DEPARTMENT OF MECHANICAL & MATERIALS ENGINEERING

MECH 447
MECHANICAL DESIGN II

MODERNIZATION OF SCORBOT-ER VII ROBOTIC ARM

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Executive Summary

The College of Engineering at the University of Nebraska - Lincoln has recently purchased a Scorbot ER-VII robotic arm. This manipulator, first manufactured in the mid-1980s, utilizes a controller and a teach pendant that can be used to execute simple commands. However, one significant drawback of this controller is its size. At the time of production, the available technologies constrained the manufacturer to build a controller that is over 1992 cubic inches in volume and weighs nearly 42 pounds. Hence, in fulfillment of the senior design project, our team was tasked with creating a new controller module using modern-day electrical components to increase the transportability of the system while also creating a unique educational tool that can be used by future students to learn the fundamentals of robotics. The approved deliverables for redesigning the controller module, along with the accompanying user interface were as follows:

- Case Design:
  - Compact, enclosed case for all controller components
  - 50% reduction in size and weight
    - Final volume under 996 Cu. In.
    - Final weight less than 21 lbs
  - Ability to support a 10lb static load
- Minimum Power Requirements:
  - Provide at least 12 volts at 2 amps per motor
- Command Execution:
  - Software developed in C++
  - Process encoder signals from each motor
  - Allow command line inputs
- Functionality:
  - Maintain full range of motion outlined in Scorbot VII user manual
  - Operate the arm with a maximum payload of 4.4 lbs
  - Manipulate the robot by rotating each motor individually

The above project was accomplished in a span of 15 weeks. During this period, the design team held weekly meetings throughout the semester with professor Palik and sponsor of this project, Dr. Nelson, to provide updates on the schedule, budget, and progress made. At the end of this period, the aforementioned deliverables were met. A compact case with a volume of 154 cubic inches and an overall weight of 0.89 pounds capable of supporting 10 pounds of the external load was 3D printed. The prototype's cost was $287.84, with a custom-designed PCB taking $67.00 of the expenses. Moreover, sufficient power was successfully provided to operate the motors. Command execution and functionality deliverables were also successfully achieved. The following report details the approach is taken to accomplish the above tasks with justifications as to the decisions made for each phase.

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Background

The advancement of robotics technologies over recent years has redefined what humans and machines are capable of achieving together. Over time, researchers and enthusiasts alike have worked on numerous aspects of this field to bring incredible ideas into life. One of the many branches within the domain of robotics is the use of robotic manipulators. Although first used as a means to handle dangerous tasks, manipulators have found their way into different sectors of industry and academics.

Recently, the College of Engineering at the University of Nebraska - Lincoln purchased a Scorbot ER-VII robotic arm to educate students about the fundamentals of robotics. This robotic arm and the accompanying controller are shown in Figures 1 and 2 respectively. The detailed specifications of this manipulator are outlined in Figure A.1 located in the appendix. Sponsored by Dr. Carl Nelson, professor of Mechanical Engineering, there was little known about the functionality of the robotic arm. Therefore, in fulfillment of the senior project for Mechanical Design II class, a team of mechanical engineering students was tasked to explore this issue.

Upon initial investigations, the senior design team was able to successfully operate the robotic arm and ensure it was in working order. Since the robotic arm performed as expected, following further discussions with the sponsor, it was decided to explore the redesigning of the controller for the robotic arm due to the fact that its many components are outdated and the case is large and quite heavy.

Figure 1. Scorbot ER-VII

Figure 2. Robotic arm controller

Problem Statement

Due to the available technologies in the mid-1980s, the Scorbot ER-VII Robotic Arm has a controller with a volume of over 1992 cubic inches and weighs approximately 42 pounds [1]. Moreover, the interface of this controller is outdated and does not use the programming languages that are common today. The senior design team was tasked to redesign and build a new controller module using modern-day electrical components and programming languages while maintaining the functionality of the entire system. It was the sponsor's ultimate goal to increase the portability of this system that is to be used as an educational tool by future students to learn the fundamentals of robotics.

Project Deliverables

Following further discussions with the advisor and sponsor of the project, a list of project deliverables were defined. The deliverables had to abide by engineering projects' requirements where they needed to be SMART (Specific, Measurable, Achievable, Relevant, Time Bound). Therefore to accomplish the redesign of the controller, four main deliverables based on these criterias were defined. The approved deliverables for redesigning the controller module, along with the accompanying user interface were as follows:

- Case Design
    - Compact, enclosed case for all controller components
    - 50% reduction in size and weight
        - Final volume under 996 Cu. In.
        - Final weight less than 21 lbs
    - Ability to support a 10 lb static load
- Minimum Power Requirements
    - Provide at least 12 volts at 2 amps per motor
- Command Execution
    - Software developed in C++
    - Process encoder signals from each motor
    - Allow command line inputs
- Functionality
    - Maintain full range of motion outlined in Scorbot VII user manual
    - Operate the arm with a maximum payload of 4.4 lbs
    - Manipulate the robot by rotating each motor individually

With regards to case design, the goal was to design a system bearing only the essential components. Hence, enabling it to be as compact as possible. Moreover, as a measuring criteria, we wanted to achieve a 50% reduction in both size and weight of the controller compared to the original design while also being able to withstand 10 pounds of external load. With Regards to the minimum power requirements, since the joints are run by 12V DC servo motors we wanted to supply a power of 12V at 2 amps per motor. For the command execution task, the team decided to write the programming language in C++ as this language is easy to understand and commonly used in many commercially available microcontrollers. Since each motor was equipped with an encoder, we also decided to process the encoder signals to obtain the whereabouts of each joint. To provide the ability for future users to easily program the arm, we also decided to implement command line inputs where they can execute simple commands. Lastly, as for the final deliverable, in order to be sure that the system has retained the full functionality as stated in the user manual of the robotic arm, we operate and examine each motor individuality and with a maximum payload of 4.4 pounds.

Project Timeline

Figure 3 shows the project timeline. The project was split into three primary phases; design, build, and testing. The design phase occupied the bulk of the schedule, as the team chose to focus their efforts on drafting a successful proof of concept before ordering a PCB and components that would eat through a considerable portion of the budget. The final several weeks of the design phase were spent creating final designs for the PCB and case before a final order was placed. The build phase took place over the final eight weeks of the project and culminated in the final testing phase. Several weeks were allocated for the build phase to allow for parts to be reordered should they become damaged or lost during assembly, the extra time also allowed the team to make small modifications to the design while troubleshooting assembly issues. The final testing stage was brief, lasting two weeks. This time was spent finalizing a test procedure followed by the final testing of the arm. Figure A.2 outlines the project schedule with specific subtasks related to each primary task.

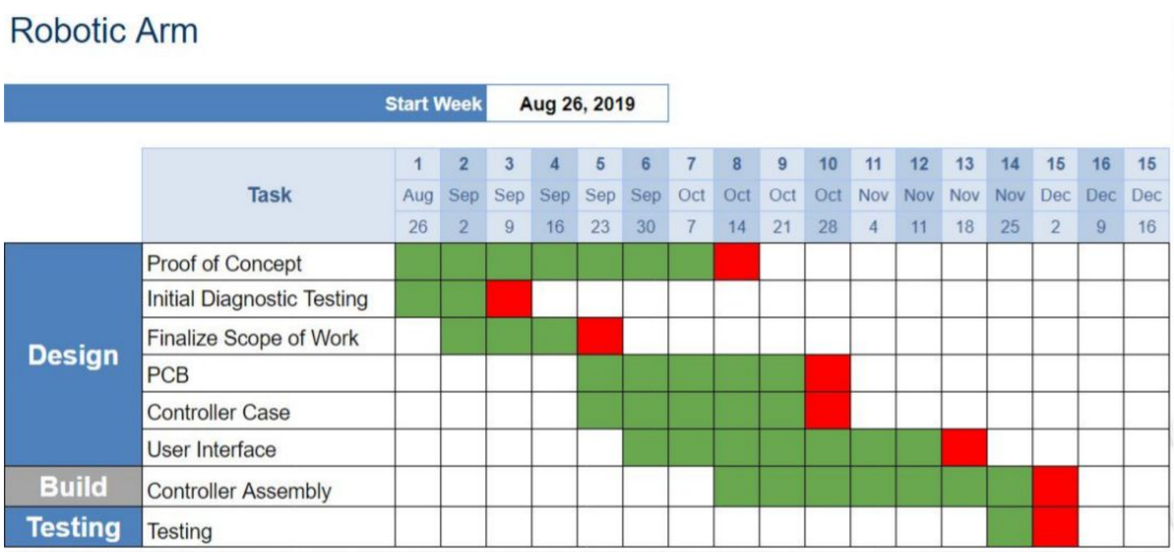

Figure 3. Project timeline

Design Constraints

The design of the controller focused on several key design constraints. These constraints were broken up into two categories: Controller constraints and Case constraints. Controller constraints were design constraints that primarily applied to the inner electronics of the controller, while case constraints applied to the requirements required of the case. The controller design was primarily driven by the complexity of the electronic components involved. To maintain an acceptable timeline, several steps were taken to ensure the simplicity of the device, the first being the selection of the microcontroller. The microcontroller selected was based on the Arduino system architecture, allowing the team to program the microcontroller quickly and with a little additional programming background. The second constraint considered was a power delivery method. The team considered using relays as a pure power delivery solution as well as DC servo drivers for more precise power delivery. The third and final constraint considered was the overall size of the components. To maintain a small package, a printed circuit board was designed and ordered, featuring as many components as possible.

The primary goal of the case was to achieve the maximum possible reduction in size. The first design constraint considered was the power requirement of the arm. Through tedious testing, it was determined a minimum of five volts at two amps was required at each motor to achieve the desired operating characteristics. The next design constraint was the number of ports required to operate all six motors, provide a power connection, and to allow for connection to a PC. The motors use nine pin d-sub (DB9) connectors to interface with the controller. The ports required to drive the overall size for the case, as their needs to be sufficient space for all required connections to be made without interfering with one another.

Design Options

With regards to the design options, the design team brainstormed two main scenarios. One being the small box as shown in figure 4, and the other being the robotic arm base as depicted in figure 5. Although the robotic arm base provides the ability to move the manipulator around easier, its size is quite large, and it would add more weight to a robotic arm that is already overweight. Furthermore, with the time at hand, it would require more time to test and analyze this base to ensure it can withstand the stress expressed by the robotic arm, hence with the high complexity of the design and requiring additional cost to manufacture, this option was not very favored in the group. On the other hand, acknowledging that the arm is to be used in an academic setting where it does not require to be moved regularly, having a small box to obtain all the required components to run it was a more feasible option. This design not only has a small size, it does not weigh much, and the simplicity in its design would reduce the cost of material as well as the manufacturing time.

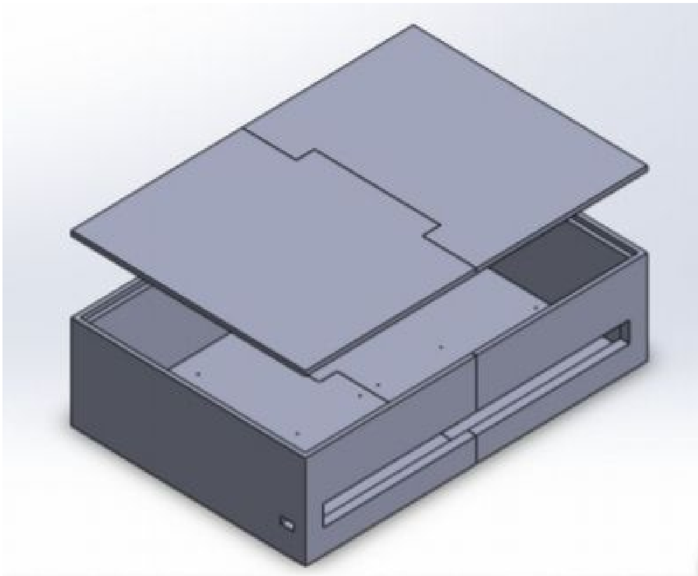

Figure 4: Small Box

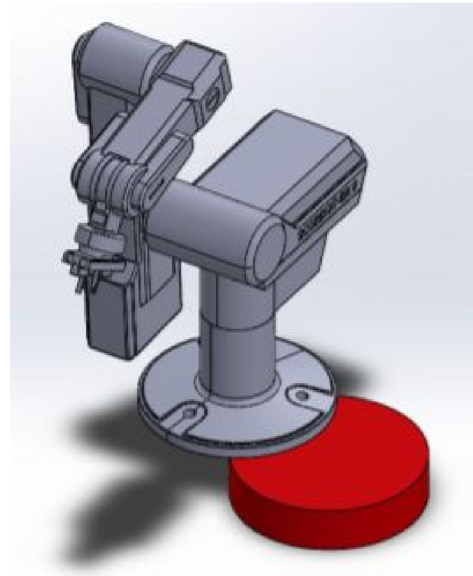

Figure 5: Robot Stand

Decision Matrix

The controller decision matrix shown in table 1 was built around four key criteria; complexity, precision, cost, and manufacturability. Complexity refers to the level of understanding required to properly install and use the electrical components. Precision is the device's ability to accurately manipulate the arm based on the commands given through the console. Manufacturability describes the level of difficulty associated with assembling the required components.

Table 2 shows the decision matrix for the case design. Four separate categories were used to analyze the case design options, the first being size. Size refers to the volume occupied by the case, with a better score going to the case with the largest reduction in size. The second criteria were weight. Along with volume reduction, minimizing weight was a key focal point of this project. The third criteria used was the structural complexity. A more sophisticated design (as would be required to support high loads) would increase both the overall cost and weight of the case. Lastly, the cost of the material was considered. The above options were examined against each other on a one to five scales, one being the worst and five being the best score. The results are shown below.

Table 1. Controller decision matrix

Controller Decision Matrix	Motor Driver Based Controller	Relay Based Controller
Complexity	4	3
Precision	5	3
Cost	3	2
Manufacturability	4	4
Total	**16**	12

Table 2. Case design decision matrix

Case Decision Matrix	Robotic Arm Base	Small Box
Size	2	5
Weight	1	5
Structural Design Complexity	2	3
Cost of Material	2	5
Total	7	**18**

Final Design

The decision matrix outlined above demonstrated that the motor driver based controller paired with the small box would make the best overall controller. The controller was built around a PCB of the team's own design, maximizing the size reduction of the controller. The PCB contains all components necessary for the functionality of the device, with the exception of the two 12 volt power supplies, which are mounted in the case but not connected to the PCB. This PCB is a two-layer board which means that their copper traces can be placed either at the top of the board or on the bottom. Figure A.3. shows a render of the custom designed PCB. In this design, the bottom of the board was reserved as a ground plane which was used as a heat sink for the motor drivers which can produce a lot of heat. This required that traces on the bottom of the board be as short as possible.

Since the purpose of this project was to reduce the footprint of the controller, the PCB board needed to be as small as possible. This also factored into the price of the PCB as they are priced based on the total area of the board. This also meant that the layout of all the electrical components on the board had to be placed within a confined space. This was especially true as some components required large traces due to their respective current requirements.

Six servo motor drivers were purchased during the initial prototyping phase. The components from these drivers were repurposed and used on the PCB to reduce cost and take advantage of components that were known to function properly. To accommodate the drivers, logic level converters were installed to allow rapid translation of signals from the arm to logic signals sent to the microcontroller. The final assembled PCB is shown in figure 6. The PCB features separate 3.3, 5, and 12-volt power rails to safely deliver different voltages to components as necessary. This was accomplished by installing voltage regulators to reduce the 12-volt input voltage to 3.3 volts and 5 volts.

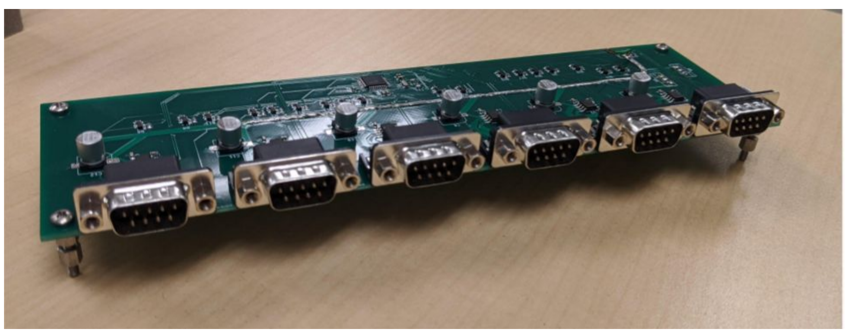

Figure 6. Custom designed PCB

It was determined that by running simple Arduino commands, the robot has indeed maintained its full motion functionality as described in the ER-VII user manual. The primary advantage associated with the Arduino architecture was its modularity and familiarity. The system is based on C++, an incredibly common language. This commonality made the task of troubleshooting code blocks much simpler as they were a plethora of resources to help fight through problems. The Arduino based microcontroller also allows future groups to improve upon the software and upgrade the firmware as they see fit. As the project currently stands, the team has several simple commands that can be loaded onto the controller for basic arm movements. The commands focus on moving one joint at a time, something that can be greatly expanded upon by future groups. The code can be uploaded to the controller via a micro-USB port on the controller.

A render of the case can be seen in Figure A.4. To reduce cost and production time, the team decided to print the box using an FDM 3D printer. The case features one large rectangular I/O slot to accommodate all six motor connections and provide room for slightly oversized connectors should they be used in the future. The case was broken into four pieces for final printing. This was due to the limitations of the 3D printer used. The pieces were then “welded” by melting the seams together using a soldering iron. Metal standoffs were melted into the bottom of the case to provide mounting points for the PCB and power supplies. Figure 7 shows the final 3D printed case with the mounted components next to the original controller for scale comparison. The drawing file for the case and the wiring schematic for PCB are also provided and shown in Figure A.5. and Figure A.6. respectively. the The case comfortably held a load of 15 pounds, 50% more than the minimum load outlined in the deliverables section. A final volume and weight of 154 cubic inches and 0.89 pounds, respectively, were achieved. This constitutes a 92% reduction in volume and a 98% reduction in total weight.

Figure 7. 3D printed case

The final cost of materials for the project was $287.84. An itemized bill of material is included in Figure A.7. The majority of the budget was put towards the PCB and power supplies. The PCB was sourced from a Chinese manufacturing company which led to a relatively high shipping cost. The power supplies were purchased from a large U.S. based component supplier but were still expensive due to their large voltage and current capacities, and medical-grade listing. Combined, these components accounted for over 40% of our total cost.

Test Procedure

The final test procedure is outlined in Appendix B. The tests focus on measuring the project's compliance with the deliverables outlined previously. The primary functions tested were the Female to Female connectors used, several aspects of the PCB functionality, and the physical design features of the case. The female to female connectors modified by the team operated properly. A null resistance reading was measured across the pins and the arm operated properly while using them. The PCB returned the expected voltages during the voltage tests, drove the arm properly, and read values from the encoders. The box was within the size and weight ranges and held 15 pounds. To summarize, all tests outlined in the Final Test Procedure were passed.

Project Status and Future Improvements

The robotic arm controller is operational and meets nearly ever deliverable outlined above. The only deliverable the team was unable to meet was that of power requirements. The goal was to deliver 12 volts at 2 amps to each motor simultaneously and while the team provided two power supplies to accomplish this they did not feel comfortable or confident in their ability to safely install them without damaging the power supplies, controller, or shocking themselves. It is intended a future group of students install the power supplies to meet the power demands of the arm. It is recommended a quick disconnect switch be installed at this time as well to provide the user the ability to rapidly disconnect power from the controller and arm.

The PCB was mistakenly installed with male DB-9 connectors instead of female connectors. This was remedied by modifying six female to female gender-changing adapters to allow the direct pass-through of electrical signals. It is recommended that a future team replace the male connectors with females to ensure the longevity of the device. Lastly, the Arduino code used to operate the robot stands at a rudimentary level. It gives the user the ability to send the arm commands by calling a set of predefined functions based on inputs such as motor speed and run time. The current software running on the controller only allows for a single axis to be moved at a time. A future team has the ability to refine the commands and generate a more user-friendly interface.

It is important to include a final safety note with the updated controller and arm. The original controller included safety measures to help prevent the arm from crashing into itself or its environment. While the updated preserves some of these features, namely the axis limit switches, no other safety features are included with the robot at this time. The team has included the following safety recommendations to help limit possible issues while operating the arm.

- Place the robot on a sturdy, elevated surface such as a workbench
- Do not leave the arm to operate unattended
- Maintain a 1 meter distance from the arm while the arm is in operation
- Disconnect the controller power source before working on the arm or controller
- Do not operate more than four joints simultaneously
    - While it is theoretically possible to operate all joints simultaneously it can be taxing on the PCB and electrical components due to the high current demand
- Be prepared to quickly disconnect the power source in case of a crash

With these safety considerations in mind, the team feels this robotic arm and controller, tenderly named “Scooter”, would prove a valuable classroom tool for a wide range of ages.

References

1. Esched Robotec. (1998). Scorbot ER-VII: User Manual. Rosh Ha'Ayin, Israel: Author

Appendix A

SCORBOT-ER VII Specifications	
Mechanical Structure	Vertical articulated
Number of Axes	5 axes plus gripper
Axis Movement Axis 1: Base rotation Axis 2: Shoulder rotation Axis 3: Elbow rotation Axis 4: Wrist pitch Axis 5: Wrist roll	 250°; 310° user programmable 170° 225° 180° 360°
Maximum Operating Radius	690 (27.2") at flange
End Effector options	Pneumatic and DCServo
Hard Home	Fixed position on each axis, found by means of microswitches
Feedback	Optical incremental encoder on each axis; 96-slot disk
Actuators	12VDC servo motors
Transmission	Harmonic drives; timing belts and pulleys
Maximum Payload	2 kg (4.4 lb.), including gripper
Position Repeatability	±0.2 mm (0.008")
Weight	30 kg (66 lbs)
Maximum Path Velocity	1000 mm/sec (39.4"/sec)
Ambient Operating Temperature	2°–40°C (36°–104°F)

Figure A.1: Specifications of Scorbot ER-VII

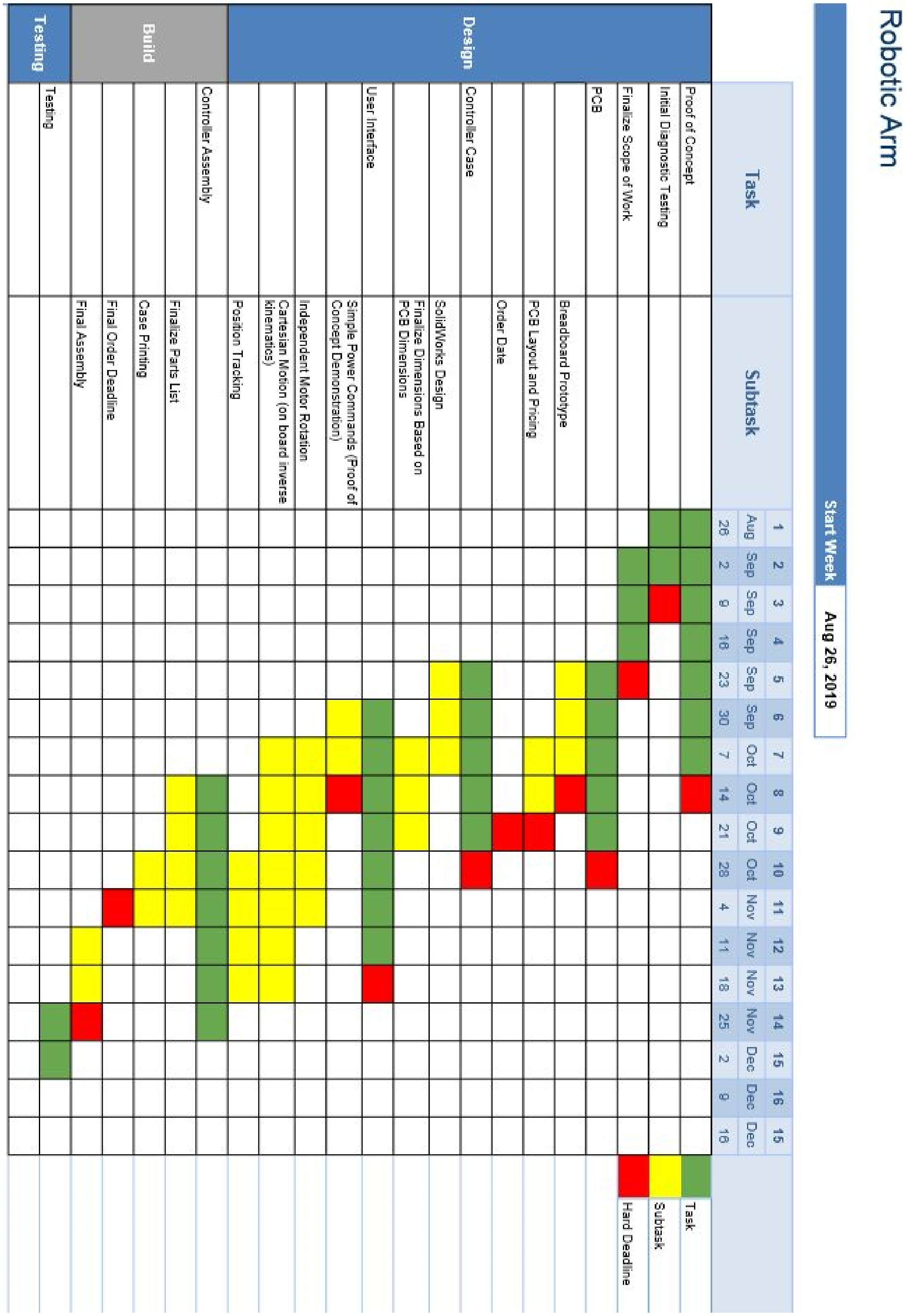

Figure A.2: Detailed Project Schedule

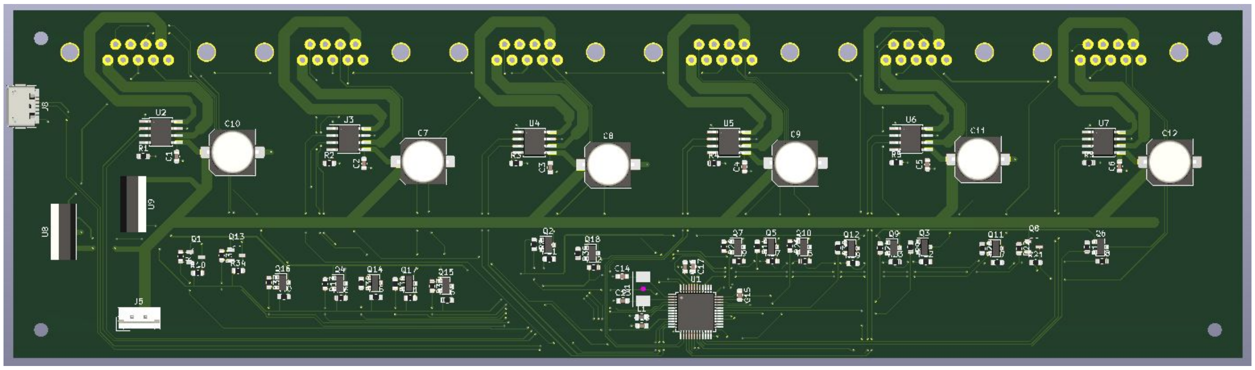

Figure A.3: PCB Render

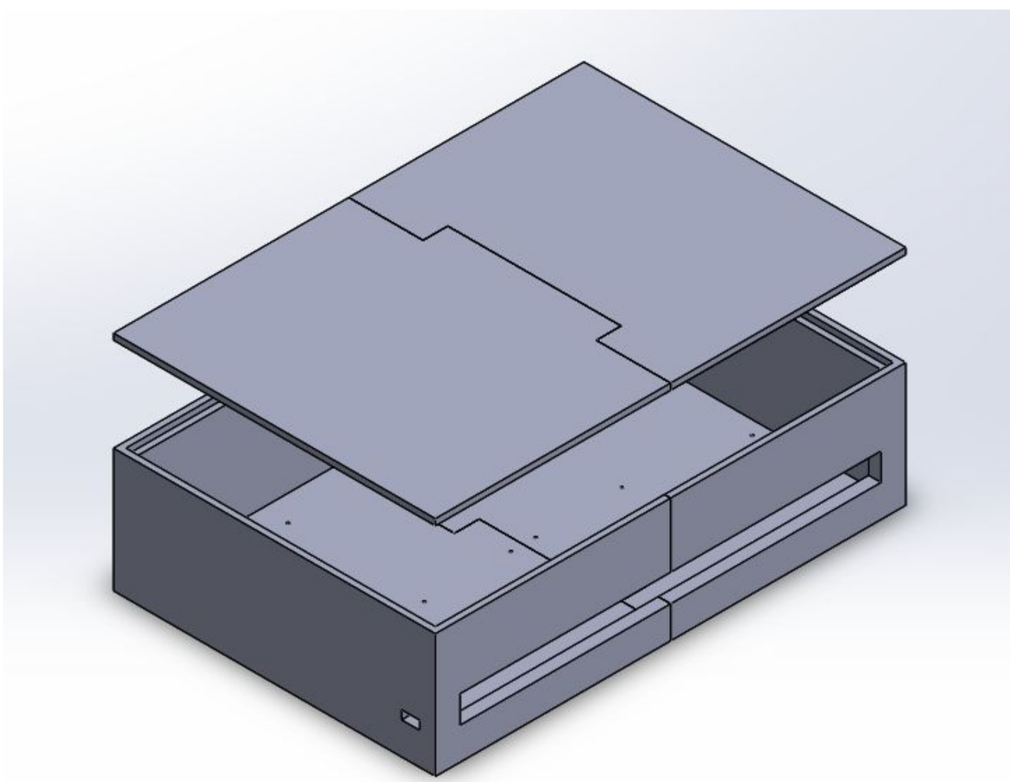

Figure A.4: Case Assembly

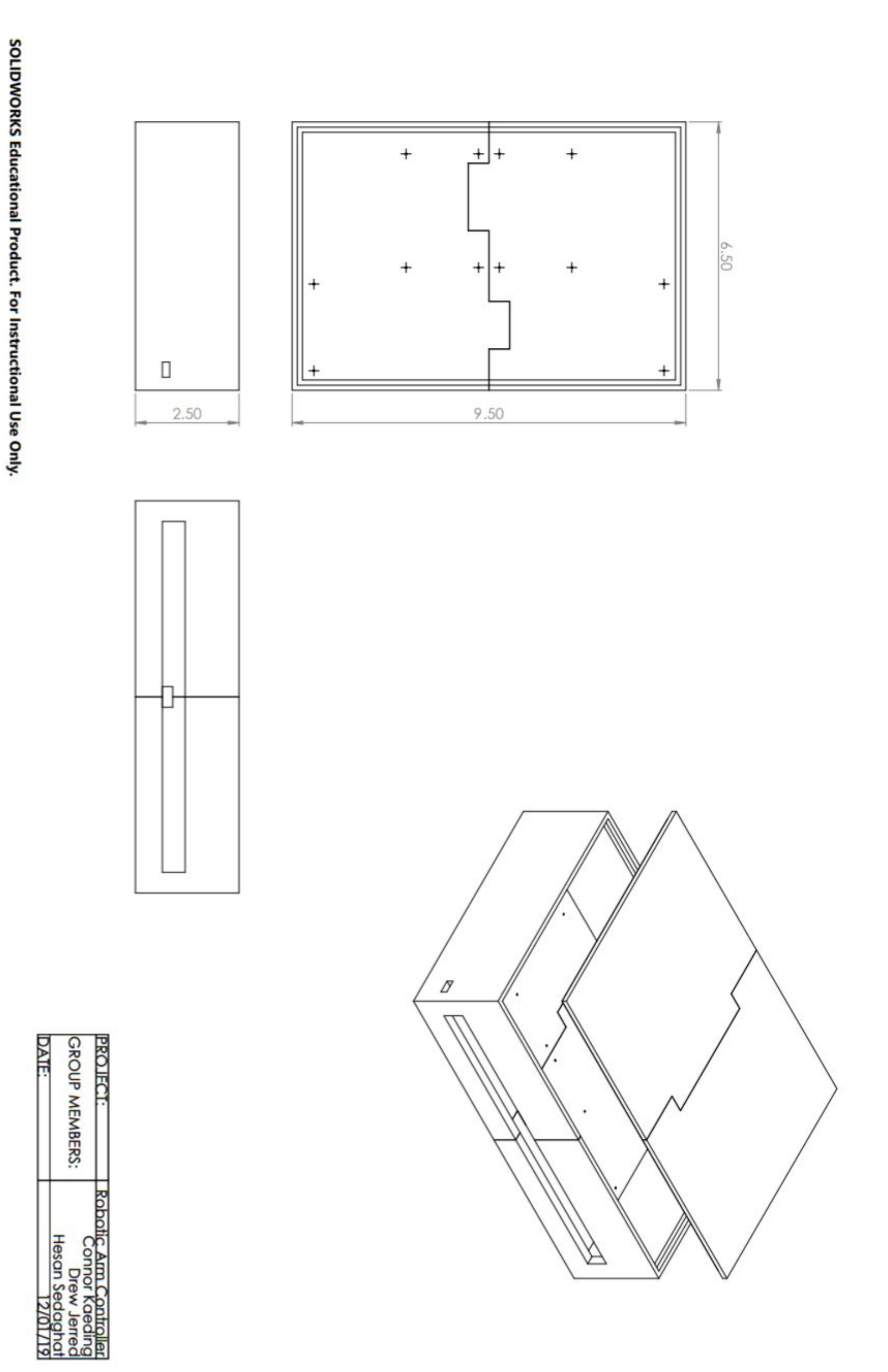

Figure A.5: Dimensioned Case Assembly

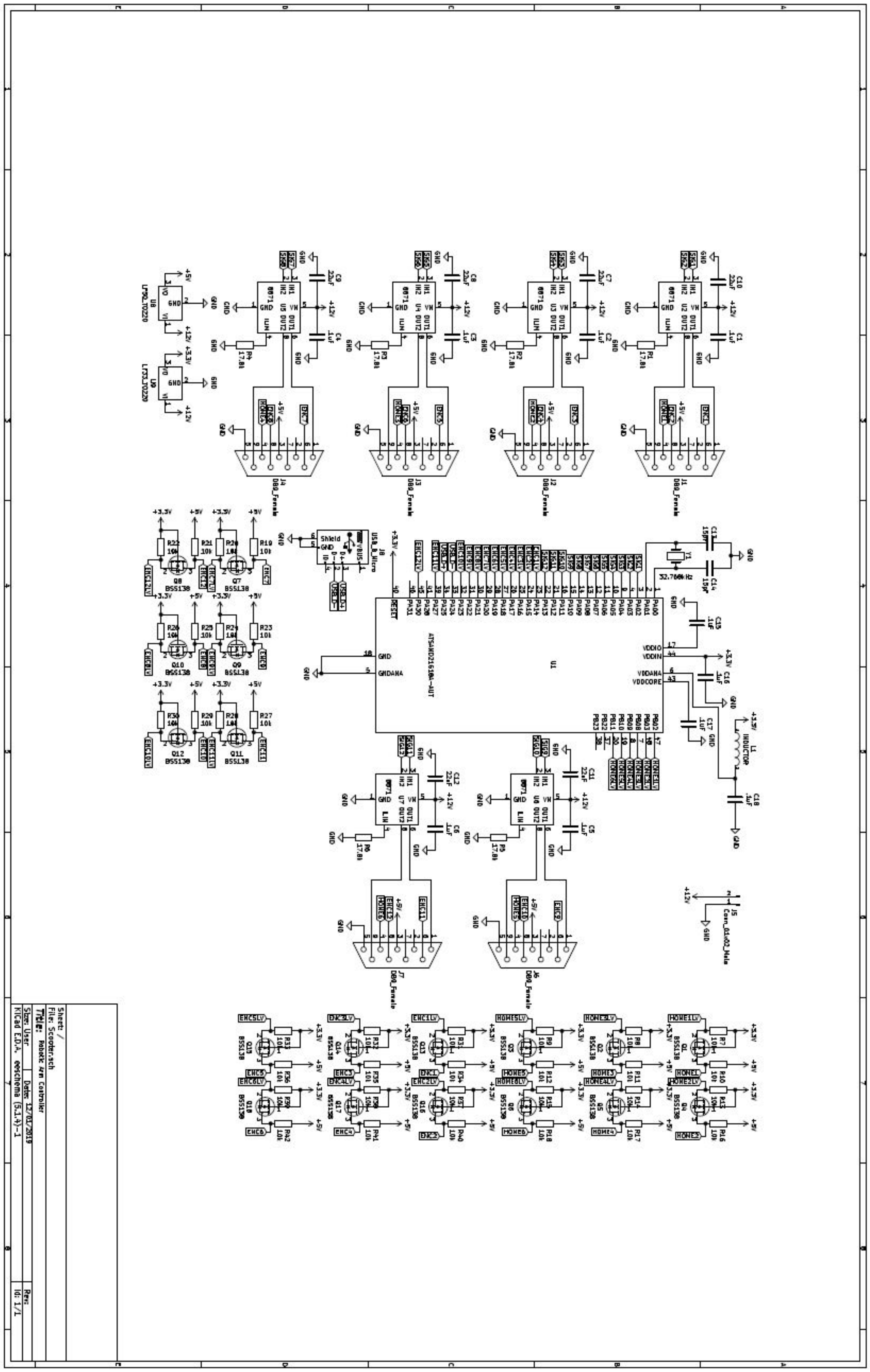

Figure A.6: PCB Wiring Schematic

	Mfr. #	Manufacturer	Description	Order Qty.	Price (USD)	Ext.: (USD)
Phase I	RPS-120S-12	MEAN WELL	Switching Power Supplies 114W 12V 9.5A 2x3 Medical	2	$32.63	$65.26
	RZ01-1C4-D012	TE Connectivity	General Purpose Relays 1 Form C 12 V 12 A	2	$1.90	$3.80
	3190	Adafruit	Power Management IC Development Tools DRV8871 DC Motor Driver BOB	6	$7.50	$45.00
					Sub Total:	**$114.06**
Phase II	ID09S33E4GV00LF	Amphenol	D-Sub Standard Connectors Filter Connector, 9pin, Socket	6	$1.11	$6.66
		Custom	Controller Case (3D printed)	1	$50.00	$50.00
		Mouser	Miscellaneous Electrical Components	1	$14.36	$14.36
		PCB Way	PCB (with Shipping)	1	$67.00	$67.00
		L-Com	Female-Female D-Sub Connectors	6	$5.96	$35.76
					Sub Total:	**$173.78**
					Total:	**$287.84**

Figure A.7: Bill of Material

Appendix B

Final Test Procedure

1. Female to Female Connectors
    a. Measure resistance through the Female to Female connectors
        i. A multimeter was used to ensure proper connections were made
        ii. A resistance of 0 should be measured between corresponding pins
    b. Driving the arm using the Female to Female connectors
        i. Connect a desktop power supply to the arm
        ii. The arm should move, ensuring proper connections were made
2. Printed Circuit Board (PCB)
    a. Voltage tests
        i. Apply a constant 12 volt source to the PCB
        ii. Measure the voltage across the connectors
        iii. If proper voltages are measured the board should be operating properly
    b. Driving the Arm
        i. Plug one of arm's motors into the PCB
        ii. Apply a constant 12 volt source to the PCB
        iii. Upload an Arduino Sketch to send commands to the Arm
        iv. Observe the arm's motion
    c. Encoder values
        i. Connect one motor to the PCB
        ii. Run a serial monitor sketch
        iii. Manually rotate the motor that is connected to the PCB
        iv. Observe the voltage change and count the number of changes
3. Case
    a. Size and Weight
        i. Calculate the box volume using measurements from SolidWorks
        ii. Measure the total weight of the box using a small scale
    b. Strength
        i. Place a five pound weight on top of the box
        ii. Continue adding weight until the total reaches 15 pounds

Contributions

Drew

- PCB design
- Breadboard prototyping
- Researched electrical components
- Helped determined design requirements
- Assisted development of test procedures and project deadlines

Hessan

- Box design
- Maintained schedule
- Assisted Drew with the PCB design
- Assisted Connor with ordering parts
- Review the arduino code
- Helped test and evaluate Scorbot ER VII
- Write and review the report

Connor

- Project Manager
- Maintained schedule
- Determined project deadlines
- Assisted Drew and Hesan with the PCB and Case when needed
- Helped develop test procedure
- Helped test and evaluate Scorbot ER VII
- Scheduled group meeting times