31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Design and Development of an Upper Extremity Motion Capture System for a Rehabilitation Robot

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Abstract— **Human robot interaction is a new and rapidly growing field and its application in the realm of rehabilitation and physical care is a major focus area of research worldwide. This paper discusses the development and implementation of a wireless motion capture system for the human arm which can be used for physical therapy or real-time control of a robotic arm, among many other potential applications. The system is comprised of a mechanical brace with rotary potentiometers inserted at the different joints to capture position data. It also contains surface electrodes which acquire electromyographic signals through the CleveMed BioRadio device. The brace interfaces with a software subsystem which displays real time data signals. The software includes a 3D arm model which imitates the actual movement of a subject's arm under testing. This project began as part of the Rochester Institute of Technology's Undergraduate Multidisciplinary Senior Design curriculum and has been integrated into the overall research objectives of the Biomechatronic Learning Laboratory.**

I. Introduction

The interaction and interfacing of humans, specifically people with certain disabilities, with robots as a technique for rehabilitation is gaining momentum [1], [2], [3]. Different populations of patients require varying systems or instruments for use from a therapy or rehabilitation standpoint. For our study, two specific groups are of interest.

The first group of people experience weakening of core muscles that are responsible for movement of the human body. This phenomenon is commonly known as muscular dystrophy. The skeletal muscles weaken progressively and over time due to cell and tissue degeneration [4], [5].

The other group of patients has a problem of handedness [6]. Handedness arises due to uneven distribution of detailed motor skills between the right and left hands in humans. Most people have right-handedness, i.e., their right-hand is better at performing tasks than their left hand. Ambidexterity is a rare occurrence, but it can be learned using appropriate methods.

The motivations for the development of an upper extremity motion capture system arise from the goal of studying these two populations of individuals. Previously, bioinstrumentation systems have been developed to evaluate the interaction between human and robots [7], [8]. We would like to create a system that captures the upper extremity motion of a patient having a motor disability via physiological and biomechanical signals extracted from the patient's muscles. These signals can then act as commands for controlling and teleoperating a robot arm which could successfully perform a task the patient is unable to perform. Additionally, we would like to observe if after using this system, a person with a particular type of handedness can be trained to increase their dexterity. Such a system could help improve their upper extremity functional capabilities.

In order to study motion as it relates to the human robot interaction issues in rehabilitation, and to successfully study the population of patients described above, an upper extremity motion capture system has been developed. The goal was to design a biomechatronic system having the ability to capture electromyographic (EMG) signals from the muscles of the human arm as well as position data of the joints.

Five main requirements were identified in the initial stages of the design of the project. These were:

- Four muscle groups required for measuring EMG activity
- Velocity measurement of limb movements
- Elbow angle, shoulder angle and angle between arm and body to be measurable
- Device should have 3 degrees of freedom
- Visual display of real time data with graphs

The complete system with a test subject is displayed in Fig. 1.

The system composition includes three functional blocks: the mechanical, electrical, and software subsystems. The brace subassembly and platform subassembly form the mechanical block of the system. The brace is designed such that the electrical subsystem is integrated with it. The motion sensors identified during the project concept selection phase were rotary potentiometers which are integrated at the shoulder and elbow joints of the brace. Electric wires from the potentiometers are run through the brace and connect to a printed circuit board (PCB). The CleveMed BioRadio device [9] which is used for measuring surface

Manuscript received June 19, 2009. This project is supported by a grant from the Semiconductor Industry Association and by the National Science Foundation under Award No. IIS-0748418.

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electromyographic (sEMG) signals, connects to surface electrodes which are routed in a similar fashion as those associated with the rotary potentiometers and the PCB. A casing was selected and is placed on the platform subassembly at a specific location. The BioRadio is clipped on one side of the casing while the PCB and batteries are contained inside it.

The software subsystem addresses the visual display requirement. Signals are acquired from the BioRadio through a network interface and real time data is then displayed on a user friendly GUI.

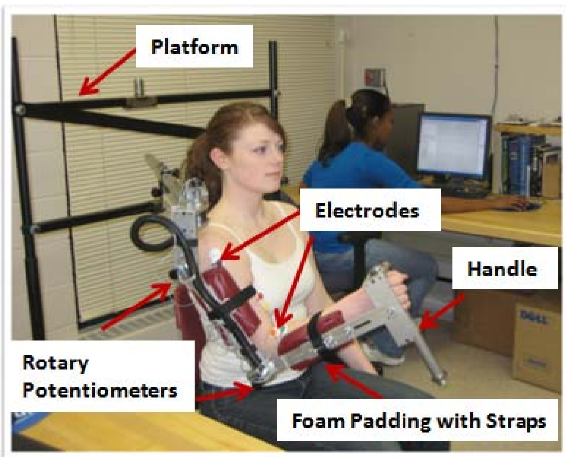

Fig. 1. Upper Extremity Motion Capture System.

II. Concept Selection of Sensors

A. Surface Electromyographic Sensors

A design requirement of the system was to assess upper extremity motion using physiological information. To meet this requirement, surface electromyographic sensors were used to evaluate and record muscle activity while a subject performed upper arm exercises. A number of different muscle groups [10] were researched to understand which would be the most important for us to target in accordance with the goals and objectives of the project. Upper arm movement is governed by the deltoid while the primary muscles for extension and flexion of the lower arm are the triceps and biceps. Lastly, the brachioradialis was chosen to be monitored as it assists the biceps and triceps muscles for movement of the forearm.

Interfacing between the device and the human body is achieved using surface dual electrodes. Electrodes were placed at the belly of each muscle, away from the innervations zones. Adjustments to the electrode placement were made if the signal was deemed too weak to be useful for analysis.

B. Motion Sensors

A 2nd design requirement was to use biomechanical information to assess motion. Several different motion sensors including accelerometers, gyroscopes, optical encoders, and potentiometers were evaluated. Considering our specific goals, signal processing, mechanical integration and position accuracy were our most important criteria. Each motion sensor was rated, and it was determined that the potentiometers suited our purposes the best.

Further analysis revealed that rotary potentiometers were the most appropriate for the project. The rotary potentiometers used are single-turn conductive plastic with a resistance of 10k ohms and +/-1% linearity tolerance with a life expectancy of 10 million cycles.

III. System Design and Development

A. Electrical Design

The motion sensors require a constant voltage supply at all times which is accomplished using two voltage regulators. A 9V battery powers the circuit, and the voltage regulators reduce the 9V signal to 2V and 4V signals. The CleveMed BioRadio accepts differential inputs limited to a range +/-2V. In order to fully utilize the input ranges of the BioRadio, the potentiometers are powered by 4V which allows the wipers of each potentiometer to swing from 0 to 4V. One differential input of the BioRadio is then connected to the wiper of the potentiometer. The other input is connected to a virtual ground which is created by the 2V offset coming from the second voltage regulator. This setup ensures that as long as the potentiometer's wiper varies between 0 and 4V as desired, the input of the BioRadio will read anywhere between -2V and +2V.

B. Mechanical Brace

The brace subassembly is designed to fit the 95th percentile of both the female and male population [11]. The basic components of the brace include the lower arm and upper arm sections that are hinged at the elbow joint to lock them together; the hand grip attached to the lower arm section; foam padding on the lower arm which was added for safety and comfort of the test subject; and lastly, the 2-axis shoulder joint. The three rotary potentiometers are integrated such that one fits at the hinged elbow joint, while the other two fit at the shoulder joint. A Solid Works model of the brace exhibiting the integration of the rotary potentiometers is shown in Fig. 2.

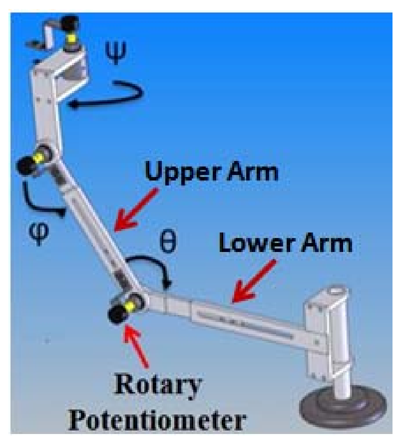

Fig. 2. Brace subassembly highlighting the major components.

C. Mechanical Platform

An additional requirement for our system was that a subject should be able to undergo testing while sitting or standing. In order to satisfy these conditions, a platform was designed to which the brace could be attached. During the concept development phase, some basic requirements of the platform were identified to be: (1) height adjustability, (2) portability, (3) compatibility with a wheelchair, and (4) provide left and right hand functionality. The actual designed platform meets all the above mentioned requirements.

D. Software Subsystem

All the software coding has been done using C++ and the development has been done in a cross-platform application framework called Qt [12].

The development of the software was done in four different stages. The first stage was to create the software – hardware interface. The next stage was to acquire data from the BioRadio and display the data in graphical form. The third stage was to develop an arm model which could render to a 3-D matrix array to depict the angles of the brace movement. The 3-D design of the human arm is obtained using a mathematical arm model consisting of rotation transformation matrices. The model uses the different angles measured by the potentiometers as its input variables and outputs the elbow and wrist coordinates in Cartesian form. θ represented the joint angle at the elbow formed by the lower and upper arm, while φ consisted of the angle at the shoulder, created by the torso and the upper arm. Finally, ψ was the rotational angle at the shoulder, depicting the rotation of the arm in the transverse plane.

The transformation matrices used for the elbow and wrist respectively are:

$$\begin{bmatrix} \cos\psi & -\sin\psi\cos\varphi & -\sin\psi\sin\varphi \\ \sin\psi & \cos\psi\cos\varphi & \cos\psi\sin\varphi \\ 0 & -\sin\varphi & \cos\varphi \end{bmatrix} \quad (2)$$

Elbow Matrix

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \quad (3)$$

Wrist Matrix

Using these matrices and coordinates, an algorithm for calculating the new coordinates are incorporated in the software code.

The final stage for the software development was to program the actual Graphical User Interface (GUI). Using Qt, all the menus, the different buttons, and the data displays are developed. The components of the menu bar are as follows:

- New Session – allows the user to create a new session
- Open Session – allowing the user to open an existing session
- Channel Window – user gets to select the channels to be overlaid on the desired channel window
- Animation – allows the user to see the animation of the arm model
- Filters – allows the user to select a filter to process the raw data

Also, the GUI has buttons which are described as follows:

- Change Capture – replay data saved before
- Start – enables user to start collecting data from the channels being graphed
- Stop – ends recording of data
- Mark – allows the user to set a marker at any location on the data

The graphs are integrated into the GUI such that a user can view data collected from all 8 channels of the BioRadio. These graphs can be overlaid if someone wants to see the motion and muscle data together.

IV. Evaluation of the System

Each independent subsystem was evaluated to ensure all specifications were met satisfactorily.

For the mechanical subsystem, joint smoothness, length adjustability of the brace, comfort of the brace, and stability of the platform were key test measures. 3 male and 3 female subjects with varying arm lengths were successfully fitted to the brace. Each test subject wore the brace for at least 30 minute durations. None of the subjects experienced discomfort when wearing the brace.

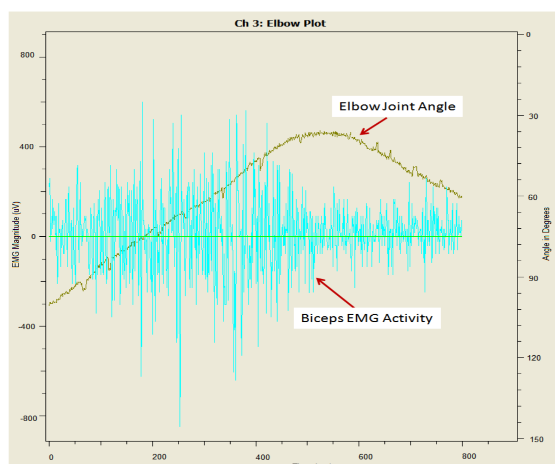

Fig. 3. Screen Shot of GUI Demonstrating Angle Data Overlaid on EMG data.

The developed GUI is robust and entirely functional. There is no visible delay between a subject's movement and data display in the GUI. All the front window buttons and menu bar options in the GUI which allow the user, for example, to save the data, calibrate the system, or process the raw data, execute appropriately and direct the user to the correct links. The graphs accurately overlay data as shown in Fig. 3 above, where each panel depicts an angle reading along with the corresponding EMG signal. The left axis measures the EMG signal in microvolts while the right axis measures the elbow joint angle in degrees. As the plot shows, EMG activity increases as the biceps muscle is flexed and the elbow joint position changes from 150° to 30°.

It was important to keep track of the dead-zone of each of the rotary potentiometers. We verified that the voltage at each of the joint extremes was either below 2V or above -2V ensuring that the dead-zone is never encountered.

Along with these specific evaluations, the performance of the system is highly dependent on the accurate calibration of the position of the joints. Each joint position was calibrated using the *calibrate* function in the GUI, and a goniometer was used to manually measure the joint angles to be inputted into the software as known angles. Three test subjects were used for system calibration. The angles measured manually were compared with those calculated by the software GUI. Matching results were obtained for 95% of the angles tested while others were within the tolerance of ±5°. Fig. 4 below

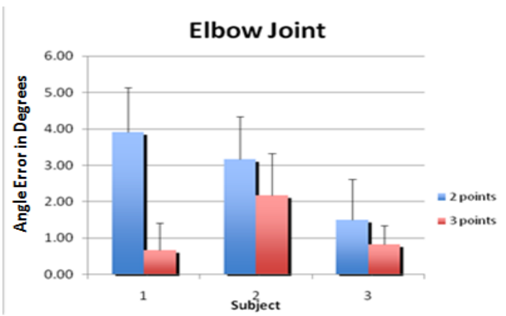

Fig. 4. Plot of Elbow Joint Calibration Testing.

depicts the summary of the elbow joint calibration testing as an example. Data is collected from three test subjects. For each test subject, calibration was performed using two or three known angles. Five other angles were then tested, and the error between the measured angle and the actual angle was tabulated for all the test subjects. The average of the five errors is plotted on the *y*-axis. The line above every bar in the plot above represents the standard deviation. As an example, for test subject 1, when calibration was done using two known angles, the average error in measurement was 4° while the standard deviation was ±1°. For three known angles, the average error was 0.6°, while the standard deviation was also ±1°.

V. Discussions and Conclusions

We have successfully developed an upper extremity motion capture system which obtains EMG data from four muscle groups of the upper arm and joint angle data using three rotary potentiometers. The system satisfies the requirements and specifications desired for future applications. The system has been tested and evaluated for functionality and robustness. So far we have used it to collect joint angle and EMG data to make preliminary correlations between an EMG signal and the angle of motion during arm reaching movements in the sagittal plane [13]. The velocity/acceleration of the arm during any movement is also expected to be correlated with the EMG signal. We hope to study that correlation through ongoing projects undertaken in the lab.

VI. Future Applications

A number of different applications are currently being assessed and evaluated. Eventually the goal is to obtain real-time control of a five degree of freedom harmonically driven robot arm using the EMG signals and angle data captured by our system as control commands.

As mentioned earlier, our target population for test subjects is a mixed population of patients having muscular dystrophy and handedness issues. We would like to see if it is possible to achieve relatively accurate teleoperation of a robot manipulator using a weak EMG signal from a patient with muscular dystrophy. If control is possible, the harmonic arm can reproduce the desired motion of the patient in order to assist him/her. Similarly, for patients with handedness, we would like to observe if we can train the non-dominant hand to obtain more accurate movements and hence more precise control. A system of this nature creates a testbed for developing more intelligent orthotics for individuals with similar neuromuscular disabilities.

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