Paradigm Shift, Technical Challenges, And Future Path of Exoskeleton Human-Computer Interaction Control Model

Hao Lin

School of Science & Technology, City St George's University of London, London, EC1M 5HD, The United Kingdom

Hao.Lin.2@city.ac.uk

Abstract. With the gradual development of exoskeleton robot hardware, the research focus should be transferred to the control model. The current field of exoskeleton control systems is undergoing a paradigm shift from traditional human-computer interaction to human-computer symbiosis. This research focuses on the control model and control strategy of an exoskeleton robot. Through a systematic review of the literature, this paper divides the current control model into four clear control paradigms: brain-less control, perceptual control, predictive control, and symbiotic control, and prospects the future human-computer interaction mode of exoskeleton. At the same time, the core characteristics, typical cases, and limitations of each paradigm are analyzed, and the four trends of human-computer symbiosis are summarized. The future development path of exoskeleton based on artificial intelligence, brain-computer interface, and new sensing technology is outlined. Brainless control can not adapt to individual differences and real-time changes, ignoring the real-time state of people. Perceptual control cannot predict or look forward to motor intention. Predictive control is complex in calculation, highly dependent on the model and data, and mostly in the laboratory stage. In the future, a close coupling and bidirectional communication man-machine relationship will be formed to form a man-machine intelligent unity.

Keywords: Exoskeleton, Control Strategy, Human-Computer Interaction.

1. Introduction

Since the birth of the exoskeleton robot, human-computer interaction has been evolving. At present, modern exoskeletons still have defects in intelligence and user experience, and there is still room for improvement in the solution of user differences. In the aspect of the exoskeleton control model, there are solutions to improve compliance through prediction [1]. However, the current mainstream scheme is still a "stimulus response" control model in essence, and there are limitations in the control model. Now, a new framework is needed to understand the evolution of the control model and guide the development direction of human-computer interaction in the future.

The exoskeleton technology was initially inspired by the natural exoskeleton of arthropods and formed the concept of "external support structure". The concept of exoskeleton can be traced back to 1890. Nicholas Yagin, a Russian engineer, proposed a walking aid device driven by air pressure. Although it is a passive auxiliary tool, it already contains the modern exoskeleton idea of using energy storage elements to assist human movement. In 1967, General Electric Company of the United States developed the world's first upper limb exoskeleton robot, Hardiman, which is driven by hydraulic and electric power. Although it is not practical due to its heavy weight (up to 680kg), energy consumption, and stability problems, the exploration of the project in human-machine coupling and force feedback control has verified the feasibility of exoskeleton technology, which is regarded as the starting point of exoskeleton research.

The exoskeleton robot control system should not only ensure that the exoskeleton can quickly and accurately respond to various human actions, but also consider the tacit understanding between the exoskeleton and different operators; that is, the exoskeleton man-machine system should have a certain learning ability to adapt to the movement characteristics of different operators [2]. At present, the research on traditional upper limb exoskeletons mostly focuses on the use of sensors to obtain human motion signals, and realize the motion assistance of exoskeleton according to the signals, which is more commonly used as an extension of tools or structures. However, with the development of artificial intelligence, brain-computer interface, and other technologies, the research of exoskeleton technology needs to turn to intelligent and personalized. In the "man-machine symbiosis" mode, humans no longer use exoskeletons, but "cooperate" with exoskeletons. The exoskeleton in this mode should have a certain learning ability, be able to better feel the user's intention, and cooperate with the user in collaborative operation. From Hardiman, who has a weight of 680kg and is difficult to adapt to the movement of users, to the exoskeleton developed by Beijing University of Aeronautics and Astronautics, which adapts to the wearer with a height of 155-190cm and an arm length of 52-75cm, the rope driven parallel upper limb exoskeleton rehabilitation robot cure-7 without mechanical structure adjustment [3]. The relevant research has made many breakthroughs in the world, with its functions continuously completed, its quality continuously reduced, and it's fit with the human body gradually improved [4].

The rapid development of key technologies such as sensors, control theory, artificial intelligence, and brain-computer interface has provided an important basis for interdisciplinary integration. Under the ideal model of "man-machine symbiosis", it will promote the application of embodied intelligence, reinforcement learning, and adaptive system theory in exoskeleton. This paper aims to systematically review the development of the human-computer interaction mode of exoskeleton robots and provide a reference for research in this field.

2. Human-Computer Interaction Dominated by Exoskeleton

2.1. Paradigm Characteristics

Although the exoskeleton represented by the Hardiman exoskeleton prototype cannot adapt to individual differences and real-time changes, it realizes the basic functions of an exoskeleton and provides a simple and stable solution for the early human-computer interaction mode of exoskeleton. This generation of exoskeleton robots is dominated by machines, which execute predefined trajectories or motion modes, ignoring the real-time state and intention of human beings. The action of the operator is simply copied and amplified, and the operator is required to adapt to the motion trajectory and speed of the exoskeleton system, so that in this human-computer interaction mode, people become passive objects and only provide motion intention for the exoskeleton. The exoskeleton becomes the leader and executes the predefined motion mode after recognizing the motion intention, ignoring the real-time state of the user and the action tendency to achieve the intention.

2.2. Classic Case

In 1965, the Advanced Research Projects Agency of the United States Department of Defense funded and promoted a number of research projects to enhance soldiers' physical functions. Among them, the most representative is the Hardiman exoskeleton project jointly carried out by General Electric Company (GE) and Cornell University. Hardiman's exoskeleton prototype applied the most advanced hydraulic transmission, electric drive, and mechanical control system at that time. In the experimental environment, it can magnify the wearer's strength by 25 times. Hardiman pioneered the master-slave control architecture, detected the wearer's joint torque through mechanical links and sensors, and transmitted the signal to the hydraulic servo valve to control the output force of the exoskeleton, forming a closed-loop system of "human input mechanical output". However, there were limitations in the technology at that time. For example, the nonlinear characteristics of the hydraulic system made it easy for the wearer to cause system vibration when moving rapidly, resulting in control failure. The parameters of its control system are fixed, which can not adapt to the movement habits or load changes of different wearers, so that the Hardiman exoskeleton prototype has only become an extension of the human body and is used by humans as a tool.

The human-computer interaction mode of the rehabilitation training robot has this characteristic. It needs to guide the patients to carry out rehabilitation training along the fixed trajectory. For example, the arm guide rehabilitation training robot calculates and optimizes the motion trajectory through the artificial potential field method or fuzzy algorithm, so as to correctly and safely guide the patients' movement. Due to the patients' lack of enough action ability and relevant medical knowledge, it is necessary to use the human-computer interaction mode dominated by an exoskeleton in this case.

3. Realize Human-Dominated Human-Computer Interaction Relationship through the Perception of Motion Intention

3.1. Paradigm Characteristics

The exoskeleton robot represented by BLEEX and HAL realizes the dominance of the user's exoskeleton, breaking the human-computer interaction mode dominated by the exoskeleton represented by Hardiman's exoskeleton. The core idea of this generation of exoskeleton robots is to sense people's motion intention through sensors such as force, torque, or sEMG. The decision-making layer mostly adopts impedance/admittance control, and the executive layer outputs appropriate and compliant motion assistance, realizing the real sense of "human-computer interaction" [5]. This has greatly improved the safety and comfort, and is the current mainstream exoskeleton technology paradigm. However, the essence of this control model is still a "stimulus response" model, which has delayed output and cannot predict or look forward to motor intention.

3.2. Classic Case

As the world moves towards the 21st century, the development of core industries and technologies such as sensors and servomotors has injected new vitality into the study of exoskeletons. The master-slave control framework initiated by the Hardiman exoskeleton project is widely used in modern exoskeletons. One of the most representative research results was launched by the University of California, Berkeley, Berkeley Lower Extremity Exoskeleton (BLEEX). The traditional master-slave control framework is improved to sensitivity amplification control. Bleex was funded by the US Defense Advanced Research Projects Agency and was successfully developed in the 2000s. Its core innovation lies in the real-time control system based on biomechanical feedback.

Bleex can sense the wearer's motion intention in real time and assist synchronously, rather than simply recognizing the motion intention and executing the predefined motion trajectory. The passive control strategy is adopted in the control system, and the motion trajectory is generated in real time by measuring the force between the human body and the exoskeleton, so as to realize the function of adapting to the human body. In the perception layer, BLEEX mainly senses physical interactions. A variety of mechanical sensors are installed in many parts, such as plantar and joints, to detect the ground reaction force and human-computer interaction force. At the same time, an IMU (inertial measurement unit) is equipped in the hip, knee, and ankle joints to collect limb angle, angular velocity, and acceleration data. At the decision-making level, the high-level controller generates the desired joint torque, the mid-level controller calculates the motion trajectory, and the low-level controller performs position-force hybrid control. At the execution level, BLEEX still employs hydraulic control, which can adjust the flow rate through proportional valves to achieve continuous and smooth output of joint torque. BLEEX has pioneered a novel sensitivity amplification control in the decision-making layer structure, which essentially utilizes a high-gain feedback mechanism to amplify the slight changes in force exerted by the wearer on the exoskeleton system [6]. The advantage of sensitivity amplification control lies in the fact that it eliminates the need for pre-programmed gait patterns. Instead, it dynamically generates motion trajectories by amplifying interactive forces, thereby adapting to the wearer's movement requirements. Sensitivity amplification control is essentially an admittance control based on interaction force. Bleex's first-generation prototype can carry a payload of 34kg and walk at a speed of 0.9-1.3m/s, significantly exceeding the standard load limit of human beings [7]. Bleex pioneered the paradigm of human-computer interaction force closed-loop control, laying the foundation for subsequent exoskeletons, such as the Lockheed Martin HULC system. The core idea of sensing motion intention through physical interaction is still the mainstream scheme of exoskeleton robot control.

Scientists' research on the perception level is not only in physical interaction, but also in the direction of decoding biological signals. The most typical example is the Hal bionic exoskeleton system developed by the Cyberdyne company of Tsukuba University in Japan. Hal creatively uses surface electromyography (sEMG) as the core input signal to perceive the weak electrical signal generated by muscle activity to identify the movement intention. It can be calibrated to build an exclusive "EMG torque" model for each user, so as to adapt to the individual differences caused by subcutaneous fat thickness and muscle fiber type [8]. Hal is a typical representative of motion intention perception through biological signals. At the same time, the design of its perception layer provides a practical basis and research direction for the follow-up research of EEG perception technology.

4. Human-Dominated Human-Computer Interaction is Realized by Predicting the Motion Trajectory

4.1. Paradigm Characteristics

The core idea of this generation of exoskeleton robots is to use models and algorithms, such as MPC, machine learning, reinforcement learning, etc., to predict the user's future movement intention or system state, and to achieve forward-looking, smooth, and adaptive control. The main research directions are continuous motion estimation based on EMG. The prediction of joint torque or angle by sEMG signal requires machine learning model to map and predict; Model predictive control (MPC) calculates the optimal control input by predicting the system state for a period of time in the future; The exploration of reinforcement learning (RL) uses RL to automatically learn control strategies to adapt to different users and tasks and reduce the dependence on accurate models. The control performance of the exoskeleton system using predictive control is higher, more intelligent, and more adaptive, which is the hot spot of the current frontier research, but the calculation is complex, and it is highly dependent on the model and data, so it is mostly in the laboratory stage.

4.2. Classic Case

Scientists and engineers have made many attempts in the field of motion intention prediction. In 2025, Sun Guoan's team published an adaptive control method for a lower limb exoskeleton based on an EMG prediction model, aiming to overcome the problems of lag in patients' movement intention recognition and poor adaptability to individual movement pattern differences. Its core innovation lies in the integration of sEMG prediction and adaptive synovial control, which significantly improves the intention response speed and personalized adaptability of the lower limb rehabilitation exoskeleton. The control method published by Sun Guo'an's team establishes a mapping relationship between "muscle activation degree - joint motion trajectory" by collecting sEMG signals from the biceps femoris, rectus femoris, and vastus lateralis, and after filtering and feature extraction. It inputs the collected sEMG signals into a dynamic model for predicting motion intentions, thereby outputting the desired motion angles and velocities of the hip and knee joints, which serve as trajectory references for exoskeleton tracking. Five healthy subjects wore lower limb exoskeletons for walking on the ground and going up and down stairs. In terms of trajectory tracking accuracy, the knee angle tracking error is $\leq\pm$ 2.5°, which is 40% lower than the traditional PID control [9]. In terms of adaptability, the controller can achieve stable tracking without resetting the parameters under the condition of a 0.5 to 1.2 meters per second step speed difference of the subjects. In terms of flexibility, the fluctuation amplitude of the human-computer interaction force decreased by 35%, and there was no jitter during gait switching. This achievement can enhance the flexibility of the system and reduce the human-computer interaction conflict through the sEMG-driven adaptive model predictive control (MPC). It is essentially a "model-driven" predictive control scheme.

Yangpengfei's team from Ningbo Research Institute of Northwestern Polytechnic University has made remarkable achievements in the field of deep learning enhanced electromechanical system control. Its compliant control exoskeleton method uses a 1D-CNN and LSTM fusion network to process multi-source sensor data (joint angle, plantar pressure, surface electromyography), and output the joint motion trajectory in the next 0.5s, with a prediction error of<3.5% [10]. The research team used the IMU data of the historical gait cycle from the lower limb inertial sensors to train a deep learning model, and realized the personalized, adaptive, and low delay compliance control of the exoskeleton. It is essentially a "Data-Driven" predictive control scheme.

Predictive control is the transition route of exoskeleton human-computer interaction to the future. It is an initiative and predictive, and is naturally suitable for multivariable collaborative optimization, so that it can provide safer, more natural, and more intelligent assistance. Although it is highly dependent on model and data, with the progress of hardware and machine learning technology, predictive control will become the only way to the future intelligent exoskeleton robot.

5. Discussion

Currently, the development of exoskeleton robots exhibits four major trends. Firstly, from response to prediction, the current mainstream directions include model-based predictive control and learning-based predictive models. Secondly, from pursuing universality to meeting personalized needs, individual differences are adapted through online adaptive control, meta-learning, and personalized parameter tuning driven by digital twins. Thirdly, from task-oriented to enabling-oriented, the ability of users is enhanced, with the ultimate goal of enhancing human abilities and promoting neuroplasticity, such as correcting deviations in human limbs. Fourthly, from unidirectional to bidirectional, exoskeletons can also transmit information to humans through channels such as tactile feedback and human-machine interface (HMI). Bidirectional HMI is the key to achieving high-level embodied intelligence, enabling bidirectional and real-time exchange of information between users and robots. Users convey their intentions to the robot through signals such as EMG, EEG, and force signals, while the robot provides feedback to the users through signals like tactile feedback and neural stimulation. This forms a biological closed-loop control system akin to the body's native control, significantly enhancing the efficiency of human-robot interaction with the exoskeleton [11].

To develop a real-time, user-friendly brain-controlled exoskeleton system that reduces false triggers and enhances the naturalness and reliability of control, J. Choi's team proposed a reliable semi-synchronous BCI control framework capable of understanding user intent in real-time and driving the exoskeleton to perform corresponding actions. The system of this achievement is divided into three parts: the BCI module responsible for EEG acquisition and signal processing classification, the user interface module responsible for visual feedback and status display, and the exoskeleton module responsible for executing actions. In the EEG signal processing, a 31-channel EEG acquisition system with a sampling rate of 500Hz is employed, and the Filter Bank Common Spatial Pattern (FBcSP) algorithm is utilized for feature extraction and classification. It has set up a classification result buffer to enhance the system's robustness against misclassifications. The exoskeleton module utilizes the RoboWear 10 lower limb exoskeleton, enabling sitting, standing, and walking, with a speed of up to 2.5km/h [11]. This system assists individuals with mobility impairments in performing actions such as standing, sitting, and walking, serving as a typical example of multidisciplinary innovation in the field of BCI and exoskeletons.

Currently, research in intelligent technologies such as brain-computer interfaces, digital twins, embodied intelligence, and adaptive shared control is driving the degree of exoskeleton-human coupling towards a tighter integration. In the future exoskeleton-human interaction relationship, the human and the exoskeleton will form an intelligently coupled, bidirectionally communicating entity. Exoskeletons are no longer merely tools or extensions of human limbs; they are partners that can predict, adapt to, and enhance human abilities. Human-machine interaction will form an intelligent unity featuring bidirectional adaptability, shared perception, and decision-making. Such a human-machine interaction mode can be referred to as human-machine symbiosis.

The four control paradigms mentioned above are not mutually exclusive; rather, they can complement each other in practical applications. The development of control strategies for exoskeleton robots is not a linear and completely isolated evolutionary relationship, but rather exhibits a multi-branch, homologous development path, representing a relationship of technological superposition and evolution. This study systematically reviews and sorts out the evolution of control models for exoskeleton robots. The development of exoskeletons is no longer merely a matter of mechanics and control, but deeply relies on interdisciplinary innovations from multiple fields such as artificial intelligence, neuroscience, biomechanics, and materials science.

6. Conclusion

The control model has undergone four significant paradigm shifts. The first stage was represented by Hardiman's mindless control, which achieved basic functions but operated stiffly and lacked flexibility. The second stage was dominated by mechanical perception control, represented by BLEEX (perceptual force) and HAL (perceptual electromyography), which achieved true "human-machine interaction" through sensors and became the current mainstream control paradigm. The third stage involves predictive control, utilizing algorithms such as MPC and deep learning to predict intentions and achieve forward-looking, smooth adaptive control, which is currently a cutting-edge research direction. The fourth stage is symbiotic control, characterized by tight coupling and bidirectional communication, which is the future development direction, aiming to form a unified human-machine intelligence. The core trend and development trajectory of exoskeleton technology is not simply about substitution, but rather about the superposition and integration of technologies. The development trend is from "response" to "prediction", from "general" to "personalized", from "unidirectional" to "bidirectional", and from "task-oriented" to "enabling-oriented", gradually deepening the coupling between humans and machines.

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This paper provides a systematic and comprehensive review of the evolution and development of exoskeleton robot control models. The authors clearly classify current exoskeleton control methods into four control paradigms: brainless control, sensory control, predictive control, and symbiotic control, and analyze their core characteristics, typical application cases, and limitations for each. The article is clearly structured and rigorously argued, offering a forward-looking analysis of the development trend of exoskeletons from traditional human-computer interaction to human-computer symbiosis. It also provides valuable insights into future control paths based on artificial intelligence, brain-computer interfaces, and novel sensing technologies. Overall, this review is broad in scope, accurate in its summary, and logically sound, making it a valuable reference for researchers in this field. The manuscript is of high quality, with no obvious technical or structural problems found. In conclusion, this paper meets the publication standards and is recommended for direct acceptance.							