Simulation of Exoskeleton's Virtual Joint Torque Control

Zhang Sheng, Zhang Hu

School of Mechanical Engineering Beijing Institute of Technology Beijing, 100081, China
zhangsheng07_bit@163.com

Abstract - The exoskeleton is developed to assist human in carrying load easily. In order to reduce the sensors between the human and the exoskeleton, ensure that the exoskeleton can track the motion of the human while reducing the torque exerted by the human and increasing the comfort of the human, we need to find out an effective control strategy for the exoskeleton. In this paper, we first analysis the theory of the virtual joint torque control for both 1-DOF model and multi-DOF model and get a conclusion that the control strategy is available in theory. Then we use SimMechanics in Simulink toolbox of MATLAB to build the system's 1-DOF model and multi-DOF model, we get some simulation results which can show that the control system's traceability is good and the power of consumption of the human can be reduced. At last, we give some advices to the next research.

Index Terms – Exoskeleton, control, simulation.

I. Introduction

The exoskeleton is a kind of robots which is designed to assist human. It reduces the burden of carrying load on the human body [1]. The exoskeletons are generally for carrying heavy objects long distance and on paths that are not possible by wheeled vehicles [2]. As early as in the 1960s, our engineers started to research on the exoskeleton. The General Electric developed and tested a master-slave system called the Hardiman in 1968 [3]. The Hardiman was a set of overlapping exoskeletons worn by a human operator. The outer exoskeleton (the slave) followed the motions of the inner exoskeleton (the master), which followed the motions of the human operator. Unfortunately, difficulties in human sensing and system complexity kept it from ever walking. The Berkeley Lower Extremity Exoskeleton (BLEEX) project is funded by the Defense Advanced Research Project Agency(DARPA),USA [4]. It was first unveiled in 2004, at the University of California, Berkeley's Human Engineering and Robotics Laboratory [5]. The BLEEX is comprised of two powered anthropomorphic legs, a power unit, and a backpack-like frame on which a variety of heavy loads can be mounted. It was capable of traveling 42 miles with a pound of batteries at the average speed 2.5 mph while carrying a 150 lb backpack. The human provides an intelligent control system for the exoskeleton while the exoskeleton actuators provide most of the strength necessary for walking. It uses the virtual joint torque control strategy to control the system to assist soldiers. This control method differs from other control methods, because it requires no force sensor between the wearer and the exoskeleton. The control strategy ensures that the exoskeleton moves in concert with the human with minimal interaction force between the two. The exoskeleton is not only used in military, but also used for civilian. Tsukuba University developed a lightweight power assist device, HAL(Hybrid

Assisted Limb). It is connected to the patient's thighs and shanks and moves the patient's legs as a function of the EMG(electromyogram) signals measured from the wearer[6, 7]. This battery-powered suit detects muscle myoelectrical signals on the skin surface below the hip and above the knee. The signals are picked up by the sensors and sent to the computer, which translates the nerve signals into signals of its own for controlling electric motors at the hips and knees of the exoskeleton, effectively amplifying muscle strength. Each leg of HAL powers the flexion/extension motion at the hip and knee in the sagittal plane through the use of DC motors integrated with harmonic drives.

In this paper, we analysis the theory of the virtual joint torque control strategy and use the SimMechanics in Simulink toolbox of MATLAB to build a model and get simulation results to show it is available.

II. Theory Analysis

A. 1-DOF

Fig. 1 depicts the block diagram of 1-DOF exoskeleton interacting with a human. This system is an open-loop system without virtual joint torque control. In order to simplify this system, we ignore the gravity and consider the system as a linear system.
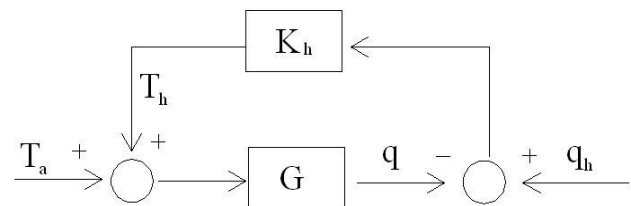

Fig. 1 Open-loop 1-DOF System Block Diagram

Where, q_h is the human's position, q is the exoskeleton's position, K_h is the impedance between the human and the exoskeleton, T_h is the joint torque applied by the human on the exoskeleton, T_a is the joint torque applied by the actuator on the exoskeleton, G represents the system transfer function.

Then we use a proportional-derivative law instead of the actuator dynamics to show the interacting between the actuator and the exoskeleton. Then we add the virtual joint torque control to this system. The closed-loop block diagram of 1-DOF system is shown in Fig. 2. Where, G' is an estimate of the exoskeleton forward dynamics, the gain function K represents the proportional-derivative law.
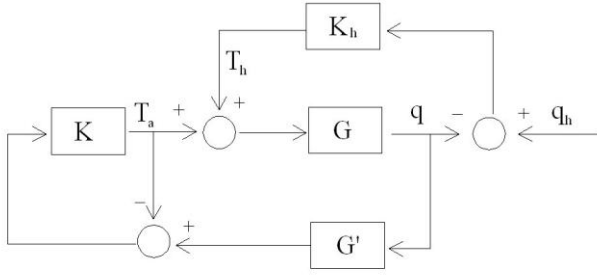
Fig. 2 Closed-loop 1-DOF System Block Diagram

The virtual joint control law can be written:

$$T_h = K_h(q_h - q) \tag{1}$$

$$T_a = K\ (qG'_h - T_a) \tag{2}$$

$$q = G(T_h + T_a) \tag{3}$$

If the system transfer function G is perfect, we have GG'=1. Let the system be a second order model of the form: $G = \dfrac{1}{BS^2 + CS}$,and the gain function K= K_p +K_dS. Using Equ. (1) (2) (3) then we have :

$$T_h = \frac{BS^2 + CS}{BS^2 + CS + K_h(1 + K_p + K_d S)} \cdot K_h \cdot q_h \tag{4}$$

$$T_a = (K_p + K_d S) \cdot \frac{BS^2 + CS}{BS^2 + CS + K_h(1 + K_p + K_d S)} \cdot K_h \cdot q_h \tag{5}$$

$$\frac{q}{q_h} = \frac{K_h(1 + K_p + K_d S)}{BS^2 + CS + K_h(1 + K_p + K_d S)} \tag{6}$$

Making a comparison between equation (4) and (5), we can know that as long as $K_p>1$, $K_d>0$, the actuator provides much more torque than the human does. It means that this control system is available.

B. Multi-DOF

We have illustrated that the virtual joint torque control is effective above. Then we use a multi-DOF model to analysis this control system. As Fig. 3 shows, we consider the human upper body as the reference system and suppose the leg is made up of 3 independent poles(thigh, shank, foot).
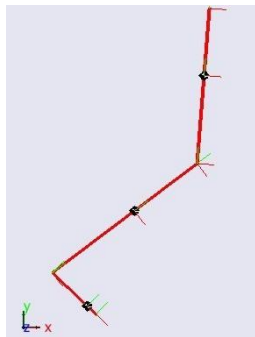

Fig. 3 Multi-DOF System Model

The dynamic equations of the multi-DOF system can be expressed as:

$$\vec{T}_h + \vec{T}_a = \vec{J}(\vec{q})\ddot{\vec{q}} + \vec{B}(\vec{q}, \dot{\vec{q}}) + \vec{G}(\vec{q}) \tag{7}$$

Where: $\vec{J}$ is the inertia matrix, $\vec{B}$ is represents centrifugal and Coriolis terms, $\vec{G}$ is the negative of the torque due to gravity.

If without the virtual joint torque control, then $\vec{T}_a$=0, it infers that:

$$\vec{T}_h = \vec{J}(\vec{q})\ddot{\vec{q}} + \vec{B}(\vec{q}, \dot{\vec{q}}) + \vec{G}(\vec{q}) \tag{8}$$

If we use the virtual joint torque control and let:

$$\vec{T}_a = (1 - \lambda^{-1})[\vec{J}(\vec{q})\ddot{\vec{q}} + \vec{B}(\vec{q}, \dot{\vec{q}})] + \vec{G}(\vec{q}) \tag{9}$$

Where $\lambda > 1$, as a gain parameter. Then:

$$\vec{T}_h = \lambda^{-1}[\vec{J}(\vec{q})\ddot{\vec{q}} + \vec{B}(\vec{q}, \dot{\vec{q}})] \tag{10}$$

Making a comparison between equation (8) and (10), we have the conclusion that the control system is also suitable for the multi-DOF.

III. Simulation

A. 1 -DOF

We use SimMechanics in Simulink toolbox of MATLAB to build the model of the 1-DOF system. The simulation results are shown in Fig. 4 and Fig. 5. In Fig. 4, the dash-dot line represents the exoskeleton angle's actual output, while the active line represents the angle's desired output. It shows that the system angle's traceability is good. In Fig. 5, the dotted line represents the human's torque, while the active line represents the actuator's torque. It can be seen that the actuator provides much more torque than the human's which means that the system is effective.
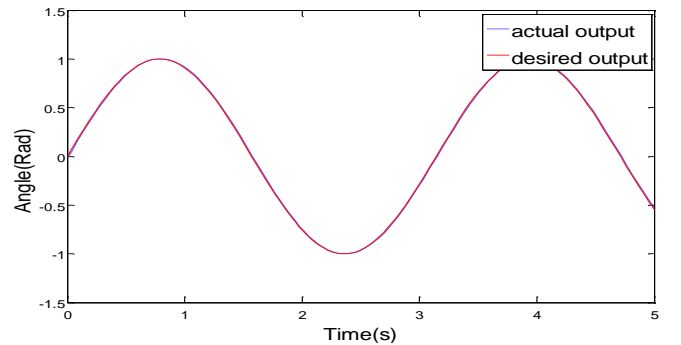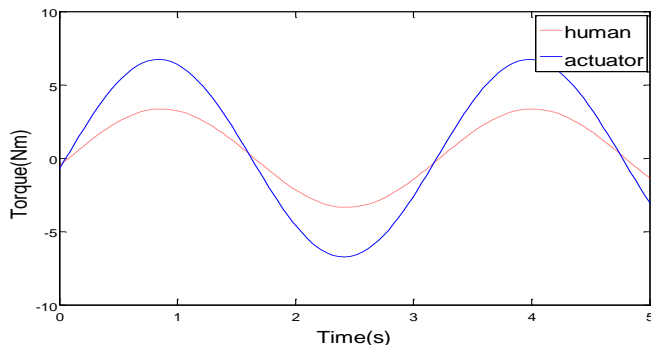

Fig. 4 Angle Track of 1-DOF System

Fig. 5 Torque Track of 1-DOF System

B. Multi-DOF

In the same way, we use SimMechanics in Simulink toolbox of MATLAB to build a multi-DOF model. As Fig. 6 shows, we build a 3-DOF system model, Ground represents the human upper body, Joint Actuator is used to drive the model and Joint Sensor collects the data, the subsystem is the virtual joint torque control module. There are 3 joints and 3 body parts in our model. We use Winter D.A's human parameters [8] to set the body parts. And the 3 '.mat' files are set according to CGA(Clinical Gait Analysis) to provide the desired output signals. When the simulation begins, the desired output signals pass through the subsystems to the joint actuators, and then the joint actuators drive the body parts to move like a human leg's track. At the same time, the joint sensors get the actual output signals of the body parts which we use to make a comparison between the desired output signals.
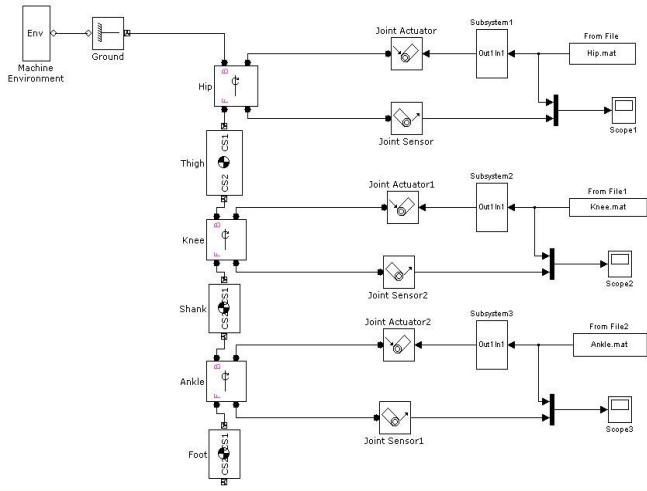

Fig. 6 Multi-DOF Control System Model

Then we have Fig. 7 and Fig. 8 as our simulation results. Fig. 7 shows Hip, Knee, Ankle's angle curves from top to bottom, the dash-dot line represents the exoskeleton angle's actual output, while the active line represents the angle's desired output. It is obviously that the traceability is good. The actual output is nearly the same with the desired output. There is only a little deviation between them. Fig. 8 shows Hip, Knee, Ankle's torque curves from top to bottom, the dotted line represents the human's torque, while the active line represents the actuator's torque. It shows that human can easily drive the exoskeleton with the actuators' assistant which means that the control system is available. But the stability is not so well in the figure. The parameters of the control system are still need to be improved.
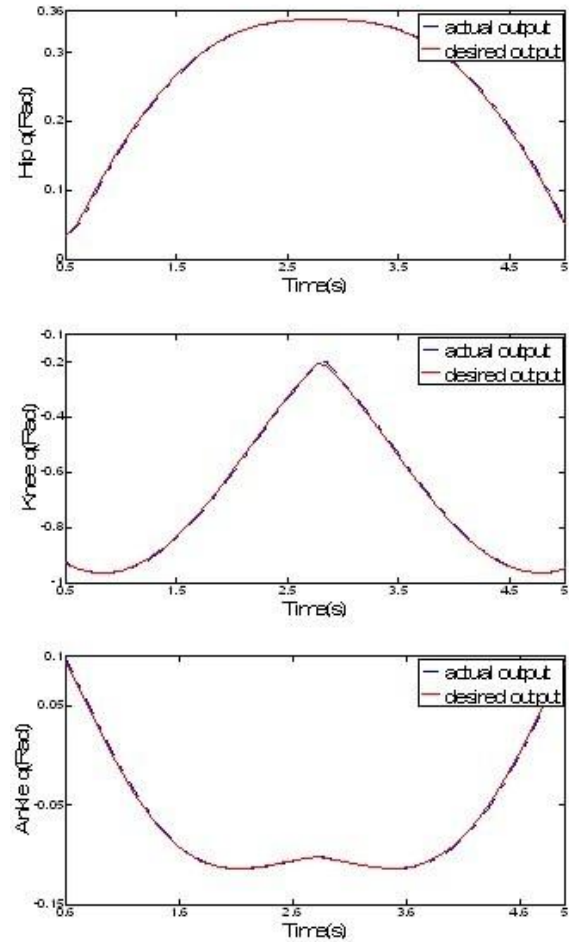

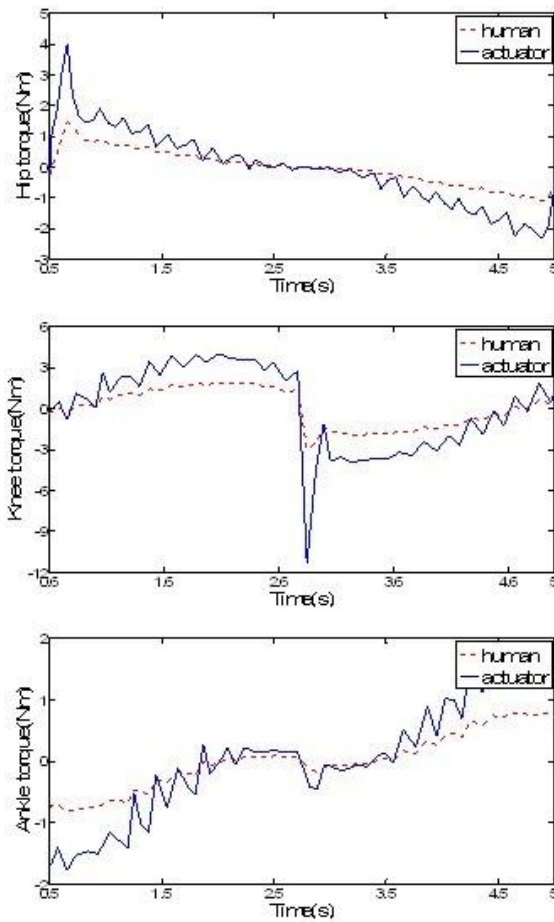Fig. 7 Angle Track of Multi-DOF System

Fig. 8 Torque Track of Multi-DOF System

IV. Conclusion

The greatest advantage of the virtual joint torque control strategy is that there is no need to set force sensors between the human and the exoskeleton so that the human can drive the exoskeleton easily. According to the simulations above, we know that the virtual joint torque control is available. The traceability is very good, but the assistant torque needs to be improved. The system parameters, such as the system transfer function, the proportional-derivative law's parameters, are relative to the improvement. We need to find out better parameters for the control system. The next research will focus on the parameters' influences on the control system's improvement and robustness.

References

[1] J R Steger, "A design and control methodology for human exoskeletons," Ph.D dissertation, University of California, Berkeley, 2006.
[2] Adam Zoss, H.Kazerooni, Andrew Chu, "On the Mechanical Design of the Berkeley Lower Extremity Exoskeleton(BLEEX)," IEEE/ASME Transactions on Mechationics, April, 2006, 11(2).
[3] H.Kazerooni, "A Review of the Exoskeleton and Human Augmentation Technology," 2008 ASME Dynamic Systems and Control Conference, October 20-22, 2008, Ann Arbor, Michigan, USA.
[4] Andrew Chu, "Design of the Berkeley Lower Extremity Exoskeleton(BLEEX), " Ph.D dissertation, University of California, Berkeley, 2005.
[5] H.Kazerooni, R Steger, "The Berkeley Lower Extremity Exoskeleton," Transactions of the ASME, March, 2006, Vol.128, pp. 14-25.
[6] Kawamoto.H, Kanbe.S and Sankai.Y, "Power Assist Method for HAL-3 Estimating Operator's Intention Based on Motion Information," Proc. of 2013 IEEE Workshop on Robot and Human Interactive Communication, Millbrae, CA, IEEE, New York, pp. 67-72.
[7] Kawamoto.H and Sankai.Y, "Power Assist System HAL-3 for gait Disorder Person," ICCHP,July,Austrlia.
[8] D A Winter, "Biomechanics of Human Movement," John Wiley and Sons, New York, 1979.