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Control Methodologies for Upper Limb Exoskeleton Robots

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Abstract - **An exoskeleton robot is kind of a man-machine system which mostly uses combination of human intelligence and machine power. These robotic systems are used for different applications such as rehabilitation, human power amplification, motion assistance, virtual reality *etc*. Successful operation of an exoskeleton robot depends on correct selection of design and control methodologies. This paper reviews control methodologies used in upper limb exoskeleton robots. In the review, the control methods used in the exoskeleton robots are classified into three categories: control system based on human biological signal, non-biological signal and platform independent control system. Different types of control methods under each category are compared and reviewed.**

Index Terms: Control methods, Exoskeleton robot, Human-machine interaction, Impedance control, Neuro-Fuzzy control.

I. INTRODUCTION

THE concept of exoskeleton is emerging from biology. Some creatures like turtles and crabs have external structure called exoskeleton, which provides safety from environment and other animals, sensory medium for outside world, attachment for muscles *etc* [1]. The structure of an exoskeleton robot consists of joints and links which are corresponding to the human body [2]. These robots are used to transmit the torque from the actuators to generate the motion [3].

Exoskeleton robots can be classified according to the place where it supports the human body. This includes upper extremity, lower extremity and full body. Design of exoskeleton robots are not straight forward and it needs lot of factors into consideration. The special features of the human anatomy should be considered in order to produce user friendly exoskeleton system. Obtaining exact human motion from exoskeleton robot is still a challenge for the researches in this field [2]. Human upper limb mainly consists of seven degree of freedom (7DoF). Some researchers have developed 7DoF upper-limb exoskeleton robots [3], [18], while some designs have limited DoF [10], [12], [17]. This paper mainly focuses on reviewing the control methodologies of upper-limb exoskeleton robots even though control methods of some lower limb exoskeleton robots [13], [19], [20] are presented. At present, many research teams have been developing exoskeleton robots [4], [5], [8], [11]. However, only few of them are at the commercialized stage [13], [16] and further improvements are necessary to make them more popular and to apply for specific tasks.

The control systems of the exoskeleton robots are completely differ from the traditional robots [3]. This is because the human operator is not only the commander or the supervisor of the system but also a part of the control loop in these control systems [1]. Hence, it is known as 'man-in-the loop' [1]. The human operator mainly makes the decisions and the exoskeleton implements the tasks. However, feedback information received by the human operator and the exoskeleton robot keeps interchanging bilaterally between each other [3]. Therefore, intelligence of the exoskeleton system is enhancing while the power of the human operator is also improved.

The principle criterion to control the exoskeleton robot, especially power assist exoskeleton robot is to work according to the user motion intention. This becomes much more important for physically weak person who are not capable of generating daily motions properly. Several exoskeleton robots are currently available for upper limb or lower limb applications [5]. Broadly, the exoskeleton robots can be classified considering their mechanical structure and the configuration of their control system. Mechanical configurations of exoskeleton robot have been reviewed many times [22]. However, there are only few cases where control systems of exoskeleton robots have been reviewed [21]. Therefore, this review is presented to understand the different form of control system configurations available for upper-limb exoskeletons. In addition, few lower limb exoskeleton control systems are also presented to show the importance of their control system configuration. This review considers recent (last seven years) literature and classifies control methodologies into three categories based on the type of input to the controller: control system based on human biological signal, control system based on non-biological system and platform independent. Further, future research directions of control methodologies of upper-limb exoskeleton robots are also presented.

Next section presents the proposed classification of control methodologies of upper-limb exoskeleton robots. Section III is devoted to review the control system based on human biological signals. Control system based on non-biological signals are reviewed in section IV. Section V presents the review of platform independent control methods. Future direction and developments are given in section VI followed by the conclusion in VII.

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II. Classification of Upper-Limb Exoskeleton Control Methods

In general, exoskeleton robots consist of two types of controllers which are working parallel to each other. Those are exoskeleton controller and human brain that includes the spinal cord and the cerebrum [12]. The most common feature of control method of exoskeleton robot (especially in power assist exoskeleton robot) is aiming to reflect the human motion intention. However, comprehensive study of human mechanics is still under research [2]. Therefore, understanding of the best control method becomes difficult and optimization of such control method is even more difficult. Control methods of upper-limb exoskeleton robots can be classified in several ways: based on input signals to the controller, based on controller architecture (configuration), based on output from the controller and other ways. In this paper, the classification is carried out based on the input signals to the controller since controller input is very much significance for the performance of the control method. Based on input to the controller, the control methods can be categorized into control method based on human biological signal, control method based on non-biological signal and platform independent control method. Figure 1 shows the ways of classification of the control methods. Figure 2 shows the classification of control methods of upper-limb exoskeleton robot based on input signals. Control methods of recent upper-limb exoskeleton robots are compared considering few points: their application, special features and applied robot. The comparison of control methodologies of different exoskeleton robots are presented in Table 1. Each category of control methods are briefly explained in next subsections.

A. Control methods on Human biological signal

The main objective of these control methods is to operate the system successfully under different disturbances generated from external environment. In case of exoskeleton robot, the objective of traditional control concept had further extended into consider the human motion intention. This is one of the interesting aspects of control methods of exoskeleton robot and one form of human biological signal called electromyography (EMG) has satisfactorily employed in some of designs [4], [5], [8], [10]. Most of EMG based control methods used with exoskeleton robots are in binary (on-off) nature [4]. EMG signals indicate the firing rate of motor neurons and it is proportional to the muscle activity levels. Therefore, EMG signals directly reflect the motion intention of the human [7]. However in real practice, the measure of motor neuron activity is not an easy task [6]. The measurement of EMG signals is carried out in two ways, using surface-EMG electrodes or using intramuscular EMG electrodes. Latter one gives the better muscle activation pattern than that of surface EMG electrodes [17]. However, as explain in [6], the EMG based control is not easy to realize due to various reasons. All EMG related parameters are subject-dependant and can be changed from day to day due to varying conditions of the skin and body size [7].

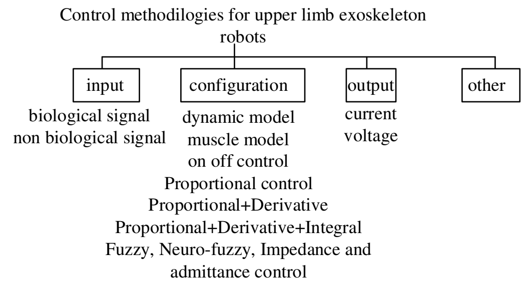

Fig. 1. Classification of control methodologies of upper-limb exoskeleton robots

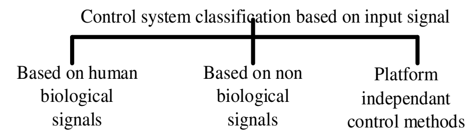

Fig. 2. Classification of control methodologies based on input signals

Incorporating muscle models (myoprocessor) and taking the advantage of the inherent electromechanical time delay in human neromusculoskeletal physiology, the system can predict the operator's intention prior to the onset of movement and thereby seamlessly integrate the operator and exoskeleton robot [3].

B. Control methods based on non-biological signal

Some exoskeleton robots have been using different techniques to extract the human motion intention [13], [17], [18] to use their control methods. EMG signals are not used under these methods and human motion intention is identified from other sensing instrumentations, such as force/torque sensors [11] or using dynamic model of the human limb.

C. Platform independent control methods

This classification includes control methods operates either human biological signal or non-biological signal. Different control strategies are presented with various exoskeleton developments [12], [15], [16], and those are implemented to enhance the features of control system of exoskeleton robot.

III. Developments in Control methods based on human biological signal

This section presents the developments in control methods of exoskeleton robot based on human biological signal. Some of the designs have developed for the rehabilitation of hand and others are aimed for rehabilitation of upper limb. Four different types of exoskeleton robots have been considered during the review and those are presented in subsequent sections.

a) Muscle-Model-Oriented EMG based Control [5]

The SUEFUL-7 is an upper limb exoskeleton robot having 7DoF and it used the muscle-model-oriented EMG based control method. EMG signal and forearm force/torque and hand force sensors are used to control the robot [5]. When EMG signal is high, it is used to control the robot, while force/torque sensor measurements are used to control the robot at low muscle activity levels.

TABLE I
COMPARISON OF CONTROL METHODS OF EXOSKELETON ROBOTS. TYPE I (BASED ON HUMAN BIOLOGICAL SIGNAL), TYPE II (BASED ON NON BIOLOGICAL SIGNAL AND TYPE III (PLATFORM INDEPENDENT CONTROL METHOD)

	Exoskeleton	Application	Control method	Special points
Type 1	NEUROExos [4]	Rehabilitation	EMG signal used. Two proportional gains are used define level of torque required.	Proportional control gains are adjusted to determine the level of comfort need to robotic user. Higher gains provides the extra torque to robot and provide comfort.
Type 1	SUEFEL -7 [5]	Power assist, Rehabilitation	EMG based impedance control.	Impedance parameters are adjusted online. Motion intention can be obtained even at low strength EMG levels.
Type 1	SUEFUL-6 [8]	Power assist, Rehabilitation	EMG with fuzzy-neuro control method. Multiple fuzzy-neuro controllers used to identify muscle activity.	Controller should train for different subjects and nature of task.
Type 1	EMG controlled hand [9]	Hand rehabilitation	EMG based control method.	Threshold value is defined to control the actuator. It helps to distinguish the real electric activity of muscle from other interferences.
Type 1	Perception assist exoskeleton [10]	Power assist	EMG control method used. Perception assist is obtained from active camera system.	Camera keeps the virtual focus is coincide with end effecter. Avoid the motion in wrong path and provide good feedback.
Type II	ABLE [11]	Not available	Force/Torque control method.	Robot disengaged system when user able do work by own.
Type II	Tendon driven exoskeleton [13]	Power assist	MFE sensors are used to obtain the human motion intention.	Uniform values and less noise levels. Light weight and small size.
Type II	Upper limb exoskeleton [14]	Power assist	Force sensor used to obtain the human motion intention.	8 force sensors are used.
Type III	Control through a Fictitious Gain (FG) [12]	Not available	Method is reduces the errors from sensor reading and optimize the operation of exoskeleton. FG controls the amount of muscle power need to operate the robot.	The gain of FG selected according to assistance need to operate robot. Minimizes the errors due to sensor reading, mechanics of human body, nature of operation.
Type III	Hybrid neuro-fuzzy compensator [15]	Rehabilitation	Improves the possibility of obtaining complex trajectories for rehabilitation. Minimize time for therapy application.	Performing complex trajectories and minimizing the expert knowledge for therapy
Type III	Admittance control upper limb exoskeleton [16]	Not available	Based on multiple force sensors. Joint space and task space admittance control is compared.	Task space control use less mean interaction energy than joint space
Type III	Motion intention recognition [17]	Power assist	Motion intention is controlled from IRD. Force sensor resistor system is used to obtain the motion intention.	Force sensing resistors are used to estimate the motion intention. Method overcomes the drawback of EMG based motion intention.
Type III	EXO-LU 7 [18]	Power assist	PID control method	Analytical method proposed to determine the parameters for PID controller under disturbances.

The controller of the robot consists with two stages (Fig. 3), first stage, input signal selection and second stage, EMG based impedance control. Impedance parameters, B (damping coefficient) and K (spring constant) are adjusted online according to the upper-limb posture and its activity level. Since torque varies with posture changes, online adaptation of neuro-fuzzy modifier is proposed. This online adaptation provides smooth operation to the robot. On the other hand, this adaptation needs to train the neuro-fuzzy modifier and it takes considerable time.

Further, control system given in [10] is also based on EMG based neuro-fuzzy modifier, which used to determine the torque required to drive the actuators in different postures during upper limb motion. Perception assistance with active camera system is used in this control system to improve the features of it when the user has vision difficulties. Active camera system provides feedback signal to control system and it helps to keep the motion intention of the user in safe trajectory by avoiding obstacles in the path.

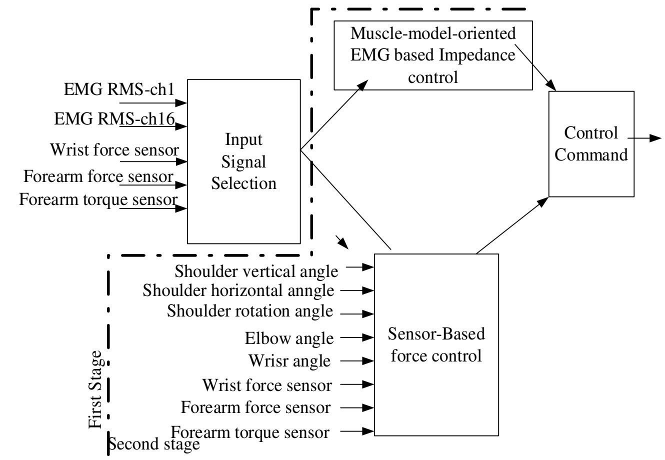

Fig. 3. Structure of control method of SUEFUL -7 [5]

b) EMG based Proportional Control [4]

NEUROExos [4] has a proportional control method based on EMG signals. Carrozza *et al* pointed that importance of understanding the accurate torque estimation for exoskeleton robot and further states that few developments are currently addressed this problem. NEUROExos is developed with proportional control method which used to estimate the torque needs to operate the robot. Two proportional controller gains K_{bic} (gain for bicep) and K_{tricep} (gain for tricep) are set one after other starting from K_{bic}. These two gains are initially set to zero and gradually increased while subject move arms freely. Further, these gains are increased until the subject feels comfortable level of assistance. The results show that exoskeleton could provide extra torque indicating effective reduction of effort spent by subject or movement generation. Therefore, this proportional control method enabled to assist motion according to the level of need of the user. Further, this method can be improved by incorporating neuro-fuzzy controller to identify the level of torque needs according to the position of upper-limb and posture changes.

c) EMG based Fuzzy-Neuro Control [8]

EMG based fuzzy-neuro control method is used in the SUEFUL-6 [8], which is designed for upper limb motion assist for physically weak persons. In addition to EMG signals, force/torque sensor signals of robot is also used as input signal to controller. When EMG signal level is low, force/torque signal is used to control the robot, while EMG control is used when EMG signal has high strength. Therefore, this avoids error motion cause by low level EMG and unexpected motion cause by external forces. Fuzzy if-then rules are constructed to control motions of shoulder, elbow, forearm and wrist and those are transferred to fuzzy-neuro controller to determine the output of the controller. Total of ten fuzzy-neuro controllers are designed for generate the motion in forearm and wrist. Fig. 4 shows the one of such fuzzy-neuro controller used in robot. The weight of controller is adjusted according to error back propagation learning algorithm. This weight adjustment enables adaptation of weights for different situations caused by change of physical and psychological conditions of user.

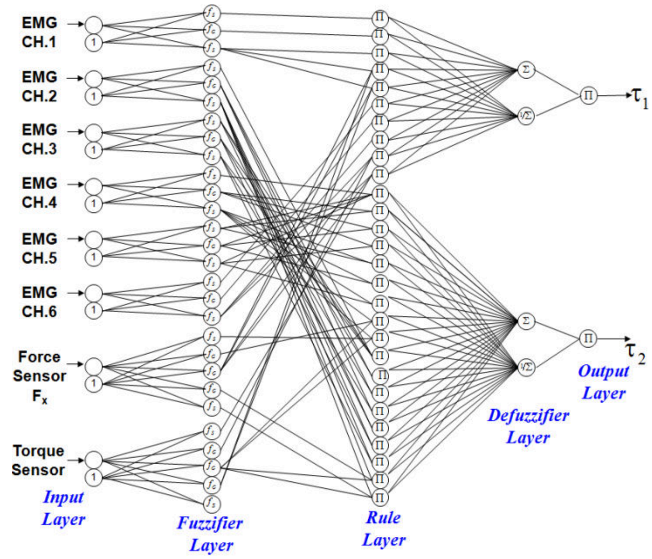

Fig. 4. EMG based fuzzy-neuro controller [8]

IV. Developments in Control System Based on Non-Biological Signal

Exoskeleton robot control methods based on non-biological signal are presented in this section. Force sensors, torque sensors, muscle fiber expansion sensors *etc* are used with exoskeleton designs [11], [13], [14]. Following control methods are identified as the state-of-the art methods and they are reviewed in next subsections.

a) Force Control of Upper-Limb Exoskeleton [14]

Moubarak *et al* [14] have proposed upper-limb exoskeleton robot with 4DoF for rehabilitation. Human motion intention is obtained from force sensors attached to the arm holder. Total eight force sensors are used and four sensors are attached to each arm holder. Control system is guided the motion of exoskeleton robot according to the training strategy. Direct and inverse kinematics used to model the robot. Its operation is verified through a Matlab/Simulink interface.

b) Force Controlled Exoskeleton Robot [11]

Nathanael *et al.* [11] have developed an upper limb exoskeleton robot with 4DoF named ABLE. This robot consists of force/torque sensors which are placed serially in a fixation mechanism chain. The inputs to the robot controller are the signals of force/torque sensors. Experiments were carried out to observe the several performance indices (PI) such as movement duration, velocity profile symmetry as given in [11]. This PI improves the feedback of exoskeleton control system. Transparency of the exoskeleton robot was defined as one of its effectiveness for control system and according to [11], when patient is capable of making movements, the function of exoskeleton robot should 'get out of the way' and not make any disturbance to the movement. Therefore, support given by exoskeleton robot is in dynamic nature and it provides effective assistive motion to the user.

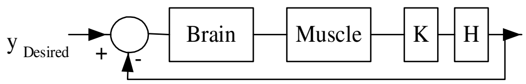

Fig.5 Control loop with FG [12]

c) Muscle Fiber Expansion Sensor based Neuro-Fuzzy Controller [13]

Tendon-driven Exoskeleton Assistive Device (TEAD) for rehabilitation of patients having muscle diseases has been developed and controlled from non-biological signals [13]. Even though TEAD is a lower-limb exoskeleton robot it is reviewed here since the control method can be significantly applied for the upper-limb robot also. Muscle Fiber Expansion (MFE) sensors are used to feed the input signal to the controller and also it generates the motion intention of the user. Neuro-fuzzy controller is used to determine the required torque of motors attached to external structure and to generate motor torque depend on motion intention. Further, these sensors are attached inside of braces and compared to the EMG sensors this is much more convenient, because slight changes of EMG electrode placement has an effect of accuracy of control output. Also MFE shows very uniform value and less noise levels compared to the EMG signals. Therefore, complicated signal processing is not needed in case of MFE sensors.

V. Developments in Platform independent control methods

Control methods describe in this section used either human biological signal or non-biological signal as an input. They can be identified as platform independent control methods. The function of these control methods is enhanced by considering special aspects.

a) Control of Exoskeleton through a Fictitious Gain (FG) in Human Model [12]

In [12], a novel concept of control method is introduced. It used Fictitious Gain (FG) in human model. The architecture of the control method is shown in Fig. 5. The method helps to identify the amount of muscle power needed and it minimizes the effect of variation of factors like, error of sensor reading, mechanics of human body, nature of operation *etc*. A person with tremor or a person suffer from cerebral palsy feels uncomfortable with their muscle activation, and reducing FG gain has accounted the high muscle contraction and this provides comfort to the user of the exoskeleton robot. The gain of FG is selected according to the assistance need to operate the exoskeleton robot. Therefore, this allows performing effective rehabilitation task for therapist and comfortable functions to patient.

b) Neuro-Fuzzy Compliance Control [15]

Fine tuning of system dynamic needs to perform variety of therapy techniques. Therefore, considerable time should be spent by the therapist as well it limits complex movements needed for rehabilitation. According to [14], compliance based rule method is proposed with combination of neuro-fuzzy compensator to automatically tune system dynamics on-line. This allows performing complex trajectories and minimizing the expert knowledge for therapy. On the other hand, this method minimizes the on-line training time for patients and makes it comfortable to use with different users who need different rehabilitation tasks. The method is platform independent. Therefore, this can be practiced with human biological signals or other method.

c) Admittance Control in Joint and Task Space [16]

Rosen and Miller [16], conducted experiment to compare the performance of Joint space and Task space in admittance control with PID controller. Task space controller uses the force interactions between the device and the user to create trajectory directly in task space. The joint space controller resolves the interaction forces into joint torque equivalents before creating trajectories in joint space. Four force sensors are used to evaluate the force/torque at joints and PID controller performs the control action. Experiments have been conducted to compare the performance in terms of power, energy and completion time. Results show that task space based control has around 11% lower in mean interaction energy compared to the joint space control.

VI. Future directions and developments

Other than to EMG signal, human motion intention can be identified through a brain signal (EEG) can be used as input signal to control exoskeleton robots. Electric potential signal generated from eye movement (EOG) can also be considered to obtain successful feedback signal to exoskeleton control system too. These signals can be combined in the controller of exoskeleton robot to get the improved control of the robot.

The performance of the control methods is based not only the controller; it may vary on selection of different components in control loop. This includes selection of final control elements or actuators, instrumentation for feedback signal, disturbance rejection (inside control loop or outside to the loop), input signals *etc*. Therefore selection of actuators and sensors play an important role in exoskeleton control system. In case of sensors, Micro-Electro-Mechanical System (MEMS) inertial sensors are much suitable to detect the changes in velocity, orientation and location in exoskeleton robots. This technology has made miniaturized sensors and which provides low power consumption, low cost, low size and weight which can be used to enhance the function of control method of exoskeleton robot.

In future developments, the aspect of control system of exoskeleton robot can be extend to take the effect of microclimate conditions present around the user and take suitable control effort to provide comfort to the user. When exoskeleton robot systems closely interact with human, safety conditions should be guarantee at maximum level. Some safety features are connected with mechanical design through stoppers. Emergency shutdown systems can be designed with electrical system. In addition, software locking system can be used in the controller to improve the safety features. Further, research is necessary to develop a proper software locking system.

Intelligent safety method can be introduced to the exoskeleton robot with help of feedback system of its control system. One of the human biological signal generated by eye ball movement called, Electrooculogram (EOG) can be used to generate the feedback signal to the controller. Therefore, when person feels any unsatisfactory motion of the exoskeleton, particular eye ball movement can be used as feedback signal and further it can be switched off the function of robot. This type of a safety method is directly connected with human function; hence it gives maximum protection to the user.

VII. Conclusion

This paper reviewed recent developments in control methodologies of exoskeleton robot during last seven years (from 2005). This review has classified control methodologies into three categories. Different control method of each category is reviewed.

EMG based control methods are extensively used by early exoskeleton robots to control them based on the human motion intention. Some drawbacks of EMG control method had identified during the review. Structure of control system is affected by its degree of freedom (DoF). Higher DoF, exoskeleton robot shows high manuability, on the other hand centralized control system is not support for its manuability. It likes a two end question and designer has to scarify one of an important selection. However, distributed control configuration is a good solution to overcome manuability against to higher DoF. Further, many designs under review has based on centralized control method and there is an opportunity for distributed control methods too. Some exoskeleton control methods have used different physical parameters for their controller. Those are not based on human biological signal and can be classified as position, force, speed, torque or combinations of it.

Further, this review has noted that majority of exoskeleton robots have been implemented non-biological signal as its control signal and research are forwarded to consider novel control concepts to extract more accurate human motion intention. Also there is a trend on combining EMG based control with sensor based control and incorporating different soft computing methods to optimize the function of exoskeleton robot. Further, novel control configurations can be developed by considering combination of biological and non-biological signal.

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