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October 8, 2012

Dr. Andrew Rawicz
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Simon Fraser University
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Re: ENSC 440 Functional Specifications for a Motion-Controlled Manipulator

Dear Dr. Rawicz,

This functional specification document from **MotiCon** is attached with this letter, which summarizes our detailed specifications for our project. In this project, the core idea is to design a system to control robotic arm manipulators by motion sensing of the arm and hands.

In this document, we described in detail the five significant components in the system: the RGB depth sensor and infrared emitter, the software, the hardware (DAC circuit and micro-controller), the user interface, and the robotic arm manipulator. Each requirement will be classified into three classes according on whether it will be on the prototype, on the final product or on both. Managers and engineers will be using this document for further understanding on this project.

MotiCon is composed of six enthusiastic and creative engineering students: Kevin Wong, Kay Sze, Jing Xu, Hsiu-Yang Tseng, Arnaud Martin and Vincent Wong. If you have any question, please feel free to contact us by phone at 778-889-9950 or by email at vpw1@sfu.ca

Sincerely yours,

Vincent Wong
President and CEO
MotiCon

Motion-Controlled System For Multi-Purpose Robotic Arm Operations

Sensor-Based Motion-Controlled Manipulator

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Submitted to: Dr. Andrew Rawicz – ENSC 440
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Executive Summary

> *Some surgeons with extensive robotic experience say it takes at least 200 surgeries to become proficient at the da Vinci and reduce the risks of surgical complications.* [7]

Undeniably, intuition is a powerful aspect in controlling robotic arms such as the "da Vinci" robot, which presents a steep learning curve due to the difficult controls and increases costs for hospitals to train surgeons and to pay for lawsuits from surgical complications [8]. Other robotic hands, such as anthropomorphic, Cartesian, cylindrical and spherical robots for pick-and-place work, also face similar issues with using complicated joystick and button controls.

Our company offers a solution for the users to control their robotic hands, by offering a system to integrate a high-resolution depth sensor to control robotic hands. The benefits of this product are to:

- Offer a simpler method of controlling a robotic arm
- Utilize intuitive hand and arm movements to control manipulators and therefore reduce the learning curve
- Offer a less expensive system by reducing the training fee for companies to train users, due to the system's intuitive controlling method
- Increase the degree of freedom by registering complicated hand movements

As with any project, our functional requirements for our motion-controlled device at **MotiCon** are broken down and prioritized accordingly. Our highest priority is to implement the proof-of-concept system to capture arm movements and relay them to robotic arm. Our medium priority items to be implemented on the proof-of-concept design, which will be on the product design as well. And lastly, the low priority requirements are to fine tune our system to a marketable final product. These three functional requirement tiers represent the three distinct developmental cycles of our system. Furthermore, at **MotiCon**, we will undergo comprehensive and thorough testing to ensure compliance with regulations and guarantee functionally accurate results.

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Glossary

Black Box:	Opaque system for the user, which cannot distinguish or easily access the different parts
CSA:	Acronym; Canadian Standards Association
da Vinci robot:	A surgical robotic arm made by Intuitive Surgical company and designed to facilitate complex surgery using a minimally invasive method
EndoWrist:	A control interface to control the da Vinci robot arm
FAQ:	Acronym; Frequently Asked Questions
FOV:	Acronym; Field of View
Kinect:	A motion-sensing input device by Microsoft, originally built for Xbox 360 game console, used to detect depth and RGB
MCMS:	Acronym; Motion Controlled Manipulator System - is the product of our company
NUI:	Acronym; Natural User Interface
OpenNI:	Open Natural Interaction is the non-profit organization responsible for developing the open sourced development library that we are using
Perfboard:	A thin and pre-drilled standard board for prototyping electronic circuit.
PWM:	Pulse Width Modulation
RGB:	Acronym; Red Green and Blue
User:	An able-bodied person
UI:	Acronym; User Interface

1. Introduction

"As far as the customer is concerned, the interface is the product." - Jef Raskin

As technology advances worldwide, controlling machines becomes increasingly difficult and complex for people. For example, as the number of degrees of freedom increases, so does the number of commands the manipulator has to receive, which increases the steepness of the learning curve and makes controlling less intuitive for users. This is an issue in the industry because companies have to spend unreasonable amounts of money to train their employees to use specific machines.

MotiCon is now offering a way of using an infrared depth sensor to remotely motion-control a robotic arm. This new technology uses the arm motion to precisely control a pre-defined manipulator, which helps users to intuitively control the robotic device. For example, the user would only have to move the wrist in order to change the orientation of the "EndoWrist" on the da Vinci robot, which is far more intuitive than using the corresponding joystick.

Imagine, a world where the only thing the user has to do is show the motion he wants the robot to perform. With our solution, industrial companies can reduce their expenses by adopting the motion-controlled manipulator because workers will easily understand this intuitive new way of controlling. Companies will not have to pay large amount for employees to be trained to their specific robotic implementations. In the medical field, biomedical devices such as the "da Vinci" robot can now be operated by hand motions of the surgeon. And for weak and frail hospital patients, robotic substitute arms can be controlled by small movements to allow hand grips for patients. With this new technology, **MotiCon** can improve the works and lives of thousands of people by transforming a simple motion into complicated robotic arm commands.

The **MotiCon** Motion-Controlled Manipulator System (MCMS) is an integrated system enabling intuitive motion control of various robotic structures by human gesture. The system consists of hardware, software, and firmware that transmit signal to each other to achieve desired physical movement. By sensing the movement of the user-operator, the **MotiCon** can intelligently understand the human motion thru the Kinect depth sensor and send processed command signals to the microcontroller that regulates the voltage to the motors incorporated in the mechanical robotics. The requirements for the **MotiCon** MCMS are described in this functional specification.

1.1 Scope

This document elaborates on the functional requirements of the **MotiCon** Motion-Controlled Manipulator System (MCMS). These requirements carry out the concept, mechanism and brief product design. These requirements will also be followed the detailed design of the **MotiCon** system in the future.

1.2 Intended Audience

The functional specification is written as guideline for every team members of **MotiCon**. The CEO, who should be in charge of project management, would measure the progress of the project development according to the functional requirements. Hardware engineers should follow the requirements as device design goals to apply the system onto all mechanical systems. Firmware engineers should refer to these requirements to assist in control signal transmission between computer and robotics ends through the development phases. Software engineers should properly take the requirements into consideration when developing the image processing and programming part to fulfill the system function of the final product and ensure compatibility between technical part and applications. Application engineers shall use this document to aid in the design of user test trials.

1.3 Classification

Throughout this document, the following convention shall be used to denote functional requirements:

[Rn-p] A specific functional requirement

The letter **n** is the functional requirement number, and **p** is the priority of the functional requirement as denoted by one of three values:

[I] These requirements are high deadline priority and apply to the proof-of-concept system only.
[II] These requirements are medium deadline apply to both the proof-of-concept system and the final production system.
[III] These requirements are low deadline priority and apply to the final production system only.

2. System Requirements

General requirements applicable to **MotiCon** MCMS for a complete system are described in the following sections.

2.1 System Overview

The **MotiCon** MCMS can be modeled as shown in Figure 1.

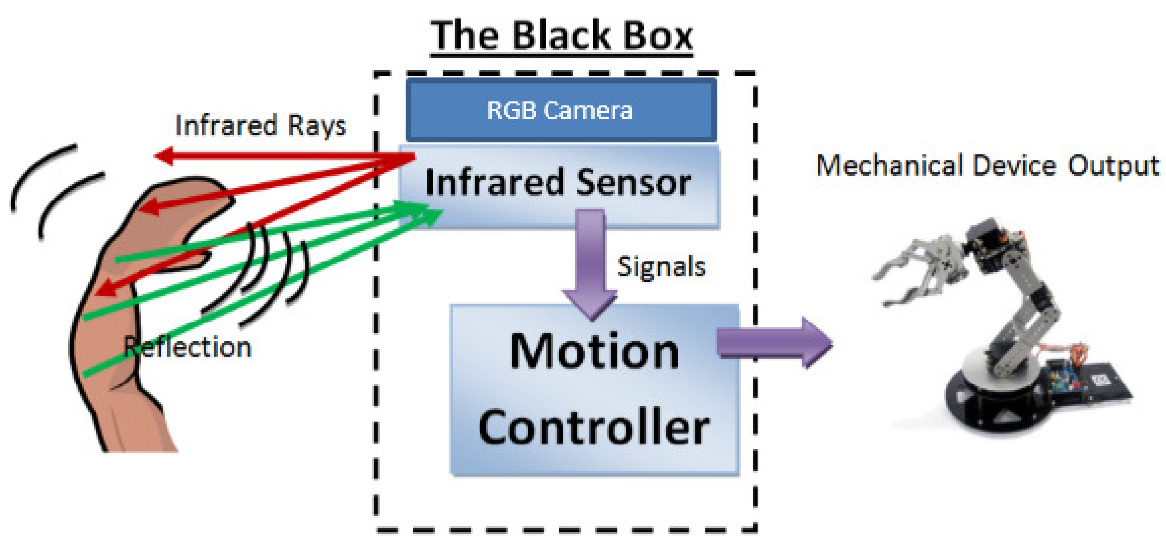


Figure 1: High-Level Model of MCMS

Similarly, a higher level description of the “Black Box” and prototype’s data flow chart is shown in Figure 2.

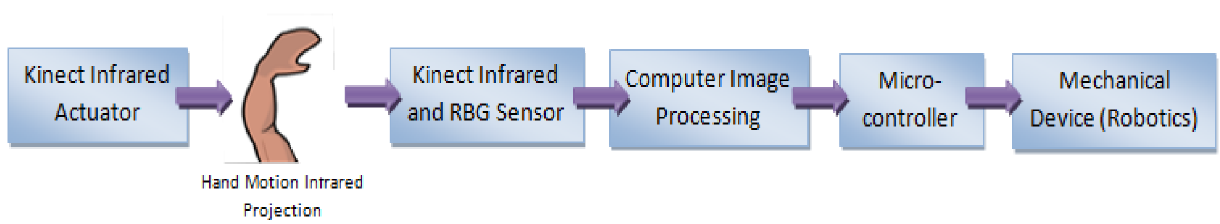


Figure 2: MCMS Black Box Dataflow Diagram

As a first step of the development of our product, **MotiCon** will focus on one robotic arm application will be demonstrated as prototype. The system consists of the infrared sensor, software, microcontroller and user interface for users. The infrared sensor detects shoulder, elbow, wrist and finger joint movements and relays that to the software system. The software program takes the start and end positions, and implements **inverse kinematics concept** to control the robotic arm.

One important aspect of the MCMS is that the user have a highly intuitive user interface to control the robotic hand instead of joysticks and mechanical button controls. The reasons our product will improve the current systems is:

- Highly intuitive
- Decreased steepness of learning curve
- Cost-effective

The motion-controlled manipulator system must accommodate to the defined terms in the glossary, henceforth referred to the User. The User is assumed to physically able-bodied and mentally stable. As suggested by Ergonomics Consultant, how intuitive controlling differs if the User is sitting and leaning with arms on a table, or standing up.

2.2 General Requirements

[R1-III] The final product must be a “Black Box” and modular
[R2-III] The final product must be aesthetically appealing to user
[R3-III] The final product must have visual feedback for user
[R4-III] The system must have an “off state” when the power is off
[R5-III] The system must have an “ready state” when the power and UI is connected
[R6-III] The system must have a UI-friendly menu when “ready state”
[R7-II] The retail price of the MCMS must be under CDN $700

2.3 Physical Requirements

[R8-II] The robotic arm must be able to withstand being rotated in any direction by the user’s range of movements
[R9-III] The construction (i.e. the frame of the product) must be balanced and portable from one location to another by an able bodied person
[R10-III] The dimension of the black box must be 10 inch x 10 inch x 10 inch (i.e. 25.4 cm x 25.4 cm x 25.4 cm) as shown in Figure 3:

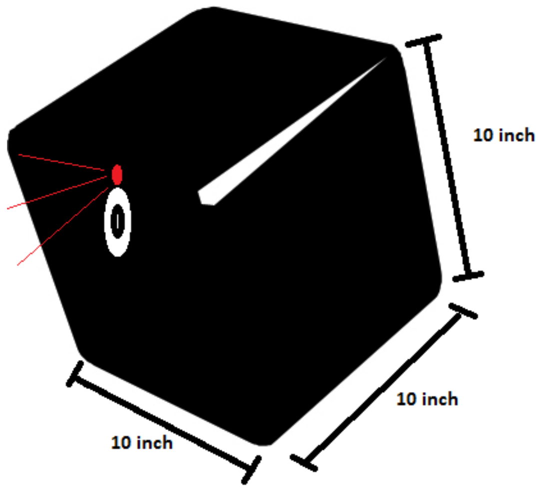


Figure 3: Black Box Dimensions

2.4 Electrical Requirements

[R11-III] The power supply must be portable, self-sufficient and enclosed [1]
[R12-II] Circuits must not have loose or cold-soldered wires
[R13-II] All electronic components must be concealed from physical interference
[R14-III] The final system, excluding the PC, must not require operation more than a single wall outlet with a supply of 110V, 60Hz AC
[R15-II] Prototype board must have accessible test points for trouble-shooting
[R16-III] The power supply must be easily accessible for replacement
[R17-II] The main voltage nodes must be easily accessible for debugging
[R18-II] The power supply must last at least 2 months prior to replacement
[R19-II] Must be electrically-isolated from interfering environmental signals [2]

2.5 Mechanical Requirements

[R20-II] Robotic Arm has to have joint angle feedback sensors
[R21-II] Robotic Arm must have external power sources [3]
[R22-II] Robotic Arm must have maximum power consumption [3]
[R23-II] Robotic Arm must indicate the main type of application [3]

2.6 Environmental Requirements

[R24-II] Microcontroller and circuit board have to withstand high temperature swings
[R25-III] Must remain operable at ambient temperatures between 18-24^{o}C and 50-60% humidity

2.7 Standards

[R26-II] The MCMS will conform to ISO 9946: Characteristics of Industrial Robot Manipulators

[R27-II] The MCMS algorithm will conform to ISO 9787: Coordinate Systems and Motions

[R28-II] The MCMS will conform to ISO 9283: Performance Criteria and methods for testing of industrial robot manipulators

[R29-I] The MCMS will conform to CSA standards [1]

2.8 Reliability and Durability

[R30-II] The system's temperature must not increase above 60℃ with a continuous usage of at least 5 hours

[R31-II] The MCMS must be capable of tracking user movements with a maximum uncertainty of ±30mm

[R32-III] The system performance must not degrade with use and must have an expected life of 10 years with regular maintenance

2.9 Safety Requirements

[R33-II] The MCMS must be equipped with emergency stop which cuts off all electronic power to manipulator in case of emergency

[R34-II] The MCMS power requirements must lie within human safety limits

[R35-III] The MCMS must react appropriately and turn off when software crashes or processor is turned off

[R36-III] The MCMS must detect and clearly indicate mechanical or electrical failure

[R37-II] The electrical components of MCMS must not melt or emit toxic fumes

2.10 Performance requirements

[R38-II] The infrared sensor must detect movement within a minimum of 800 mm and maximum of 4000 mm.

[R39-II] For ranges up to 50cm, the depth resolution is at most 1.5 mm and at the range of 5 cm, the depth resolution is at most 5 m.

[R40-III] Horizontal resolution has to be 640 x 480 and 45 degrees vertical FOV and 58 degrees horizontal FOV

[R41-II] There should be minimal delay between the response of the robotic arm to arm movements

2.11 Usability Requirements

[R42-II] The MCMS must have intuitive GUI to specify parameters

[R43-II] The user must not require personal protection equipment to operate the system

[R44-I] The system must be usable by one able-bodied person

3. RGB Depth Camera and Infrared Emitter

The RGB depth camera detects color with a normal CCD sensors and depth with infrared sensors. By using the infrared emitter which emits invisible infrared light and measuring how long the light takes to return after reflecting off the object, the depth of the object away from the sensor can be measured. The depth camera and emitter must be small and modular enough to be designed into the "Black Box" structure and effective to capture motion.

3.1 General Requirements

[R45-III] Must cost less than $100 for an RGB Depth Camera and an Infrared Emitter

[R46-III] Must be able to capture with high resolution of at most 1.5 mm at range of 5cm, if not lower.

[R47-III] Must be able to capture accurate movements while in a vibration test

3.2 Physical Requirements

[R48-III] Both sensor and emitter must be compact, not exceeding 4.25 inch x 1.30 inch x 1.02 inch

[R49-III] Both sensor and emitter must be light weight, not exceeding 7.41 oz or 0.13 kg

3.3 Electrical Requirements (Based on Kinect sensor)

[R50-III] Powered by single USB 2.0 (i.e. power less than 2.5W)

[R51-III] Frame rate is at least 30 fps

[R52-III] FOV must be at least 73^{o}diagonal

[R53-III] Range is at least 6 inch to 3.25 feet

3.4 Safety Requirements

[R54-III] Infrared emitter must not exceed 950nm/7 mW [4]

[R55-III] Level of exposure directly in eye of personnel must not exceed $10mW/cm^2$ [4]

4. Software Program

The primary functionality of the software is to compute and deliver accurate values representing the positioning of the natural interface, which will include the segment angles corresponding to each of the user's joints. The Infrared (IR) light source is configured to emit a diverging beam, and therefore the resolution becomes worse and worse as the user's distance to the source increases. With low resolution for signal acquisition, the uncertainty for tracking user movements increases proportionally. In order to resolve this issue introduced by the Infrared light source and acquisition system, numerical compensation can be implemented to correct for errors in motion tracking. Such compensation algorithms can include filtering of high frequency movements, or averaging multiple samples of data to increase greater signal to noise ratio (SNR).

4.1 General Requirements

[R56-II] Measurement of distance between the center of the user's palm and the user's should joint must be accurate to within ±2.0% of the absolute length

[R57-II] Must filter out motion frequency components greater than 4 Hz

[R58-II] Must establish proper serial connection to one or multiple microcontroller via the Universal Serial Bus (USB) ports.

[R59-II] Must calculate the corresponding scaled values in voltages to be sent to the microcontroller for accurate operation of the manipulator

[R60-II] Calculated voltages values must be averaged over 3 samples before being sent to the microcontroller

5. Hardware

The hardware packaging of our system consists of a microcontroller to output controlling signals to the motors and to receive feedback signals of the robotic arm joints, and a digital-to-analog circuit. The circuit will consist of a separate power supply, feedback circuitry and DAC circuitry, all hooked to the microcontroller. In order to fit the requirements of a lightweight portable “Black Box” system, the hardware packaging must be as compact as possible and be rugged enough to withstand vibration or physical abuse.

5.1 Microcontroller

5.1.1 General Requirements

[R61-II] The microcontroller will have at least two times more outputs as the number of actuators on the manipulator

[R62-II] The microcontroller will have at least as many analog inputs as sensors on the manipulator

[R63-III] A cooling system must control the heat flow

5.1.2 Electrical Requirements

[R64-III] The microcontroller must be isolated from external interferences

[R65-II] The output currents should never exceed the limit values of the microcontroller

[R66-I] The microcontroller should be powered by the computer performing image processing through an USB cable

[R67-III] The microcontroller should use the same power source as the other electrical components of the product

5.1.3 Performance Requirements

[R68-I] All the manipulator’s actuators should be controlled in a limited time

[R69-I] The microcontroller must communicate with the computer performing the image processing through a USB cable

[R70-III] The microcontroller should be able to perform image processing and actuators controlling

[R71-II] The microcontroller will receive the analog output of the manipulator’s sensors

5.1.4 Usability Requirements

[R72-III] The microcontroller’s software should be easily modified or updated only by qualified personnel

[R73-II] The microcontroller should be easily accessible in case of fixing or updating

5.2 Circuit

5.2.1 General Requirements

[R74-III] All elements of the circuit must be precisely and definitively soldered on a PCB

[R75-I] All elements of the circuit must be precisely soldered on a perfboard

[R76-II] The boards must be stabilized into the entire system and hold on vibrations and displacements

5.2.2 Electrical Requirements

[R77-III] The circuit components must be isolated from external and internal interferences

[R78-II] The electrical power required by the actuators must be supported by all elements subjected to it

5.2.3 Safety Requirements

[R79-III] The circuit must be secured for the user due to the high level of currents

6. User Interface Unit

Intuitive operability of the Natural User Interface (NUI) is key to the application design and usability. The interface will be purely controlled by motion and gestures of the user and the system will provide visual feedback of manipulator orientation.

6.1 General Requirements

[R80-I] The system will produce a visual feedback with a display resolution of at least 640x480 on the user monitor for viewing real-time orientation of robotic device

[R81-I] The NUI will provide a display window with resolution of at least 640x480 showing User's real-time tracking status

[R82-II] The tracking window will additionally contain a menu controlled by the user's left hand

[R83-II] The NUI features will contain three options: Start Tracking, Stop Tracking, and Recalibrate

[R84-II] The Menu List will consist of three options: save mode, load previous path, real-time

6.2 Usability Requirements

[R85-II] Height of the user must be greater than 900mm, and must be smaller than 2500mm

[R86-I] User must be standing at a range of 500mm to 3000mm from the IR Sensor, as displayed in the following figure

[R87-I] User must operate in a spatial volume with a size of at least $2m^3$, as shown in the following figure

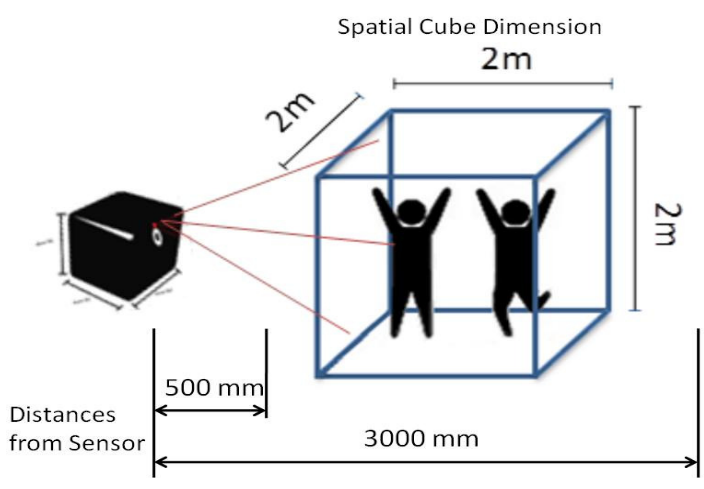


Figure 4: User Spatial Volume Distance and Dimension Specification

7. Robotic Arm Manipulator

The robotic arm manipulator functions to demonstrate our system and to further incorporate the physical actuation in real time. The robotic arm must meet the following specifications to ensure optimal integration with our system.

7.1 General Requirements

[R88-II] The robotic arm has no dangerous part, such as sharp, hot or squeezing parts
[R89-II] Strong attachment between assemblies of parts
[R90-III] Maximum loading or weight us clearly stated

7.2 Electrical Requirements

[R91-II] All actuators' maximum speed can follow the human arm motion
[R92-III] All actuators' resolution can operate desired tasks
[R93-II] Power cords and connections are safely insulated

7.3 Mechanical Requirements

[R94-II] The robotic arm must have a horizontal reach of 12.6 inches or more
[R95-II] The robotic arm must have at least 5 degrees of freedom
[R96-II] The robotic arm must be able to do a lifting capacity of 100g or more

8. User Documentation

The User Documentation will provide our customers on step by step detailed guidance on how to operate the MCMS and the program installed in the final product, requiring only a small learning curve for the user to become accustomed with how to operate the whole system.

8.1 General Requirements

[R97-III] All manuals will be in English, French, Chinese and Spanish

[R98-III] Instructions are described for audience without any engineering or scientific background

[R99-III] Pictures, flow charts and tables are provided for further explanation

8.2 User Manual Requirements

[R100-III] The user manual shall teach the user how to connect and operate the device

[R101-III] The user manual shall educate user proper care of the device

[R102-III] The safety guide section should provide user potential harms and warnings of using this device

[R103-III] Troubleshooting and FAQs sections should be presented at the end part of the user manual

8.3 Hardware Manual Requirements

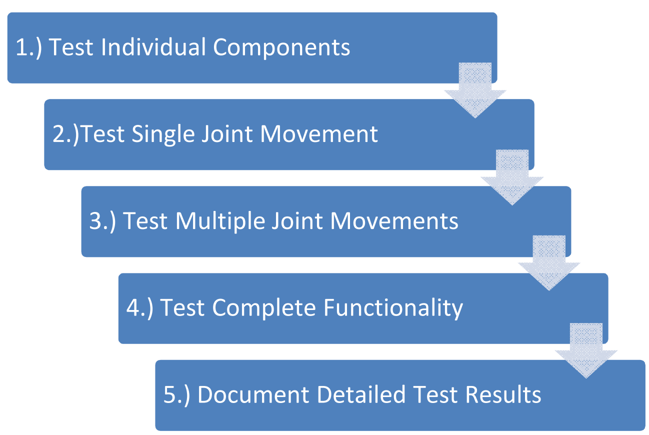
[R104-III] A quick guide about how to connect and operate of the robotic arm and the black box kit

[R105-III] A safety guide should be provided to explain the potential harms and warnings of the robotic arm

9. System Test Plan

To ensure a fully functioning prototype, **MotiCon** intends to implement a rigorous test plan in order to test individual modules, the final prototype and the final product. Module tests will be conducted on the RGB depth sensor and infrared emitter, software SDK, hardware, user interface, and robotic arm manipulator throughout the development process to verify basic functionalities and each module connects properly. Once the basic capturing of one-joint movements to relay robotic movement is completed, we will begin developing for multiple joints and testing each movement as a complete set. We will begin testing trivial scenarios such as moving the shoulder joint, elbow joint, wrist joint and gripper. Once the basic range of movement and velocity has been confirmed, the finished prototype and product will be put through a series of realistic scenarios that simulate the professions of the intended users, such as grabbing small objects.

Our test plan will go as follows:



9.1 Individual Component Testing

Individual module testing will be performed on each aspect of the project as they are completed. These tests include, but are not limited to the following.

RGB Depth Sensor and Infrared Emitter

- Ability to capture depth and RGB signals of a moving subject in real-time
- Ability to capture a subject with an acceptable resolution depth
- Ability to capture a subject within an acceptable range

Software

- Ability to calculate joint angle values
- Ability to use inverse kinematics mathematic to solve movements
- Ability to output correct signals to be converted to analog voltage on motors

Hardware

- Ability to convert the PWM digital output to high-current analog voltage for DC motors
- Ability to detect robotic arm position by servo control, and to compensate for uncertainties in motion thereof

User Interface

- Ability to select parameters prior to controlling robotic arm
- Ability to provide users with visual feedback for robotic arm position

Robotic Arm

- Ability to move accordingly to the human hand
- Ability to perform movement from start to end point using inverse kinematics
- Ability to pinching motion

This test will also test to make sure after integration of the components; one joint movement can be relayed to the robotic hand.

9.2 System Integration Testing

After integration, this test is to ensure each component is fully functioning to relay any sensor-detected arm movements to be relayed to robotic arm movements.

9.3 Typical Usage Scenario

The robotic arm will be tested to pick up various objects, such as to pick up the following objects:

- Pencil
- Screw drivers
- Books
- Box

Also the robotic arm will try to perform hand gestures made by the user.

10. Conclusion

The motion-controlled manipulator is offering a new way of controlling a variety of robotics, from simple excavators to more complicated machines, such as the “da Vinci” surgical robot. This document provides clear and concise requirements with regards to each specification of the motion-controlled manipulator; qualitatively and quantitatively. Relevant federal and international standards have been referenced to demonstrate that our project operates in accordance with the regulations concerning the safety, health and welfare of the general public. Following this strict set of guidelines, each member of our company is excited and enthusiastic in developing a simple and intuitive manipulation system which may one day redefine the existing user interfaces in the control and operation of robotics.

11. References

[1] Canadian Standards Association International, "CSA C22.2 NO 60950-1-07-CAN/CSA Information Technology Equipment Safety Part 1", Canadian Standards Association, Mar. 2007

[2] International Electrotechnical Commission. *IEC 60601-1:1988 Ed.2.0 Medical electrical equipment – Part 1: General requirements for basic safety.* London: International Electrotechnical Commission, 1988.

[3] International Organization for Standardization, *ISO 9946:1999 Manipulating industrial robots – Presentation of characteristics*. Geneva, Switzerland: International Organization for Standardization, 1999.

[4] International Electrotechnical Commission. *IEC 60825-12:2004 Ed. 1.0 Safety of Laser Products.* Geneva: International Electrotechnical Commission, 2004.

[5] Borenstein, Gregg. Making Things See: 3D Vision with Kinect, Processing, Adruino, and Makebot. O'Reilly. Media Inc. 2012.

[6] Gyung Tak Sung, Inderbir S Gill, Robotic laparoscopic surgery: a comparison of the da Vinci and Zeus systems, Urology, Volume 58, Issue 6, December 2001, Pages 893-898, ISSN 0090-4295, 10.1016/S0090-4295(01)01423-6.

[7] Barocas, Daniel A. et al. Robotic Assisted Laparoscopic Prostatectomy Versus Radical Retropubic Prostatectomy for Clinically Localized Prostate Cancer: Comparison of Short-Term biochemical Recurrence-Free Survival. 2009. Vanderbilt University Medical Center: Nashville Tennessee, USA.

[8] Gyung Tak Sung, Inderbir S Gill, Robotic laparoscopic surgery: a comparison of the da Vinci and Zeus systems, Urology, Volume 58, Issue 6, December 2001, Pages 893-898, ISSN 0090-4295, 10.1016/S0090-4295(01)01423-6.
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