БЪЛГАРСКА АКАДЕМИЯ НА НАУКИТЕ • BULGARIAN ACADEMY OF SCIENCES

ПРОБЛЕМИ НА ТЕХНИЧЕСКАТА КИБЕРНЕТИКА И РОБОТИКАТА, **69**
PROBLEMS OF ENGINEERING CYBERNETICS AND ROBOTICS, **69**

София • 2018 • Sofia

Exoskeleton for rehabilitation

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Abstract: *In this work, the design and development of an active orthotic system for rehabilitation is presented. The orthosis (exoskeleton) is assistive device with a wearable structure, corresponding to the natural motions of the human. The exoskeleton structure includes left and right upper limb, left and right lower limb and central exoskeleton structure for human torso and waist and provides support, balance, and control of different segments of the body. The device was fabricated with light materials and powered by pneumatic artificial muscles that provide more than fifteen degrees of freedom for the different joints. The actuation of the exoskeleton is inspired by the human limbs musculoskeletal system, and mimics the muscle-tendon-ligament structure. The system can operate in three modes - Assistive Mode; Haptic and rehabilitation device and Motion tracking system with data exchange with virtual reality. The exoskeleton can be used for human interaction with virtual environments where motion tracking and force feedback are required. The system would be of great importance to people with limited mobility for assistive and rehabilitation tasks.*

Keywords: *active orthosis; exoskeleton for upper limbs, lower limbs, haptic device, Control, artificial muscles, joint articulation, rehabilitation robotics.*

1. Introduction

Exoskeletons are currently being developed for the military and medical applications, to assist in rehabilitation, to increase the mobility of the elderly or to support factory workers while performing manual work. An exoskeleton is a wearable robotic device with joints and limbs corresponding to those in the human body. The main purpose of the exoskeleton is to compensate the lack of force in the joints and support the user's body weight so as to minimize the loading on the joint [1] or for gait assistance [2, 3, 4] by supplying assistive torque at the knee joint during dynamic activities of daily living [5]. There are different prototypes of exoskeletons that use different actuators, e.g. ultrasonic motors, pneumatic rubber artificial muscles, and air bag actuators [6, 7, 8] etc.

Haptic or force-reflecting interfaces are robotic devices used to display touch or force-related sensory information from a virtual or remote environment to the user [9, 10]. Many upper limb exoskeletons with different mechanical structure and actuation, with or without force feedback haptic devices, have been presented in the literature [11-20]. The known exoskeletons working in virtual reality are commonly for one or both upper limbs. In most cases, these devices are grounded and they provide a limited range of interaction in virtual reality. Lower-limb exoskeletons are also currently being developed to assist elderly or disabled people in walking.

The main task of our project was to create an exoskeleton for the whole body with a wearable structure and anthropomorphic workspace including: exoskeleton for upper limbs as a haptic device providing force feedback of the limbs during the interaction in a virtual reality; exoskeleton for the torso and lower limbs that minimize the load on the lower limb joints by providing assistive torques and control the virtual avatar movements.

2. Description of the system

A model of the whole exoskeleton was designed in Solid Work. Based on the structure scheme in Figure 1, the device was build-up like a branched serial kinematics structure consisting of rotational joints and functioning as a powered exoskeleton. The whole exoskeleton structure includes left and right upper limb, left and right lower limb and central exoskeleton structure corresponding to human torso and waist, supporting upper and lower limbs Antagonistic acting pneumatic muscles are used for moving the limb units. The total number of degrees of freedom for the whole exoskeleton structure is $h = 5+5+6+6+7=29$ and the number of actuated joints is $h_a = 4+4+3+3=14$. The *Upper limb exoskeleton* has 4 d.o.f. corresponding to the natural motion of the human arm from the shoulder to the elbow but excluding the wrist and the hand. The *Lower limb exoskeleton* has 6 d.o.f. corresponding to the natural motion of the human lower limb from the hip to the foot. The exoskeleton mechanical structure as a wearable device has to fulfil the design requirements for low mass/inertia, safety, comfort, anthropomorphic extensive range of motion, etc.

Emergency stop and user activated alarms are fitted to the system hardware and linked to the overall control system to ensure that the user will not be injured by the system.

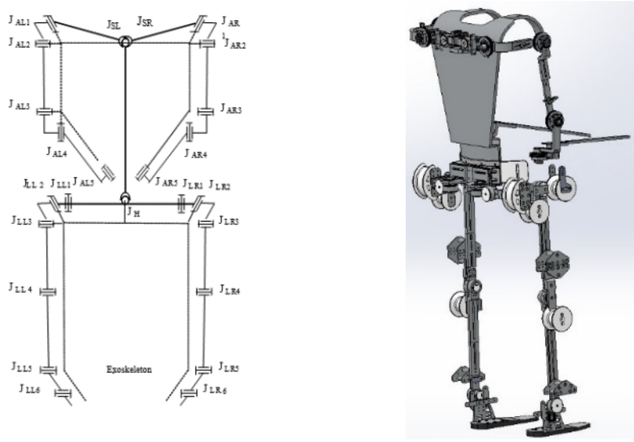

Fig.1. Whole Body Exoskeleton: a) Kinematic structure, b) CAD Design.

The Active Orthotic Systems (AOS) can operate in three modes:

- Haptic and rehabilitation device;
- Assistive Mode with active orthosis in cases of impaired muscles;
- Motion tracking system with data exchange with virtual reality.

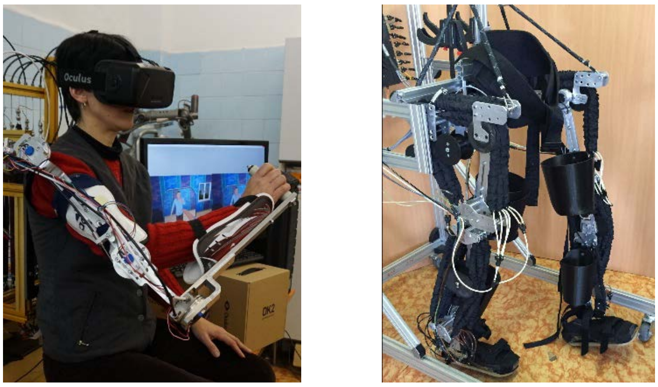

Fig.2. Real prototype: a) Upper Limb Exoskeleton; b) Lower Limb Exoskeleton

The work includes:

- *An Active Orthosis for Upper Limbs* – haptic device with force-feedback that can display sensory information from a virtual reality to the user. The orthosis consists of a novel construction produced by carbon, actuated by pneumatic actuators and controllers with force-reflecting interface;
- *An Active Orthosis for Lower Limbs* - assistive locomotion device actuated by pneumatic artificial muscles and adjustable joint torque;

- *A Control System for joint actuation* and force feed-back from VR. Joints actuation is achieved by producing appropriate antagonistic torques through antagonistic action of pneumatic actuators applying impedance control.
- *ExoInterface* - graphic user interface for exoskeleton calibration, communication and interaction with virtual reality.

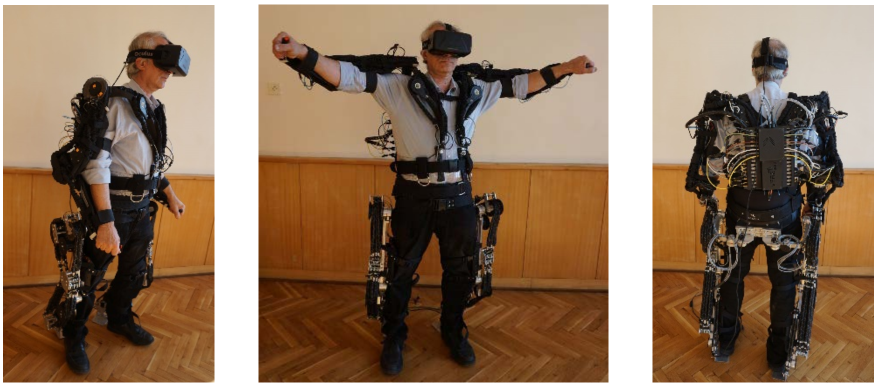

Fig.3. Active exoskeleton for upper and lower limb actuated by pneumatic muscles

The first prototype was designed from aluminum (Fig. 2) and actuated by pneumatic muscles working in antagonistic manner. The second and third prototype is constructed from plastic and carbon to fulfil the design requirement for lightness and structure with low mass/inertia characteristics (Fig. 3). The main details are manufactured using a 3D printer from PLA plastic. The most loaded parts like axes and bearings are manufactured from steel. The exoskeleton arm segments are designed so that it can be easily used by the 'typical adult' with only minor changes to the set-up.

3. Control System

The control system of the exoskeleton contains multiple micro-controller units (MCUs) to support the following tasks for each joint: actuation, sensing, signal processing and control. The proposed control technology is based on feedback information from visual and pressure sensors, position (magnetic encoders) and force sensors (strain gage) mounted in each joint of the exoskeleton. The body balancing and supporting exoskeleton system is provided also with two insoles with tactile switches and a set of accelerometers. The prototype sensor system provides information for joints rotation in real-time. The Master controller determines the position of the limb and exchanges the data with the PC ExoInterface program and virtual environment (Fig. 4). ExoInterface program transfers the data through the internet by UDP protocol in order to map the avatar in the virtual reality. The avatar in the virtual reality may perform an action or movement and thereby activate the corresponding limb sending new information about forces applied to the end effector.

The Control algorithm analyses the motion and received information and decides an appropriate joint position or new orientation of the body.

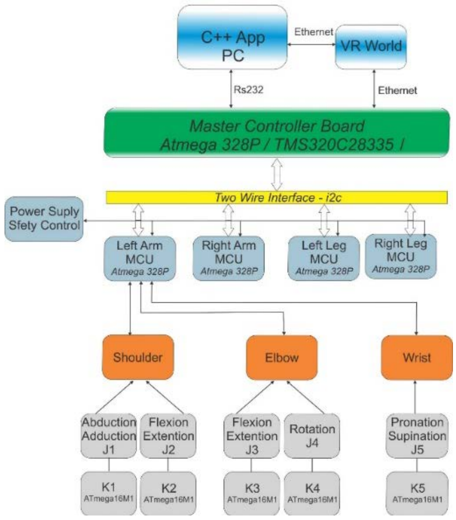

Fig.4. Distributed Control

The Upper limb exoskeleton acts as a *haptic device* that displays force-related sensory information from the virtual avatar. The *Local control system interprets the applied forces at the end effector* of the avatar and sends the commands to drive the *corresponding segments* of the exoskeleton. The MCU determine the joint position by computing the torque and carry out commands to the pneumatic muscles by signalling the solenoid valves to open or close. As a result a *Joint torque control* is implemented in each joint.

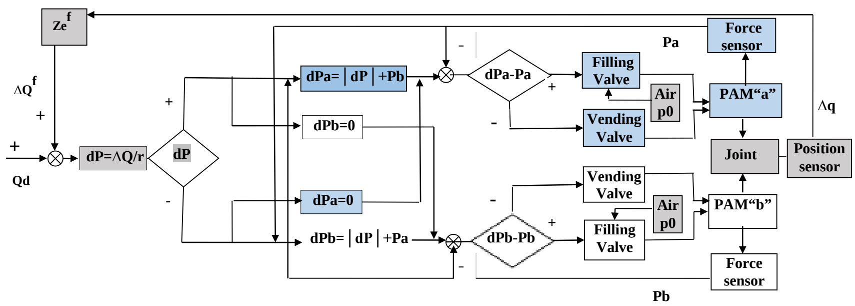

Fig.5. Joint Torque Control

The joint control is achieved by producing appropriate antagonistic torques through antagonistic action of pneumatic actuators applying *Impedance Control* (Fig.5). Impedance controlled systems detect the motion commanded by the operator and control the force applied by the haptic device. When the system operates in force feedback mode, it can generate a virtual kinematic constraint to the user movements corresponding to the contact with a surface.

A group of two or more pneumatic muscles can be used for actuation of different joints. Establishing a maximum torque in the joint of antagonists muscle actuators, it is assumed, that one muscle group is active in one direction, when the other is passive and vice versa. This is achieved by switching the filling valve to achieve the desired joint moment. However, the muscle bundles with zero pressure always participate with a force in the joint antagonistic equilibrium, as they are elastic. If we denote by *Pa* and *Pb* forces in passive muscle groups (at zero pressure), the desired force of an active muscle bundles is calculated by equations:

$$dPa=Pb+|dP|; \quad dPb=Pa+|dP|, \tag{1}$$

$$dP = \Delta Q / r \tag{2}$$

where $|dP|$ is the force module set by the desired torque Q_d in the joint, r is the radius of the pulley, $Z_e^{\,f}$ represents the dynamic model of the exoskeleton in joint space.

The range of each muscle depends on the operating pressure, *p*. The torque regulation in the joint position are analysed by means of pressure variation $p_a=f_a(Q,q)$, $p_b=f_b(Q,q)$ which are used to control the moments in the joints.

Gravitational components of joint moments were rated according to the *model for gravity compensation* of the exoskeleton arm.

Antagonistic acting pneumatic muscles are used at the same manner to move the lower limb units. The design task here was to create a lower limb with active joints, where the torque can be adjusted within wide limits according to the needs of the operations. The design problem was solved with BG Patent Reg. No 112139/06.11.2015, "Lower limb with active joints". The actuation structure includes pneumatic artificial muscles and tensioning pulley to reduce variable moment in the leg joints.

4. Motion Tracking System and Data Exchange with Virtual Reality

A Graphical User Interface, ExoInterface has been created for exoskeleton calibration, communication and data exchange with the virtual reality (Fig.7). ExoInterface program is the main interface between the exoskeleton’s controller, the virtual reality environment and the user. Data transfer between the exoskeleton and virtual avatar has been performed in 3D Unity virtual Engine trough the VERE Platform server. The server is located at the University of Barcelona. The communication is realizing through the internet and bidirectional data exchange between the ExoInterface program and virtual reality is performed in real time. HMD Oculus Rift is used for visualization in the virtual system. A *first optical tracker* (HMD *Oculus Rift*) is used to track the head position and orientation, and a *second (Exoskeleton system) to track the rigid frame* of the upper-limb exoskeleton. The two reference frame are fused in a single reference system and together *are used to track the position and orientation of all human body (Fig.6, 7).*

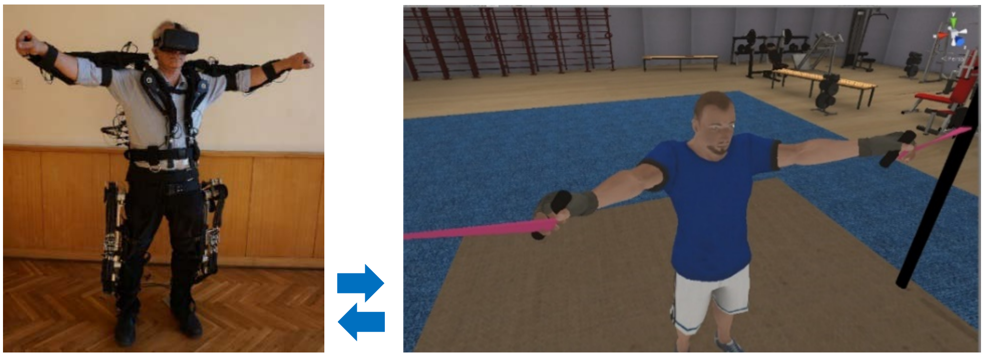

Fig.6. Exoskeleton Data Exchange with Virtual Avatar

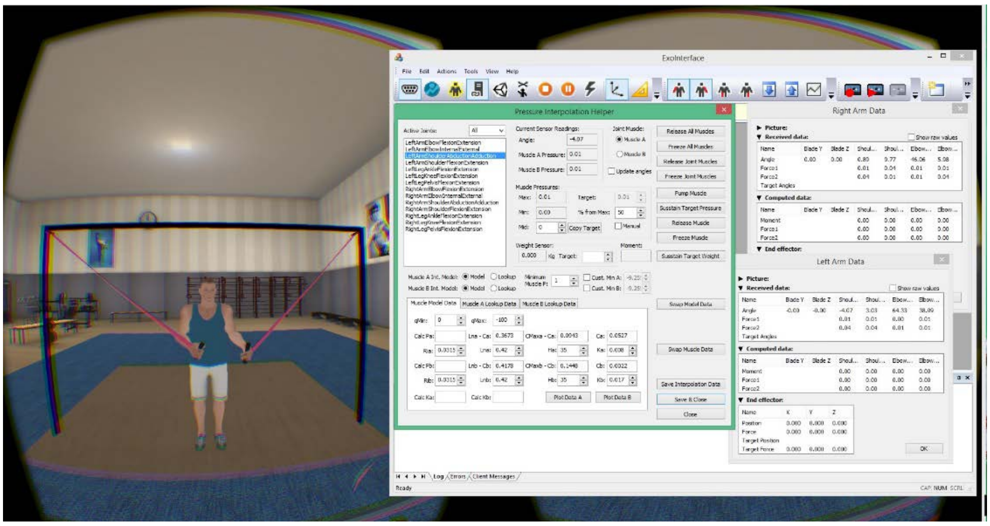

Fig.7. ExoInterface. Graphic User Interface for exoskeleton calibration, communication and data exchange with virtual reality.

Actual tests have been performed between IM-BAS in Sofia and UB in Barcelona with very low latency between the Exoskeleton and the Virtual avatar. The avatar and the exoskeleton were moving in the same way and speed. Data transfer is performed at 170Hz.

5. Results and discussions

A GIM virtual environment suitable for the realization of the physical exercises *Virtual Weight Lifting and Pilates* (from a first person perspective) has been created. An experiment has been completed in virtual reality where participants were either embodied in a weak or strong body. The measurements have been taken and the following set of variables recorded - forces applied and retrieved from the exoskeleton, tracking data for later playback and evaluation, embodiment questionnaires. The effect of embodiment with different types of bodies on personal strength has been examined. The torque regulation possibilities in the joint or in the joint position are analysed by means of pressure variation. Three-dimensional characteristics *joint torque – muscle contraction - pressure* are used for torque control of the joints by monitoring the muscles pressure and positions in the actuated joints (Fig. 8).

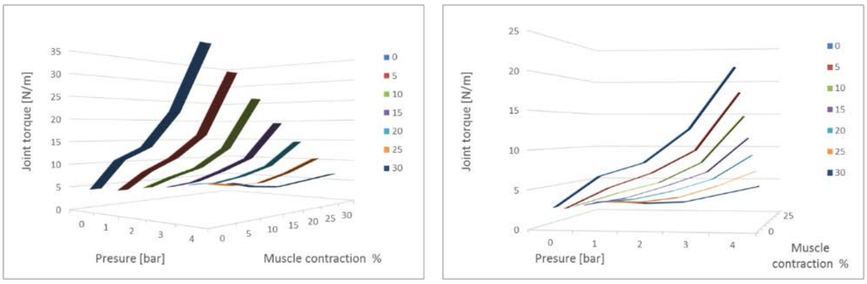

Fig.8. Characteristics in 3D: joint torque/ joint position /pressure for a bundle of muscles antagonists

The values of the physical damping and stiffness of the actuators and transfer elements of the exoskeleton are evaluated experimentally. When both muscles groups work antagonistically in a single joint the system ensures easy joint control, bidirectional actuation without backlash and possibility for stiffness joint variation.

Conclusion

The design and development of an active/assistive orthotic system has been carried out. The orthotic system consists of a novel lightweight wearable structure for the whole body with anthropomorphic workspace and includes: exoskeleton for upper limbs as a haptic device providing force feedback of the limbs during the interaction in a virtual reality; exoskeleton for the torso and lower limbs that minimize the load on the lower limb joints by providing assistive torques and control the virtual avatar movements. Program “ExoInterface” for exoskeleton calibration, communication and interaction with virtual reality has been developed.

One of the main achievements of the active/assistive orthotic system is the multifunctionality - AOS combines the motion tracking system, haptic and rehabilitation device in one wearable structure with force feed-back and anthropomorphic workspace covering the full range of human motions.

The proposed system can be used for application where both motion tracking and force feedback are required, such as human interaction with virtual environments.

The system would be of great importance to people with limited mobility for assistive and rehabilitation tasks

Acknowledgement

This research was supported by the European Commission through FP7 Integrated Project VERE [grant number 257695]; Bulgarian Science Found [grant number DN 07/9].

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Екзоскелетон для рехабилитации

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Резюме: *В этой работе представлена разработка активной ортопедической системы для рехабилитации. Ортез (экзоскелетон) является вспомогательным устройством со структурой, соответствующей естественным движениям человека. Структура экзоскелетона включает левую и правую верхнюю конечность, левую и правую нижнюю конечность и центральную структуру экзоскелета для торса и талии человека и обеспечивает поддержку, баланс и контроль над различными сегментами тела. Устройство было изготовлено из легких материалов и оснащено пневматическими искусственными мышцами, которые обеспечивают более пятнадцати степеней свободы для разных суставов. Приведение экзоскелетона в действие вдохновлено костно-мышечной системой человеческих конечностей и имитирует структуру мышц-сухожилий-связок. Система может работать в трех режимах - Вспомогательный режим; Хаптический и рехабилитационный и система отслеживания движения с обменом данными с виртуальной реальностью. Экзоскелетон может использоваться для взаимодействия человека с виртуальными средами, где требуется отслеживание движения и ответная реакция. Эта система будет иметь большое значение для людей с ограниченной подвижностью для ассистивных и реабилитационных задач.*