Augmenting Locomotion in an Anthropomorphic System

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ABSTRACT

A powered orthosis has applications ranging from assisting the elderly to augmenting astronauts. An assistive control scheme is developed that uses the force from a slave actuator to augment the force of a master actuator. This can be used to augment a closed-loop control scheme applied to the master actuator. Initially, actuator augmentation is explored both theoretically and experimentally using a simple mechanical system. The control scheme is then applied to a scale model of human lower limbs on a stationary bicycle to investigate the feasibility of a powered orthosis using pneumatic muscle actuators.

Keywords: Actuator Augmentation, Pneumatic Muscle, Exoskeleton, Powered Orthosis

1. INTRODUCTION

Statistics Canada reports that 10.5% of Canadians have some form of mobility disability [1]. This includes difficulties walking on flat hard surfaces, climbing stairs, carrying a 5 kilogram object for 10 meters, or standing for 20 minutes. A powered orthosis could assist physically limited patients to increase their mobility and quality of life.

The objective of this research is the analysis, design and development of technology to augment an anthropomorphic system during locomotion. The general philosophy is that the performance of an actuated mechanical or biomechanical system can be improved if supplementary actuators are integrated into the framework. In particular, this analysis is performed with a view towards augmenting human locomotion with powered exoskeletal devices (also called orthotic devices). The benefit of a powered orthosis ranges from rehabilitating and assisting patients with weakened or poor motor control, to augmenting healthy individuals to increase their endurance and strength [2, 5, 6].

Many of the exoskeletal devices developed to date are based on position control to track the motions of the user e.g. [2]. For the device to support an external load, it must act between the user and the load such that the orthosis bears the weight. Although this configuration relieves the user from supporting the weight of the external load and the assistive device, it does not assist the movement of the user's body. If a controller is implemented that is force-based rather than position-based, the orthosis can amplify the user's forces and reduce the required effort to perform an activity. The benefits of this approach are demonstrated both theoretically and experimentally in this work.

2. ACTUATOR AUGMENTATION

A general control scheme is developed that allows a slave actuator to augment the function of a master actuator. In the context of this research, the master is the human user, and the slave is the powered orthosis. To implement actuator augmentation, a closed-loop control algorithm, such as PD, is applied to the master actuator and the force output is measured. This measured force is used as the reference input to a force controller that drives the slave actuator operating in parallel. The force generated by the slave actuator augments the force from the master actuator, thus reducing the force output required from the master actuator while achieving a similar system output.

Consider a typical ideal DC motor model as shown in Figure 1. The model can be separated along the dotted line to split the electrical from the mechanical components and gain access to the torque, which is necessary to determine the effect of multiple actuators coupled to a common mechanical system.

To assist the DC motor with a second DC motor, consider Figure 2. The master actuator, $Motor_1$, is controlled in a typical manner using a PD control scheme. The torque, τ_1, applied by $Motor_1$ on the me-

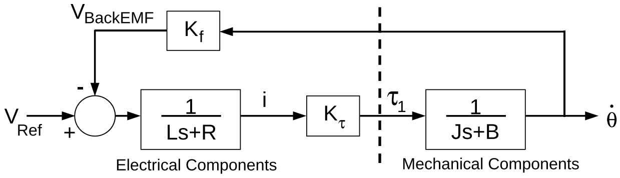

Figure 1: Typical DC motor model.

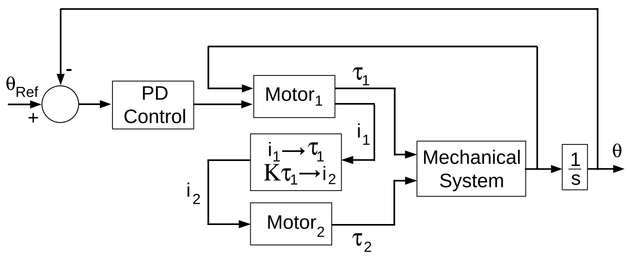

Figure 2: Proposed control scheme.

chanical system (which includes the mechanical components of the motors) can be determined indirectly by measuring the current, i_1, and multiplying it by the torque constant K_{τ_1}. This torque is multiplied by a proportional gain K_{Gain}, and the result is converted back to a current using K_{τ_2}. This current, i_2, is used to drive the slave actuator $Motor_2$ to act on the common mechanical system and assist $Motor_1$. Note that the $\dot{\theta}$ output of the large common gear is used to calculate the back-EMF of $Motor_1$. Also note that since $Motor_2$ is driven by a current source, it is independent of the back-EMF.

The theoretical viability of the actuator augmentation scheme is explored with a simple system consisting of two electric motors that are independently geared to drive a large common gear as shown in Figure 3. The large gear is coupled to a wheel suspending a mass that creates a load torque on the system.

Proposition: *Given the mechanical system shown in Figure 3, and the control system in Figure 2, a stable position controlled system can be found using a PD controller with suitable gains.*

The output equations from the two motors are as follows:

$$\tau_1 = K_{\tau_1} i_1 \tag{1}$$

$$\begin{aligned} \tau_2 &= K_{\tau_2} i_2 \\ &= K_{\tau_2}\left[(K_{\tau_1})(K_{Gain})\left(\frac{1}{K_{\tau_2}}\right) i_1\right] \\ &= (K_{\tau_1})(K_{Gain}) i_1 \end{aligned} \tag{2}$$

$Motor_1$ and $Motor_2$ are each coupled to a gear of radius r_1 and r_2 respectively, which drive the large common gear of radius r_G. The small gears include the

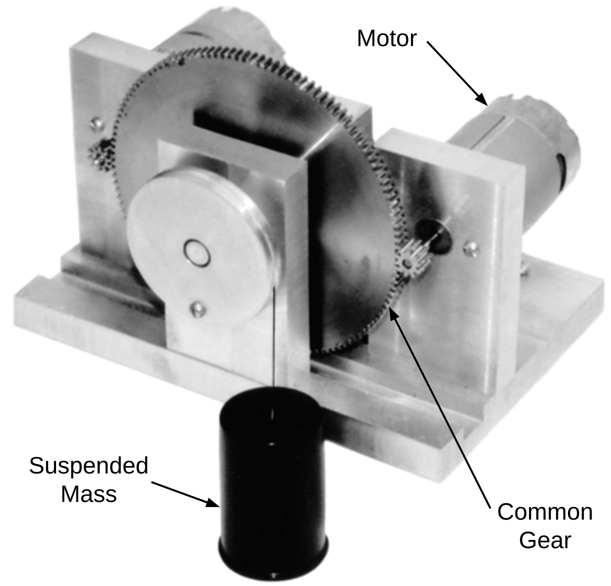

Figure 3: Dual motor experiment.

inertia and damping of the motors and are driven by τ_1 and τ_2. The common gear supports the load mass that applies a torque τ_M. The dynamic equations for the mechanical components are as follows:

$$J_G \ddot{\Theta}_G = \tau_M - \tau_{1G} - \tau_{2G} \tag{3}$$

$$J_1 \ddot{\Theta}_1 + B_1 \dot{\Theta}_1 = \tau_1 - \tau_{1G} \tag{4}$$

$$J_2 \ddot{\Theta}_2 + B_2 \dot{\Theta}_2 = \tau_2 - \tau_{2G} \tag{5}$$

To combine these equations, the following constraints are required:

$$\Theta_1 = -\frac{r_G}{r_1}\Theta_G \tag{6}$$

$$\Theta_2 = -\frac{r_G}{r_2}\Theta_G \tag{7}$$

Substituting into Equations 3, 4, and 5 and combining:

$$\left[J_G + \left(\frac{r_G}{r_1}\right) J_1 + \left(\frac{r_G}{r_2}\right) J_2\right] \ddot{\Theta}_G + \left[\left(\frac{r_G}{r_1}\right) B_1 + \left(\frac{r_G}{r_2}\right) B_2\right] \dot{\Theta}_G$$

$$= \tau_M - \tau_1 - \tau_2$$

Finally, converting to the Laplace domain (and assuming zero initial conditions):

$$\Theta_G = \frac{\tau_M - \tau_1 - \tau_2}{\left[J_G + \left(\frac{r_G}{r_1}\right) J_1 + \left(\frac{r_G}{r_2}\right) J_2\right] s^2 + \left[\left(\frac{r_G}{r_1}\right) B_1 + \left(\frac{r_G}{r_2}\right) B_2\right] s}$$

From this equation, it can be seen that the torque inputs τ_1 and τ_2 from $Motor_1$ and $Motor_2$ are a linear summation. Finally, substituting Equations 1 and 2:

$$\Theta_G = \frac{\tau_M - (K_{\tau_1})(1 + K_{Gain}) i_1}{\left[J_G + \left(\frac{r_G}{r_1}\right) J_1 + \left(\frac{r_G}{r_2}\right) J_2\right] s^2 + \left[\left(\frac{r_G}{r_1}\right) B_1 + \left(\frac{r_G}{r_2}\right) B_2\right] s} \tag{8}$$

The result of Equation 8 indicates that the system will behave the same as if a single, larger motor was used to drive the common gear. Closing the remaining feedback loops and applying Routh Hurwitz results in similar stability criteria as for a single motor.

This analysis of the system suggests that if the master motor (representing the human) is operated using closed-loop position control, the slave motor (representing the powered orthosis) can assist the master in a stable fashion using the proposed actuator augmentation scheme. With ideal electric motors, the problem simplifies to a system using a single, larger motor. However, in order to make the response of the dual motor system identical to that of a single motor, the control parameters have to be adjusted to compensate for the additional torque, inertia and damping. This signifies that for a powered orthosis, some training may be required by the users in order to match their assisted gait to their desired gait.

3. DUAL MOTOR EXPERIMENTAL RESULTS

Although the theoretical case suggests that the actuator augmentation scheme should be stable, the theory does not include friction, backlash, filter delay, or other nonlinear effects. To demonstrate that the system will work in practice, experimental results were conducted with the setup depicted in Figure 3.

The results of position control are shown in Figure 4 (the reference is a step response from 0 to 5000 counts). Note that during the unassisted position control, the slave motor was mechanically disconnected from the system so the master actuator did not have to drive the inertia and friction of the inactive slave motor.

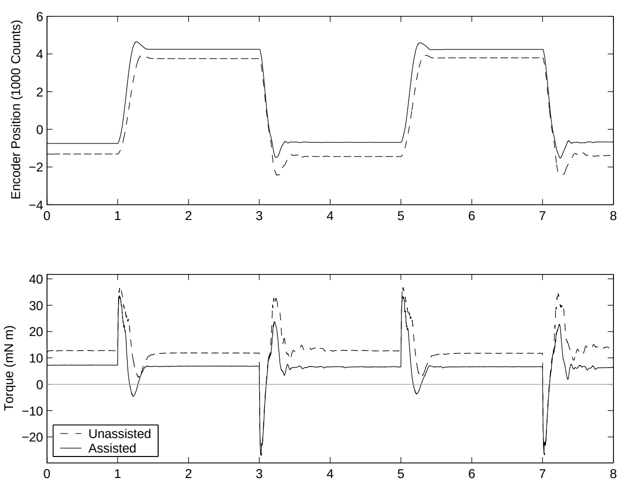

Figure 4: Position control results.

The results demonstrate that the addition of the second actuator, with an assistive gain of one, reduces the torque required by the primary actuator by 46% compared to a theoretical decrease of 50% (some of the assistive torque is lost to the friction of the slave actuator). The time to reach steady state is slightly faster for the assisted case as more torque is available. Note that transients during the rising edge of the step response are not at the average assistance level. This is in part due to a low pass filter used to remove noise from the current measurement of the master motor, as well as amplifier saturation.

To more clearly demonstrate the torque reduction, the control scheme for the master actuator was changed to a velocity regulating PI control. After the initial zero-load resting position, the results presented in Figure 5 clearly show a reduction of the torque output of the master actuator without any amplifier saturation or transients to complicate comparison. This highlights another important aspect of the actuator augmentation scheme. No modifications of the slave actuator control were required to change between position and velocity control. The slave actuator will provide assistance regardless of the control scheme applied to the master actuator because it utilizes the existing control loop.

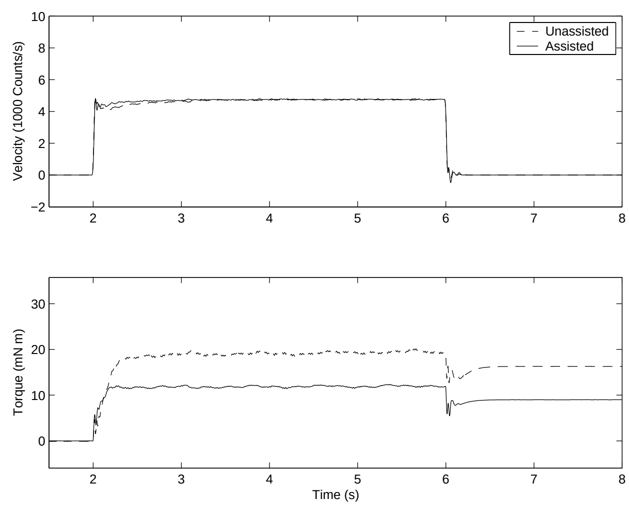

Figure 5: Velocity control results.

Two extreme cases of the assistive scheme reveal some interesting results. In theory, there is no limit to the assistive gain with the appropriate control modifications. The torque required by the master actuator only needs to be large enough to provide a reference signal for the slave actuator. However, the maximum assistive gain is limited by the noise in the system. In this experiment, it was found that with a first order low pass filter of approximately $600Hz$ applied to the current measurements, the assistive gain could still be set well above 100, with the appropriate controller gain modifications, before the quality of the output began to significantly degrade. By decreasing the bandwidth of the filter on the current measurements, the assistive gain can be further increased, but with some impact on the performance of the system.

The other extreme case to consider is low loads on the common mechanical system. When the external load is removed, the only force opposing motion is friction. In this case, the benefits of the second actuator are almost negligible because at an assistive gain of one, all of the torque generated by the slave is used to overcome its own friction. Friction may be the primary determinant of the benefits of actuator augmentation. Depending on the external load compared to the friction between the actuators and the common mechanical system, the benefits of actuator augmentation can vary from significant to negligible.

Outside of the application of powered orthotics, this control scheme may be useful to retrofit underpowered systems, or where physical constraints do not permit a single actuator of appropriate size.

4. AUGMENTING HUMAN PERFORMANCE WITH A POWERED ORTHOSIS

The human body effectively achieves position control during gait by placing the limbs in such a way that stable motion is obtained. Drawing an analogy to the dual motor system, consider Figure 6. The forces of the human muscles (the master actuators) act on the skeleton (the common mechanical system) to produce a desired motion. To augment the human, estimates of the muscle forces can be inferred with techniques such as electromyography (EMG), which monitor the electrical activity in a contracting muscle. The force estimates are used as reference inputs to a force controller that drives the slave actuators, which in turn act on the human. Locally the orthosis operates under open-loop position control, but by integrating the human into the actuator augmentation scheme, the human user closes the position feedback loop with proprioceptive and kinesthetic feedback mechanisms. As the apparent force required to achieve the desired motion becomes reduced, so does the user's neural drive to individual muscles. This reduces the reference inputs to the orthosis slave actuators, which reduces their force output, thus closing the position control loop. While the use of EMG as a force estimate for a powered orthosis has been demonstrated before [5, 6], the actuator augmentation control scheme provides a theoretical basis on which any actuator or appropriate force sensor can be used.

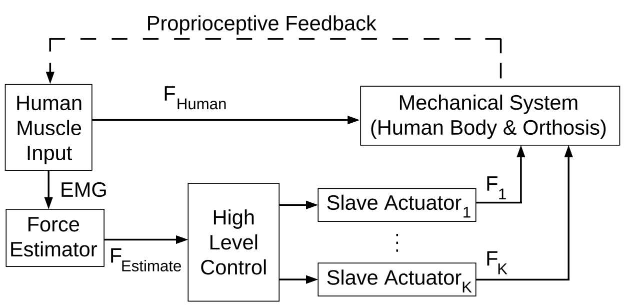

Figure 6: Augmenting human muscles.

As discussed in the dual motor experimental results, the benefit of an assistive actuator is limited by the friction between the slave actuator and the common mechanical system. The relatively low friction muscular-skeletal system allows the human body to conserve energy by making use of the natural pendulum motion of the leg during the swing phase of gait. If relatively small electric motors were used as the assistive actuator in a lower limb orthosis, substantial gearing would be required, which would reduce the back-drivability and bandwidth of the actuator. Using a highly geared electric motor would require that the motor be driven throughout the entire gait cycle, losing the energy savings of the pendulum motion. Also, without actuator compliance, any lag in the system could result in user discomfort [5].

A more appropriate selection of actuator is the Pneumatic Muscle Actuator (PMA). PMA's are constructed by combining a rubber lining with a helical braided mesh shell. When the PMA is pressurized, the structure produces an axial contraction with the radial expansion. PMA's are naturally compliant which is a benefit in terms of back-drivability and safety, but requires the application of nonlinear control techniques to compensate for the nonlinearities and achieve accurate control. Despite the nonlinearities associated with PMA's, a preliminary analysis [3], which considers the feasibility of the entire system, indicates PMA's are the most promising actuator technology for this application. In particular, this is due to the high power-to-weight (1000 W/kg) and power-to-volume (1.1 W/cm^3) ratios [4].

5. PNEUMATIC MUSCLE BICYCLE EXPERIMENT

In order to demonstrate the actuator augmentation control scheme on an anthropomorphic system, a one degree of freedom scale model of human lower limbs was constructed and mounted on a stationary bicycle (see Figure 7). The limbs are assisted by two PMA's affixed to the thighs that generate torques at the knee joints. An electric motor is coupled to the crank, and the applied torque is inferred from the drive current.

To investigate actuator augmentation on the bicycle model, two controllers are implemented. The motor, representing the human contribution, is velocity controlled with a PI controller and an adaptive feed-forward component to compensate for the nonlinearities of the mechanical system. The PMA's are controlled using a lookup table to determine the required operating pressure to achieve the desired reference torque. The level of assistance is governed with a proportional controller that scales the motor torque measurements used in the PMA lookup table.

The experimental results in Figure 8 demonstrate the beneficial nature of the actuator augmentation

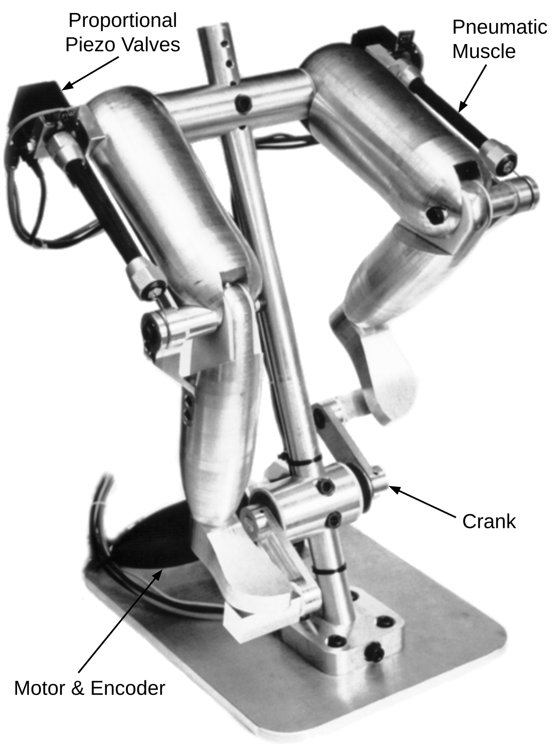

Figure 7: PMA bicycle experimental apparatus.

control scheme. In the assisted case, the PMA actuators reduce the power requirements of the master actuator (representing human) by 40%. Simulations predicted an improvement of 52% [3] in the regions outside of pressure saturation (grey), but the difference can be attributed to modelling nonlinearities.

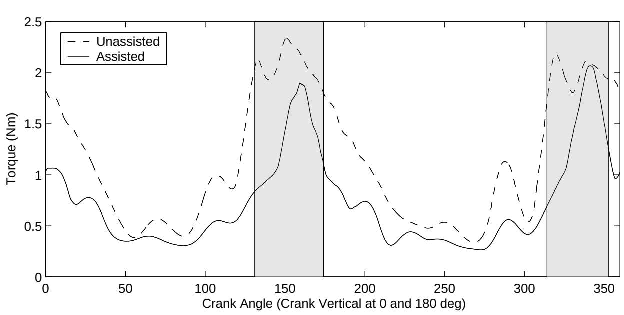

Figure 8: PMA bicycle experimental results.

The frequent variations in torque are due to significant backlash in the gear train of the electric motor. Since the backlash is not representative of human function, this motor is being replaced and more detailed results of this experiment will be presented in a future paper.

6. CONCLUSIONS

This work has demonstrated the development and application of actuator augmentation. The application of this control scheme to the dual motor experiment clearly shows the benefit of using slave actuators to reduce the load on a master actuator. The potential application of this control scheme to a powered orthosis was explored through the use of a scale model of human lower limbs mounted on a stationary bicycle. Pneumatic muscles were used to successfully augment an electric motor representing the human pedalling.

The use of actuator augmentation for a full scale orthosis is particularly promising because the human becomes an integral part of the control loop. The human body is a difficult subject from which to draw accurate force measurements, but by incorporating the human into the control loop, the orthosis automatically gains the human's flexibility and adaptiveness to new environments. Balance, coordination, gait patterns, path planning, knowledge of the environment, and obstacle avoidance are all imparted on the orthosis by the actions of the user. Since actuator augmentation makes use of the existing control schemes applied to the master actuator, the human user is not restricted to specific activities.

7. REFERENCES

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