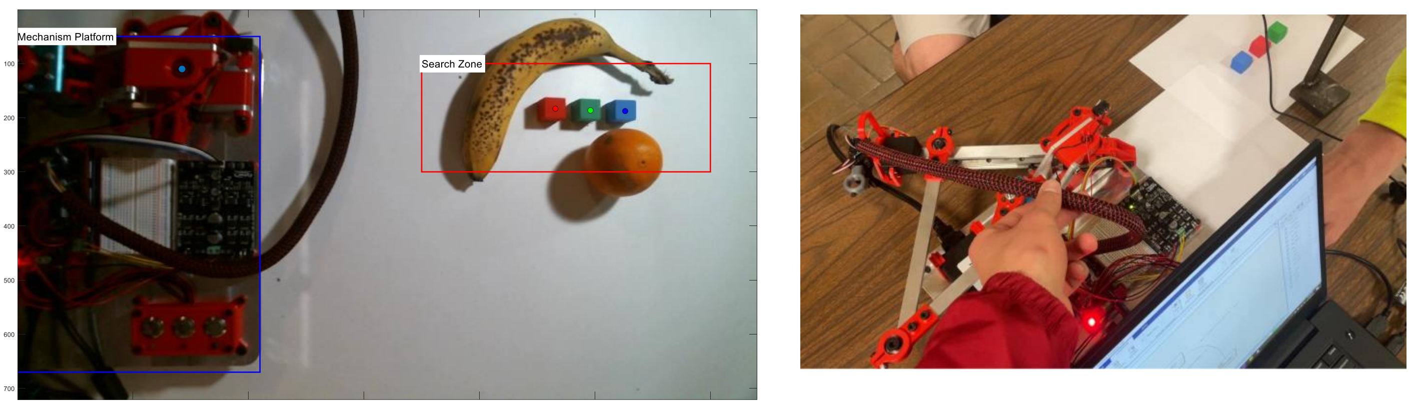
Figures 14 and 15 showcase student’s implementation of the final project. In Figure 14a the multi-body space exploration rover can be seen. The rover can move on the xy-plane and rotate about the z-axis. Additionally, the left and right wheel spin and are used to steer the space rover. The arm on the rover is not functional and is only used to depict the actual hardware arm that will be used for sorting and placing objects. On the other hand, Figure 14b shows the Simulink modeling done to implement the mobile kinematics**,** shows the path the rover followed and how well it tracked the x and y trajectories.



(a) (b)

Figure 14. a) Simscape multi-body model of space rover and arm b) Implementation of mobile kinematics and rover tracking performance as it moves to the various locations

Figure 15a shows the image captured and utilized to identify the location of the objects (cubes) to be sorted using image processing techniques. In Figure 15b, the mechanism arm is shown preparing to the determined object locations.



(a) (b)

Figure 15. a) Visual system capturing and identifying object locations b) Space mechanism moving to object locations

Overall, the project was a success with students working together to accomplish what at first seemed a complex and monumental task. Students worked well together and after this experience could envision some of the necessary steps that would be required to implement in practice.

Faculty Observations

There were only eight students enrolled in the initial offering of the new course, and therefore we are basing our initial evaluation of the course on faculty observations made during the course. Future offerings of the course will include higher enrollment and a more detailed survey to assess particular desired outcomes. All students taking the course were senior level students, and all students successfully completed the course. Faculty observations from the course were encouraging. Students reported strong satisfaction and value with the labs, projects, and homework developed. Students were impressed with the delivery of the class for a first time offering. One particular student mentioned they had enrolled in the class due to scheduling necessity and reported that they were glad they had to take the course since they learned a ton and loved working with Simulink. Another student mentioned that they finally understood what is meant by a PID controller and how it works. Students were also particularly excited about both the midterm project and the final project as these projects pulled all of the concepts together nicely. Through informal discussions with students, it was clear from a faculty perspective that students had a much better understanding of how the fundamental mathematics connects to the physical hardware implementation. Based on the positive anecdotal results from the pilot offering, we anticipate offering future versions of the course to obtain more formal feedback.

Conclusion

This paper describes the course structure and the unique hands-on learning experiences that students were immersed in and served to engage and motivate students learning. The course focused on the mathematical modeling, simulation, and control of an innovative, planar pick and place mechanism that can change its topology within its workspace to provide an enriching educational experience for students. From this pedagogical experience students saw the direct application of the lessons learned in the classroom with real-world simulation and control of a reconfigurable space mechanism. Additionally, students were exposed to research results obtained relating to the development of the space mechanism platform and gained a holistic view on how to use model-based design for the realization of the control of the space mechanism. In the future, the course will be transitioned from a 10-week course to 15-week course as Milwaukee School of Engineering has transitioned to a semester curriculum. This will provide opportunities to expand and improve course content with the ultimate goal of providing exceptional and valuable educational experiences for our students.

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