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Force Feedback Control of Lower Extremity Exoskeleton Assisting of Load Carrying Human

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Abstract. Lower extremity exoskeletons are wearable robot manipulators that integrate human intelligence with the strength of legged robots. Recently, lower extremity exoskeletons have been specifically developed for rehabilitation, military, industrial applications and rescuing, heavy-weight lifting and civil defense applications. This paper presents controller design of a lower-extremity exoskeleton for a load carrying human to provide force feedback control against to external load carried by user during walking, sitting, and standing motions. Proposed exoskeleton system has two legs which are powered and controlled by two servo-hydraulic actuators. Proportional and Integral (PI) controller is designed for force control of system. Six flexible force sensors are placed in exoskeleton shoe and two load cells are mounted between the end of the piston rod and lower leg joint. Force feedback control is realized by comparing ground reaction force and applied force of hydraulic cylinder. This paper discusses control simulations and experimental tests of lower extremity exoskeleton system.

Introduction

Exoskeletons are wearable robots that integrate human body with robotic machines into a single system by combining human intelligence with strength and endurance of robots. Exoskeletons are designed and used for many applications such as rehabilitation, military, industrial heavy-weight lifting and civil defense [1-14]. Studies on exoskeletons started about 50 years ago. The first active exoskeleton named Hardiman was developed at General Electric in 1965 [1]. It was powered by electrical actuators controlled by a master–slave follower system. Bulky and complex structure of Hardiman caused some safety problems and the project failed. In 1970, the Mihajlo Pupin Institute in Belgrade developed different types of exoskeletons powered by various actuators, such as hydraulic drivers, pneumatic drivers, and dc servo motors for rehabilitation of disabled individuals [2]. More recently, a walking aid exoskeleton named HAL has been developed at Tsukuba University for individuals with gait disorders [3]–[5]. HAL is powered by electrical actuators and use a hybrid control system that consists of an autonomous posture controller and a power assist controller. The intended motion of the user is determined by using electromyography (EMG) sensors and ground reaction force sensors. HAL can successfully walk and carry its own power supply. The Kanagawa Institute of Technology has developed a full-body "wearable power suit," powered by unique pneumatic actuators [6]. It has been used in limited applications without a need for a portable power supply. Another exoskeleton BLEEX has been developed at the Human Engineering Laboratory of UC, Berkeley [7]–[12]. BLEEX is an energetically autonomous exoskeleton capable of carrying its own weight plus an external payload. BLEEX comprises two anthropomorphic legs driven by hydraulic actuators, more than 40 sensors some of which are embedded in the shoe pads, a hybrid power supply, and a backpack-like frame on which a variety of heavy payloads can be mounted. BLEEX is the first energetically autonomous lower extremity exoskeleton capable of carrying a payload.

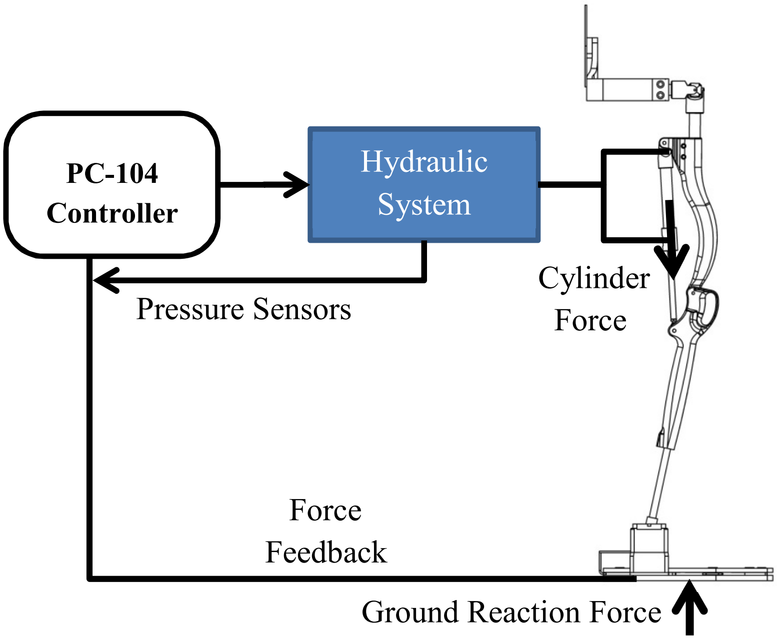


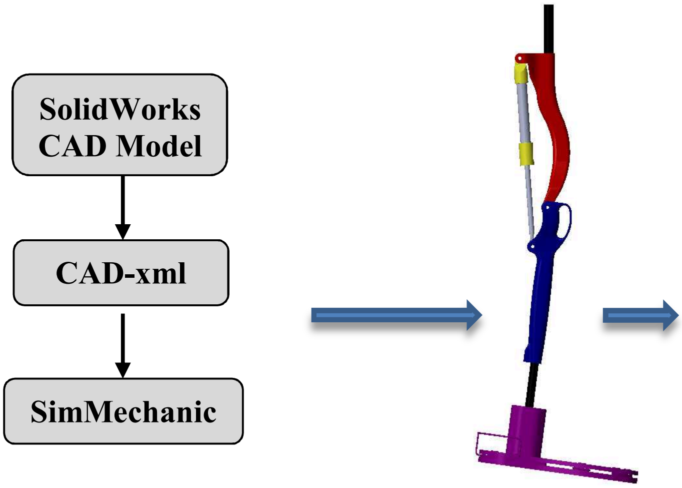
Fig. 1. Force control for exoskeleton system.

Fig. 2. Lower extremity exoskeleton system

Proposed lower extremity exoskeleton is developed to support human walking, sitting, and standing motions synchronously with human and also actuator system is designed to take significant portion of external load carrying by the user. Hydraulic system of exoskeleton consists of two cylinders, two servo valves, four pressure sensors, an accumulator and a power unit. Servo valves provide cylinders' position and velocity simultaneously according to measured force signals. Force control for lower extremity exoskeleton is accomplished in dynamic simulations, control system design, PI controller optimization and experimental works. Initially dynamic behavior of exoskeleton is obtained by importing 3D-Cad model to Matlab/SimMechanics software for simulations and uncontrolled results are achieved. Ground reaction force signal taken from exoskeleton shoe is feed backed to PI controller. Thus, PI controller acts to hydraulic cylinder which applies opposite reaction force to balance external load of the user. Ground reaction force is calculated to obtain appropriate cylinder force by using kinematic equations in simulations online. Also PI controller is optimized to find most suitable gain parameters for force control of experimental tests. In addition to them experimental works are realized to verify simulation results. The schematic force control block diagram and proposed exoskeleton system are given in Figure 1 and Figure 2 respectively.

Controller Design and Results

Modeling stages of exoskeleton system is shown in Figure 3. In this modeling technique solid model of exoskeleton obtained from SolidWorks software in terms of shape, size, mass and inertia characteristics, is imported to Matlab/Simulink/SimMechanics software. An interface program which transforms CAD files into an XML file is used in order to perform this process. Therefore components assembly relations must be determined carefully before converting. Simulation models are seen in Figure 4. Afterwards dynamic behavior of proposed system is obtained and simulated by using simulation models.



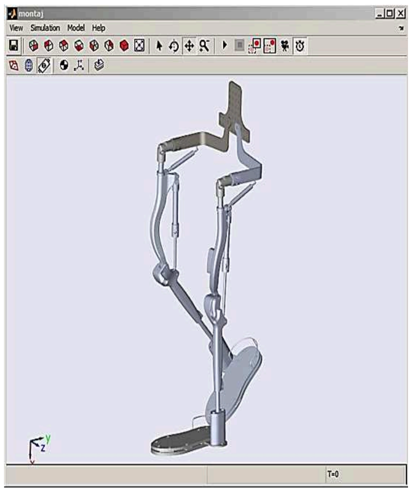


Fig. 3. Modeling stages of exoskeleton system.

Fig. 4. Simulation models of exoskeleton.

The exoskeleton system has two servo valves to control two hydraulic cylinders. Input of servo valves is 0-10V analog voltage. Priority control architecture and controller are designed on the main observation computer outside of the exoskeleton system. Designed control software is installed to the PC104 -based compact computer which is developed for mobile applications and produced by embedded board technology. Simulation based control algorithm is uploaded to embedded board by using Matlab/XpcTarget. A simple kernel of XpcTarget software works on embedded board. In this way system is purified from software errors of complex operating system.

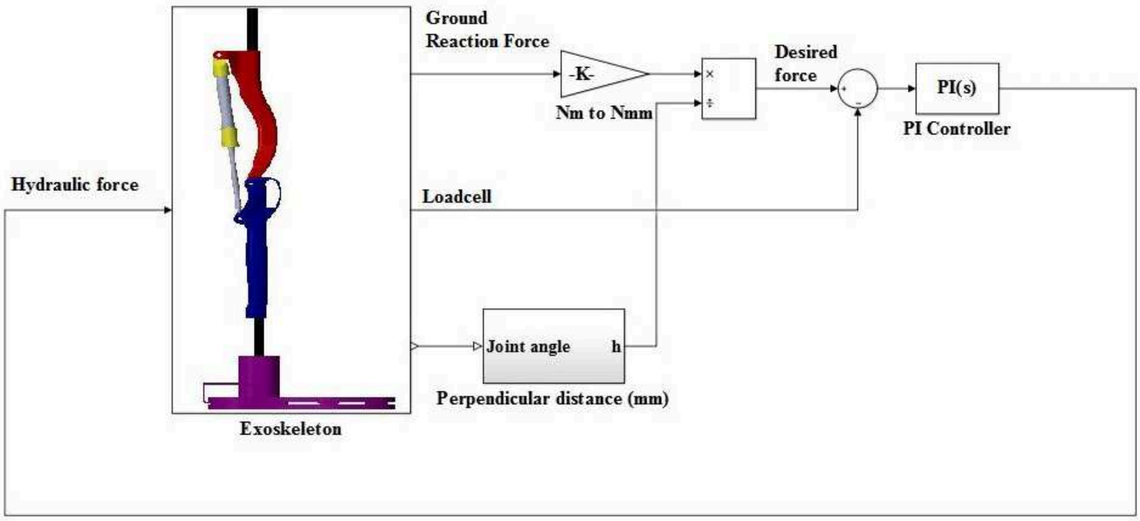


Fig. 5. Simulink control block diagram of exoskeleton system.

Data acquisition cart of embedded board converts controller digital output and analog force signals from bottom of shoe and cylinder load cell to analog and digital signals for servo valve and controller respectively. In addition to this cylinder pressure signals from pressure sensors on hydraulic power unit are transmitted to controller. Matlab/Simulink control block diagram is given in Figure 5. Control system designed on Simulink interface is converting to C codes while installation process begins. During this operation any intervention from the user is not expected. Unless there is any error this process runs automatically. Next step a program compiled on main computer via an ethernet connection is loaded on mobile computer and real time independent control is realized. Initially for force feedback control of proposed exoskeleton system, proportional and integral (PI) control is designed and gain parameters are optimized by using Simulink auto tune option for PI controller according to input and output signals. Proportional and integral parameters are obtained as 52.35 and 34.49 respectively. Also these parameters are used in experimental works. Two different moment signals obtained from ground reaction forces as seen in Figure 6a are applied as disturbance inputs to find force control performance of desired PI controller. Force control responses for trapeze and sinusoidal disturbance moment inputs are given in Figure 6b and 6c. Moreover uncontrolled results for sinusoidal disturbance moment are shown in Figure 7.

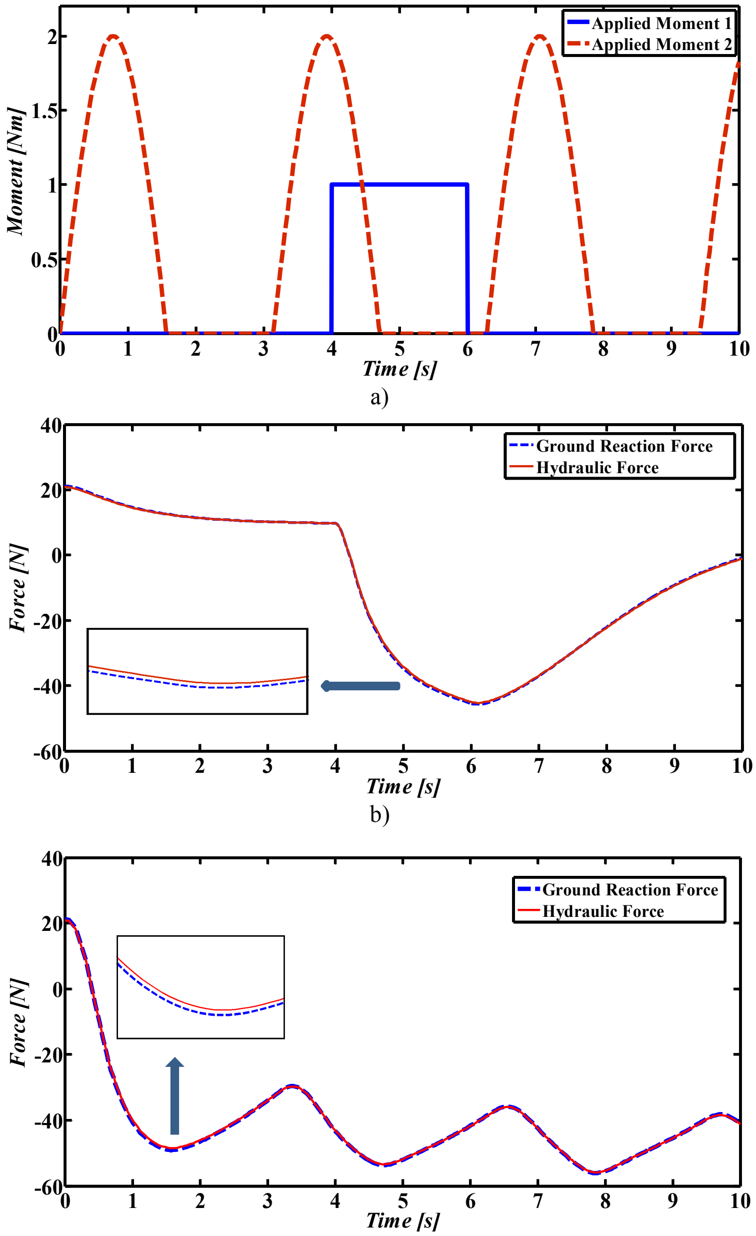


Fig. 6. a) Disturbance moments, b) and c) Force control responses for trapeze and sinusoidal moment inputs.

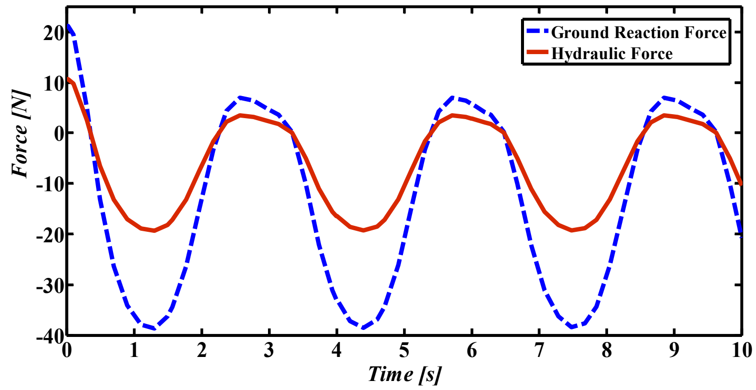


Fig. 7. Uncontrolled results for sinusoidal disturbance moment.

Conclusion

This paper presents force feedback control for a lower-extremity exoskeleton assisting of a load carrying human. Dynamic model based simulations and experimental tests of lower extremity exoskeleton system are realized. Also a PI controller is implemented for force feedback control according to desired control criteria and different disturbance moment signals successfully both in simulations and experimental tests.

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