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Active Exoskeleton Control Systems: State of the Art

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Abstract

To get a compliant active exoskeleton controller, the force interaction controllers are mostly used in form of either the impedance or admittance controllers. The impedance or admittance controllers can only work if they are followed by either the force or the position controller respectively. These combinations place the impedance or admittance controller as high-level controller while the force or position controller as low-level controller. From the application point of view, the exoskeleton controllers are equipped by task controllers that can be formed in several ways depend on the aims. This paper presents the review of the control systems in the existing active exoskeleton in the last decade. The exoskeleton control system can be categorized according to the model system, the physical parameters, the hierarchy and the usage. These considerations give different control schemes. The main consideration of exoskeleton control design is how to achieve the best control performances. However, stability and safety are other important issues that have to be considered.

Keywords: exoskeleton, control, upper limb exoskeletons, lower limb exoskeletons, Human interaction.

1. Introduction

The exoskeleton is an electromechanical structure worn by operator and matching the shape and functions of human body. It is able to augment the ability of human limb and/or to treat muscles, joints, or skeletal parts which are weak, ineffective or injured because of a disease or a neurological condition[1-3]. Moreover, it merges the machine power and the human intelligence in order to enhance the intelligence of the machine and to power the operator. The exoskeleton works mechanically in parallel with human body[1] and can be actuated passively and or actively.

The history of the active exoskeleton can be traced back to the 1960s. The US military had developed several exoskeletons to augment and amplify the soldier ability for military purposes [4]. Then, the General Electric Company developed two-armed master–slave manipulator used for handling radioactive equipment. The master is an exoskeleton type robot worn by the operator and its motion was reproduced by the two-arm slave unit [5]. Moreover, the John Hopkins University designed the upper limb exoskeleton type to help elbow flexion of paralyzed people [6]. Almost at the same time, the Beograd anthropomorphic exoskeleton was designed for lower limb application [7]. The development of the exoskeleton has been increased in various implementations.

The implementation of the exoskeleton can be classified into three main groups: human power augmentations, haptic interactions and rehabilitations. Firstly, the human power augmentations; Kanazawa Institute of Technology developed the full body exoskeleton for augmenting the nurse's power to take care of the patient [8]. In addition, University of Tsukuba has developed some generations of Robot Suit HAL (Hybrid Assistive Limb) to physically support a user's daily activities

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and heavy work [9]. The last is the BLEEX, a lower limb exoskeleton from Berkeley University. The BLEEX has been designed to augment the human limb so that the wearer is able to carry significant load easily over various terrains [10].

The second application of the exoskeleton is the haptic interactions. The first haptic exoskeleton is the Handyman and the Hardiman robot designed by GE Company in the early 1970s. It was a master-slave tele-operation system [5]. In the last decade, Gupta et al have developed the five DOF haptic arm exoskeleton for training and rehabilitation in virtual environment[11]. As Gupta et al, Carignan et al have developed an exoskeleton haptic interface for virtual task training. Then, Pierra et al have designed EXOSTATION, a complex haptic control station that allow the user to remotely control the virtual slave robot[12].

The rehabilitation is the last exoskeleton application. The rehabilitation exoskeletons have been developed for many purposes. They are implemented in either the lower limb for gait rehabilitation or the upper limb. The treadmill gait trainer is one implementation of gait rehabilitation. The LOKOMAT exoskeleton is an example of the early treadmill gait trainer[13, 14]. Moreover, there are many other treadmill exoskeletons besides LOKOMAT such as LOPES[15, 16], ALEX[17] and ANdROS[18]. In addition to treadmill gait trainer, the over-ground gait trainer has also been developed such as HAL [9] from University of Tsukuba, EXPOS from Sogang University[19], the lower limb exoskeleton from Shanghai Jiao Tong University[20], and Vanderbilt exoskeleton [21]. On other hand, the upper limb exoskeletons for rehabilitation have also been developed intensively, such as IntelliArm[22], SUEFUL-7[23], EXO-UL7[2], ARMin III[24], MGA [25, 26], L-Exos [27], RUPERT IV[28], BONES[29], WOTAS [30], UTS Exoskeleton[31, 32], and Pneu-Wrex[33].

So many exoskeletons existed today can be viewed from two aspects, mechanical and control system aspect. Mechanical characteristic of the exoskeleton has been reviewed many times. Gopura et al reviewed mechanical aspect of upper limb exoskeleton [34] [35], Bogue et al discussed the recent development of the exoskeleton [36], Diaz et al presented review of the lower limb exoskeleton for rehabilitation [37] as well as Yang et al [38] and others [39] [40]. However, the exoskeleton control system is rarely reviewed. Of the few is Jimenez-Fabian et al [41] who discussed the control system in the ankle exoskeleton and Lo[40] who gave small part view on the control system of upper limb exoskeleton. To fill the gap of knowledge in the exoskeleton control system, this paper presents the review of the control system architectures of the existing exoskeleton for last decade briefly.

2. The Exoskeleton control systems

2.1. Model-based Control systems

One of the exoskeleton control system categories is model-based control system. In general, according to the model used, the control strategy for the skeleton can be divided into two types: the dynamic model and the muscle model based control [40]. The dynamic exoskeleton model is derived through modeling the human body as rigid links joined together by joints (bones). This model is formed from combination of inertial, gravitational, coriolis and centrifugal effects[1, 40]. The dynamic model can be obtained through three ways; the mathematical model, the system identification and the artificial intelligent method.

The Mathematical model is obtained by modeling the exoskeleton theoretically based on physical characteristics of the system. The good example of this control system is the BLEEX, a 6-DOF lower limb exoskeleton[10]. In each leg, four DOF joints are hydraulically actuated while the rest are passive. The flexion-extension and abduction-adduction at the hip, flexion-extension on the knee and planar-dorsa flexion at the ankle are actuated while rotation and abduction-adduction at the ankle and rotation at the hip is passively actuated by using steel springs and elastomers[42]. The BLEEX only relied on its dynamic model to aid the user's movement, without any force/torque sensor to detect the interaction between the user and the exoskeleton[42, 43]. The control goal is to attain the system with high sensitivity. However, this sort of control aim demands the precise dynamic model. Three different dynamic models for the BLEEX have been developed and their variations are based on the walking cycle phases. They are the single support, the double support, and the double support with redundancy. Each dynamic model has different control mechanisms[44].

The second way to obtain the dynamic model is the system identification method. This method is used since it is difficult to attain a good dynamic model by using theoretical mathematic model. The BLEEX researchers have implemented the least square method for swing phase control[44]. The least square is utilized to estimate the parameter of the dynamic model based on the pairs of input-output data. Besides, Aguirre-Ollinger et al also employed the recursive least square method to estimate the dynamic model parameters of one DOF lower exoskeleton[45].

The last method for attaining the dynamic model is the artificial intelligent method. Its popularity to solve many non-linier problems has attracted some researchers to employ in in the dynamic model identification. Xiuxia et al used the wavelet neural network to identify the dynamic model of exoskeleton[46]. They implemented the wavelet neural network in the virtual joint torque control as inverse dynamic model. The inputs are the exoskeleton joint angular, the joint angle velocity, and the joint angle acceleration with the joint torque as the output. The network was trained using the input-output data of the system so that the network behaves as the inverse dynamic model.

Beside the dynamic models, the muscle models have been used in the exoskeleton control schemes. Unlike the dynamic model, the muscle model predicts the muscle forces deployed by the muscles of the human limb joint as a function of muscle neural activities and the joint kinematics[47]. The input is the Electromyography (EMG) signals and the output is force estimation. The muscle model can be obtained by using either the parametric or non-parametric muscle model.

The parametric muscle model is commonly implemented using the hill-based muscle model [47, 48]. The hill-based model can be regarded as the biological and the mechanics of the musculoskeletal limb model. It is composed of three elements: a contractile element (CE), a series element (SE), and a parallel element (PE)[47]. In addition, it generates the output as the function of EMG neural activity and the muscle length. Rosen et al employed the hill model to estimate the force of the elbow joints[48]. This estimation was used as control input for 2 DOF of active upper-limb exoskeleton. Cavallaro et al incorporated the genetic algorithm to search the optimum parameters for the hill model to improve the performance of rosen's work to control 7-DOF upper limb exoskeleton[49].

Different form the parametric muscle model, the non-parametric muscle model does not need information of muscle and joint dynamic [50]. Kiguchi et al utilized the neuro-fuzzy network to adjust the parameters of the relation of the EMG and the user's joint torque[23, 51]. The relation was presented in the muscle model matrix which the parameters are the output of the neuro-fuzzy network. This control scheme was utilized to control 7 DOF upper limb exoskeleton to help the motions of shoulder vertical and horizontal flexion/extension, shoulder abduction/adduction, elbow flexion/extension, forearm supination/pronation, wrist flexion/extension, and wrist radial/ulnar deviation of physically weak individuals[23] [51].

2.2. Hierarchy based Control System

From the hierarchy point of view, the exoskeleton control system can be grouped into three levels, which they are task level, high-level and low level controllers. The task level controller is the highest level controller. It is performed based on the task designed. The next level is the high-level controller. It is responsible to control the force of human–exoskeleton interaction based the information from the task level controller. The last is the low level controller which is the lowest level. Its duty is to control the position or force of the exoskeleton joints. This controller contacts directly to the exoskeleton. The examples of each controller will be presented throughout the next section.

2.3. Physical parameters based control system

Based on the physical parameters, the exoskeleton control system can be classified into position, torque/force, and force interaction controllers. The position control scheme is commonly utilized to make sure the exoskeleton joints turn in a desired angle. As an example is PD controller in the ARMin III robot [24], as depicted in Fig. 1. Because of rehabilitation aims, some exoskeleton axes have fixed joint position. For these axes, the PD position controller is implemented so that the axes fixed at predefined angle position.

The position controller is mostly implemented as low-level controller. The MGA upper limb exoskeleton employed the PD position controller as low-level controller[25], the RUPERT IV used the PID position controller in the inner-loop controller[52] and UTS exoskeleton employed PD position controller[31]. Moreover, the HAL utilized PD position controller [53], L-Exos used slide mode PD controller [54], Aguirre-Ollinger et al utilized LQ position controller[45], Gomes et al implemented the H∞ controller[55], and Rehab-Robot used PID feedback controller[56].

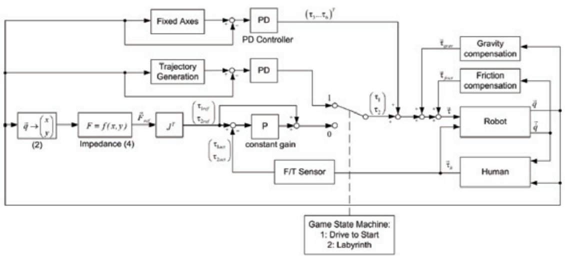

Fig. 1 The ARMIN III control system [57]

The next type of physical parameter-based control system is the torque/force controller. It is generally applied in the low level controller as well. The control system of ARMIN III in Fig. 1 shows the implementation of force/torque controller as the low-level controller. The high level controller is the impedance controller which controls the interaction force between human and the exoskeleton. The output of the impedance model is the force that becomes the reference force for the force/torque controller such that the force/torque of the exoskeleton is close or equal to the force reference. Another example is the low-level controller of the L-Exos, a 5 DOF exoskeleton with haptic interface. Other exoskeleton such as Pnue-Wrex[58], WOTAS[30], Lokomat[13], LOPES[59] and ANdROS[18] applied torque/force controller as their low-level controller.

Besides the position and the torque/force, the interaction force between human and the exoskeleton are considered in the exoskeleton robot. The interaction force controller is applied as the high-level controller. The main goal is to provide proper help for the users in performing a task so that the force of human-exoskeleton interaction goes to zero. The interaction force can be controlled by either the impedance controller or the admittance controller. The basic concept of the impedance controller is it accepts position and produces force. While, the admittance is the opposite of the impedance controller; it accepts the force and yields the position[60].

The impedance controller is an extension of position control and it does not only control the position and the force but also control a relation and an interaction between the exoskeleton and the human body[60]. The impedance controller architecture contains the impedance model and the force/torque controller. The impedance model receives the error position of the joints and yields the force values that become the force references for the next stage, the force/torque controller. The force controller will try to guarantee the forces exerted by the exoskeleton are equal or close to the force references. ARMin III in Fig. 1 implemented the impedance controller. Others systems like SUEFUL-7[51], Pnue-Wrex[58], WOTAS[30], Lokomat[13], LOPES[59] and ANdROS[18] are also using same controller.

Besides the impedance control, the admittance control was utilized to control the force of human-robot interaction [61]. It contains the admittance model and the position control. The admittance model receives forces and produces positions, rather than receives positions and produces forces. The position controller will control the angle of exoskeleton joints based on the position references from the output of admittance model. Fig. 2 is an example of admittance controller for MGA upper limb exoskeleton[25]. Other instances are EXo-UL7[62] [63], iPAM[64], UTS[25], one DOF lower limb exoskeleton [65, 66].

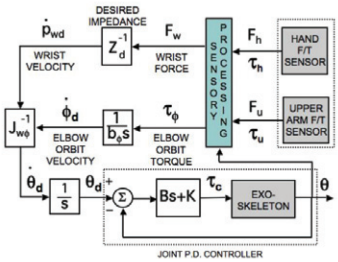

Fig. 2 The admittance controller for the MGA[25]

The impedance/admittance model represents the force of human-exoskeleton interaction. In most cases, the model parameters are fixed in the design. However, in some cases, these parameters need to change in order to adapt the high external changes such as the physical user condition. Therefore, the adaptive controller is required. Kiguchi et al utilized the neural-fuzzy networks to adapt internal parameter of impedance model[67].

2.4. Usage based Control systems

The exoskeleton control system can also be categorized according to the sort of applications such as the virtual reality controller, the tele-operation controller and the gait controller. Most upper limb exoskeletons have used the virtual reality controller in performing therapy exercises. This controller guides and helps the patient to carry on the tasks such as a virtual object reaching task in RUPERT [52], an object moving by virtual hand, a ball game, and a labyrinth game in ARmin [57], a virtual wall painting task in MGA[25], and a reaching and motion constrain task in L-Exos [68]. In those applications, the exoskeletons are considered as haptic devices.

The ball game therapy in Armin is an example of virtual reality controller, as seen in Fig.3. The patient has to catch the virtual ball rolling down to inclined virtual table. The virtual controller generates the reference trajectories and gives a proper help to the patients if they are off the track by sending error information to the high-level controller. This controller is complemented by the impedance controller as high-level controller and the gain force controller as low-level controller [69]. Improvement in trajectory generation was implemented in RUPERT III by using adaptive reference generator[70].

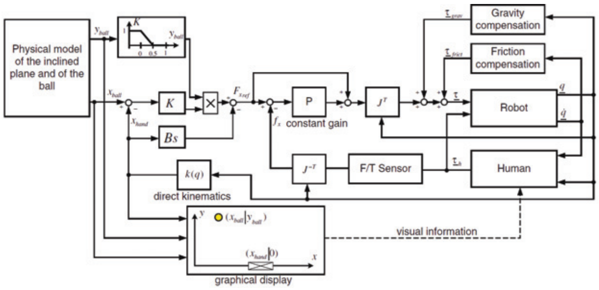

Fig. 3 Virtual reality controller in Armin III[69]

The second application is the tele-operation controller in type of master-slave controller. The exoskeleton worn by operator is the master and the manipulator robot in another side is the slave. By moving the exoskeleton, the slave robot will move accordingly. EXOSTATION[12], the haptic exoskeleton based control station, and ESA[71], human arm exoskeleton, are as examples [71]. The main difference of the tele-operation controller and the others is it controls the interaction force between the slave robot and the environment rather than the interaction force between human and the exoskeleton.

The last usage-based controller is the gait pattern controller which is implemented in lower limb exoskeleton. The LOPES[59] control system represents this control strategy. It contains three level controllers. The first level is the observer that determines the patient's gait phase for the virtual model controller (VCM) and assures the safety of the patient. The next level is the VCM. The VCM representing the training intervention is implemented using the impedance controller based on the virtual spring[59]. The last level is the torque/force controller. This controller maintains the torque/force exerted by the each joint exoskeleton close or equal to the desired torque/force from the VCM. Similar scheme to the LOPES's observer is the Vanderbilt exoskeleton employed finite state machine to move from one state to another state[21]. To improve the gait pattern controller, the adaptive gait pattern controller has been developed. LOKOMAT[13] employed the gait adaptation by using invers dynamic model while Gomes et al have proposed the gait pattern adaptation based on the artificial neural networks [55].

3. Discussion

No exoskeleton existing nowadays implements all aforementioned controllers in one system. However, most of them combine several controllers according to the goal of design. ARMIN III is an example. As depicted in fig. 3, it uses a P controller as the force/torque controller in the low-level controller; an impedance controller in the high-level controller and a ball trajectory generator as the virtual reality controller. This combination can give a good controller model for the future.

The next development of the exoskeleton control system has to meet several considerations and demands. Firstly, it has to be able to assist the user as needed according to the physical condition of the users. Most frequent method used for this purpose is the interaction force controller using the impedance or admittance controller. However, the impedance or admittance models used are mostly fixed and will not consider the user's physical condition. Another demand for next exoskeleton control is the ability to detect the user's intention beforehand. Many efforts have been done to fulfill this demand by developing musculoskeletal model based on the EMG signals. However, the uses of EMG signals have had a number of problems such as the different users give different EMG signals. Another problem when using EMG signals is the system will not work properly if it is applied to the user with muscle disorder. To overcome this problem, a hybrid controller that combines the EMG-based and sensor-based controller is required.

The next consideration when designing exoskeleton control system is the modularity. When an exoskeleton has many DOFs and or deals with complex tasks, the centralized controller will be not effective anymore. Therefore, distributed controllers are needed. Not many exoskeletons under review implemented this idea. Safety is the next urgent thing that should be incorporated in the exoskeleton control system. Very few exoskeletons considered the safety aspect in the control system. Most of them implemented safety in the mechanical design only. The last issue in designing controller for the exoskeleton is the stability. In general, the instability is caused by high-frequency and high-amplitude external perturbation induced by robot-human interaction. This disturbances need to consider because they can cause vibration and then decrease the exoskeleton performance.

4. Conclusion

The exoskeleton control system can be classified into several groups based on the model, the physical parameter, the hierarchy and the usage. The variation control system implemented and utilized today need improvement to meet the need of the next exoskeleton control system such as the assist as needed, the user's intention detection, the modularity, the safety and the stability. All these aspects have to be considered and incorporated in designing the control system for the exoskeleton to give better performance and better future implementation.

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