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Series Elastic Actuator Control of a Powered Exoskeleton

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***Abstract*— A motorized upper extremity orthosis based on the passive WREX system is being developed. The orthosis is a 4 dof arm controlled by user residual force inputs. The arm is intended for people with neuromuscular weakness due to muscular dystrophy or spinal muscular atrophy. Previous work determined that actuation in parallel with gravity balancing springs required less torque than actuation in series. Compliance is achieved by using a series elastic actuator (SEA) by placing torsional springs between the motors and the WREX. A torque control was implemented on the SEA at the joint level. The response of the control law was characterized without disturbances. The SEAs were then attached to the orthosis to test the response with disturbances, and the control provided accurate joint torques.**

I. INTRODUCTION

This paper presents a torque controller for series elastic actuation of an assistive device under human direction. The assistive device is the Wilmington Robotic Exoskeleton (WREX), which is a gravity balanced upper limb orthosis for children with muscular weakness such as musclular dystrophy and spinal musclular atrophy. The WREX has four degrees of freedom to allow full range of motion, which is assisted by gravity balancing elastic bands [4]. Typically, the WREX is attached to a wheelchair or to a body jacket. A picture of a passive WREX is shown in Fig. 1. WREX is a commercial product (JAECO Orthopedic, Hot Springs, AR).

Fig. 1. Subject wearing the WREX

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An external power source has been added to the WREX to overcome two current problems [3]:

1) A child with muscular weakness often has difficulty in raising his arm above his head, even with the WREX.

2) The child cannot lift a substantial weight, because the device only balances the mass of the child's arm.

Series elastic actuators were introduced to address these two issues, while providing softness for the user and accurate torque control. The control of SEAs has evolved through significant prior research. In 1986, Spong presented a method to eliminate the effect of elastic joints [5]. Pratt was one of the first to intentionally use elasticity [2]. Wyeth suggested using the motor as a velocity source instead of a torque source [11]. Series elastic actuators have been used in a number of exoskeletons because of the inherent compliance [7] [1]. Reinkensmeyers has actuated the WREX using pneumatic actuators, however, the pneumatic actuators were difficult to control due to non-linear behavior. Also, the device targeted adult stroke patients in rehabilitation, which is a different population group and task definition than the target of the work in this paper [9]. Hydroelastic actuators have also been designed recently for exoskeletons, however this was not deemed appropriate for the WREX [6].

II. MATERIAL AND METHOD

A. Motorized WREX

The motorized WREX developed for this project is shown in Fig. 2. It consists of 4 degrees of freedom - 2 at the shoulder and 2 at the elbow. The joints are partitioned so that two (elbow elevation and shoulder elevation) are anti-gravity; and 2 (elbow and shoulder rotated in the horizontal plane) are not affected by gravity. This configuration is retained from the passive WREX [4]. The two anti-gravity joints are actuated in a hybrid set up which comprizes of elastic bands and SEAs. The other two joints are passive. An ATI(ATI, Apex, NC) force/torque sensor is placed between the user and the powered WREX. The goals of the project is to measure the user intention force and apply the appropriate actuation to assist the user in moving easily with or without a weight at the hand. The control method was tested in Simulink as well as in experiment using xPC in Matlab. The experimental setup is shown in Fig. 5. The motor is a FaulHaber brushed DC motor type 2342 S 012 CR with a 134:1 gear head. The motor is powered using an Advanced Motion Control 12A8 amplifier. A US Digital E4P Optical encoder recorded the motor joint angle. The device was connected to a target PC through a NI PCI-6040E and a NI-6601 DAQ board. It was controlled at 1000Hz in realtime by Matlab xPC.

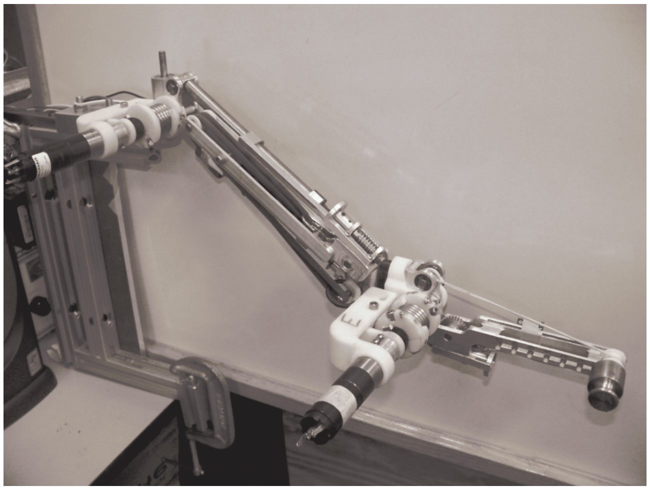

Fig. 2. Experimental setup of WREX with an SEA at the shoulder and elbow joint

B. Series Elastic Actuators

A series elastic actuator is used to create softness for the user as well as achieve accurate torque control. Torque control is used because the series elastic element acts as a natural, compliant torque sensor. The output torque can be measured by multiplying the angular displacement of the spring by its stiffness. The measured torque can be used as a feedback signal. A torsion spring is the elastic member that connects the motor to the device Fig. 3. The equation

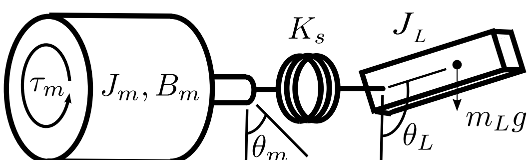

Fig. 3. Schematic of Motor

of motion for the motor is:

$$\tau_m = J_m \ddot{\theta}_m + B_m \dot{\theta}_m + K_s(\theta_L - \theta_m) \tag{1}$$

where τ_m is the motor torque, θ_m is the motor angle, θ_L is the load angle, K_s is the spring stiffness and J_m and B_m are the effective motor inertia and damping, which include the gear ratio. In this section, θ_L is held constant and is considered a disturbance.

C. Controller

The control method uses a PI controller with velocity feedback, similar to the control suggested by Wyeth [11], with an additional feedforward term. This feedforward term is equal to the desired torque output. In an ideal model, this term should cause the output torque to be equal to the input motor torque under steady state conditions. To compensate for dynamics, model uncertainty, and friction, the PI loop corrects errors in the desired torque, while the velocity feedback increases the damping, to allow the gains of the PI control to be sufficiently high to produce accurate torque control while maintaining stability. The block diagram of the control architecture is shown in Fig. 4

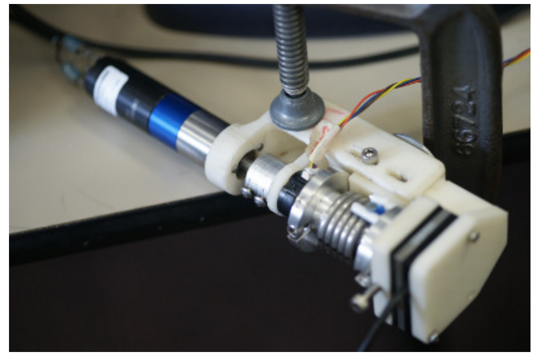

Fig. 5. Picture of Experimental Setup

D. Results

Several physical parameters were determined experimentally, $J_m = 0.01\ kgm^2$, $B_m = 0.21\ Nm/(rad/s)$, and $K_s = 2.51\ Nm/rad$. The gains were determined experimentally as $K_p = 30$ and $K_i = 10$ for the outer PI control and $K_v = 1.2$ for the velocity feedback. First the step response was found, which is shown in Fig. 6. Second, the frequency response was determined using a chirp signal. The experimental results were fitted to a transfer function using the system identification toolbox in Matlab. The results are shown in Fig. 7

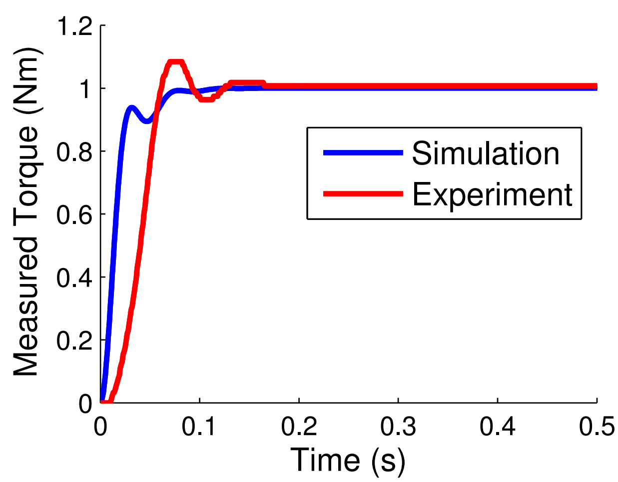

Fig. 6. Step Response of Control on Series Elastic Actuator

From the step response, the experimental controller has a settling time of approximately 0.15 seconds with minimal steady state error. From the frequency response in Fig. 7, the controller has a bandwidth of about 20 rad/s. There is a slight discontinuity shown in the experimental response around 20 rad/s because the response was fitted in two

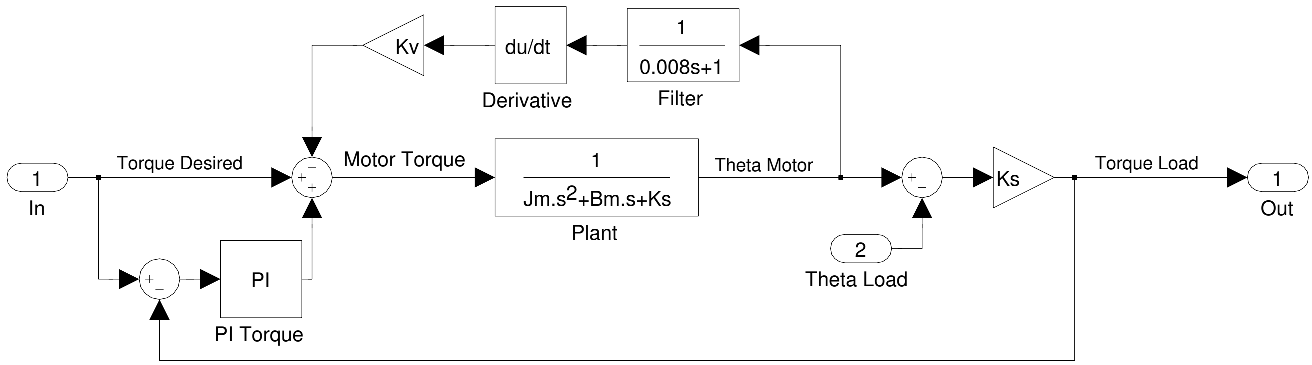

Fig. 4. Block Diagram of Torque Control

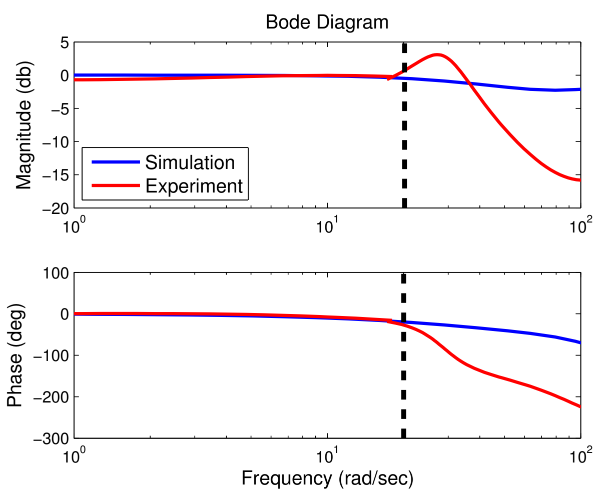

Fig. 7. Bode Diagram of Torque Control on Series Elastic Actuator

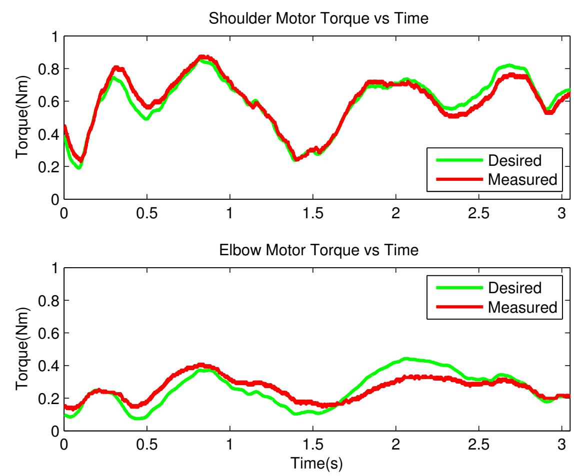

Fig. 8. Sample torque trajectory during human interaction. The desired torque is from the force sensor

parts, which overlap, to accurately characterize the motor non-linearities. In both figures, the difference between the simulated and experimental response is due to unmodeled time delay and motor saturation. It has been shown that the controller provides reasonable torque control up to 20 rad/s or 3.18 Hz in the absence of disturbance.

To test the controller with disturbances, the SEAs were attached to the WREX shown in Fig. 2.

The ATI force sensor was attached to a table used to input torque commands to the motors. The sensed force of the operator was transformed into joint torques, while the WREX with attached SEAs was free to move. One example of the desired torque and the torque produced by the SEA for both motors is shown in Fig. (8). It can be seen that the proposed control provides accurate torque control at the joints even with dynamic interaction between the joints.

III. DISCUSSION

Based on the needs of the current WREX, it was decided to add a series elastic actuator to provide a soft feel for the user and allow torque control. However, the added flexibility introduced new control challenges. The presented PI controller with velocity feedback was found to provide accurate torque control in the presence of disturbances within the bandwidth needed for human motion. The controller reduces the series elastic actuator as a torque source, which any type of controller, such as PD, computed torque, or impedance could be used as a higher level control. The controller is similar to those presented by Pratt [2], Wyeth [11], and Vallery [8]. This is comparable to the 3.5 Hz bandwidth of the Pneu-WREX [10]. This is acceptable for human interaction, because the frequency range of a person with a disability will be substantially lower than the normal human motion of 4-8 Hz [1]. Further research could implement these previously suggested strategies on the WREX and compare if one controller provides more accurate control then the other. Now that the WREX has an accurate torque source, a higher level controller can be implemented to control the interaction between the user and the device. This higher level controller will address the two mentioned problems of limited range and limited carrying ability, as well as stability.

The subsequent steps in the WREX project will be to use the force sensor when attached to the orthosis and control the interaction between the user and the WREX to address the two previously mentioned shortcomings: limited range and limited strength.

IV. CONCLUSION

A Series Elastic Actuator was added to the WREX. A PI control law with torque feedforward and velocity feedback was presented and tested. The inner torque control was able to provide accurate torque control up to 20 rad/s with the load angle fixed. It was shown that the inner loop can control the torque when attached to an unrestrained WREX.

V. ACKNOWLEDGMENTS

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