

POWER AUGMENTATION IN REHABILITATION ROBOTS

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Abstract

A force-assist mechanism has been developed to mount on the Chameleon - a wheelchair mounted rehabilitation robot. The device will amplify the forces applied by the user, making it possible to lift a large weight with a smaller force. This paper describes the preliminary test bed study and details a pilot study currently in progress to investigate the precision and accuracy of the Chameleon under varying gains on the force-amplifier.

Introduction

The Chameleon is a body-powered rehabilitation robot designed at the Extended Manipulation Laboratory of the duPont Hospital for Children. It is designed to be an easy-to-use, cost-effective, multi-degree-of-freedom, wheelchair-mounted robot [1,2] to assist people with SCI or similar disabilities perform their daily living tasks.

The current Chameleon design, shown in Figures 1, 2, and 3, consists of a head operated input device that controls a mechanical arm and gripper. The input control uses pitch (nodding the head "yes") and roll (shaking the head "no") to correspond to flexion/extension and horizontal abduction/adduction of the shoulder joint respectively. The input

site of the Chameleon is a mouthpiece that the user grips with his or her teeth. Moving the mouthpiece in three dimensions maneuvers the master (Figure 1). A direct mechanical linkage of Bowden cables currently controls the pitch and roll joints.

The moment arm of the input device (R in Figure 1.) is much smaller than the moment arm of the mechanical arm (r in Figure 2.). The direct mechanical linkage from the cable dictates that the torque at both joints must be equivalent. Because the moment arm is smaller, even if a light object is lifted, a large force is required at the input site, which corresponds to a large force applied by the temporomandibular joint (TMJ).

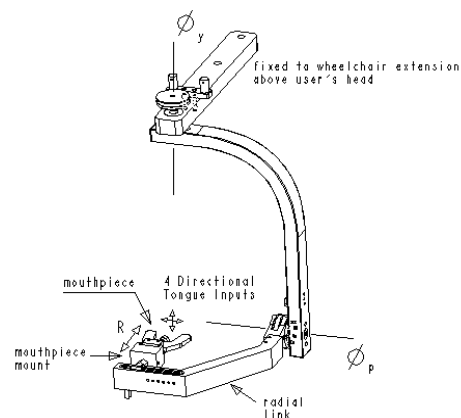


Figure 1. Master (Input) Component of Chameleon

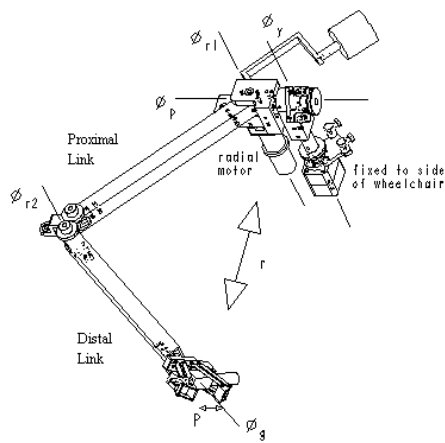


Figure 2. Slave (Output) Component of Chameleon

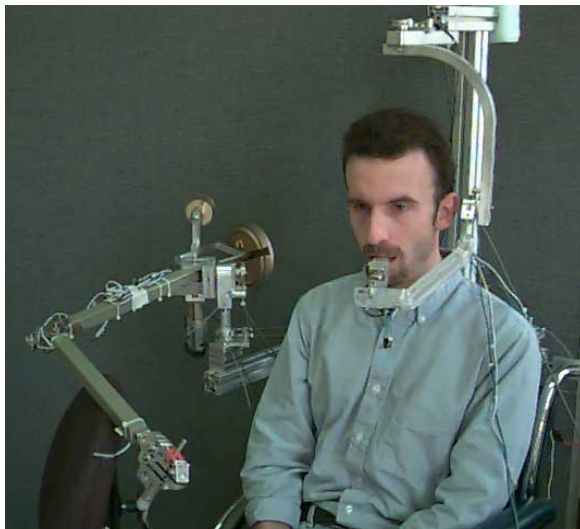


Figure 3. User with Chameleon

The goal of this project is to implement a force amplification device at the pitch joint to assist with lifting loads in order to eliminate the pain and fatigue that are currently encountered at the input site. Ideally, the user will be able to lift a heavy load using only a small amount of force.

The user must be aware of the weight of the object in the gripper, so that he can

sense when an object has been grasped or has been dropped. The user must also be able to determine if he has contacted an obstacle. Additionally, the system must be stable.

Adding a force-assist mechanism offers a significant reduction in user strength requirements and provides added precision and accuracy to movements of the Chameleon. The proposed power-assist device is novel in that it provides power assistance while maintaining a constant position relationship between the user and the robot movements.

Background

With one exception, there are currently no rehab robots that offer the user a sense of force or contact with the environment. Workstation robots such as the ProVAR do not offer a direct coupling between the user and robot. When a user is controlling the robot with a joystick control such as the one used in the ProVAR, he does not receive any feedback from the robot except for visual position feedback, which makes control more difficult [3].

The Helping Hand [4,5] and the MANUS [6] are two rehabilitation robots that can be mounted on the wheelchair and controlled with a joystick or a switch-pad. These two robots are completely motorized and do not offer any force feedback to the user. The Magpie [7] is an example of a wheelchair mounted, mobile robot that the user operates with his or her foot and leg motions. This design does provide sensory feedback due to the cable

connection; however, the system is totally body powered.

An important feature of cable-operated prosthetic and orthotic devices is extended physiological proprioception (EPP) [3]. EPP allows the operator of a device to sense its static and dynamic characteristics through physical sensations that mimic the natural sensations of movement. The addition of EPP to a rehabilitation robot greatly improves ease-of-use and functionality because the user has a sense of his position in the environment and he is not constantly forced to watch the end-effector of the device [3].

Test-Bed Development

In order to determine the proper control scheme for the power augmentation system. A test-bed has been designed to mimic the system of pulleys, cables, and lever arms in place on the existing Chameleon. The test-bed consists of two

pulleys with lever arms attached that apply a force at a distance from the center of each pulley. The cable is rigidly secured to a third pulley mounted to a motor located in the center of the test-bed, as shown in Figure 4. A Force Sensing Resistor (FSR™) is mounted in a casing to ensure even force distribution, and is mounted in tension in order to sense the forces transmitted through the cable. From the data we found that, within the range that we were testing, it was most appropriate to use a third order polynomial equation (1) to relate the applied force to the sensor voltage. The R^2 value of ~ 0.9995 was a good fit for this system.

$$F_h = \frac{R_1 * F_i}{L_1} \quad (1)$$

Governing Equations

The equations that govern the system are based on Figure 4. The torque applied

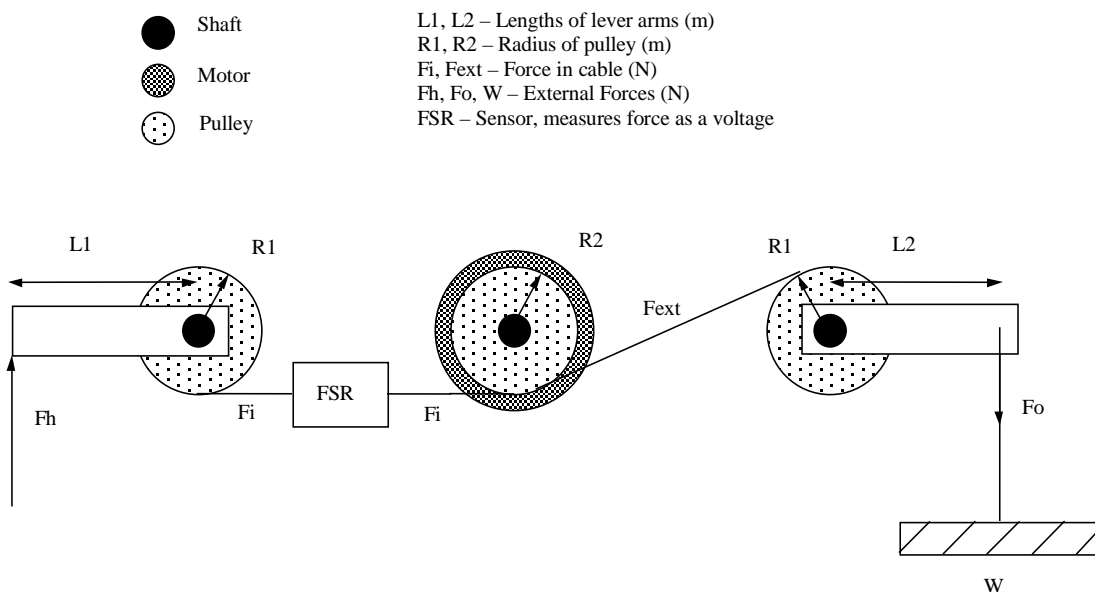


Figure 4. Force-assist Test-bed Schematic

by the human is identical to the torque in the left side of the cable, so the force in that cable can be expressed as a function of the force applied by the human:

$$F_i = 0.73*V_i^3 - 1.03*V_i^2 + 2.95*V_i - 0.21 \quad (2)$$

Where F_i is the force in the left side of the cable, F_h is the force applied by the human, R_l is the radius of the pulley and L_l is the length of the lever arm. The external torque applied is identical to the torque in the right side of the cable and therefore the force in that cable is a function of the external weight:

$$W = \frac{R_l * F_{ext}}{L_2} \quad (3)$$

As before, W is the external weight, R_l is the radius of the pulley, L_2 is the length of the second lever arm and F_{ext} is the force in the right side of the cable. The force required by the motor must be equal to the difference between the force in each section of the cable in order to maintain static equilibrium. The torque required by the motor can then be expressed as a function of the forces in each part of the cable:

$$T_m = R_2 * (F_{ext} - F_i) \quad (4)$$

We require that the force applied by the human be some reduced value (α), of the external weight.

$$F_h = \frac{W}{\alpha} \quad (5)$$

Substituting equations (2), (3) and (5) in equation (4) and accounting for the

gearing of the motor, we can redefine the torque required by the motor as:

$$T_m = (\alpha \frac{L_2}{L_1} - 1) * F_i * R_2 * C \quad (6)$$

C is a constant describing the behavior (gearing/speed reduction) of the motor.

From the equation relating torque and current in a motor:

$$T_m = K_t * I \quad (7)$$

or

$$T_m = K_t * \frac{V_c}{R}$$

K_t is the torque constant of the motor, supplied by the manufacturer. V_c is the voltage needed to drive the motor and R is the resistance of the circuit. Solving for V_c and substituting in equation (7) the general equation for the voltage sent to the motor can be written as:

$$V_c = \frac{R}{K_t} * (\alpha \frac{L_2}{L_1} - 1) * F_i * R_2 * C \quad (8)$$

This is the equation used in the *Labview* program, where R , R_2 , K_b , α , L_1 , L_2 , and C are all constants, F_i is the force sensed by the FSR and V_c is the calculated voltage sent to the motor.

Force Discernment Test

The average human is able to discriminate between weights that vary by more than 8% [8]. A preliminary test was conducted to determine whether the system was accurate to within this range for two different weights at different

gains. The test was conducted by resting the input lever on an ATI Force Sensor and measuring the effective force at the input site. For example, it is expected that if the human lifts 0.2 kg at a gain of 1.0, it will require the same input force to lift it as it will to lift a 1.0 kg weight at a gain of 5.0.

We conducted a series of trials in order to determine the accuracy of the system. First we set six expected forces ranging from 1.2 to 4.2 kg. Then, knowing the five masses we would use, we calculated the gains that, when paired with each of the masses, would yield the expected forces. Each mass/gain pair was tested five times to determine the repeatability of the trial, and the average percent error from the expected force was calculated. A total of 150 trials were conducted. A sample of the data is shown in Figure 5. This shows the average deviation for five trials that were expected to yield the same force of 2.00 N.

Mass	Gain	Exp Force	Avg Force
0.55	2.67	2.00	1.55
0.75	3.65	2.00	1.43
0.95	4.63	2.00	1.53
1.05	5.12	2.00	1.90
1.55	7.57	2.00	2.10

Figure 5. Sample Trial Data

Figure 6 shows the averaged actual data plotted against the expected data (the line $y=x$) for all of the trials. Clearly as the expected force increases, the actual force decreases from the expected value. This is not a serious problem because the actual force is still lower than the expected force, which does not pose a concern to the user.

After conducting the trials we calculated the t-distribution for the samples. The results for each weight were tested for 95% confidence. We found that the data fell within -17.5% to -5.9% of the expected average overall.

Evaluation

The goal of this testing is to analyze the behavior of the force-assist mechanism working in conjunction with the Chameleon. In our testing, we will only be operating the Chameleon with two degrees of freedom: roll and pitch of the head. These movements correspond to horizontal abduction and adduction of the shoulder and flexion and extension of the shoulder. We will not include the flexion and extension joint of the elbow or any of the operations of the gripper at this stage as we are interested only in the efficacy of the power assist device, rather than the functionality of the Chameleon.

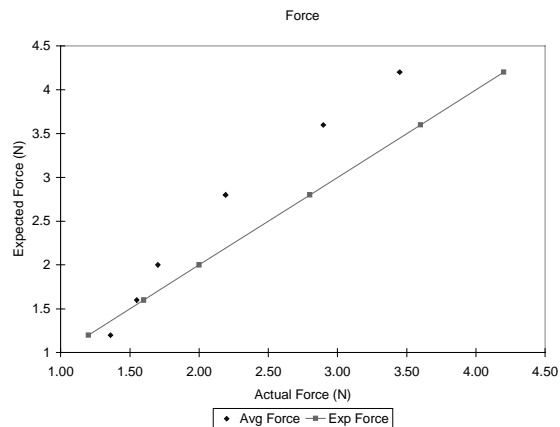


Figure 6. Actual Data vs. Expected Data

We want to evaluate the effect of adding force assist in the performance of two joints of the Chameleon. In order to

analyze the force-assist mechanism, one test, a Fitts' movement test, will be repeated three times with the force-assist mechanism/Chameleon setup. In the test, the user will hold a laser pointer in the gripper of the Chameleon arm. On the wall at a distance of six feet away will be a collection of targets of three different sizes in a grid formation. The user will be asked to point the laser pointer back and forth between two pre-selected markers of the same size – moving diagonally in order to combine the motions in the horizontal and vertical planes. Time will be recorded as the user repeats the trajectory a total of ten times. The time will then be averaged over the ten trials to yield an average value for one task. This test will help determine how performance is effected when strength is added to the system.

Each of the trials will be repeated with the Chameleon gain set at three different levels, the max gain that the system can sustain ~7.0, zero gain and a mid range gain ~3.5. This test will give us a measure of how the control of the Chameleon is affected by changing the gain.

Experimental Design

The independent variable in this study is the level of gain set on the system. The dependent variable is the index of performance (bits/sec) as calculated using Fitts' Law. This data will be statistically analyzed using a one-way ANOVA test for repeated measures. We will also study how our data correlates to Fitts' Law, which relates speed and precision measurements in target

acquisition tasks. Additionally, we will use the subjects' responses to the Likert-type questionnaire (1= strongly disagree, 2= disagree, 3= neutral, 4= agree, 5= strongly agree) which will be filled out at the end of each day, for a descriptive analysis study.

Discussion

Informal testing has yielded significant power assistance for the Chameleon. This has made using the device much lighter and as a result, easier to use for extended periods of time. We propose that the addition of the power assist mechanism to the Chameleon will decrease the amount of force and time needed by the user to acquire targets at no sacrifice to his precision movement abilities. Upon completion of the testing for this project, we will determine whether the addition to the Chameleon is a worthwhile expenditure, and if it is deemed successful, the power augmentation system will be utilized in other projects.

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References

- [1.] Stroud, S., Rahman, T. "A Body Powered Rehabilitation Robot" Proceedings of the RESNA '96 Annual Conference. Pp. 363-365. June 1996.
- [2.] Stroud, S., Rahman, T. "A Body Powered Rehabilitation Robot" Proceedings of the RESNA '97 Annual Conference. Pp. 387-389. June 1997.
- [3.] Childress, D., Heckathorne, C., Grahman, E., Strysik, J., Gard, S. "Extended Physiological Proprioception (E.P.P.) An Electronic Cable-Actuated Position-Servo Controller for Upper-Limb Powered Prostheses". <http://pele.repoc.nwu.edu/progress/jrrd.dva.9009.EPP.html>
- [4.] Sheredos, S., Taylor, B., Cobb, C., Dann, E. "The Helping Hand Electro-Mechanical Arm". Proceedings of the RESNA '95 Annual Conference. Pp. 493-495. June 1995.
- [5.] Sheredos, S., Taylor, B. "Clinical Evaluation of the Helping-Hand Electro-Mechanical Arm". Proceedings of the RESNA '97 Annual Conference. Pp. 378-380. June 1997.
- [6.] Kwee, H. "Integrated Control of MANUS Manipulator and Wheelchair Enhanced by Environmental Docking". Robotica. Vol. 16. Pp. 491-498. 1998.
- [7.] "MAGPIE-Its Development and Evaluation". Internal Report: Oxford Orthopaedic Engineering Centre. Nuffield Orthopaedic Centre. Headington, Oxford, England. 1991.
- [8.] Cohen, S., Ward, L. Sensation and Perception. Pp. 260-261. Harcourt Brace Jovanovich Inc. San Diego. 1984.

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