March 19, 2015

Dr. Andrew Rawicz
School of Engineering Science
Simon Fraser University
Burnaby, British Columbia
V5A 1S6

Re: ENSC 440W Design Specifications for a Rehabilitation Exoskeleton Hand Device

Dear Dr. Rawicz:

The attached document, *Design Specifications for a Rehabilitation Exoskeleton Hand Device*, describes the technical designs for our product, the RexoGrip, which is our ENSC 440W engineering capstone project.

Our design specifications provide a set of design solutions for the functional specifications of our device, in regards to the proof-of-concept model. This document will include an overall system design, as well as include more specific sections that highlight the designs for the finger, wrists, and frames.

Our team at Rexos is composed of several dedicated and experienced students of various engineering backgrounds: Anton Khomutskiy, Joshua Law, Tony Lee, Seungjun Lee, and Doug Tao. If you have any questions or concerns about our document, please do not hesitate to contact me at (604) 805-7561 or by e-mail at leetonyl@sfu.ca.

Sincerely,

Tony Lee
Chief Executive Officer
Rexos Ltd.

Enclosure: *Design Specifications for a Rehabilitation Exoskeleton Hand Device*

REXOS

Design Specifications for a

Rehabilitation Exoskeleton Hand Device

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Issued Date: March 19, 2015

Revision: 1.03

Executive Summary

This design specification aims to set out a detailed description of the designs for the proof-of-concept model of the RexoGrip. The design specifications in this document are meant for a proof-of-concept model of the RexoGrip, so only functional requirements pertaining to proof-of-concept are discussed.

This design specification will contain sections targeted at outlining design choices for the electrical, software, and mechanical components of the RexoGrip. The RexoGrip will use four servos to provide actuation to the frame. A set of tactile push buttons, two per finger, for four fingers, totalling eight push buttons will be used to allow the user to control exoskeleton movement. A diagram detailing the electrical connections between the servos, microcontroller, push buttons, and power supply will also be included. A detailed description of the program sequencing and a flowchart will be given in the section for software. Additionally, a detailed test plan will be described for normal usage cases and extreme usage cases.

Due to the mechanical complexities in the exoskeleton frame for the hand, our team will be developing two mechanical designs in parallel. Later in the development cycle, after both designs have been tested for functionality, a final design will be chosen by March 31st, 2015.

By following this schema for the development stage, we can ensure that our team can deliver a working prototype of our product by April 17th, 2015.

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Glossary

A - Amperes, the unit of current measured as coulombs/second

CSA – Canadian Standards Association

CAD - Computer Assisted Design

IEC – International Electrotechnical Commission

ISO – International Organization for Standardization

LED – Light Emitting Diode

Motor Shield – Motor controller board that acts as the interface between the microcontroller board and the motor(s).

N - Newtons, the unit of force measured as $\frac{kgm}{s^2}$.

Phalange – A long bone located in the finger, also known as a finger bone.

Plexiglas – Poly (methyl methacrylate), a transparent thermoplastic also marketed as Acrylite.

PVC - Polyvinyl Chloride, a common material for making pipes.

RexoGrip – Product name for Rexos' exoskeleton hand device with power assistive functionalities.

Typical Weather Conditions – Normal weather conditions on an average day in Vancouver, British Columbia.

UNO – Universal Network Object

V - Volts, the unit of electrical potential.

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1 Introduction

The RexoGrip is a powered exoskeleton device that is designed to fit over a user's hand. The RexoGrip will provide the user power assistive capabilities on each finger to perform curling of the fingers which mimics a gripping motion. The RexoGrip will have the ability to detect upwards or downwards movement of individual fingers to actuate the device. In this design specification proposed by the team at Rexos, design solutions satisfying requirements of the RexoGrip will be outlined.

1.1 Scope

This document outlines the specifics of the RexoGrip and details how each functional specification laid out in *Functional Specifications for a Rehabilitation Exoskeleton Hand Device* [1] as applied to the proof-of-concept model is met. Only functional specifications designated with a "-I" or "-II" will be addressed in this document, and any instances where specifications are modified or neglected will be noted in the relevant section(s).

1.2 Intended Audience

This design specification document will be used by the engineers at Rexos to ensure that specifications are met throughout the development cycle and during the implementation process. The test plans described in this document will be used to validate the final revision.

2 System Specifications

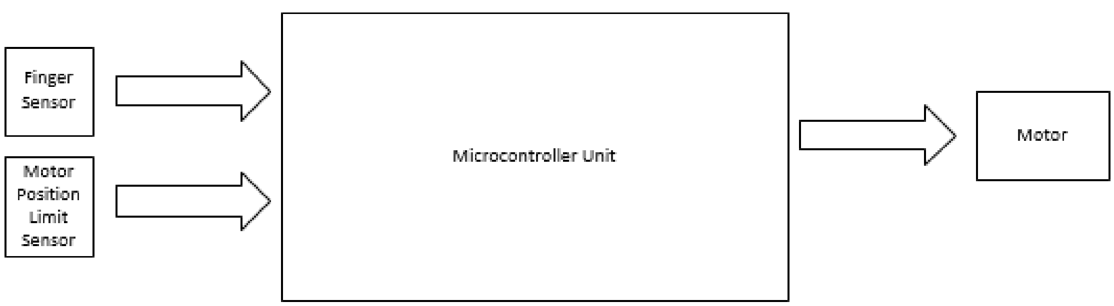

Figure 1 - System Overview of the RexoGrip

As shown by Figure 1 above, the RexoGrip system contains three core electrical components. These three components are the sensors, microcontroller unit, and the motors.

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For each finger, there are two finger sensors which correspond to either an upwards or downwards movement of the finger. These sensors will always be in either an on or off position. When the sensor is in on position, it will send a signal to the microcontroller unit.

When the microcontroller receives a signal from the finger sensor, the program will check the position of the motor. If the motor can move in the desired direction, the microcontroller will then pass on the signal to the motors to actuate a set amount. If the motor has reached the travel limit in the desired direction, the microcontroller will not send the actuation signal to the motor.

The system will abide by the following general requirements:
[R23-II] The device must be operable under continuous use.
[R37-II] All electronic components of the device must be properly secured.
[R40-II] Under normal operating conditions, the device must not overheat or catch fire.
[R42-II] The device must not cause bodily harm to the user during operation.

The following two specifications were reworded for clarity:
[R7-II] The device should be lightweight*, not weighing more than 500g*.
[R21-II] The device must be fully operational under ~~normal~~ *room* temperatures (~~10°C to 30°C~~ *21°* C).

These specifications were omitted from the proof-of-concept model:
~~**[R18-II]** The device must have a mechanical limiter to prevent injury.~~
[R33-~~II~~ *III*] The device must be resistant to electrostatic discharge.
[R39-~~II~~ *III*] The device must have an electrical emergency stop.

To conform to these requirements, as a general test case the RexoGrip will run in 10 minute segments in a normal room setting to validate that none of these requirements are violated.

3 Frame

To accomplish our mechanical design of the exoskeleton frame, we are currently running two designs in parallel, which will be defined as Plan A and Plan B. Plan A will be manufactured via 3D printing, whereas Plan B will be assembled after using hand tools to machine the components. Future design revisions will need to be considered to implement the push buttons for use as finger movement sensors.

[R43-II] The failure of any mechanical components of the device must not cause any harm to the user.
[R48-II] The user should have no difficulty putting on the device.
[R49-II] The user should have no difficulty taking off the device.
[R50-II] The device should not be intrusive.
[R53-II] The frame's material must not cause catastrophic failures.
[R54-II] The frame must account for structural stresses.
[R55-II] There must be no protrusions that can snag and cause harm.

When designing the mechanisms and choosing materials, these specifications will be referred to.

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3.1 Plan A

The purpose of the mechanical mechanism is to provide a medium for power assisted movement of individual fingers, through force applied by motorized actuation. The frame itself is designed from several smaller modular components, but can be broken down into three major key components: the base frame, finger frames, and actuation mechanism.

The finger frame is the most basic component, and is comprised of three semi-ringed sections (modeled below in Figure 2), one for each phalange. Each section has an internal radius of 15mm, 3mm thickness, and a length of 20-24mm depending on the user's measurements. Each section is left open along the underside to allow for easy fastening and removal through Velcro straps wrapped around the specifically made cut-outs. The sections are linked together with rivets along the underside to ensure rigidity and flexibility, allowing the user to move each section independently without interference. The individual finger frames are designed and measured to match that of the user, to ensure a snug fit and increase controllability.

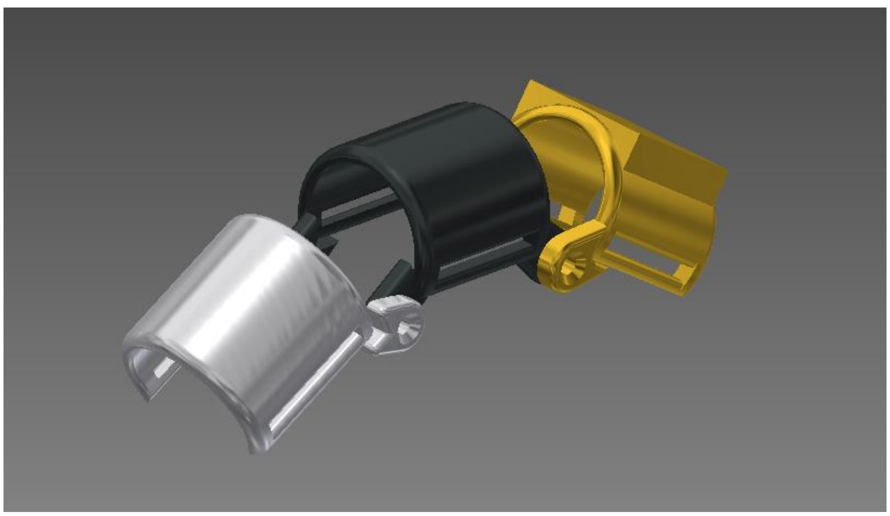

Figure 2 - Finger Links

The base frame is comprised of a plastic elliptic shell encompassing the palm, 80mm wide, 36mm radius at the thickest, and 5mm thick. The base frame serves as a platform for mounting the individual finger frames, the actuation motors, and the actuating mechanisms. The fingers are mounted to the base frame with staggered knuckle joints, to ensure the user has the ability to fully pivot their knuckles. The back portion of the base plate serves as a mounting point for the motors, which are configured in two columns and facing in opposite directions. This configuration is used to maximize the amount of space available on the back of the hand.

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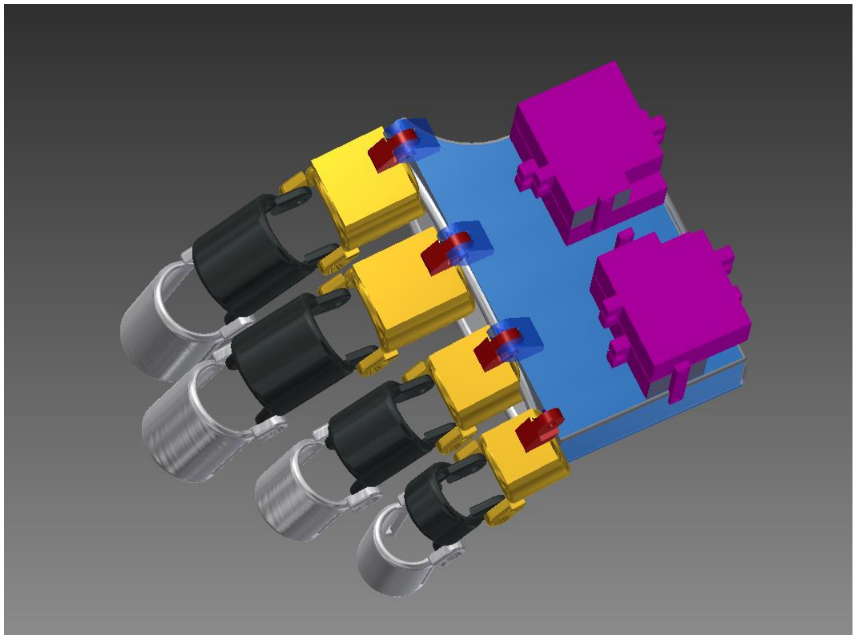

Figure 3 – Overhead View of Complete Device

Finally, the actuating mechanism is shown as the following.

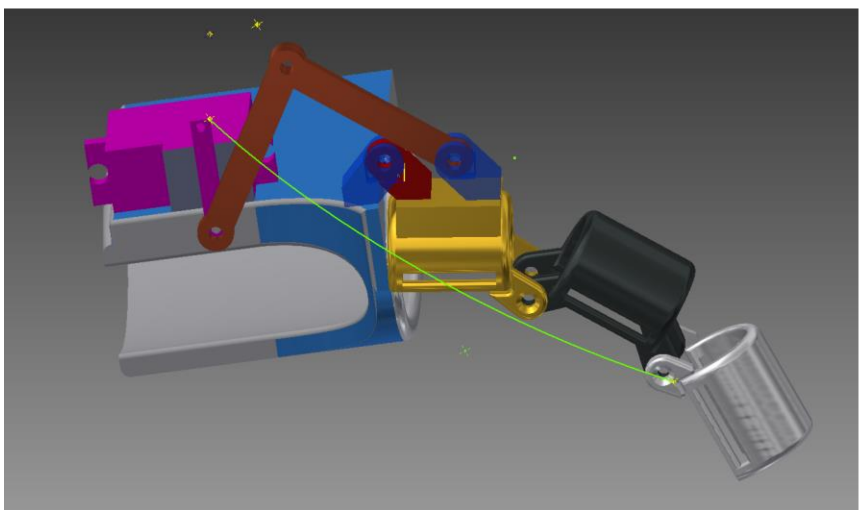

Figure 4 - Actuating Mechanism

The mechanism is designed to allow for movement of both the inner and outer sections of the hand. The green line, in Figure 4 and Figure 5, represents an elastic material tied to the second joint. As the motors actuating push the links, causing the inner palm to close, the elastic tied to the reverse end pulls in the opposite direction and closes the outer section of the hand. The actuating links connecting the finger to the joints are 34mm each in length, and are connected to the propellers of the motor. All of this combined gives us the final design.

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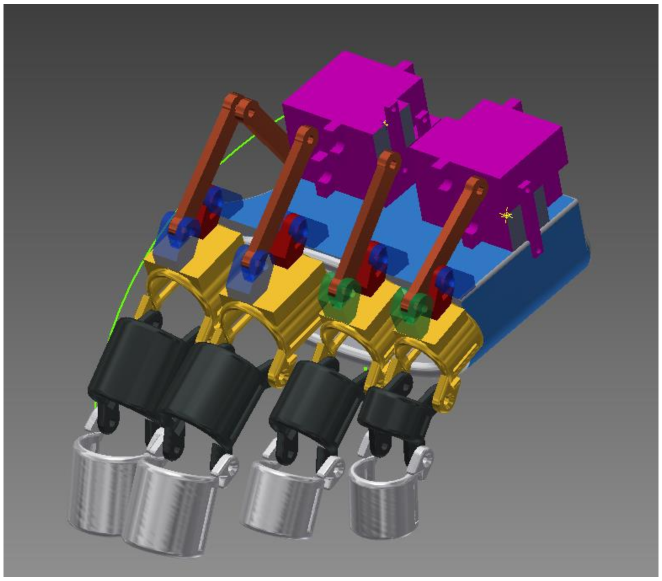

Figure 5 - Frontal View of Device

3.2 Plan B

The purpose of the mechanical mechanism is to use the force applied by the motor to move a finger in the desired direction. There are two main components in the mechanical part of the device.

The first component is a plastic plate mounted on top of the hand and affixed with two Velcro straps which wrap around the hand in front of and behind the thumb. The bottom surface of the plate has foam padding attached to provide a comfortable fit for the backhand. Servo motors and the mechanical joints for each finger (except thumb) will be mounted on top. Figure 6 shows a crude representation of how the assembly would look with the base plate attached to the joints.

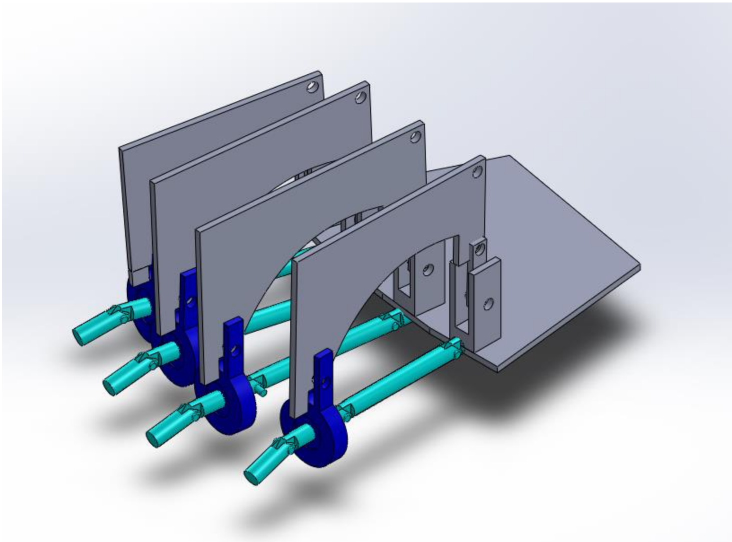

Figure 6 - CAD Mockup of Hand Assembly Sans Motors

The servo motors are attached in pairs to the plastic plate using aluminum braces. The motors in each pair are attached together with a double sided tape so that the largest sides are facing each other and the rotating shafts are on opposite ends. That way, the motors take less space on top of the plastic plate. The joints are attached to the plate using the same corner braces on the edge of the plate located right above the knuckles.

The second component consists of Plexiglas joints that apply force from the motor onto the finger to bend it up and down. The largest section of the joint is cut out from Plexiglas 5 mm thick and has a semi-oval cut out along its longer side to provide enough space when the middle phalange is bent. The Plexiglas shape is attached to the middle phalange with a ring cut out from a PVC pipe, 1 inch in diameter. The Plexiglas shape and the ring make a joint in conjunction with an aluminum strip bent into a U-shaped brace and attached to the ring (coloured dark blue). A 1/8 bolt acts as the shaft and the ring has foam padding on the inside for a tight fit to the finger. The other end of the rectangular shape has two shafts, one in each corner. The bottom shaft makes a joint with a small rounded Plexiglas rectangle that in turn is connected to the U-shaped brace on the edge of the plastic plate on top of the hand as shown in Figure 7. Another 1/8 bolt is used as the shaft in this brace with two washers, a nut and thread lock applied to secure it. The top shaft in the rectangular shape forms a joint with the other rounded Plexiglas rectangle that has its other end connected to a blade mounted on the servo motor shaft. Therefore, the force transferred from the motor is applied on the ring to push or pull the finger.

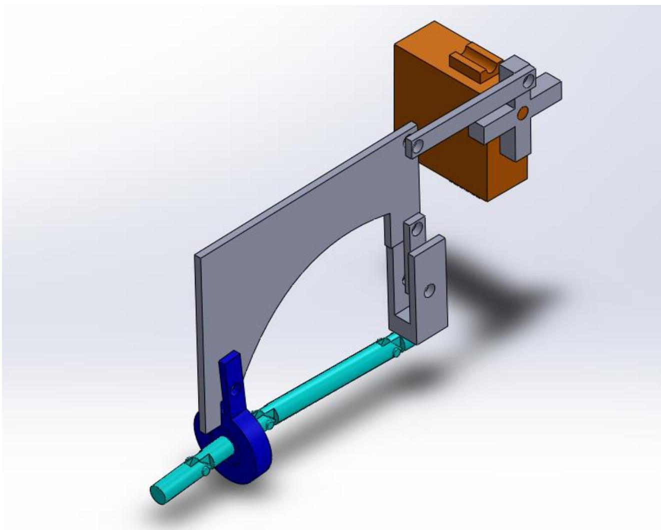

Figure 7 - CAD Mockup of Single Finger Mechanism with Motor Attached

The HS-5085MG servo motors come with their own set of blades, however the provided blades are too small to produce sufficient range of motion. Therefore, a Plexiglas piece is attached with glue on top of the provided blade to increase the lever size. In its neutral state the lever points straight up, normal to the plastic plane. To bend the finger up or down the lever will move clockwise or counter-clockwise, transferring force through the joints.

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4 Software and Microcontroller

4.1 General Software

For our proof-of-concept model, the following requirements will be covered:

[R68-II] The program will run on the Arduino platform.
[R69-II] The program must be able to read input data from sensors.
[R72-II] The program must be able to track the position of the motors.
[R73-II] The program should have a start-up sequence to calibrate the device to a default position.
[R74-II] The program must have a software stop to prevent injury.

Additionally, the following requirements have been modified to our design changes:

[R70-II] The program must be able to control ~~stepper~~ *servo* motors.
[R71-II] The program will send output signals to control up to ~~five~~ *four* motors.

Upon startup or reset of the device, the microcontroller will run a startup sequence. This startup sequence will direct the servo motors to go to a predefined default position, defined to be 0 degrees.

The device will then enter an idle state until one or more finger sensors are activated by the user. Upon actuation, it is then checked which finger will need to be moved and the direction of the movement. This decision will be determined by the program by checking state of all the finger sensors to find out which sensors are in the "HIGH" state, which is obtained by actuation of the sensor.

In the next step, the current position of the motor will be checked to validate whether it is allowed to move in the desired direction. If the servo has hit the upper limit as tracked in the program, the up movement will be cancelled. Similarly if the servo has reached the lower limit, the down movement will cease.

If all the checks are passed, the servo will move 1 degree in the desired direction and return to the idle state. A flowchart of this sequence of events is shown in Figure 8 below.

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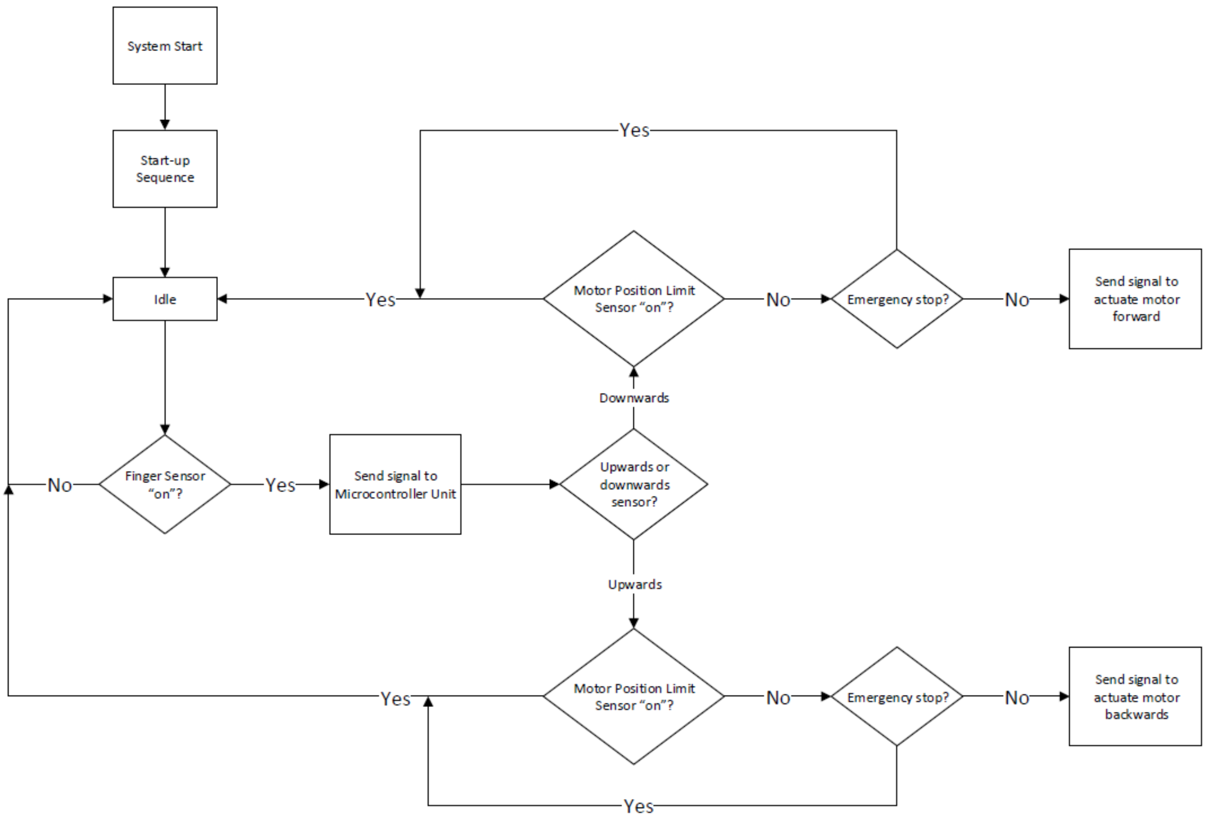

Figure 8 - Software Flowchart

4.2 Microcontroller

The microcontroller chosen for our product will be the Arduino Uno. This microcontroller will fulfill the following requirements:

[R57-II] The microcontroller unit must be able to operate in real-time.

[R58-II] The microcontroller unit must be able to accept input from ten analog sensors.

[R59-II] The microcontroller unit must accept up to five simultaneous inputs.

Whereas this requirement has been modified for the scope for the scope of our current design.

[R60-II] The microcontroller unit must be able to output signals to control up to four motors simultaneously.

The Arudino Uno has 13 available digital pins for use. 8 of these pins will be used for the finger sensors and 4 will be used for the servo motor control.

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4.2.1 Arduino Pin Assignment

This section will cover the external connections of any components to the microcontroller board. Referring to Figure 9, the pin connections to the microcontroller board will be configured in accordance with Table 1.

Table 1 - Arduino Uno Pin Assignments

Pin	Type	Function
Digital 0	Input	Index finger up sensor
Digital 1	Input	Index finger down sensor
Digital 2	Input	Middle finger up sensor
Digital 3	Input	Middle finger down sensor
Digital 4	Input	Ring finger up sensor
Digital 5	Input	Ring finger down sensor
Digital 7	Input	Pinky finger up sensor
Digital 8	Input	Pinky finger down sensor
Digital 6	Output	Control index finger servo
Digital 9	Output	Control middle finger servo
Digital 10	Output	Control ring finger servo
Digital 11	Output	Control pinky finger servo

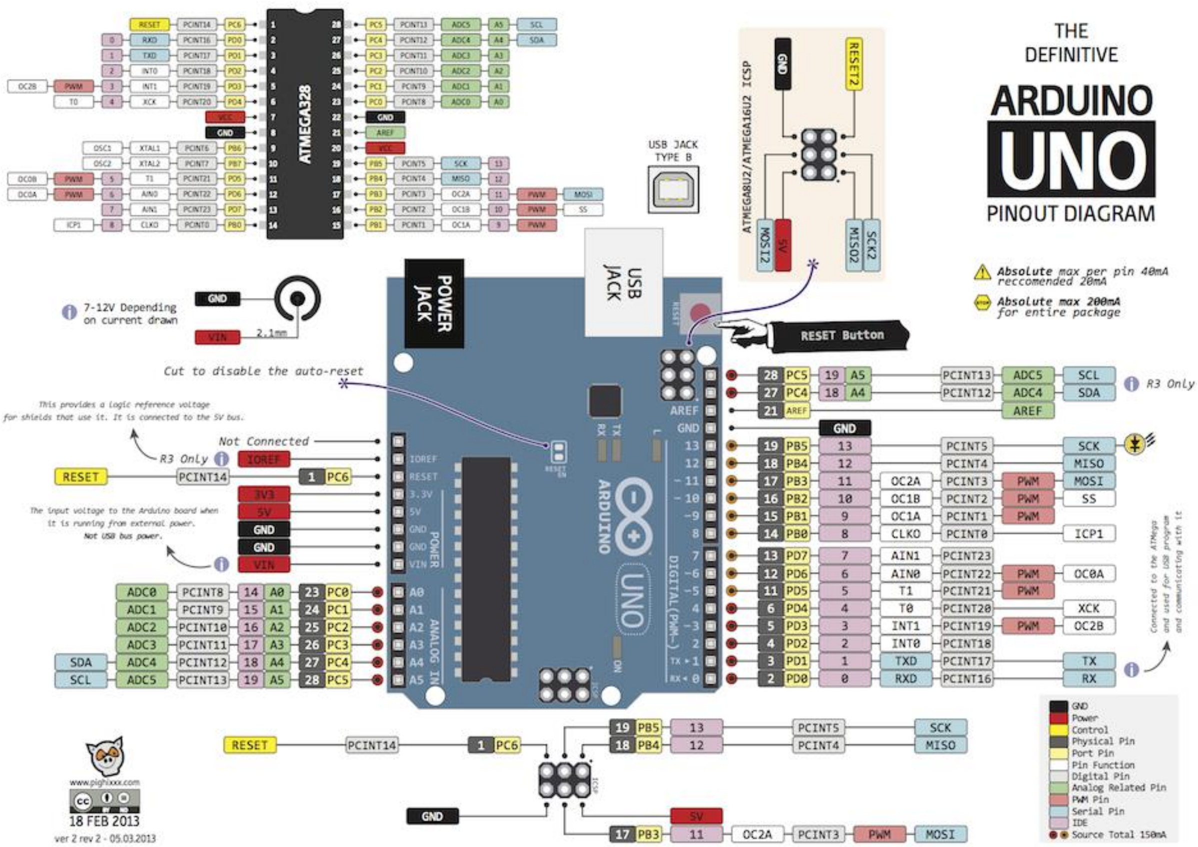

Figure 9 - Arduino Uno Pin Layout [2]

5 Hardware

5.1 Electrical System

[R13-II] All wiring must be electrically insulated from the rest of the device [3].
[R14-II] Any exposed cables must be neatly tied together.

To satisfy these two requirements, the RexoGrip system will require organized cable management. Where possible, exposed wiring will be grouped together and sleeved using electrical tape. Referring to Figure 10 below, it can be seen that all motors and push button finger sensors will be powered by a component power supply. This separate component power supply is necessary because the alternative is to power these components through the microcontroller board, which is more hazardous in case of current overload. In the case that all components are active, the currents drawn will not pass through the microcontroller board.

A simplistic overview of the connections between electrical components is shown below in Figure 10.

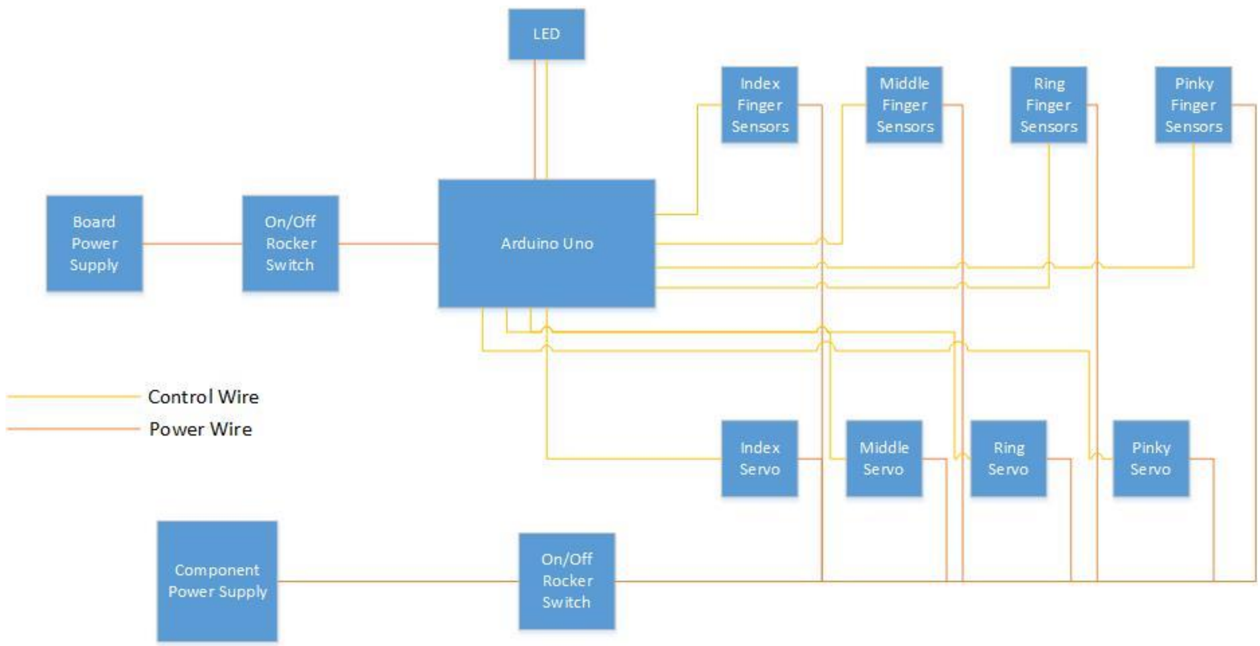

Figure 10 - RexoGrip Electrical Component Layout

5.2 Part Description

5.2.1 Motor

Specifications covered in this section include:
[R75-II] The motor must be able to actuate a mechanical device.
[R78-II] The motor must be controllable in speed and direction.
[R79-II] The motor must have enough torque to move a finger without resistance.

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The RexoGrip design has changed to using the servo motor HiTec HS-5085MG, rather than the Portescap 26DBM10D2U-L stepper motor. This change was necessary after testing of the stepper motors proved they were unsuitable for our device due to their size and heat output. The switch to this motor resulted to the following modifications to our requirements.

[R76-II] The motor must meet or exceed the performance specifications stated in the manufacturer's datasheet [4].
~~**[R77-II]** The motor must actuate in a linear motion.~~
[R80-II] The motor must ~~be lightweight~~ *weigh no more than 50g*.
[R83-II] The motor must be powered by a ~~12V~~ *4.8V* power supply [4].

The HS-5085Mg servo has a torque of 3.6kg/cm, with an idle current of 3mA and running current 230mA drawn per 60° of movement. These servos operate at 4.8V and also only weigh 21.83g, making them excellent for our use compared to our first choice of the stepper motors. The HS-5085Mg servo motor is shown in Figure 11. The use of this motor satisfies all the requirements listed prior.

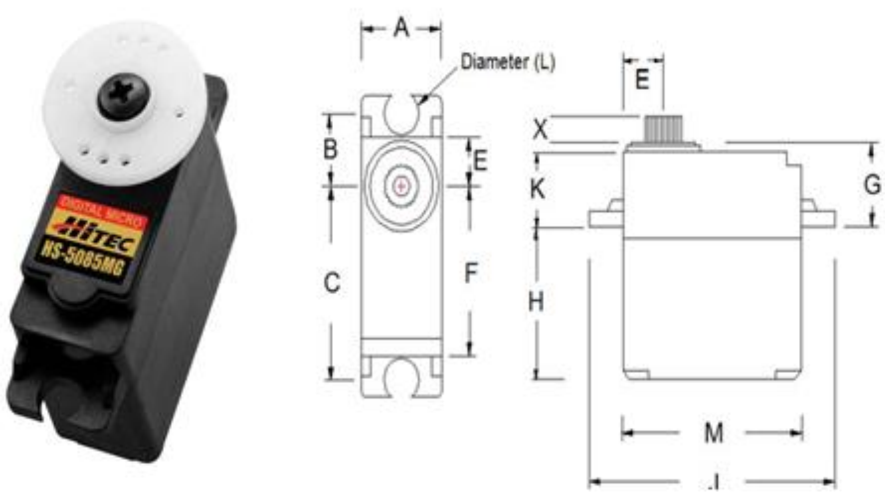

Figure 11 - Servo Motor Diagram

5.2.2 Microcontroller Unit

The microcontroller chosen must meet the following requirements:
[R34-II] The microcontroller unit must be operational as long as it is not turned off manually or its power supply is not disconnected.
[R38-II] The microcontroller unit must have a case to prevent physical damage.
[R57-II] The microcontroller unit must be able to operate in real-time.
[R58-II] The microcontroller unit must be able to accept input from ten analog sensors.
[R59-II] The microcontroller unit must accept up to five simultaneous inputs.
[R63-II] The microcontroller unit must be in an enclosure [5].
[R65-II] The microcontroller board shall use a 9V power supply [6].

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Due to the limitation of time, we will not attempt to implement the thumb in our device. Also, because of the change in motors, the motor shield is no longer necessary, leading to the following revisions in specifications:

[R60-II] The microcontroller unit must output signals to control up to ~~five~~ four motors simultaneously.

~~**[R66-II]** The motor shield shall use a 12V power supply.~~

~~**[R67-II]** The motor shield must be able to supply a minimum of 0.15A per motor.~~

The Arduino Uno R3 was chosen to control all the motors and sensors for the RexoGrip. The Aruino Uno utilizes an ATmega328 microchip to complete instructions executed on the microcontroller. The ATmega328 chip provides 6 PWM channels, 6-channel 10-bit analog to digital converters, and 20 programmable input or output pin lines [7]. The Arduino Uno R3 was chosen due to it fulfilling the minimum PWM channel and input/output pin lines needed.

5.2.2.1 Power

The Arduino Uno (shown in Figure 12**Error! Reference source not found.**) accepts a 6-20V DC input, which is then converted by an onboard 5V regulator. Higher voltages are also accepted but will result in additional head generation on the microcontroller board from the regulator. The USB port connection of the Arduino Uno provides a 5V DC to the microcontroller, delivering a maximum of 1.2A. A 9V source will be used to supply power through the 2.1mm DC barrel jack [6].

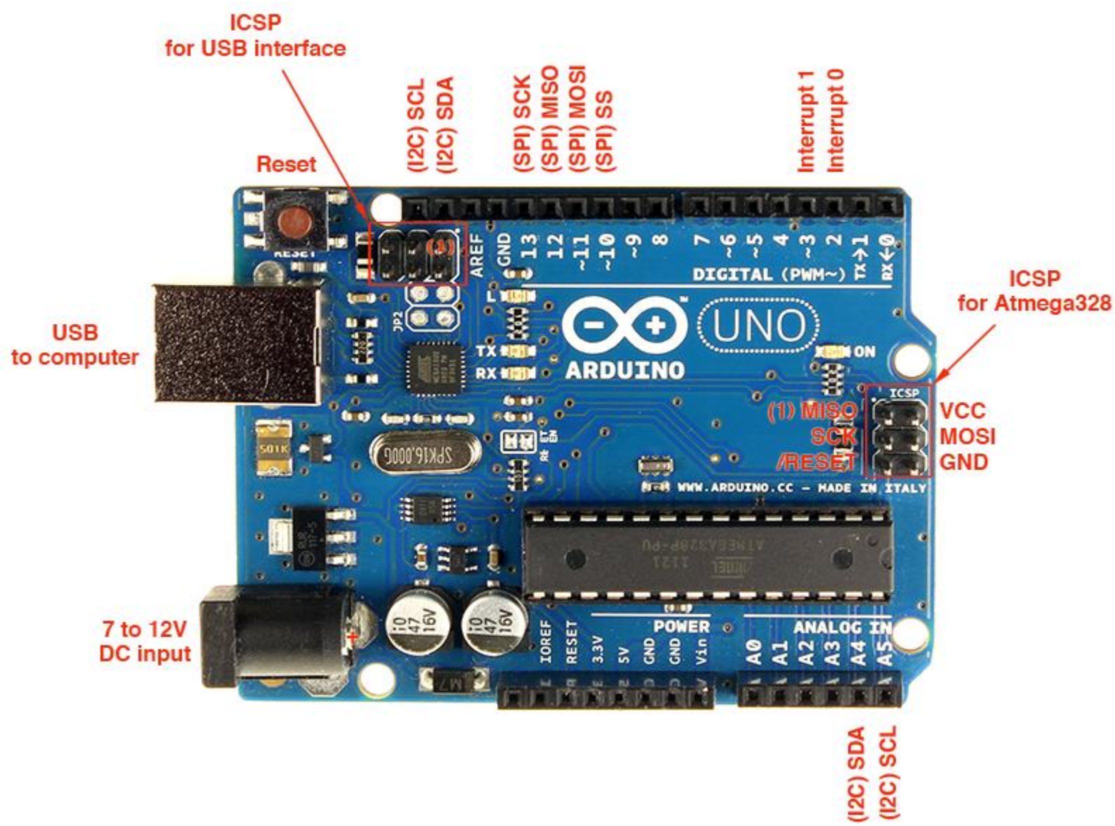

Figure 12 - Arduino UNO R3 Microcontroller Board [8]

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5.2.3 Push Button

[R4-II] The device must have two input sensors per finger, to control upwards movement and downwards movement.
[R46-II] The device must accept pressure sensitive input from the user's finger movements.

To meet these specifications, we chose push buttons as input sensors for the servo motors. The switches chosen are rated for maximums 50mA and 12V DC [9] which is less than operating conditions, and are small form to reduce the overall weight of the device.

Figure 13 - Tactile Button Switch

5.2.4 Power Supply

The following specifications will be addressed in this section:
[R84-II] The power supply should not be an explosive hazard under normal use.
[R85-II] The microcontroller must have a separate and standalone power supply.
[R86-II] The motor control board must have a separate power supply.
[R88-II] The power supply must be easily accessible.
[R93-II] The power supply for the microcontroller must be rated at a maximum of 9V.

The following specifications were slightly reworded:
[R41-II] The ~~battery of the~~ *device* must ~~not have any~~ *be protected* in case of leakage.
[R94-II] The power supply for the motor control board must be able to provide at least ~~12V~~ *4.8V*.

Due to a change in power supply, the specifications below will now be applied to the prototype model only.
[R15-~~II~~ *III*] The power supply shall be rechargeable from a standard wall supply of 120V at 60Hz AC or provide an adapter for international standards.
[R92-~~II~~ *III*] The power supply must be rechargeable.

The RexoGrip proof-of-concept model will use a 9V battery cell as the microcontroller board power supply, as these battery cells are easily obtainable and are cost effective. Additionally, they will have already satisfied the safety standards under normal use. The servo motors and push buttons will be powered by a separate 5V power supply that is independent of the microcontroller's power supply.

5.2.5 Power Switch

[R2-II] The device must have a dedicated on/off switch.
To meet the above specification, simple single pole-single throw rocker switches (as pictured below in Figure 14) will be included in series between the microcontroller board power supply and microcontroller DC barrel jack, as well as between the motor shield power supply and motors.

Figure 14 - Rocker Switch, Power Supply Cut-Off

6 Test Plan

The system test plan for the RexoGrip will comprise of sets of parametric tests and functional tests. Tests will be carried out in a modular approach, first testing individual components of motors and subroutines, and then gradually progressing to whole system tests. This section will describe these tests in detail.

6.1 Unit Testing

6.1.1 Normal Case Tests

Scenario 1. Index Finger Upwards Actuation: The upwards finger sensor will be actuated by the index finger moving upwards, sending the signal to the microcontroller unit. The microcontroller unit will then send the signal to move the motor backwards, causing the frame to pull upwards on the user's index finger. This sequence of actions will continue until the motor activates the motor position limit sensor. The same test plan can be actioned similarly for downwards actuation.

Scenario 2. Multiple Finger Upwards Actuation: Additional tests that use the basic principles outlined in the above test case will be used for this scenario. This case will test the simultaneous upwards actuation of two, three, four and five finger actuation using the sequences of outlined in Scenario 1. The purpose of this test is to ensure the maximum current drawn by all motors can be safety handled by the device.

6.1.2 Extreme Case Tests

Microcontroller Unit to Motor: A specific software plan will be written to implement this test. Upon pressing the reset button on the microcontroller unit, the motor will run a one-time sequence. This sequence will consist of the motor actuating forwards 5000 steps, followed by a 3 second delay, and then actuate 5000 steps backwards to return to the beginning position.

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Force Exertion: A specific hardware plan will be implemented to test for force exertion per finger. Using a load cell, we will move the index finger driven by a motor, and exert a force onto a load cell.

Finger Movement Speed: A specific software plan will be written to implement this test. Upon pressing the reset button on the microcontroller unit, the motor will run a one-time sequence. This sequence will consist of the motor actuating towards the upper movement limit, and then towards the lower movement limit, and then return to resting position. This will repeat 10 times to ensure reliability and repeatability.

7 Conclusion

In this specifications document prepared by Rexos, the proposed design solutions to meet requirements for the RexoGrip have been outlined. By following the concepts outlined in this document as closely as possible, our team will endeavour to ensure the integrity of our final device. The team at Rexos aims to be able to deliver a working proof-of-concept device by April 17th, 2015.

Works Cited

[1] Rexos, "Functional Specifications for a Rehabilitation Exoskeleton Hand Device," 2015.

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