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Modeling and Control of an Upper-Body Exoskeleton

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***Abstract*-In this paper we propose an upper body exoskeleton to augment a soldier's ability to maneuver and fire a heavy weapon. After describing the initial design concept, we model the system dynamics both using Lagrange's method and the SimMechanics software package. We derive a controller for our upper body exoskeleton, loosely inspired by the novel approach used on the Berkeley Lower body Exoskeleton (BLEEX). The approach is to combine the Computed Torque method, along with a nearly marginally stable linear feedback law. The resulting controller can track the wearer's movement with without the need to measure muscular activation levels. We simulation results for the controller with a human torque input. The contributions, while modest, are an important first step in evaluating the feasibility of this approach for an upper body exoskeleton**.

INTRODUCTION

As battlefield weaponry and equipment becomes more complex, the limiting factor for an infantryman's effectiveness becomes his or her own physical performance. Special operations forces, such as the Navy SEALs, routinely carry in excess of one hundred pounds of gear on missions, with the average soldier carrying closer to sixty pounds. While special operations personnel are specially picked and conditioned to handle such physical stresses, ordinary foot soldiers cannot be expected to handle the extra physical requirements easily. Recent advances in exoskeleton technology may offer a solution to the heavy loads experienced by soldiers.

Exoskeletons are artificial external linkages, worn by the user, along with a series of *actuators* and *sensors* to augment the user's strength and movement. These devices provide soldiers with an outer superstructure that moves with the soldier to augment their physical performance. Strength, endurance, and load-bearing capability are all improved while wearing a functional exoskeleton. In 2001, the Defense Advanced Research Projects Agency awarded contracts to Sarcos Research Corporation, the University of California, Berkeley, and the Oak Ridge National Laboratory to begin development. By 2003 Sarcos Research Corporation had begun development of an upper body exoskeleton while the University of California, Berkeley developed the Berkeley Lower Extremity Exoskeleton (BLEEX) lower body exoskeleton (see Fig. 1). Sarcos Research Corporation began the final phase of development in 2005 and successfully developed a prototype exoskeleton that will be tested by the United States Army in 2008 [1].

An alternate target application for exoskeletons is in the area of rehabilitation and assistive technologies for handicapped or injured people. An example of an upper body model is TWREX [2,3] (see Fig. 2) and a lower body model is LOPES [6].

Fig. 1: The BLEEX exoskeleton, from [1].

The long term goal of our research is to explore the use of an upper-body exoskeleton to enhance the marksmanship of a normal foot soldier. Our plan is to develop a control system that will bear the load of a soldier's weapon. The control system will keep the weapon steady by rejecting disturbances in the system until the soldier decides to move the aim point of the weapon. This paper describes the load bearing component of the control system. An important criteria for our design is that we wish to avoid the need to use physiological sensing, explained in the next section, to provide a feed-forward signal for our control system.

I. RELATED WORK

There are two main challenges in developing exoskeleton technology. One is in designing a physical device that is compatible with the human user who intends to wear it. Developing actuators and power sources favorable with capacity-to-weight ratios is a persistent challenge. For example, DARPA contracted

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Oak Ridge National Laboratories to develop a myofiber (artificial muscle actuator) for use in exoskeleton applications [1]. We do not address such challenges here.

The second challenge is in the control architecture. The goal is to have the exoskeleton track the user's movements fluidly and precisely. This begs the question: what is the reference signal that the exoskeleton should track? One approach is to attempt to use physiological sensing, such as measuring electro-muscular activation signals [7]. These signals are used as movement commands to the exoskeleton. While promising, we feel this approach requires more research before being ready to implement in a field scenario.

Fig. 2: The T-WREX rehabilitation system, from [3].

In contrast, the control system used in the BLEEX lower body exoskeleton [4], developed by the University of California, Berkeley, does not use such measurements. In fact, it does not even use force measurements at the points of contact between the human and exoskeleton. Instead it uses a dynamic cancellation technique (a.k.a. computed torque, or feedback linearization) to effectively render the skeleton and load weightless. In addition, the control system, in isolation, creates a near marginally stable feedback loop (lightly damped) that tries to maintain zero angular velocity at the joints. The premise is that the control system needs to be exceptionally responsive to give the wearer the perception that it is tracking his movements. However, the final performance is not oscillatory, since the human is also part of the feedback loop and their natural response adds additional damping. Since this approach has been successfully implemented on a lower body exoskeleton, we decided to attempt to extend it to our upper body design.

Our approach towards our control system will be similar to the design of the BLEEX control system. We will use an accurate dynamic model to develop a control system that is close to marginal stability. However, unlike the approach in [4], we will not design our control system entirely in the Laplace domain. Our control design will be based on joint torques but will still attempt to cancel the dynamics of the system by exactly matching the parameters of the system. The biggest difference between the BLEEX and our exoskeleton is the fact that our exoskeleton will assist the upper body instead of the lower body. Finally, the control system for the BLEEX controls the dynamic movement of the exoskeleton; our control system will attempt to hold the upper body still to assist in marksmanship.

II. DESIGN APPROACH

For our project we decided to develop an upper-body exoskeleton that attaches via a passive link at the shoulder, elbow, and wrist. Dynamically the exoskeleton and arm behave like two four-bar mechanisms attached to one another. The shoulder's elevation DOF will be actuated, along with the elbow. The wrist and shoulder azimuth are passive joints. Each joint will have an angular position sensor (an optical shaft encoder). Note that a subscript *1* refers to an upper arm quantity, and *2* to a lower arm quantity; while a *h* subscript refers to the human arm, and an *e* to the exoskeleton. A visualization of the design appears in Figure 3. The right linkage represents the human arm and the left the exoskeleton. The base of the model near (x,y)=(0,0) represents the shoulder joint. At y=.29 the upper arm ends and the forearm begins. The position y=.58 is the wrist joint.

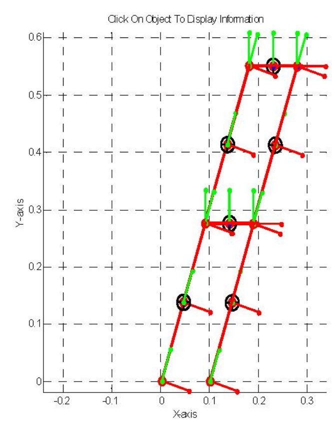


Fig. 3: SimMechanics visualization of the human arm (right) and exoskeleton (left).

A. SIMMECHANICS

SimMechanics, a SIMULINK program from Mathworks, allows users to model mechanical systems and evaluate their reaction to different inputs. By using SimMechanics we were able to simulate a dynamic model of the arm and exoskeleton (see Fig. 4). We defined our human upper arm, human forearm, exoskeleton upper arm and exoskeleton forearm as body blocks with masses and moments of inertias using the parameter values annotated above. We then placed sensors at the human elbow and shoulder. By using a sensor block we measured the angular position, velocity and acceleration at both the human elbow and shoulder joints. These values become important in our computation of the control system, contained in the embedded MATLAB function of the SimMechanics diagram.

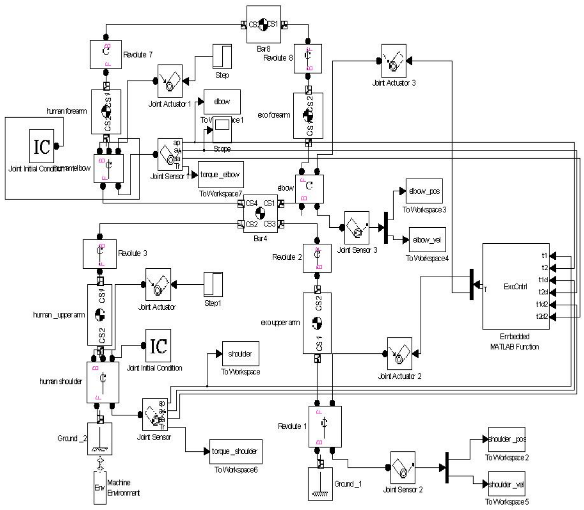


Fig. 4: SimMechanics model of exoskeleton and arm with the control system included as an embedded MATLAB function.

By using this SimMechanics model we can actuate and sense any joint in the model. We can input any signal we choose to the shoulder, elbow, and wrist. Outputs such as angular position and velocity are then recorded to see how the system responds to the various inputs. This flexibility will allow us to see how well the control system works in many different scenarios. Furthermore, we will investigate how the system will respond if the model of the system is not completely accurate. As stated previously, the control system attempts to cancel out the dynamics of the model; we want to see how the system responds if those dynamics are slightly different than expected. By using a simulation first we will be able to conduct the experiment without running the risk of physical injury.

B. DYNAMIC MODEL

To develop the analytical dynamic model of the arm we used Lagrange's method to determine the equations of motion of a two-link with point masses at the distal ends of its links [5]. Lagrange equations require the computation of a mass's position and velocity in order to determine the kinetic and potential energy associated with that mass. After finding the kinetic and potential energy we then took partial derivatives to develop the following equations of motion:

$$T_e = M_e \ddot{\theta} + V_e + G_e \qquad (1)$$

where, the upper and lower arm angles are $\theta_e = [\theta_{e1}, \theta_{e2}]^T$ and the input torques $T_e = [T_{e1}, T_{e2}]^T$,

$$M_e = \begin{pmatrix} m_1 l_1^2 + m_2 l_1^2 + m_2 l_2^2 + 2 m_2 l_1 l_2 \cos\theta_2 & m_2 l_2^2 + m_2 l_1 l_2 \cos\theta_2 \\ m_2 l_2^2 + m_2 l_1 l_2 \cos\theta_2 & m_2 l_2^2 \end{pmatrix}$$

$$V_e = \begin{pmatrix} -2 m_2 l_1 l_2 \sin\theta_2 \dot{\theta}_2 \dot{\theta}_1 - m_2 l_1 l_2 \sin\theta_2 \dot{\theta}_2^2 \\ m_2 l_1 l_2 \sin\theta_2 \dot{\theta}_1^2 \end{pmatrix} \text{ and}$$

$$G_e = \begin{pmatrix} m_1 l_1 g \cos\theta_1 + m_2 l_1 g \cos\theta_1 + m_2 l_2 g \cos(\theta_1 + \theta_2) \\ m_2 g l_2 \cos(\theta_1 + \theta_2) \end{pmatrix}.$$

Note that the parameter values for our arm are: l_1 = 29 cm, l_2 = 29 cm, m_1 = 2.6 kg, m_2 = 1.5 kg.

With no loss of generality, we assume in our simulations that the parameters for the human and the exoskeleton arms are identical. Therefore the dynamics of the human arm are identical in form

$$T_h = M_h \ddot{\theta} + V_h + G_h.$$

C. CONTROL SYSTEM

In order to design the exoskeleton control system, we rearrange (1)

$$\ddot{\theta}_e = M_e^{-1}(-V_e - G_e + T_e) \qquad (2)$$

We employ a computed torque approach to linearize the natural non-linear dynamics of the system - effectively cancelling gravity and inertia.

$$T_e = \hat{\mathrm{G}}_\mathrm{e} + (1\text{-a})^{-1} (\hat{\mathrm{M}}_\mathrm{e} \ddot{\theta}_\mathrm{e} + \hat{\mathrm{V}}_\mathrm{e}) \qquad (3)$$

where the "hat" represents our best estimate of the system dynamics. The value a is used to scale the sensitivity of the control input. Assuming our estimated dynamics match the true dynamics, if we substitute (3) into (2) when $a = 0$, we will only have the desired input left as the dynamics of the system.

$$\ddot{\theta}_e = \tau \qquad (4)$$

However, picking a $\neq$ 0 increases the sensitivity of the controller to the arm's movement. Typically we attempt to pick a such that the quantity $(1\text{-}a)^{-1}$ is large. For our simulations, we used a = 1.95. As stated before, this method can only be successful if we have a good dynamic model of the system.

The new input $\tau = K\dot{\theta}$, will be selected based on pole placement in such a manner as to give the arm a nearly marginally stable equilibrium point at $[\dot{\theta}_1, \dot{\theta}_2] = [0, 0]$.

We then computed a human input using a modified gain controller. The input was calculated using another embedded MATLAB function in the simulation (not shown in Figure 3). We defined desired shoulder and elbow angles and computed the human torque input. The equation for the torque computation is as follows:

$$T_h = G_h + \begin{pmatrix} K_1 * \theta_{h1} \\ K_2 * \theta_{h2} \end{pmatrix} - \begin{pmatrix} B_1 * \dot{\theta}_{h1} \\ B_2 * \dot{\theta}_{h2} \end{pmatrix}$$

where G_e is the G_e matrix from (1). Our K and B values are as follows: $K_1 = K_2 = 3$, $B_1 = B_2 = 10$.

III. RESULTS

We currently have developed a working simulation for the upper arm and exoskeleton, including the computed torque controller. In this simulation we supply an initial condition to the system but no inputs to the human arm and allow the control system to keep the system stable. The control system is able to keep the system near the desired operating point using positive feedback without going unstable.

For the first two simulations, we assumed that an angle of zero for both the elbow and shoulder correlated to a vertical arm and exoskeleton. A positive angle for either the elbow or shoulder was equivalent to a clockwise angular rotation. There was no human input for either simulation; we wanted to see the effect of only the control system. Therefore the control system was only implemented in the first simulation. We ran both simulations for 100 seconds; the simulation showed consistent results during the entire running time. Our figures only show the first five seconds of the simulation for ease of viewing.

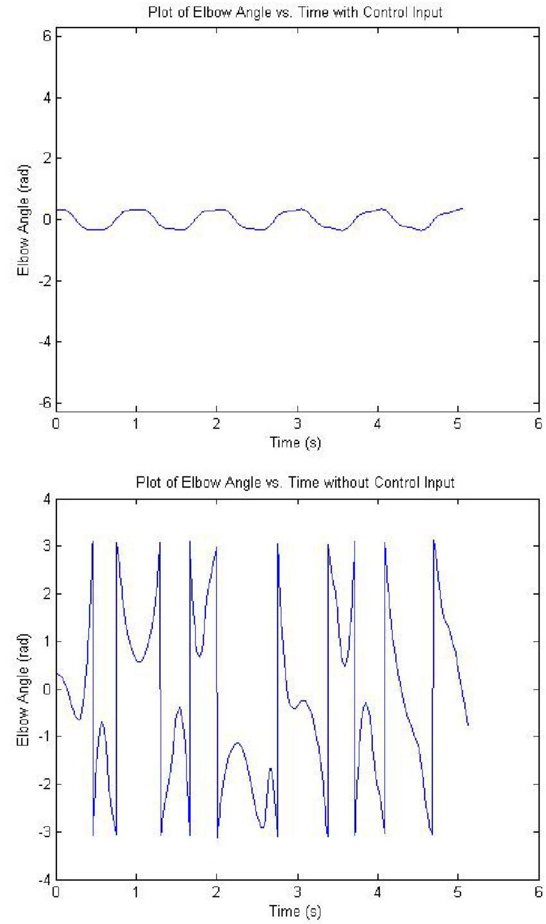
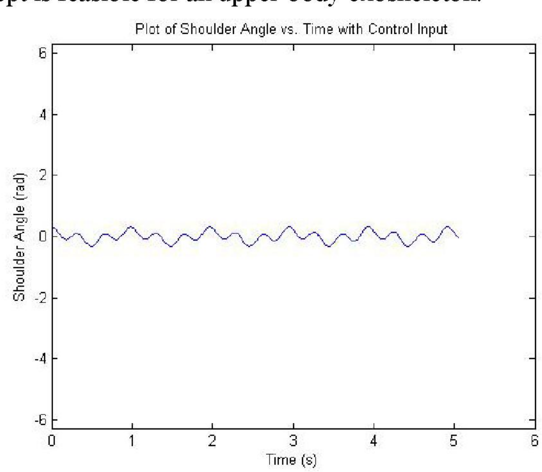


Fig. 5: Plots of human elbow position vs. time with and without the control system input

In Figure 5 we present the plots of elbow position over time both with the controller implemented and without the controller. It is obvious that the elbow joint is unstable without the input torques of the exoskeleton. Without the controller the elbow rotates freely and uncontrollably. Once the controller is implemented, however, the angle of the elbow stays within -0.4 and +0.4 rad. While this is not the ideal result of zero change in the elbow angle, this result shows that the controller concept is feasible for an upper-body exoskeleton.



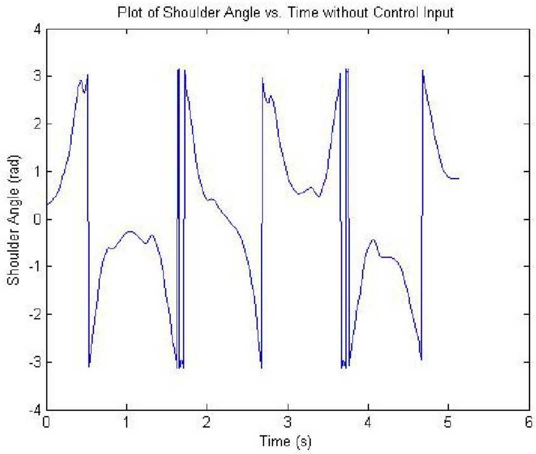


Fig. 6: Plots of human shoulder position vs. time with and without the control system input

Similarly, the shoulder angles of the simulation follow the pattern of the elbow angles. The simulation without the controller results in an unstable, freely swinging shoulder. On the other hand, the simulation with the controller limits the movement of the shoulder to angles between -0.6 and +0.6 rad.

These results are favorable because the goal of the controller is to cancel the dynamics of the system and render the system essentially weightless. Because the system is weightless, the overall system becomes marginally stable. We know it is marginally stable since the elbow and shoulder oscillate around a certain value. However, the oscillations do not increase or decrease; the magnitude is relatively stable throughout the simulation. Like the BLEEX control scheme, our controller makes the system very sensitive to inputs. Without any inputs, the system is marginally stable, which is the desired outcome. When the human is added to the system, the human arm input will make the system stable.

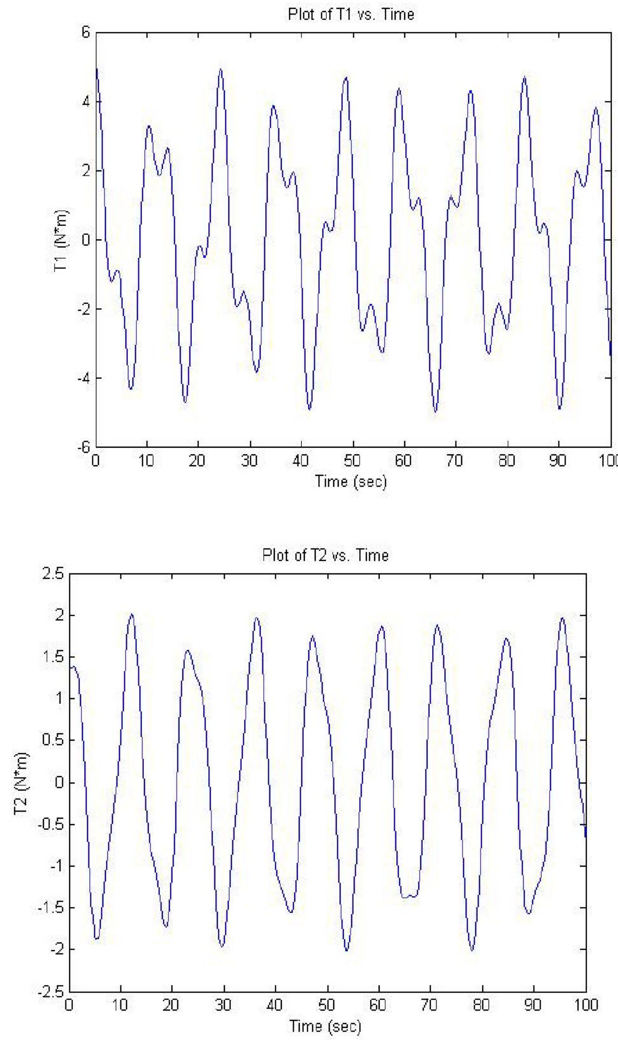


Fig. 7: Plots of input torques T1 and T2 over time

In these plots we see the input torques computed by the controller. The shoulder input, T1, is slightly larger than the elbow input, T2. However, both torques are relatively small. T1 never exceeds 5 N*m and T2 is less than half of T1. Therefore we anticipate that implementation of this control system will not require excessive amounts of motor torque.

When we implemented the controller with the human input, we kept the arm at a stable position. This result is shown in Figure 8.

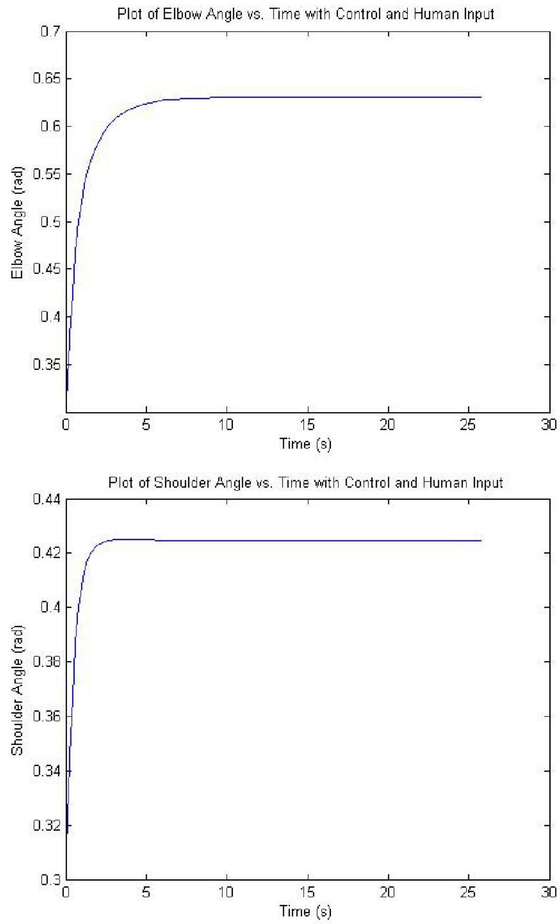


Fig. 8: Plots of elbow and shoulder angles over time with control and human inputs

In the simulation, both the elbow and shoulder joints were started at some angular initial condition. While the desired θ was the same for both joints, the two angles failed to agree. However, this simulation does not account for steady-state error in the angles. If this were a real human, the person would be able to move their arm to the desired position. The objective of this control system is to evaluate the torques experienced by the shoulder and elbow during movement. If movements are easier, i.e. the torques are reduced, then our control system will be successful. Therefore, we assume the human will be able to move their arm easily and are not concerned with the final position of the arm itself in simulation.

We will continue to explore simulations that examine joint position, velocity, torque, and Cartesian position of end effector vs. time. We will examine the forces the exoskeleton will exert on its wearer as a function of time in the following scenarios:

- Perfect dynamic model, slow human movements.
- Imperfect dynamic model, slow human movements.
- Perfect dynamic model, rapid human movements.
- Imperfect dynamic model, rapid human movements.

We expect to quantify a tradeoff between stability and the forces exerted by the exoskeleton on the human. This tradeoff will give us further insight into designing a more responsive control system for our upper-body exoskeleton.

V. CONCLUSION

In this paper we propose the use of an upper body exoskeleton, to be worn by a soldier, to aid in holding, maneuvering and firing a heavy weapon. After describing the initial concept design, we model the system dynamics both using Lagrange's method and using the SimMechanics software package. We derive a controller for our upper body exoskeleton, loosely inspired by the novel approach used on the Berkeley Lower body Exoskeleton (BLEEX). The resulting controller avoids the need to measure muscular activation levels. We have provided the results of our initial simulations, showing that the controller keeps the arm stable. We expect a dominant theme of the analysis to be a tradeoff between stability and the forces the human experiences while wearing the exoskeleton. This is especially important since the control approach requires exact model knowledge, while is obviously impractical in a field setting. The contributions, while modest, are an important first step in evaluating the feasibility of this approach for an upper body exoskeleton.

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