Overview of Human-Machine Interaction of Pneumatically Actuated Industrial Exoskeletons

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Abstract: *Increasing human physical strength is a long researched area. Mainly military applications have been developed in order to increase the load-bearing capacity of the soldiers. However, in addition to military developments, healthcare and industrial applications are also gaining prominence. In this paper, the development directions of industrial exoskeletons with an emphasis on pneumatically operated devices are reviewed. An essential part of this paper is the analysis of the human-machine interaction. With our research results, we want to contribute to disseminating exoskeletons and facilitating adaptation to related areas.*

Keywords: *Exoskeleton, pneumatics, industrial application, human-machine interaction*

1. Introduction

The exoskeleton is an external frame attached to the user's human body. It senses the user's movement, and based on that, it multiplies the force exerted by the human, thus increasing the physical strength of the wearer. The equipment has been developed primarily for military applications [1] [2]. However, it can be stated that successful experiments have also been carried out in civilian applications. Full-body exoskeletons are used for most military applications, but only support devices have been developed to move or hold the given body part for some target tasks. Each exoskeleton must be optimized for a specific task to be performed. Therefore the materials used and the possible solutions are wide-ranging. In order to use human power optimally, more attention has been paid to the development of continuously operated exoskeletons in industrial applications. One type of these devices is the pneumatically operated exoskeleton, which can be operated indefinitely from a built-in industrial compressed air network. In this review paper, the development directions of civil exoskeletons are reviewed, and then the human-machine interaction in the case of pneumatically operated exoskeletons is examined in detail.

2. Development of non-military exoskeletons

The first exoskeletons were not developed for military purposes but to improve movement coordination in health care. The first 'exoskeleton' was developed and tested in 1969 at the Mihajlo Pupin Institute in Belgrade in the former Yugoslavia under the leadership of Miomir Vukobratović. With this device, the movement or motion of the patients was facilitated, thus supporting the work of the doctors and promoting the patients' rehabilitation. Based on practical experience, the device had continuously been developed, whereby it was achieved that the device could perform the same movement several times in succession, with a variable amount of force. With this, the researchers aimed to enable patients to perform individual rehabilitation exercises without less and less machine help, eventually using their muscle power [3]. Yugoslav researchers made further improvements, as the first device was only partially kinematically programmed, its propulsion was pneumatic, so it was unable to track every detail of human motion. Nevertheless, research continued so that by 1974, the first device using electric motors could be completed, which was successfully used in medical applications [3]. Based on the research, Vukobratović developed the theory of zero-momentum point [4] [5] and the theory of control of bipedal robots [6].

By the 1960s, research into the robotization of specific industrial processes was already underway, but there were processes where human activity was essential. Therefore, support equipment development to increase the force required for each work process has also begun [7]. In addition, recognizing the benefits of using exoskeletons in healthcare, industrial developments have also taken place. Besides full-body support devices, equipment that facilitates arm or hand movement and lifting were also developed in this area. The manufacturing and operating cost of these devices is significantly lower than for full-body exoskeletons, and has therefore been widely used in many industrial areas, particularly in the automotive industry [8] (Fig. 1).

Fig. 1. Industrial upper limb exoskeletons [9]

These exoskeletons primarily reduce the use of the user's manual force by taking over part of the load, thus also reducing failure caused by fatigue. A possible grouping of upper-limb exoskeletons is depicted in Fig. 2 [10].

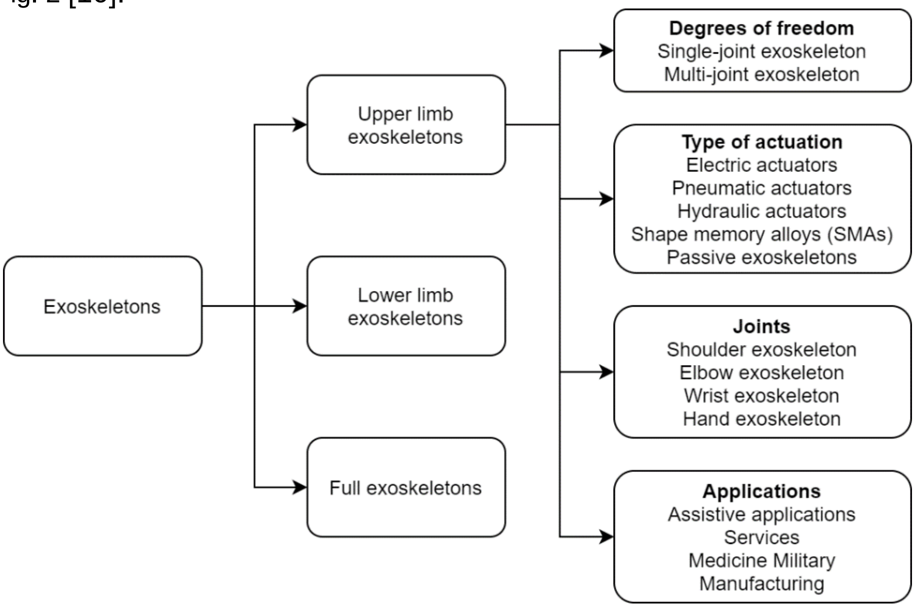

Fig. 2. Grouping of upper limb exoskeletons (based on 0)

In the following, the functional characteristics of industrial exoskeletons with pneumatic actuators are reviewed, focusing primarily on the human-machine interaction.

3. Functional characteristics of exoskeletons

During the operation of upper-limb exoskeletons, the force sensor built into the device measures the interaction force, then directly controls the motor current during signal processing and amplification, proportional to the torque exerted by the device. The man-exerted torque that rotates the exoskeleton element attached to the arm around the pivot point is added to the torque exerted by the device. The movement of the exoskeleton arm may not be exactly the same as the movement of the user. In this case, the control unit further changes the power of the motor until the movement of the exoskeleton arm and the user arm is approximately the same. The key to the proper functioning of the exoskeleton is the control device regardless of the application field. The control diagram is shown in Fig. 3.

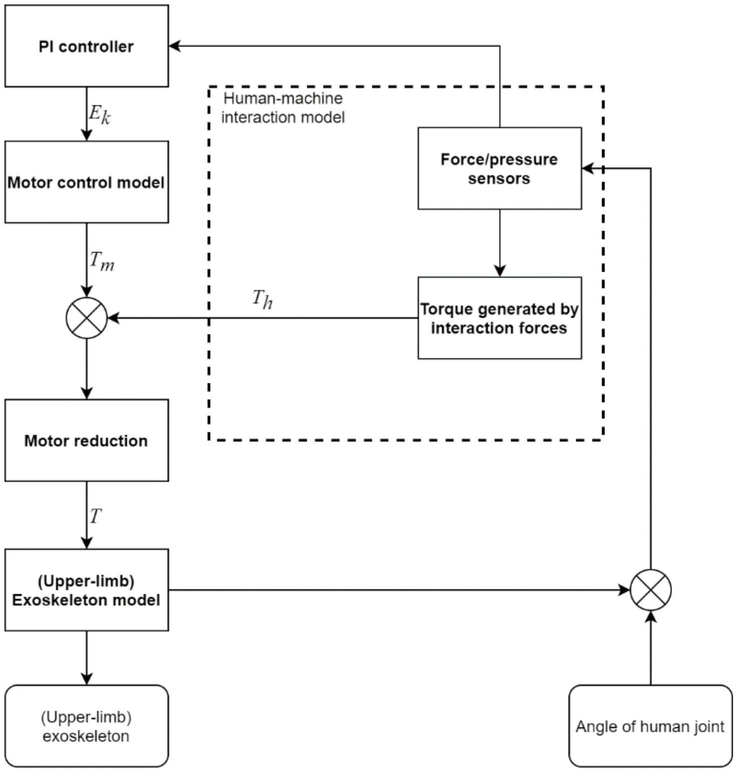

Fig. 3. The control diagram of exoskeletons

The elements (arms) of the exoskeleton can be identified as a nonlinear dynamic system, which is illustrated in Fig. 4.

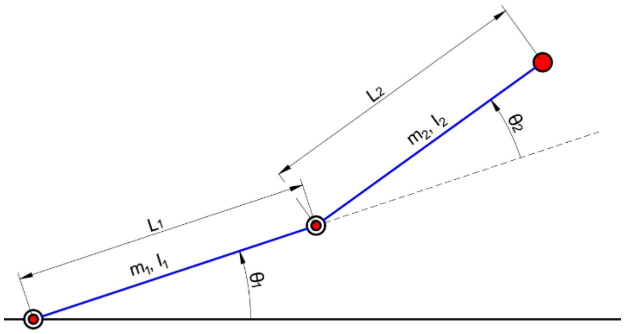

Fig. 4. Schematic of a nonlinear dynamic system

In the figure above (Figure 4), $L1$ and $L2$ are the lengths of the elements, m_1 and m_2 are their masses, I_1 and I_2 are their moments of inertia, and θ_1 and θ_2 are their rotations with respect to the horizontal. T_q is the torque vector of the actuators and $H(\theta)$ is the $N \times N$ inertia matrix of the system.

The mathematical model of this simple two-element system is derived by the Euler-Lagrange equation:

$$T_{q1} = H_{11}\ddot{\theta}_1 + H_{12}\ddot{\theta}_2 - h\dot{\theta}_2^2 - 2h\dot{\theta}_1\dot{\theta}_2 \quad (1)$$

$$T_{q2} = H_{22}\ddot{\theta}_2 + H_{21}\ddot{\theta}_1 - h\dot{\theta}_1^2 \quad (2)$$

where,

$$H_{11} = m_2L_1^2 + I_1 + m_2(L_1^2 + L_2^2 + 2L_1L_2cos\theta_2) + I_2 \quad (3)$$

$$H_{12} = H_{21} = m_2 L_1 L_2 cos\theta_2 + m_2 L_2^2 + I_2 \quad (4)$$

$$H_{22} = m_2 L_2^2 + I_2 \quad (5)$$

$$h = m_2 L_1 L_2 sin\theta_2 \quad (6)$$

3.1. Human-machine interactions

In the field of exoskeletons, the analysis of human-machine interaction is emphasized as an essential but complex task. The problem is particularly complicated when it comes to prostheses, as the task of the exoskeleton, in this case, is also to maintain weight while aiding movement. Although the paper's primary focus is on upper-body exoskeletons, the subsection also discusses interaction issues for lower-body exoskeletons, providing some inspiration for possible solutions to human-machine interaction and control engineering.

For the exoskeleton, the primary input is the measured interaction force and its magnitude. The device can change the motion states (e.g., standing position, movement). Some solutions are also used for working point linearization, but these solutions work primarily in simulations because robustness might be lost in the real environment. Another disadvantage is that force sensors of such accuracy are expensive and sensitive to the multidirectional force and torque present in human walking. Instead, the standard method for characterizing reaction force is to capture motion, which is used in general to study human motion. Some authors have further refined modeling of reaction forces, such as Kalman filters: for example, in [11], the gait and speed of the walker are estimated. In [12] the force load of the ground expressed on the ankle was studied using the lower-limb model using nonlinear Kalman Filtering Methods.

In another approach, the exoskeleton is implemented as a brain-machine interface. In this case the signals induced by the motor cortex of the brain can be used directly to control the device in addition to or in place of the force sensors. Interaction based on EEG signal processing is still widespread (e.g., [13]). Recently the method of electromyography (EMG) has been used to control exoskeletons (e.g., C. Fleischer [14]). In this case, muscle activation is measured by electrodes. The human-machine interaction based on electromyography is illustrated in Fig. 5.

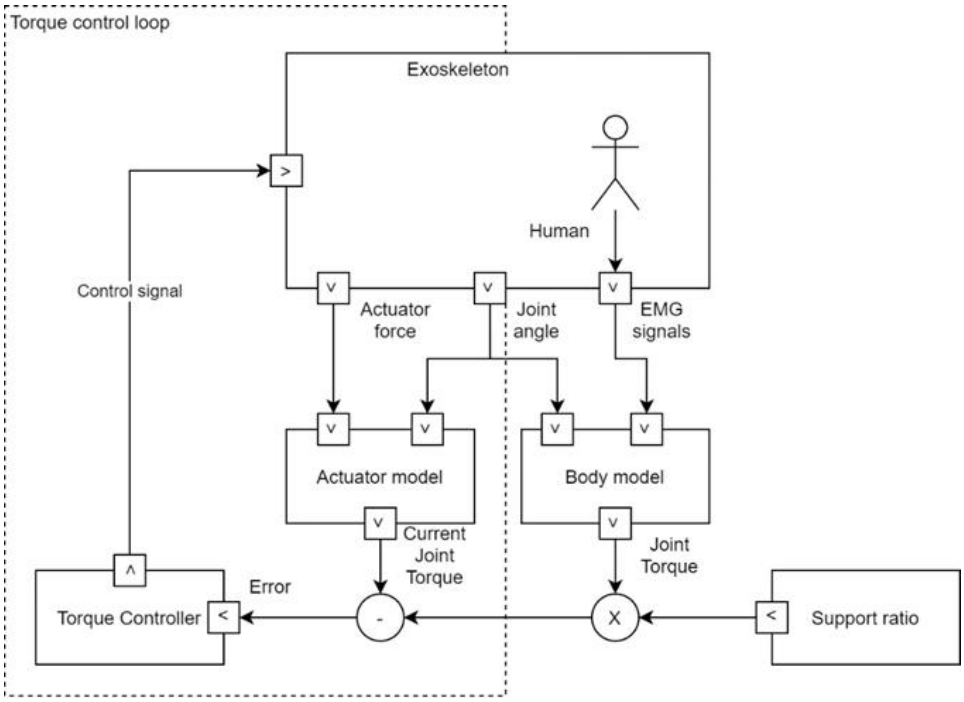

Fig. 5. Human-machine interaction in the case of exoskeletons

It is a challenge that human from a control point of view is a nondeterministic actor whose movement can only be estimated, therefore modeling the expected interaction is also complicated. In order to be able to model the interaction and the ergonomic aspects, it is advisable to review the latest breakthroughs. A common robust control method in case of humanoid robots is the Lyapunov Control Function (CLF) method and its complementation by quadratic programming (CLF-QP) [14]. In the case of exoskeletons, CLF is most easily applied by studying phase variables, therefore the trajectory of human motion is modulated. In this case, however, the control model considers only basic human dynamics based on biomechanical research [16]. For this reason, this model cannot be used, for example, in the case of prosthesis control. Extending CLF-QP, model-independent control or model-dependent control can be used [17]: More accurate and robust trajectory tracking can be achieved with the latter. In some cases, predefined (offline) trajectories can also be traced. In many cases, the most critical components are the knee and ankle joints, which are typically controlled by robust-passivity (RP) or robust sliding mode (RS) controllers with predetermined excitation-response model-dependent control.

Many authors test complex control (and in many cases, an initial estimate of tuning) using simulations. In case of simulations, the big challenge is to model the human motion system properly. However, simulation is also necessary in other use cases so that it can be considered as an actively verified area (OpenSIM) [18]. Another exciting question is how a haptic interface, even in virtual reality environments, may be suitable on the exoskeleton. In this case, the interaction interface covers not only the tracking and estimation of human movement, but also the perception of touch [19].

In other research, human motion is modelled by an analytical mathematical model, whose starting point is the creation of a limb model. In one example, S. Jatsun et al. [20] replace the foot with simple elements, equipped with a 2DOF gauge on each joint. The measurements were also verified by a numerical simulation based on a cascade control based on the inverse kinematics of the foot. Specifically for upper limb models, different model representations had appeared [21]. In one particularly interesting approach used the theory of screws to model the upper limb of the human [22].

The operation of the exoskeleton requires adequate torque, which can be generated by electric motors, hydraulic / pneumatic or linear actuators. The selection of the proper actuator is already critical during the design phase, as they affect the weight of the equipment and the applicability of the exoskeleton. It is advisable to choose an actuator that has a high power-to-mass ratio and can exert high torque and precise movement. Each actuator has its advantages and disadvantages. In the present study, we focus on pneumatic actuators.

3.2. Pneumatic exoskeletons

The advantage of pneumatic actuators is lower impedance and lower weight compared to electric actuators. They require low maintenance, are suitable for continuous operation and can be shut down under load without endangering the user. Compared to hydraulic and electric exoskeletons, pneumatics provide fast and flexible operation. Their biggest disadvantage, however, is their lower accuracy, which limits their field of application. Because they require a pneumatic power supply to operate, they are generally suitable for stationary tasks. In the case of a compressed air network, which is often available in industrial plants, the area of use can be increased by creating several connection points 0.

Pneumatic exoskeletons consist of pneumatic cylinders, which are operated by compressed air at a suitable pressure and solenoid valves 0-0. The functional diagram of the pneumatic exoskeleton is shown in Fig. 6.

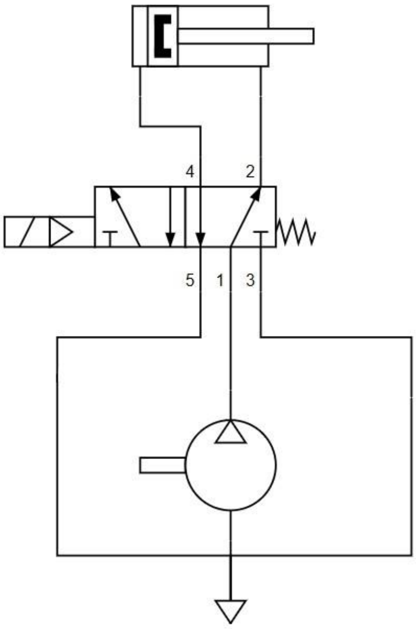

Fig. 6. Functional diagram of a pneumatic exoskeleton

There are also full-body pneumatic exoskeletons as described in 0. Recyclable, lightweight materials have been used with safety and environmental considerations taken into account. The structure works with pneumatic cylinders that are suited to human anatomy. The structure helps the movement of different muscle groups (biceps, triceps, legs and deltoid muscles). In addition to physiotherapy applications, these exoskeletons can also be used in industry, for example for lifting heavy objects or for work that requires constant hand support. The parts of the device are pneumatic cylinders, solenoid valves, compressed air pipes and transducers. The upper limb part is designed to be easily resizable. Two cylinders are mounted to the frame, they are the same size but operate in opposite directions. Examples of pneumatic exoskeletons for industrial use are shown in Fig. 7.

Fig. 7. Pneumatic exoskeletons for industrial use 0, 0

4. Summary

This article provided an overview of pneumatic exoskeletons for industrial use. The focus was on upper-limb exoskeletons with a particular emphasis on the interaction capabilities with humans. Throughout this article, the control- and interaction-model of full- and lower-limb exoskeletons have been discussed. The purpose of this article is to point out the possible dimensions of optimization of the exoskeleton applications for a specific task.

This article pointed out, that the control model is vital for proper interaction with humans. There are numerous approaches for modelling, some based on analytical methods and empirical studies based on biometrical studies. More recent methods are based on robust control methods (robust-sliding, robust passive) based on Lyapunov control methods. Besides the overview of computational methods of control, the interaction platform have been also discussed (force sensors, EEG, electromyography).

Acknowledgments

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