

March 19, 2015

Dr. Andrew Rawicz  
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Re: ENSC 440 Design Specification for the Musical Rehabilitation Assistance System

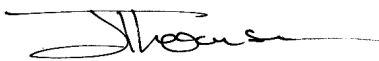
Dear Dr. Rawicz:

Find attached the Design Specification for the Musical Rehabilitation Assistance System (MRAS), our project for ENSC 440 - Capstone Engineering Science Project. The system is a wearable device designed to provide useful feedback for ambulatory rehabilitation patients. The project's purpose is to improve the experience of the rehabilitation process for the patient, as well as supplement the overseeing physiotherapist's involvement.

The following design specifications apply to the proof-of-concept model of the MRAS. Design stretch goals, specified in the functional specification document, are discussed but will not be implemented in this phase of development.

If the reader has any questions or comments, please feel free to contact Harmony Innovation by email at [harmonyinnovationPP@gmail.com](mailto:harmonyinnovationPP@gmail.com).

Sincerely,

A handwritten signature in black ink, appearing to read "J Thomson", with a long horizontal flourish extending to the right.

James Thomson  
Project Manager  
Harmony Innovation

ENCLOSED: Design Specification for the Musical Rehabilitation Assistance System

# Functional Specification for the Musical Rehabilitation Assistance System



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## ACKNOWLEDGMENTS

We are grateful to the following people for their contribution in the development of this project:

- Dr. Jaimie Borisoff, Principal Investigator at iCord, whose work with 6-axis motion-tracking devices connected to sensory feedback systems, along with his personal guidance, has helped immensely in our software development.
- Ian Denison, Physiotherapist at GF Strong Rehabilitation center, who provided significant support on the overall usefulness of MRAS device in the rehabilitation process. His professional insight shaped how MRAS can be improved in future design, specifically in the final production phase. His suggestions also influenced design features that will be in the POC model, and improved the scalability of the MRAS as it moves toward final production.

## EXECUTIVE SUMMARY

The design specification for the Musical Rehabilitation Assistive System (MRAS) provides a set of detailed descriptions for the design and development of the proof-of-concept (POC) model. Please know that these specifications apply to the POC only. Therefore, only requirements assigned “A” or “P” will pertain to this document, in accordance with the document *Functional Specification for the Musical Rehabilitation Assistive Device* [1].

This document presents the design plans for the MRAS and provides practical justification for Harmony Innovation’s design decisions. Design improvements for future iterations of MRAS will be discussed in this document and will here on out be referred to as stretch goals. Note that these goals will not be implemented in the POC.

The MRAS is physically implemented via the use of a wearable kit, a vest worn by the patient, containing the Electronics; sensors, microcontroller, Bluetooth wireless card and wiring. The Electronics will track the patient’s movement, and transmit that motion data to the Software.

On the Software side, the data will be analyzed, compared, and forwarded to the music player. This design will allow the music platform, which will be implemented using MIDI protocol, to provide the appropriate audio feedback based on the motion data from the sensors. The Software will employ an algorithm that allows the feedback to dynamically adjust based on the quality of the motion. Any control functions used by the therapist to set the mode of the MRAS will also be implemented in Software, as communication with the Electronics is two-way compatible.

In terms of resource requirements, justification for Electronics specifications of the MRAS will be provided. Software used to implement the algorithm will also be discussed and the high-level architecture for it will be shown.

Harmony Innovation deems their design process to be on schedule in accordance to the plans outlined in the *Functional Specification for the Musical Rehabilitation Assistive Device* [1].

## TABLE OF CONTENTS

Acknowledgments.....	ii
Executive Summary .....	iii
Table of Contents .....	iv
List of Figures .....	v
List of Tables.....	v
Glossary .....	vi
1. Introduction .....	1
1.1 Scope .....	1
1.2 Intended Audience .....	1
2. System Specifications.....	2
3. Overall System Design .....	3
3.1 General Requirements .....	3
4. Kit Design .....	4
4.1 Straps .....	5
4.2 Enclosure Placement .....	6
4.3 Kit Wiring .....	6
5 Electronics Design .....	7
6. Software Design.....	11
6.1 Analysis and Comparison Algorithm Design .....	11
6.2 Audio Feedback Design .....	11
7. System Test Plan.....	13
7.1 Electronics Testing.....	13
7.2 Kit Testing .....	13
7.3 Software Testing .....	13
7.4 System Testing.....	14
8. Conclusion .....	15
9. References.....	16
Appendix A: Kit Enclosure Mechanical Drawings .....	17

## LIST OF FIGURES

Figure 1: High level graphic model of the MRAS.....	2
Figure 2: High level architectural overview of the MRAS.....	3
Figure 3: Expanded view of the Controller .....	4
Figure 4: Expanded view of the MSU enclosure .....	5
Figure 5: Arm and leg strap placement .....	6
Figure 6: Signal flow diagram from the MSU to MIDI module.....	12
Figure 7: MRAS development plan with milestones.....	13
Figure 8: Schematic drawing of Controller enclosure bottom .....	17
Figure 9: Schematic drawing of Controller enclosure top .....	18
Figure 10: Schematic drawing of MSU enclosure bottom .....	18
Figure 11: Schematic drawing of MSU enclosure top .....	19

## LIST OF TABLES

Table 1: Electrical Interconnection Diagram for Bluetooth Module .....	7
Table 2: Functionalities of the MSU pins.....	8
Table 3: Electrical Interconnection Diagram for Sensor 1 .....	9
Table 4: Electrical Interconnection Diagram for Sensor 2.....	10
Table 5: Electrical Interconnection Diagram for Sensor 3.....	10
Table 6: Electrical Interconnection Diagram for Sensor 4.....	10

## GLOSSARY

<b>Ambulate</b>	To move from place to place, walk. Commonly used in the medical community. From the Latin root <i>ambulare</i> . [8]
<b>ANSI</b>	American National Standards Institute.
<b>AWG</b>	American Wire Gauge: a universal standard used to represent the gauge of an electrical conductor.
<b>CAT5</b>	Category 5 cable, which is widely used for telecommunications wiring, namely Ethernet.
<b>I2C</b>	A serial communication protocol for small electronics. I2C buses support one or more masters with many slaves.
<b>Controller</b>	Arduino microcontroller, Bluetooth plugin adapter, battery, status LEDs, switches, and its enclosure.
<b>CSA</b>	The Canadian Standards Association.
<b>Electronics</b>	All electronics in or attached to the MRAS. This includes the MSUs and the Controller.
<b>Kit</b>	All parts of the MRAS used to connect to the patient. This includes the vest, sensor straps, and housings for all electronics.
<b>LED</b>	Light-Emitting Diode: low power lights for status indication on the Controller.
<b>MIDI</b>	Musical Instrument Digital Interface: a technical standard that describes a protocol, digital interface and connectors and allows a wide variety of electronic musical instruments, computers and other related devices to connect and communicate with one another. [2]
<b>MRAS</b>	Musical Rehabilitation Assistance System.
<b>MSU</b>	Modular Sensor Unit: includes sensors, circuitry to connect to data and power ports, and the MSU input port.
<b>Patient</b>	A generic term used to identify the individual receiving therapy. The patient is between 150-200 cm (5'0"-6'6") tall.
<b>PC</b>	A personal computer running a Microsoft Windows operating system, with the necessary peripheral software to execute the Analytic Algorithm.
<b>POC</b>	Proof-of-concept. This is a stage of the design defined in the Functional Specification for the Musical Rehabilitation Assistive Device [1]

<b>Run State</b>	State of the Software during an active therapy session. In this state, the Software collects active data for comparison to baseline data and generates feedback.
<b>Software</b>	All programs needed to operate the MRAS. This includes the Analytic Algorithm software, the Controller firmware, the MIDI Controller and Sample Library.
<b>Spec/Speccking</b>	Referring to specifications of a particular component.
<b>Strap</b>	Fabric bands used to attach the MSU to the patient.
<b>Therapist</b>	A generic term used to identify the individual administering therapy. This may include physiotherapists, nurses, doctors, recreational therapists, rehabilitation therapists, or any similar medical professional.



## 1. INTRODUCTION

The Medical Rehabilitation Assistive System (MRAS) is a wearable device that will track and analyze a patient's ambulatory movements and provide useful audio feedback. The device is separated into three design areas: Electronics, Software, and Kit. The Kit, worn by the patient, houses the Electronics. Sensors contained within the Electronics will read the motion and transmit data to the Software, which will analyze the data and return feedback in the form of music. Harmony Innovation's goal is to enhance the ambulatory rehabilitation process for both the patient and the therapist. The MRAS will allow the patient to evaluate their performance when the therapist is not directly involved or when they are left on their own. This design specification describes the technical details for the design of the Electronics, Software and Kit.

### 1.1 Scope

This document specifies the design of the MRAS and coordinates with the functional requirements described in *Functional Specification for the Musical Rehabilitation Assistive Device* [1]. Included are all requirements for the POC system as well as a relevant set of requirements for future versions of the MRAS. Functional requirements designated either priority A or P apply to the POC and will be discussed in detail. Mechanical drawings for Kit components and high-level architectural flow diagrams for the design are included as appendices.

### 1.2 Intended Audience

The design specification is to be used by Harmony Innovation personnel. Engineers are advised to consult the document for reference to the design specifications and confirm that these requirements are included in the POC product. Testers are advised to refer to the document to ensure that the MRAS is functioning in accordance with design.

## 2. SYSTEM SPECIFICATIONS

Figure 1 shows the high level overview of the MRAS. The MRAS will operate in a Run State during the patient’s therapy. MSUs will send data to the Controller, which will in turn transmit the data via Bluetooth to be read by the Software in real time, and provide appropriate audio feedback. The therapist will enable this Run State in the Software after inputting the appropriate patient information. The POC design will contain one set of information for our model patient, while a production product would contain a database of different presets for patients of various physical characteristics.

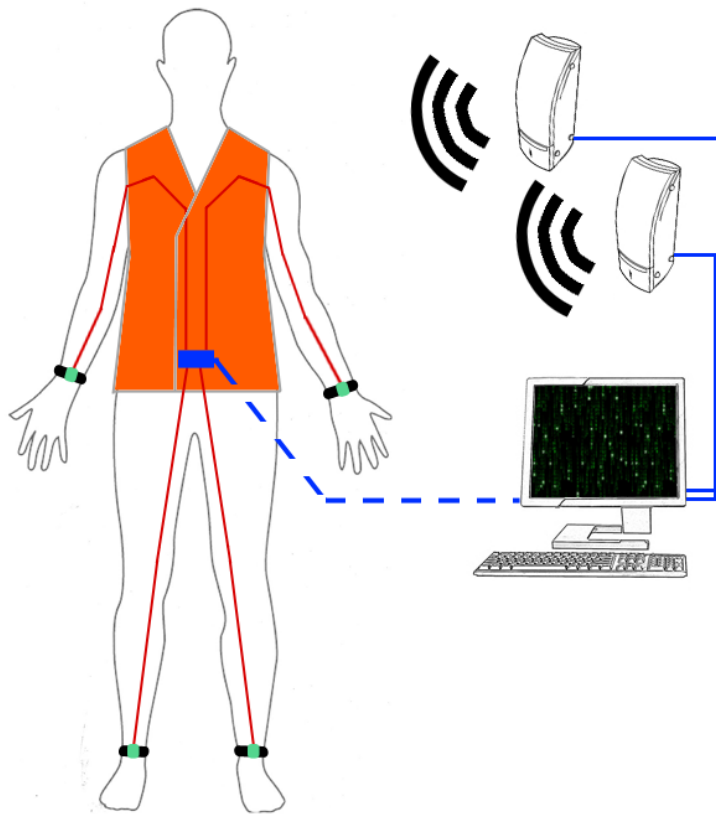


Figure 1: High level graphic model of the MRAS

### 3. OVERALL SYSTEM DESIGN

A high-level overview for the overall design of the MRAS will be discussed here. System design for each area of the MRAS will be covered in their respective section.

#### 3.1 General Requirements

Figure 2 below shows a general overview how the entire system implemented in MRAS is designed. This will provide an organized and simplified reference as to what is involved in each area's design. Furthermore, it provides information about which areas components of the MRAS are placed in. Full detail is provided in its respective section of the document.

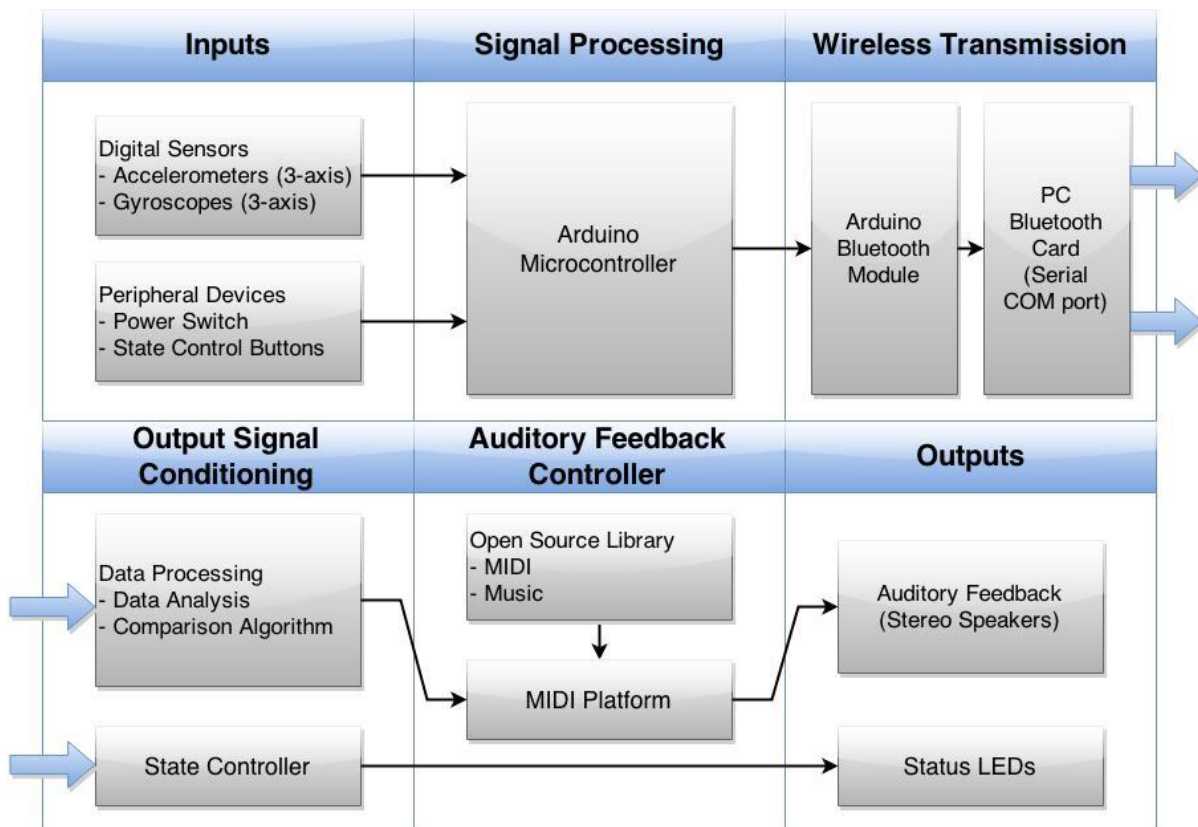


Figure 2: High level architectural overview of the MRAS

## 4. KIT DESIGN

Figure 1 includes the proposed mechanical design for the MRAS. The mechanical components of the MRAS are entirely implemented in the design of the Kit. The Kit consists of a standard wearable, lightweight vest with designed modifications to include the Electronics of the system. That is, proper extensions to the chest have been designed to place the sensors on the limbs of the patient.

Figure 3 shows an expanded view of the Controller. The Controller enclosure is additively manufactured from ABS plastic. It houses the microcontroller, CAT5 connectors, Bluetooth wireless card and 9V battery. It has access ports for USB, AC adaptor and five MSUs by CAT5 connection. See Appendix A for schematic drawings of the enclosure.

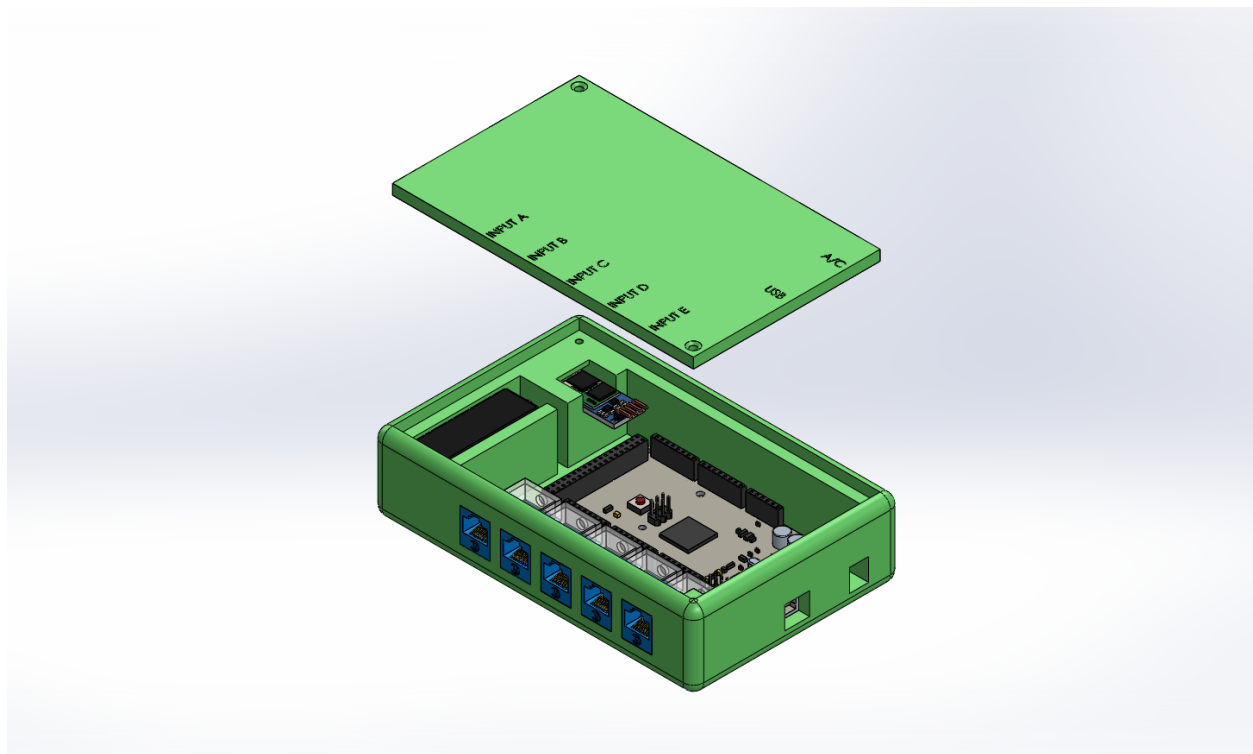


Figure 3: Expanded view of the Controller

Simple straps using Velcro material are designed to wrap around each desired limb for easy removability of the MSU. On the top surface of each strap, a fitted compartment is designed to hold the MSU enclosure and a side is open for connections to run to the Controller. All the wires exiting the controller are in place on the vest and concealed by wide piece of fabric to avoid clutter and disturbance to the patient. This fabric is soft and has biaxial stretch property, which maximizes the comfort level of the patient [5]. The controller is placed on the bottom right of the vest, which will rest in

front of a patient's hip. The two extensions running to the legs are passing over the thighs and the other two extensions are passing over the shoulder to the back the elbow and finally the wristband that contain the MSU.

Each extension contains identical enclosures for the sensor contained within. All enclosures will be manufactured via additive manufacturing from ABS plastic. This material is chosen for its availability, as the POC need only be functional, not final. This plastic is also lightweight and low cost.

Figure 4 shows the design of the MSU enclosure. This design adheres to requirements in section R5.1. During the design phase, requirement R5.2.4-A, that the vest will fit various body types, has been reprioritized to R5.2.4-F, and it will not be required for the POC. The POC is designed to fit our model patient, meeting requirements R5.2.2, to accommodate individuals from 150-220cm, and R5.2.3, be of a size and similar to a commercially available traffic vest. The production version of the MRAS will involve selecting proper material and dimensions to withstand physical duress such that R.5.2.1, R.5.2.5, R.5.2.6 are satisfied.

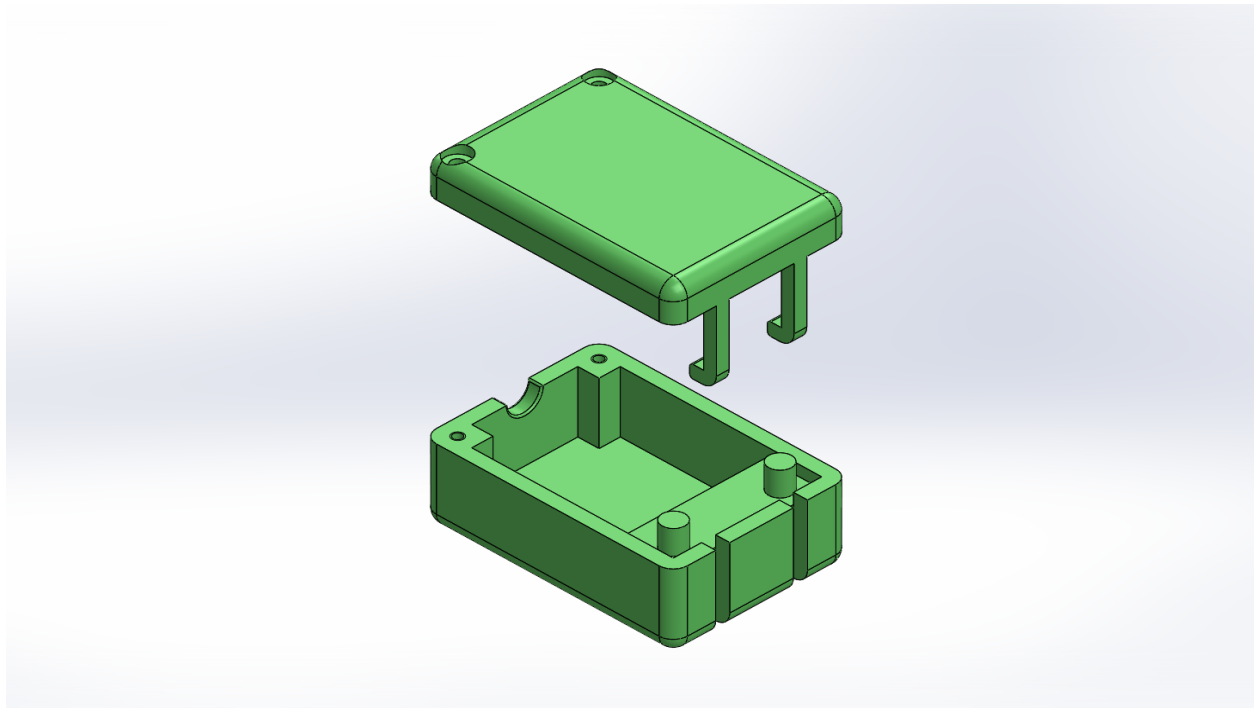


Figure 4: Expanded view of the MSU enclosure

#### 4.1 Straps

The MRAS Kit is designed by extending wire from the Controller, located on the vest, to the MSU on each limb. Each MSU will be secured within a strap that will wrap

around the limb and hold in place. These straps have been designed using washable material that is easily attached and removed from the limb. The MSU enclosure is removable from each strap such that strap can be machine-washed. The vest component of the Kit has been designed with proper housing compartments for when the straps are removed from the patient and the MRAS is not in use.

## 4.2 Enclosure Placement

Each MSU used in the MRAS design is placed within an enclosure. Where these enclosures are secured on the Kit ultimately determines where the MSU will be situated. The MSU is positioned on the patient's wrist, and is secured within a strap around that extremity. Figure 5 left shows the placement of the strap on the patient's arm. The leg MSUs will be identically secured via strap, which will be placed just above the ankle. Note that these placements are all based on the model patient for POC design. Figure 5 right shows the placement of the strap on the leg.



Figure 5: Arm and leg strap placement

## 4.3 Kit Wiring

The design of electrical wiring of components will be discussed in Section 5. However, the physical wiring runs apply to the kit, and proper routing of the cables will be discussed here. The vest has been designed to conceal the cables being run from the controller enclosure to the MSUs. The wire is also removable from this concealment so that the vest can be cleaned.

## 5 ELECTRONICS DESIGN

The Electronics of the MRAS consists of the following electrical hardware:

- SunFounder Arduino Mega Microcontroller
- Kootek Arduino GY-521 MPU-6050 6-axis Gyroscope Accelerometer
- KEDSUM Arduino Wireless Bluetooth Transceiver Module
- Standard Duracell 9V Battery

The Arduino microcontroller was chosen for its open source nature and ease of use. The Mega version was chosen over the UNO for its flexibility with respect to quantity of pins and its marginal price difference over the latter. The sensors and Bluetooth module were selected because of their attractive price, but more importantly for their compatibility with the controller. All components used in the MRAS design are manufactured to readily function with the Arduino microcontroller. The standard 9V battery is cheap and provides enough power to energize the entire system reliably. Future versions of the MRAS will incorporate a rechargeable, removable battery. Note that requirements R4.1.10 through R4.1.12 refer to a design involving the system being powered by AC power from a standard wall outlet. These requirements have been abandoned for the POC.

The following interconnection diagrams show the electrical connections of the MRAS. The normal operating current of each MSU, with all functions enabled, is 3.8mA [3]. Physically, the conductors used are standard 24AWG Ethernet CAT5 cable. This gauge of conductor is rated for a maximum current of 577mA per conductor [4]. This apparent over-compensation in conductor choice is not an inconvenience to the design in any way. CAT5 cable is cheap, widely used, and readily available. As a result, it is easy to work with as the required male/female connectors are also conveniently acquired and implemented into the design. The named Ethernet ports need not be shown in the interconnection diagrams, as they are simply physical implementations of the electrical connections.

BLUETOOTH MODULE			MICROCONTROLLER	
VCC	<----->	3.3V		
GND	<----->	GND		
TXD	<----->	SCL (Digital pin 1)		
RXD	<----->	SDA (Digital pin 0)		

Table 1: Electrical Interconnection Diagram for Bluetooth Module

The Bluetooth module is wired directly to the Arduino controller. Table 1 illustrates the interconnections of the Bluetooth module.

The electrical design of the MRAS needs to be configured such that the Arduino controller can function with multiple sensors. The pins on the controller are configured for this functionality. Specifically, we have used an additional Arduino IDE library to generate a second I2C serial bus. Each MSU has a VCC, AD0, SCL, SDA, GND, INT pin that is to be connected between the Arduino and each MSU. The pins and their functionalities are listed in the table below.

MSU Pin		Functionality
VCC	<----->	To power the MSU (3.3V)
GND	<----->	Ground connection
SCL	<----->	Serial clock for synchronization
SDA	<----->	Data transfer bus
AD0	<----->	Ground connection
INT	<----->	Interrupt signal pin

Table 2: Functionalities of the MSU pins

The SDA and SCL pins are two wires used in the I2C protocol that control data transmission and clock synchronizations respectively. The Arduino microcontroller is a master on these buses and the sensors are slaves. The I2C serial protocol uses slave-defined addresses to choose which slave is actively communicating with the master. Because the MPU-6050 sensor has only 2 slave addresses set by AD0, we cannot address the 4 sensors on a single I2C bus. With a second I2C bus, we simply design the system to contain one pair of sensors on the default bus, while the second pair is connected to a second I2C bus. This configuration allows 4 sensors to work with the system without the addition of extra hardware such as multiplexers, while keeping read speed high.

Additional configuration to the microcontroller involves setting digital pin 2 as another 3.3V VCC terminal to avoid any potential fan-out issues. Pins 20 and 21 provide the SDA and SCL signal lines, respectively, of the default I2C bus. Pair 1 consists of sensors 1 and 2 that are connected to the default bus. Tables 3 and 4 illustrate the interconnections for Pair 1. Note that any interconnections that require a similar pin are implemented using proper splicing methods when terminating.



Digital pins 10 and 11 have been configured to provide be SDA and SCL signal wires, respectively, for the second I2C bus. Pair 2 consists of sensors 3 and 4 connected to the additional I2C bus. Tables 5 and 6 illustrate the interconnection for Pair 2.

This summarizes the design configurations required for the microcontroller to function with the 4 required sensors of the MRAS.

Each MSU is soldered to a CAT5 cable with the controller end terminated via male Ethernet connector head, which will then connect to the control box via Ethernet port. This port will be built into the control box and will already be electrically extended to the Arduino board. This design allows each individual MSU to be connected or disconnected from the controller enclosure. The MSUs are removable from their straps and hung on the vest when not in use. The Electronics will be powered by a standard 9V battery, which is housed next to the Arduino in the controller enclosure.

There will also be incorporated peripheral devices located on the cover plate of the controller enclosure. These include a power on/off switch, simple push buttons to conveniently toggle the states of the MRAS system, and LEDs for state indication.

SENSOR 1			MICROCONTROLLER	
VCC	<----->	3.3V		
GND	<----->	GND		
SCL	<----->	SCL (Digital pin 21)		
SDA	<----->	SDA (Digital pin 20)		
ADO	<----->	GND		
INT	<----->	Digital pin 3		

Table 3: Electrical Interconnection Diagram for Sensor 1

SENSOR 2			MICROCONTROLLER	
VCC	<----->		3.3V	
GND	<----->		GND	
SCL	<----->		SCL (Digital pin 21)	
SDA	<----->		SDA (Digital pin 20)	
ADO	<----->		GND	
INT	<----->		Digital pin 4	

Table 4: Electrical Interconnection Diagram for Sensor 2

SENSOR 3			MICROCONTROLLER	
VCC	<----->		3.3V	
GND	<----->		GND	
SCL	<----->		SCL (Digital pin 11)	
SDA	<----->		SDA (Digital pin 10)	
ADO	<----->		GND	
INT	<----->		Digital pin 5	

Table 5: Electrical Interconnection Diagram for Sensor 3

SENSOR 4			MICROCONTROLLER	
VCC	<----->		3.3V	
GND	<----->		GND	
SCL	<----->		SCL (Digital pin 11)	
SDA	<----->		SDA (Digital pin 10)	
ADO	<----->		GND	
INT	<----->		Digital pin 6	

Table 6: Electrical Interconnection Diagram for Sensor 4

## 6. SOFTWARE DESIGN

### 6.1 Analysis and Comparison Algorithm Design

The software design of the MRAS needs to satisfy two vital functions. The system must first analyze the data that is transmitted to the PC from the hardware. This analysis function involves organizing the data into a readable format, and then compares it to another set of data that has already been defined on the PC. This pre-defined data represents the desired ambulatory motion for each limb of the model patient. The first function of the software compares the received data to the pre-defined set using a comparison algorithm, and stores the results of the comparison. The second function of the software is to provide the audio feedback for the patient. The data analysis determines how correct or incorrect the motion of the patient is. The first function will pass these comparison results to the control inputs of the second function, the MIDI player.

The method of the comparison algorithm involves reading various data points along the patient's limb motion. The algorithm draws inspiration from a comparison algorithm created by Dr. Jaimie Borisoff [7]. The pre-defined data consists of the path of the desired motion, along with a series of three-dimensional envelopes extending out from the desired path. For each data point that is analyzed and compared to the preset path, it is placed in one of these envelopes. This allows for the feedback to have dynamics based on its divergence from the preset path. The design of the audio feedback is discussed in Section 6.2. The degree of positive or negative feedback will vary based on how close or how far the received data is from the desired path. For the POC of the MRAS, Harmony Innovation has defined a single preset data set that comprises the desired walking motion, designed for the model patient whom will demonstrate the POC. During commercial use of the MRAS, the desired motion will vary based on the body type and measurements of the patient using the product. Therefore, future iterations of the MRAS would include a pre-defined database of ambulatory motions for various characteristics. The therapist would select the patient's measurements in the database, and the desired motion for that specific patient would be loaded and used for comparison.

### 6.2 Audio Feedback Design

This element of the software is simpler than the comparison algorithm. However, the nature of the audio feedback requires a discussion of the design that is implemented in the MRAS. Harmony Innovation has chosen to use the MIDI protocol for the audio playback. It is lightweight, open source, and free of cost. Furthermore, MIDI allows separation of the audio feedback into channels. The MRAS uses four independent audio channels. Since the patient is providing up to four sets of data, one for each limb in motion, we can associate each set with a channel of the audio. This results in four

independent but harmonious feedbacks being provided to the user. For the POC design, the audio used is in the form of a string quartet. As such, we can use a channel to represent each individual instrument of the arrangement. Ultimately, each instrument is controlled by the data provided by the limbs of the patient. Based on the performance of a specific limb, determined by the data comparison to the desired motion, the associated instrument in the music will be affected.

The challenge for Harmony Innovation is to design this feedback such that the information provided to the user remains helpful to their rehabilitation. There are several parameters that can be controlled through MIDI. For simplicity, the MRAS POC will control the channel volume. This design choice should mitigate any possible annoyance factor when negative feedback is given to the user. The goal above all is to improve the rehabilitation process, not to discourage the patient. Alternative forms of feedback such as pitch control or additional noise could undoubtedly cause problems in this regard. As the MRAS moves towards a final production state, other parameters such as pitch and timing could be manipulated, and such methodology would be developed based on user feedback.

Each MSU will provide x-, y- and z-axis rotation and acceleration data to the software by way of the Controller. Each axis will be analyzed against a preset envelope, and assigned a PASS/FAIL score. A PASS will be assigned a value of 1 and a FAIL will be assigned a score of 0. These three scores will be summed and multiplied by 40. Therefore, if all axes are within the envelope, a score of 120 will be sent to the channel volume control. Figure 6 below shows a simplified signal flow from the MSU to the MIDI module.

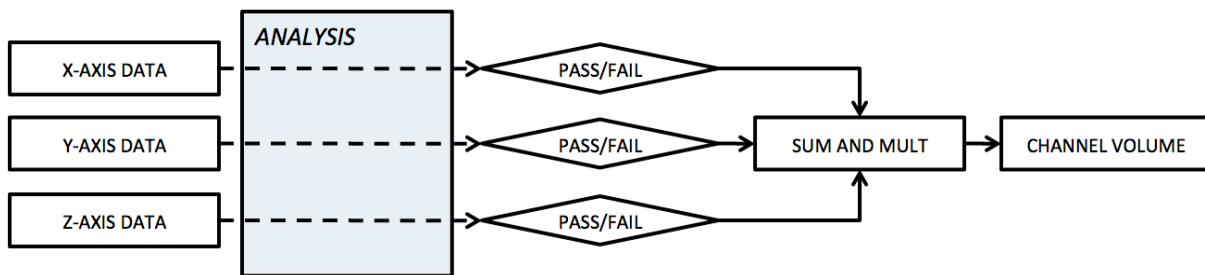


Figure 6: Signal flow diagram from the MSU to MIDI module

## 7. SYSTEM TEST PLAN

In order to properly test the MRAS, testing will be performed during the Development, Integration and Testing phases. Figure 7 shows the current project schedule.

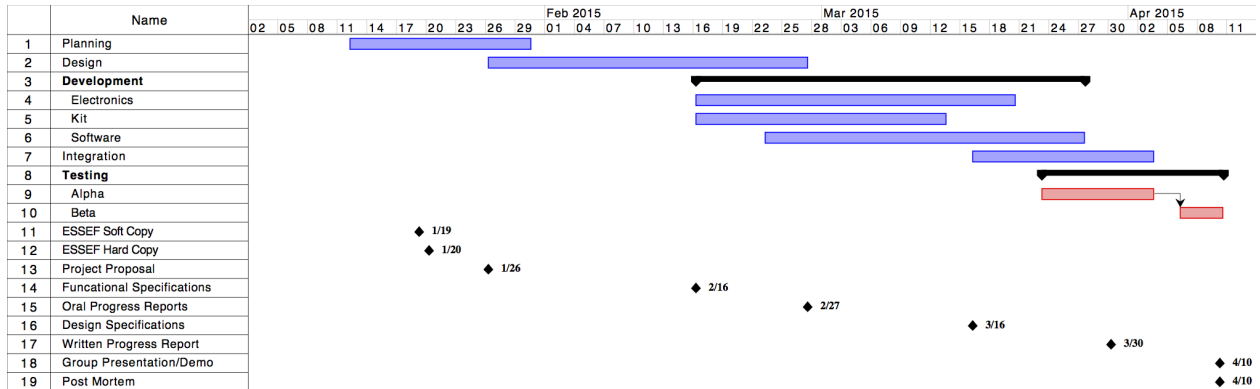


Figure 7: MRAS development plan with milestones

### 7.1 Electronics Testing

Testing in the Development phase will be focused on verification of individual parts. By checking that they are functionally sound, we reduced the likelihood of issues due to component failure. As parts were assembled into subsystems, functional testing continued to ensure that there was good current flow between the MSU and the Controller.

During the Integration phase, testing will focus on the communication of data between the Electronics and Software. Initial tests will verify that signal is being sent wirelessly to the Software. Subsequent testing will revolve around the quality of the data being sent to reduce the signal-to-noise ratio where possible.

### 7.2 Kit Testing

Kit testing will be primarily done in conjunction with other parts. The concerns for the Kit are durability, comfort and integration with the Electronics. Testing will ensure that the straps meet size requirements, and that the straps will survive regular use and cleaning. Further testing will revolve around housing the Electronics and ensuring that the MSUs and Controller are easy to nest and remove.

### 7.3 Software Testing

Software testing will refine the inputs to tune the output values to produce the desired MIDI signal. This output will then be routed into the MIDI Controller, which will receive the signal, communicate with the sound library, and send the appropriate

sound to the speakers. As the Software is refined, the number of data channels will increase, and testing will focus on ensuring separation between sensor channels and that playback is correct for each channel.

## 7.4 System Testing

At the end of the Integration phase, it is expected that the Electronics, Kit and Software are all functional and that there is basic marriage between them. Entering the Alpha Testing phase, the focus will be on tuning the data stream so that the outputs align with expectations. A standard user path is defined based on conversation with Dr. Ian Denison from GF Strong Rehabilitation Centre [9]. The MRAS will be tested along this standard user path to identify common sources of error. Changes to the system, as well as additions, will be allowed during this phase. Issues will be tracked and resolved based on priority and severity. System testing will also be used to tune the optimal positioning of the MSU on each limb.

The following functional modes will be tested:

- Each limb is moved independently to verify a complete signal path from the MSU to the speakers.
- Limb pairs (arms or legs) are moved to verify that channel integrity is maintained.
- All four limbs perform synchronous motion to ensure complete system functionality.

The following failure modes will be tested:

- Left arm is held static while the other limbs move normally.
- Right arm is held static while the other limbs move normally.
- Both arms swing in unison while the legs move normally.
- Both legs move in unison while the arms move normally (hopping).
- Simulation of asynchronous leg strength; one slow step, one quick step.

## 8. CONCLUSION

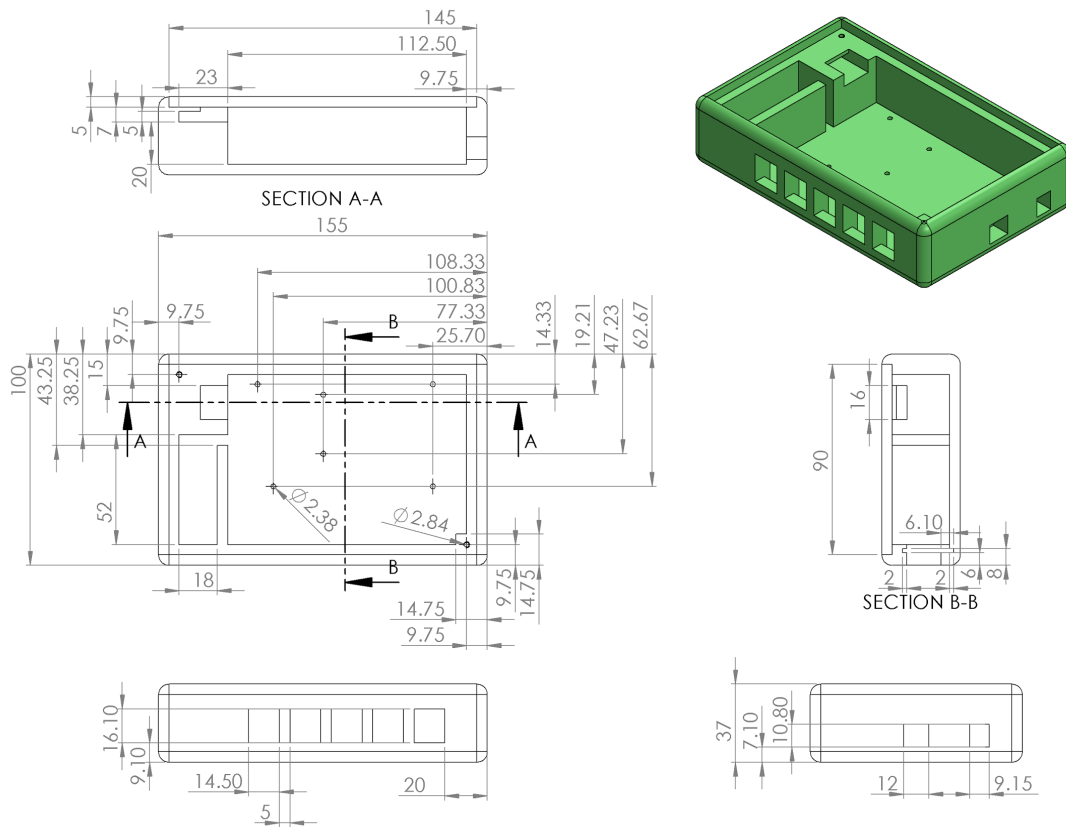
This document proposes design solutions to accommodate the functional specifications of the Musical Rehabilitation Assistance System. As development of the MRAS continues, these design specifications will serve as a guideline for meeting those functional specifications. The included test plan provides assurance that the stated functionality is in place and working as designed. This design specification lays out clear goals for the MRAS development.

## 9. REFERENCES

- [1] Harmony Innovation, “Functional Specification for the Musical Rehabilitation Assistive System”, Simon Fraser University, Burnaby, BC, Canada, February 2015.
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## APPENDIX A: KIT ENCLOSURE MECHANICAL DRAWINGS



**Figure 8: Schematic drawing of Controller enclosure bottom**

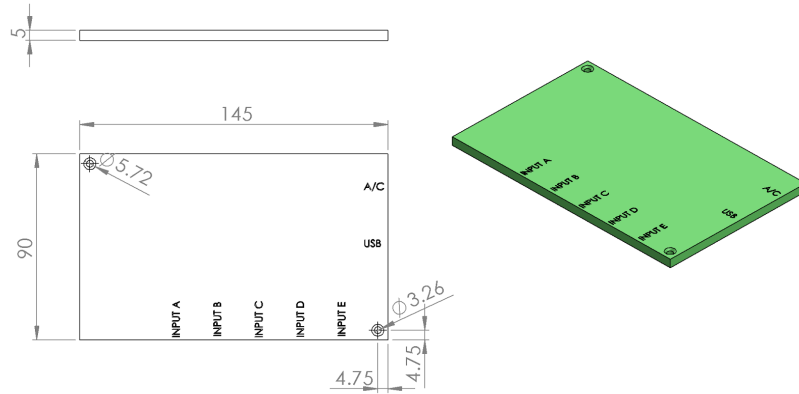


Figure 9: Schematic drawing of Controller enclosure top

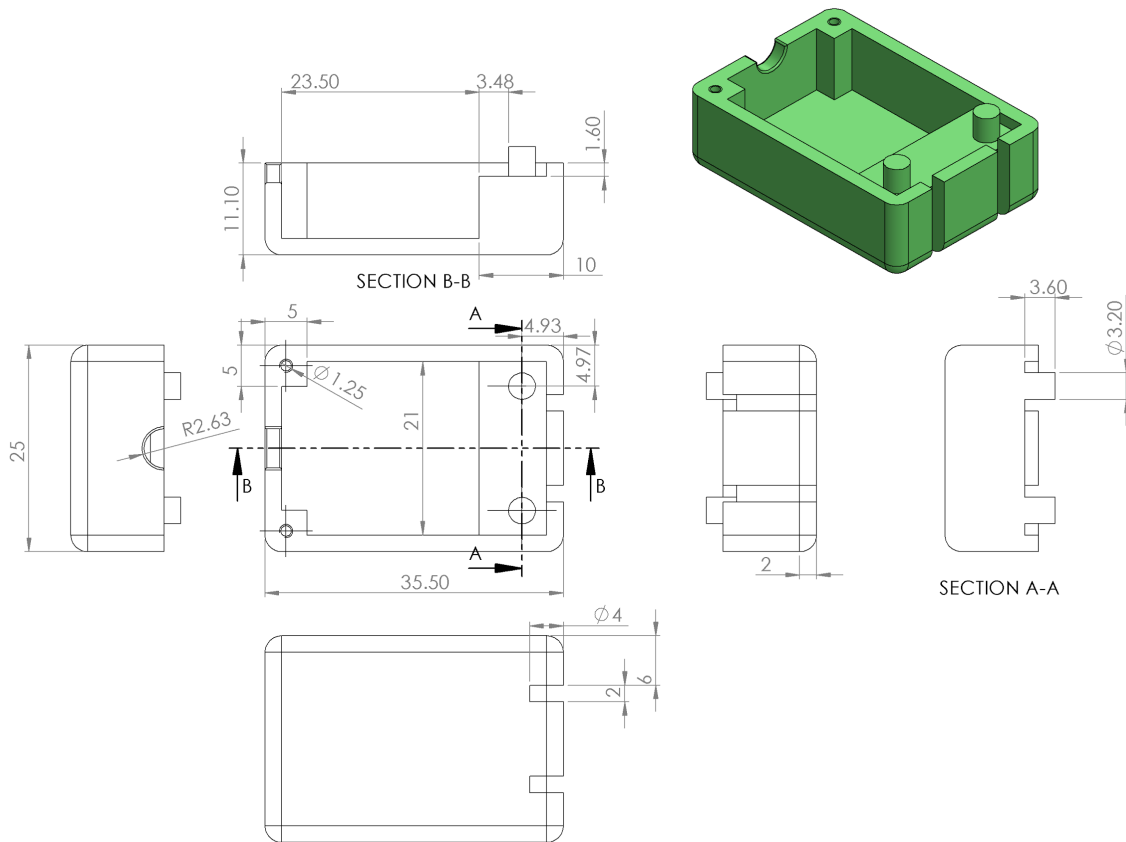


Figure 10: Schematic drawing of MSU enclosure bottom

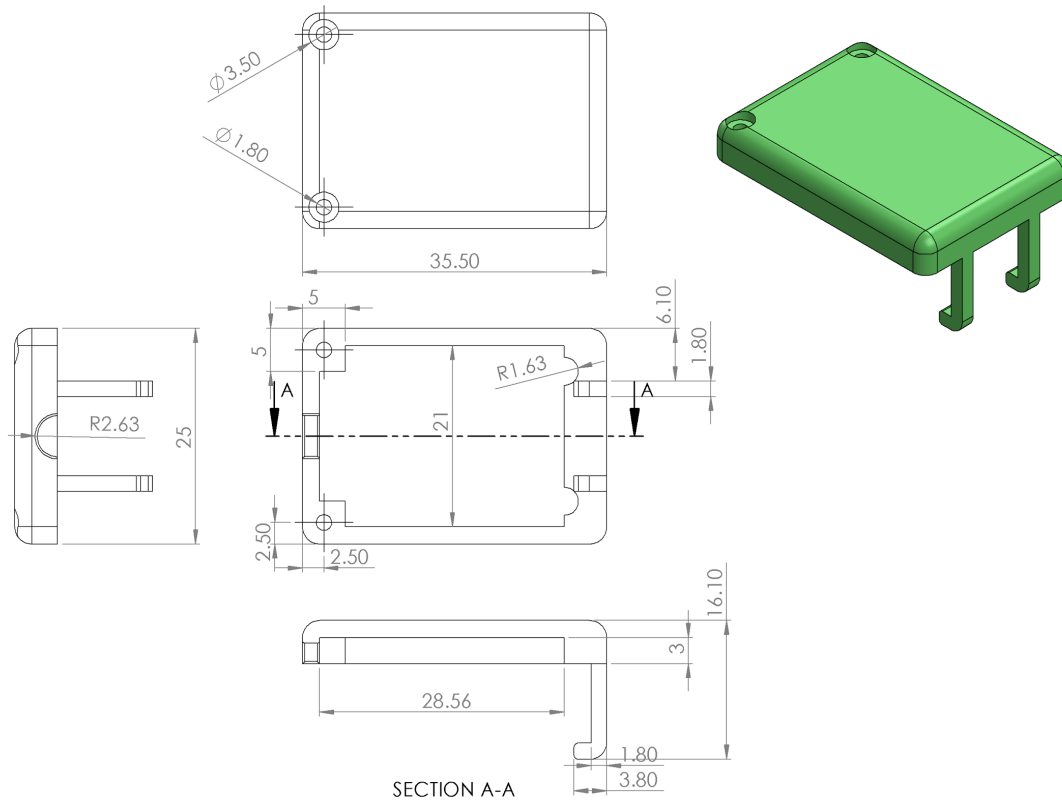


Figure 11: Schematic drawing of MSU enclosure top