A Two-Bit Binary Control System for an Orthotic, Hand-Assistive Exoskeleton

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***Abstract*—A combined 450,000 Americans suffer from multiple sclerosis, chronic carpal tunnel syndrome, and muscular dystrophy; debilitative disorders that result in a loss of muscle strength and dexterity within the afflicted individual. A controlled orthotic exoskeleton presents a solution by amplifying a user's residual strength to restore precision pinch and/or power grasp motions. In order to optimize system response time and control accuracy, a two-bit binary state control algorithm was designed using LabVIEW v8.5. The states of the control system were refined using positional and object-sensing information supplied via negative feedback from Hall effect angular sensors and force sensing resistors. Forearm EMG was recorded and used to characterize hand strength with and without the mechanical assistance generated from the hand-assistive exoskeleton. The control system was tested using simulated sensor feedback data and has proven to be a robust design. The controller will be integrated with a glove-like, hand-based exoskeleton. The complete system was designed to restore hand functionality through the amplification of precision pinch and/or power grasp.**

I. INTRODUCTION

A combined 450,000 Americans suffer from debilitative disorders, such as multiple sclerosis, chronic carpal tunnel syndrome, and muscular dystrophy, which result in a loss of skeletal muscle strength and dexterity. An orthotic hand-assistive exoskeleton presents a non-invasive treatment as compared to surgical and/or pharmacological methods. Controlled by the user's residual strength, the glove-like exoskeleton allows a previously disabled individual to better perform tasks such as a precision pinch and/or power grasp (i.e. opening a door and maintaining desired prehensile forces on an object). While the power grasp functionality was achieved through the mechanical aspect of the device, the restoration of dexterity and the achievement of synergistic motion lie primarily within the device's control algorithm.

Currently there are two predominating controller methodologies: binary and variable. The majority of binary control algorithms operate such that all system outputs exist between two states, usually an 'ON' state and an 'OFF' state. The controller reads the input signal, checks it against a predefined threshold, and sets the output state accordingly. A binary control algorithm that was utilized in the development of another hand exoskeleton was found to allow for faster object interactions through increased system response times, but at a cost of a decrease in control precision. This was readily noticeable in cases of pinching more delicate objects [1].

Variable control designs relate system output signals proportionally and linearly to input control signals. Saturation of the output occurs if the input signal falls outside of a predefined range. In contrast with binary control, variable control systems exhibit a relatively greater level of control precision for more delicate objects; however this was contrasted with a slower response time when compared to other binary algorithms.

Our objective was to design a digital control system with the benefits of binary and variable control architectures. Our design uses feedback from force resistors and angle sensors to modulate motor control in order to more effectively model the natural control of the human hand.

II. CONTROL SYSTEM ALGORITHM

A. *Two-Bit Binary Input Controller*

A binary control algorithm effectively operates as a $N+1$ state controller with N being the number of thresholds used (in the binary case $N=1$ and for variable $N=\infty$). In order to improve system response time and control accuracy as compared to a simple binary controller, the state limit was set to four ($N=3$). As a result, the two-bit binary control algorithm consisted of four levels of flexion and extension control with thresholds based off the maximum value of the input signal (Fig. 1).

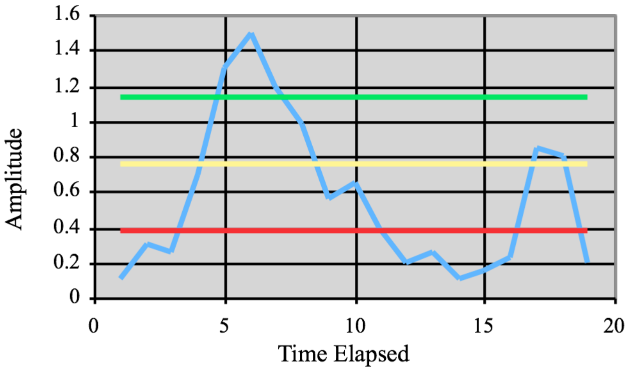

Fig 1. Graphical illustration of a two-bit binary control algorithm. The control signal (shown in blue) is subdivided into four distinct regions by the thresholds (shown in green, yellow, and red).

B. *Joint-Angle and Palmar Resistance Controller*

We attempted to mimic the natural physiology of the human hand by incorporating negative feedback from joint-angles and palmar resistance measurements. Joint angles are continuously measured by the digital control system and compared against a set of pre-defined regions. If a single joint angle existed outside of its predefined range, then all system output states would be forced to zero, preventing any system output that could result in phalangeal hyperextension.

In addition, resistance measurements from the palmar side of the hand were quantified to detect the presence of an object. These resistance measurements were grouped based on their applicability to either the precision pinch or the power grasp. If a resistance measurement surpassed a pre-defined threshold, then the flexion output states would be reduced accordingly to allow for more accurate control of delicate motions.

III. HARDWARE AND FEEDBACK

A. *Digital Control System*

The two-bit binary control system was implemented for the index finger, thumb, and the remaining finger group (Fig. 2) on a laptop computer using LabVIEW v8.5. The orthotic, hand-assistive exoskeleton control system contained 23 analog inputs, 4 analog outputs, and 4 digital outputs. A virtual interface displayed on the laptop computer allowed for real-time viewing of all input and output signals.

B. *Position and Force Feedback*

To achieve accurate measurements for flexion and extension data, force sensing resistors (FSR) are placed on both the ventral and dorsal sides of the tips of both the index finger and thumb. FSRs are also attached similarly to the ring finger providing an overall characterization of the flexion and extension data of the middle, ring, and small finger group. To increase movement accuracy of the index finger, FSRs are attached to the ventral and dorsal sides of its proximal phalange.

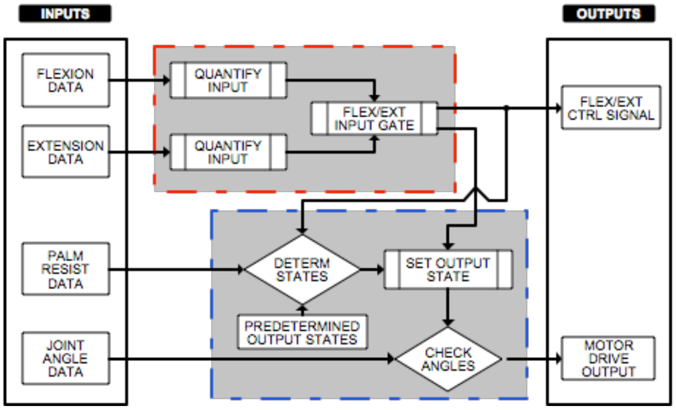

Fig 2. Control system operational flowchart per motor driven output. Input controller (red) and output controller (blue) shown respectively. Note that the 'Flexion/Extension Control Signal' is a digital output that defines the direction for each motor drive signal.

To sense palmar resistance data, FSRs located on the palm were divided into two groups: precision pinch and power grasp groups. The precision pinch group consisted of 2 FSRs located on the index finger and thumb. The power grasp group included the precision pinch grouping and an additional 4 FSRs located on the middle, ring, and small finger group and lower portions of the index finger and thumb exoskeletal extensions. To measure joint angles, Hall effect sensors were attached to all finger joints on the exoskeleton.

C. *Strength Analysis*

The ability of the hand-assistive exoskeleton to assist a power grasp will be quantified through the recording of the electromyography of the forearm muscles. The ratio between the integrated mean-corrected EMG activity of an effort as compared to a experimentally determined maximum value is described as:

$$\%_{EMG-Utiliz} = \frac{1}{K}\cdot\left(\int_{t-T}^{t}[EMG_{Raw}(i) - mean_{T}(EMG)]di\right)\cdot 100 \qquad (1)$$

where T is the sample time used, EMG_{Raw} is the raw EMG data, $mean_T(EMG)$ is the mean value of EMG_{Raw} over time T, and K is the experimentally determined maximum value.

IV. CONCLUSION

We developed a digital controller system with the benefits of binary and variable control architectures, and that uses feedback from force resistors and angle sensors to modulate motor control. Control system functionality was verified through simulation of sensor and feedback data. The digital controller is being integrated with a hand-based exoskeleton, and the entire system will undergo a quantitative and qualitative performance assessment. Test subjects will be fitted with the device and the user's grasping strength and precision control will be quantified. A qualitative analysis will also be performed where the wearer will provide feedback during the completion of lifting and grasping tasks, evaluating ease of use and comfort of the hand-assistive exoskeleton.

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