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Abstract: The exoskeleton-type system is a brand new type of man–machine intelligent system. It fully combines human intelligence and machine power so that machine intelligence and human operator's power are both enhanced. Therefore, it achieves a high-level performance that neither could separately. This paper describes the basic exoskeleton concepts from biological system to man–machine intelligent systems. It is followed by an overview of the development history of exoskeleton-type systems and their two main applications in teleoperation and human power augmentation. Besides the key technologies in exoskeleton-type systems, the research is presented from several viewpoints of the biomechanical design, system structure modelling, cooperation and function allocation, control strategy, and safety evaluation.

Keywords: exoskeleton-type system, man–machine intelligent system, review, key technology

1 INTRODUCTION

The exoskeleton-type system is a kind of man–machine system centered by human. It is always designed as an external mechanical structure whose joints correspond to those of human body or limbs. It combines the human intelligence and the machine power so that it enhances the intelligence of the machine and the power of the human operator. As a result, the human operator can achieve what he is not capable of by himself [**1–3**].

The research of exoskeleton-type systems boomed in the late 20th century, when researchers from the United States, Japan, Germany, and other countries introduced many novel concepts of man–machine systems. Then the exoskeleton-type systems have been developed rapidly accompanied with great achievements in mechanical and electronic engineering, automation technology, biological, and material science. Due to the bottleneck of the artificial intelligence and the limitation of the automatic robotics, the exoskeleton-type system through its special advantages has become a highlight in the field of mechatronics and robotics. Its exciting applications have covered the robotic bilateral teleoperation with force feedback, virtual reality (VR), entertainment [**4**] as well as the power amplifier and physical rehabilitation. This paper reviews its development history and presents the current advancements of exoskeleton-type systems. Also discussed are biological and artificial concepts, important research topics, and especially the key technologies of the exoskeleton-type systems.

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2 THE BASIC CONCEPT OF THE EXOSKELETON-TYPE SYSTEM

The concept of the exoskeleton-type system is an extension of the exoskeleton in biology, in which the exoskeleton is a kind of external covering on an animal to protect or support the creature, e.g. the shell of a crab. It serves not only as a protective covering over the body, but also as a surface for muscle attachment, a water-tight barrier against desiccation, and a sensory interface with the environment. In a way, the metal full-body armour of knights can be called an exoskeleton as it provides a hard shell or skin to protect the knight in a battle. Scientists, however, are extending the idea even further. Exoskeletons now refer to

Table 1 The comparisons between the exoskeleton technology and that concept in biology [**5**]

Function	The biological exoskeleton	The exoskeleton technology	Application
Support	Supporting the body of the invertebrates	Supporting physically disabled patient or walking assistance	Rehabilitation robotics or power amplifier
Enhancement	Enhancing the power of animals	Strengthening the human operator	Assistance equipments
Protection	Protecting the animal's body	Protecting the human operator	Automatic armour for soldier, rescue devices or safe manipulation for the radioactive materials in nuclear plant
Sensing and data fusion	Obtaining the information, acting as the sensorium	Interface of human operator and the environment and making data fusion with information obtained by the human operator	Telerobotics, VR

'supersuits' or systems that expand or augment a person's physical abilities. They help a person lift or carry heavier loads, run faster, and jump higher. In the military, exoskeletons will help a soldier fight better since he can be better protected, carry more weapons and equipment, and have more strength than a 'normal' person has. The exoskeleton-type system makes full use of the human intelligence and the power of the machine to greatly enhance the performance of the man–machine system. Table 1 explains some analogies between the exoskeleton in the man–machine system and its concept in biology [**5**].

Basically, the control architecture of exoskeleton-type systems is quite different from the traditional intelligent robotics. Figure 1 illustrates a typical scheme of the exoskeleton-type system. In this control architecture, the human operator is not only the commander or the supervisor of the system, but also a part in the control loop, called 'man-in-the-loop'. In the loop, the human operator mainly makes decisions and the exoskeleton implements tasks. But feedback information received by the human operator and exoskeleton keeps interchanging bilaterally between each other. The human operator simultaneously acts as a feedback block in the looped control system. This is intuitive that the human operator receives the feedback from environments and optimizes the control target. And if necessary, the exoskeleton can also take the duty of data fusion, data processing, and even assist the human operator with decisions. It puts more emphasis on the combination of the human intelligence and machine power, and their information exchanging, so that the man and the exoskeleton are coupled together and both are irreplaceable. The intelligence of the machine system is enhanced while the power of the human operator is also strengthened. Consequently, the exoskeleton-type system has higher integrated intelligence and stronger adaptability to unstructured environments.

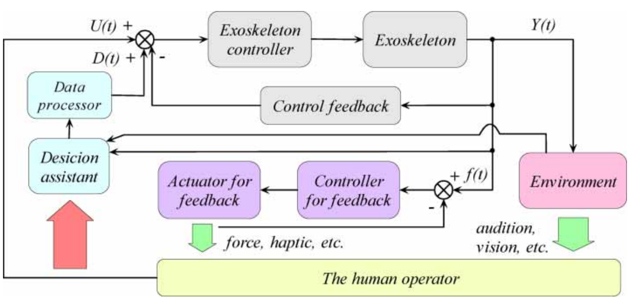


Fig. 1 The scheme of the exoskeleton man–machine intelligent system

3 REVIEW OF THE DEVELOPMENT HISTORY AND CURRENT ADVANCEMENTS

In the mid-20th century, NASA details the background of 'man–machine relationship between intimate partners' in the report for large-scale space exploration. With the ebb of artificial intelligence (AI) in the 1960s and 1970s, several researchers calmed down and thought out the research of AI. As the philosopher Hubert Dreyfus argued in his book 'What computers can't do? The limitation of artificial intelligence', traditional symbolic AI is a dead horse [**6**]. Dreyfus presented four progressively weaker interpretations of the physical system hypotheses that he termed the biological, psychological, epistemological, and ontological assumptions of traditional AI. At the end of last century, many researchers realized that adding human intelligence is a potential alternative method of addressing the problems faced by AI research up to a certain extent. Among them, Lu and Chen [**1**] from Zhejiang University put forward the concept of humachine [**3**], which indicates the specific method to construct a man–machine system. The exoskeleton-type system is such a typical structure to realize the couple of man and machine and set up their new relationship in the human-centred intelligent system.

Basically, the development history of exoskeleton-type systems can be divided into three stages. In the early stage, exoskeleton-type systems were usually used as the master-arm for telerobotics [**7–9**], the tools for human upper-limb or fingers posture measurement [**10–12**], or the simple rehabilitation devices for physically disabled patients [**13**, **14**]. With development of the force reflect and haptical feedback research in the 1990s, the exoskeleton-type systems with force feedback were widely employed in the robot bilateral teleoperation. As the force feedback is added to the system, the human operator has the feeling of doing the work directly instead of through the exoskeleton device, so that the performance of the telerobotic system is improved. This marks the exoskeleton technology coming into a new stage, in which the application of exoskeletons expands rapidly to other fields, including power amplifier, haptic device in VR, rehabilitation, and so on. Most exoskeletons completed or being studied in process sprang out. Nowadays, the exoskeleton technology is forging ahead towards a new phase with special purposes, dedication, and high integration.

In the following sections, the exoskeletons by their two prominent applications – robot teleoperation and power augmentation – are introduced.

3.1 Exoskeletons in teleoperation

As mentioned above, an exoskeleton-type system highly integrates the sensing, data fusion, and data transmission as well as force feedback, so that it can generate the realistic feeling as if the human operator is doing the work directly. This transparent character enhances the intuition of teleoperation and control efficiency, especially in a different structure based robot master–slave control. The exoskeleton with force feedback is regarded as one of the best master arms in telerobotics.

In the 1970s, GE created the exoskeleton master system for robot teleoperation. Afterwards, the research groups from the University of Washington [**15**], Ohio State University, and Stanford University also did some related work [**16**, **17**]. However these devices are importable and need to be fixed on their bases as shown in Figs 2(a) and (b).

Compared with the importable exoskeleton-type master arm, another kind of the exoskeleton-type master arm is ungrounded with light weight. It is used by being seated on the shoulder of human operator. NASA and the Korea Institute of Science and Technology (KIST) have done some research about this kind of exoskeleton. In the KIST two sets of devices, pneumatic cylinders and electric brakes, were employed as force feedback actuators, as shown

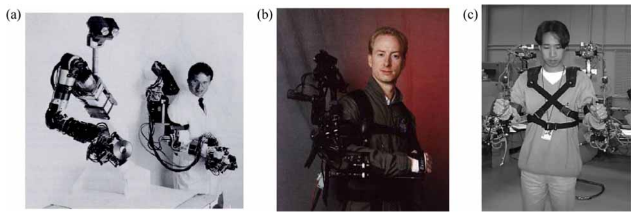


Fig. 2 Exoskeleton-type master arm: (a) exoskeleton master of GE; (b) exoskeleton arm of Stanford [**16**]; (c) KIST exoskeleton arm with electric brakes [**18**]

in Fig. 2(c). Furthermore, a 3RPS parallel mechanism was creatively introduced into the exoskeleton arm design for shoulder and wrist three-degree-of-freedom joints [**18–20**]. Additionally, Bouzit *et al.* [**21**] integrated the Hall sensors for displacement measure, micro-actuators for force feedback, control circuits onto a data glove, and developed the CyberGrasp exoskeleton-type system (Fig. 3). This device is used for VR and can provide force feedback up to 16 N each to the thumb, index, middle, and ring fingertips.

In our previous work [**22**, **23**], a six-degree-of-freedom wearable exoskeleton arm, ZJUESA, for underwater manipulators bilateral teleoperation was developed, as shown in Fig. 4. Because of the different structure between the master and slave manipulators, a general workspace mapping method was proposed [**24**].

Specially, there is a kind of virtual exoskeleton in this series. This work describes a vision-based human–machine communication system that allows a computer or a control unit to 'see and track' the motion

Fig. 3 The CyberGrasp exoskeleton-type system [**21**]

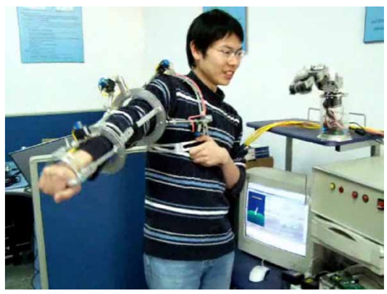


Fig. 4 The six-degree-of-freedom ZJUESA exoskeleton system

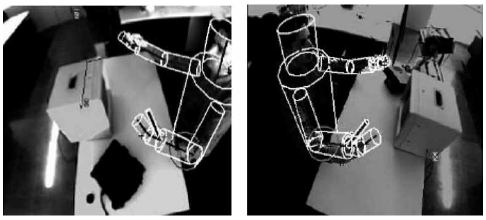


Fig. 5 The virtual exoskeleton [**25**]

of the upper limb of the human operator for some simple teleoperation task, as shown in Fig. 5. Due to its specialty, a few researchers from the Institute for Robotics and Computer Science in Spain are working in this field [**25**, **26**]. They studied its applications in the teleoperation of underwater manipulators on remotely operated vehicles (ROV). However, the virtual exoskeleton is short of force and haptic feedback.

3.2 Exoskeletons for power augmentation

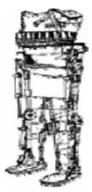
Body supporting and power amplification are two main functions of the exoskeletons on animals. According to this principle, researchers all over the world investigated a few types of exoskeletons as power amplifier to help human operators finish the work with heavy loads. The robotics laboratory at UC Berkley designed a system called 'Human Powered Extender' to help workers on the assembly line [**27**]. It decreases the burden on workers. When the worker ports a load with 100 kg, with the help of an exoskeleton-type system, he only feels a little weight (about 5 kg) while the remaining 95 kg weight is supported by the exoskeleton-type system. Neuhaus *et al.* [**28**] proposed concept designs for an underwater swimming exoskeleton-type system. These designs are biologically inspired to strengthen the driver and improve the poor maneuver. From references [**29**] and [**30**], a wearable power-assist device based on a curved pneumatic muscle actuator (PMA) was designed. It can be directly put on like a coat because of its lightweight and soft texture.

In this field, the walking assistive exoskeleton (Fig. 6) is always the hotspot [**31**]. By combining the human operator and the robotic body together, it simplified the challenges of gait stability of the automatic biped walking robot. The human operator plans the gait in real-time, meanwhile the exoskeleton decreases the load of the human operator during walking and assists human to cover further distances for longer periods with over-mounted loads on a physical interface basis. Table 2 lists the achievements of walking assistive exoskeletons in the last century [**32**, **33**].

Power-assisted exoskeletons have been developed since 1948, when a Russian biomechanicist named

Fig. 6 Walking assistive exoskeleton: (a) HAL-5 system [**34**]; (b) BLEEX lower limb exoskeleton [**31**]; (c) exoskeleton leg for human's walking power augmentation of Zhejiang University

Table 2 The history and achievements of walking assistive exoskeletons in the last century [**32**, **33**]

	1948	The exoskeleton-type system with motor actuators designed by Professor Bernstein
	1960	Hardyman system, designed by GE company. The soldier can drive it by its hydraulic system to strengthen him and load more weapons
	1970	Designed with 87 kg
	1971	Developed by Professor Vukobratovic. It is used to assist patients for walking
	1990	Gehhilfe system

Nicholai A. Bernstein thought up plans for an above-the-knee, electric-motor driven prosthesis to provide movement to casualties of war, but was never implemented. And then the first functional exoskeleton was built by General Electric in 1968 and was called the Hardyman. It closely resembled the power loader seen in the 1986 science fiction film *Aliens*, and was hydraulically powered. The problem with the design was that hydraulics required pumps and bladders occupied almost a room. The Russians experimented with a few more designs, but a Yugoslavian scientist, M. Vukobratovic, came up with the first anthropomorphic exoskeleton to restore basic movement to paraplegics in 1972. A similar product named Gehhilfe by the German prosthetics company Otto Brock was also developed for the same reason in 1990.

In recent years, a major technological breakthrough has taken place with the developments of relative disciplines. The hybrid assistive limb (HAL) series developed by Professor Yoshiyuki from Tsukuba University was utilized to realize the waling aid for the gait disorder person [**34**]. Some sensors such as angle sensors, myoelectrical sensors, floor sensors, etc. were adopted in order to obtain the condition of the HAL and the operator. And it had hybrid control systems, which consist of the autonomous controller such as posture control and the comfortable power assist controller based on biological feedback and predictive feed forward.

The Defense Advanced Research Projects Agency (DARPA) proposed a project, Exoskeleton for Human Performance Augumentation (EHPA). With the aim to strengthen the human operator, the system contained two hydraulic driven metal legs, an in-built power supply source and a backpack-like frame for load. Via the information detected by more than 40 different sensors, the computer in the backpack-like frame made the decision and steered the whole system. A hybrid power source supplied the energy for hydraulic actuators and control systems.

Additionally, the labs in Nanyang Technological University and Kanagawa University have also reached some achievements in these years. The brief introductions of these two systems can be found in references [**35**] and [**36**].

However, the key point of this kind of exoskeleton-type system is how to prospectively detect the motion of the human operator. This insight ensures the exoskeleton to follow the motion of a human operator rather than counteract the human operator causing unnecessary resistance. Commonly, electromyography (EMG) signals on upper and lower limbs were utilized to detect the motion tendency of the human operator. Some novel perspective control algorithms were put forward, for example, the novel control strategy based on an adaptive network-based fuzzy inference system (ANFIS) controller was explored to associate the planar pressure with the human operator walking gait on the exoskeleton leg [**37**].

Another exciting application of exoskeletons occurs in the areas of physical disability and paralyzed rehabilitation. Since MIT created the first rehabilitation exoskeleton arm for muscle dystrophy patients, Golden Arm and MIT-MAUS in 1970s and 1990s, respectively (Fig. 7(a)), Stanford University developed the Arm Guide and MIME prototype systems in 2000 and Rutgers University managed the researches on the lower limb exoskeleton rehabilitation system.

The Lokomat designed by Hocoma AG, Switzerland, was a bilateral robotic orthosis that was used in conjunction with a body-weight support system to control patient leg movements in the sagittal plane [**38–40**]. It can adjust the training gait style according to the bio-feedback of the patient, as shown in Fig. 7(b). Also HapticWalker was designed based on the principle of programmable footplates so that the patient's feet were attached to two footplates, which moved his feet on arbitrary foot trajectories [**41**].

4 THE KEY TECHNOLOGIES OF EXOSKELETON-TYPE SYSTEMS

In this section, the key technologies in exoskeleton-type systems development are discussed. It includes biomechanical design, system structure modelling, cooperation and function allocation between the man and exoskeleton, control strategy, and system safety evaluation.

4.1 Biomechanical design

Exoskeleton-type systems are designed to invent a machine that could successfully track the human motions or assist the human to cover further distances for longer periods with over-mounted loads on a physical interface basis. This translates into a number of biomechanical design specifications.

The exoskeleton should be anthropomorphic and ergonomic, not only in shape but also in function. It can be very broadly described in terms of two classes:

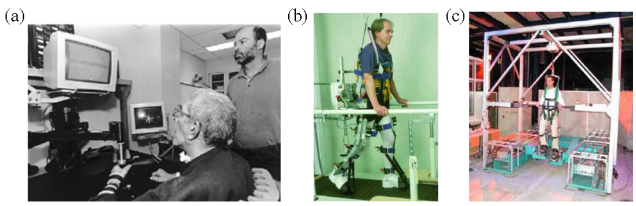


Fig. 7 Rehabilitation exoskeleton-type systems: (a) MIT–MAUS exoskeleton arm; (b) Lokomat rehabilitation exoskeleton [**38**]; (c) haptic walking system [**41**]

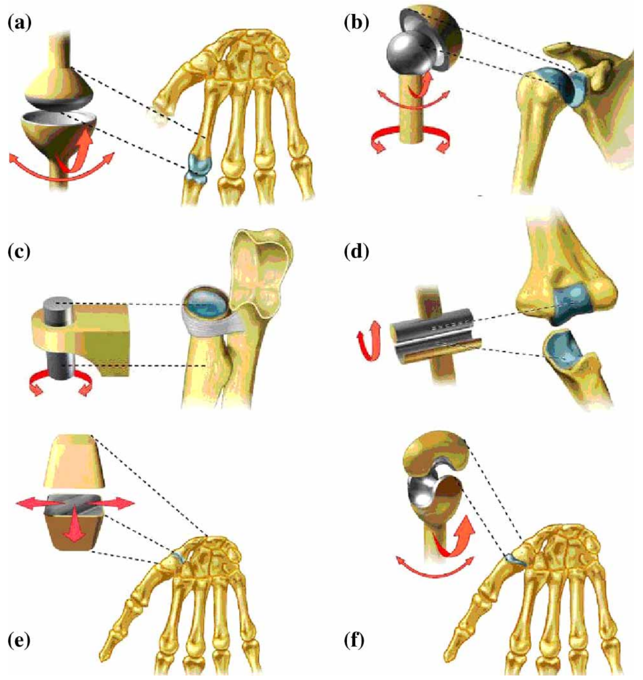


Fig. 8 The six fundamental models of synovial joints [**42**]: (a) condyloid joint; (b) ball-and-socket joint; (c) pivot joint; (d) hinge joint; (e) planar joint; (f) saddle joint

1. The exoskeleton should be analogous to the human limbs and trunk in the case of joint positions and distribution of degrees of freedom. As a result, it is important to investigate the atlas of the human limb and trunk during motions. Synovial joints are the main components for human motion. In accordance with their forms of motions, they can be cataloged into six fundamental joints [**42**] as the planar joint, hinge joint, pivot joint, condyloid joint, saddle joint, and ball-and-socket joint [**43**] (Fig. 8).

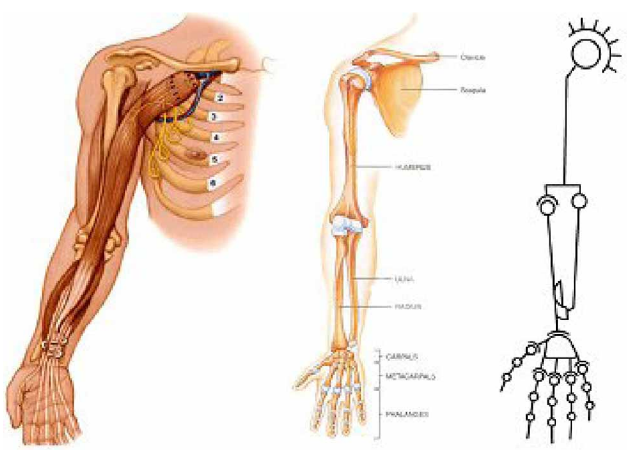


Fig. 9 The motion model of human upper limb

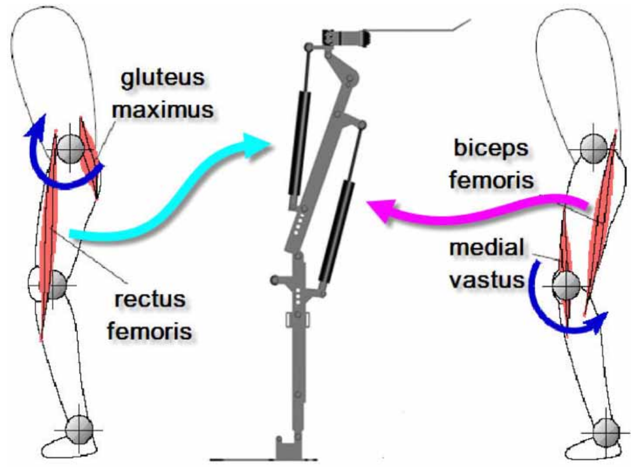


Fig. 10 Design of exoskeleton leg structure from human leg representative muscles for motion of knee and hip

Figure 9 describes an example of the human upper limb model based on the foregoing joint models.

2. The actuations in exoskeletons should be allocated in the corresponding position to the representative muscle in human limb and trunk, in order to simulate the function of muscles during the process of the human operator moving [**44**]. As is well known, the hip motion is generated by the extension/flexion of the *rectus femoris* and the *gluteus maximus*, while the extension/flexion of the *biceps femoris* and the *vastus maximus* produces the extension/flexion of the knee. To adequately simulate the muscle activity during walking, for the aim of building an anthropomorphic leg, one actuator is adopted to simulate the function of the *rectus femoris* and another to simulate *biceps femoris*, as shown in Fig. 10.

Additionally, the exoskeleton structure should be length adaptable. That is, all of the parts on the exoskeleton structure should be adjusted in a broad range of length, thereby accommodating average people with different physiques. Under these circumstances, the premise on which the exoskeleton is expected to be ergonomic, highly maneuverable, and technically robust so the wearer can move, bend, and swing from side to side without noticeable reductions in agility can be established.

4.2 System structure

To construct an exoskeleton-type system in a more maneuverable and pragmatic way is still an open and challenging issue. Comparing with traditional intelligent robot systems, exoskeleton-type systems have a much closer connection with their human operators. In the working process, the exoskeleton-type system makes full use of the intelligence of the human operator and power of the machine, and combines these merits together. It also copes with the information sensing and exchanging between the human operator and the machine. Due to its specialization in structure, it is hard to give out a universal exoskeleton-type system model.

In previous work, a model of human–machine intelligent system was proposed [**3**]. In this model, the whole system can be regarded as three main layers: sense, decision, and execution. The sense layer locates at the top. It fuses the information data from human operator as well as machine sensors. The decision layer, according to the sensing information, organizes the activities in the whole system, including human tasks and machine works. The bottom layer, namely the execution layer, is responsible for the work implementation, which can be finished by human handwork or auto-machine as the case may be. Definitely, the exoskeleton and its human operator have interaction with each other in each layer. The relationship of the whole system can be concluded as shown in Fig. 11.

Apparently the routine 1-2-3-4 represents that the work is operated only in hand while the routine 5-6-7-8 represents the work implementation by means of automatic machine. The man–machine interface bridges these two sites. In the exoskeleton-type systems, the wearable exoskeleton acts as such an interface with its properties of friendliness, usability, transparency, etc. The machine is not only a tool but also possibly an autonomous agent, and some coherence must be maintained between the human's and machine's actions on the environment. The human and the machine become the complementary components of the system. Therefore, the capabilities of each are exploited to their full capacity, thus achieving a level of performance that neither could achieve alone.

4.3 Cooperation and function allocation

Function allocation between the human and machine raises another important issue for study and design of the exoskeleton-type system. The initial renowned contribution to task allocation fields was made by Fitts in 1951 [**45**]. In his work, a solution was put forward by attempting to decompose an activity on a general basis into elementary functions and to allocate each one to the best efficient device, the human operator or the machine, for that function. However, such an approach was rapidly criticized because of its irrationality in the allocation process [**46**]. For example, according to the above-mentioned solution of Fitts, a task should be executed by the allocation of the detection function to the machine, of the resolution function to the human, and of the execution function back to the machine. Obviously, this is not very efficient. Also, as technology advances, the number of factors in which the abilities of humans exceed those of the machines decrease. If each task is allocated to whichever achieves the highest level of performance at that function, the importance of the human in the system is reduced and their role becomes minimal. As a result of these criticisms, a number of developments have occurred in the field of task allocation. One important change is viewing the human operator and machine as complementary components of the system. This promotes both the human operator and the machine to achieve a level of performance that neither could achieve alone.

However, there are some points that should be noted. The function allocation with complementary concept is good for the exoskeleton-type system promotion. But it cannot ensure that human operators will not exert their responsibility over the entire exoskeleton-type system or even again take up manual control. Their loss of expertise, because of the consequence of designing machines that play autonomous roles, either performing low-level functions or high-level functions, makes them likely to reach a poor performance. In addition, a few phenomena in exoskeleton-type systems have posed the awkward problem of shared supervision. More often than not, the exoskeleton-type systems aim to reduce the workload of human operators when they are confronted with increasing requirements. The division of the supervision into two independent fields, the human operator's and the exoskeleton's field, generates complacency and leads the intelligent machine, not alleviate the workload in terms of operator's supervision of the overall exoskeleton-type system [**47**]. In response to complacency, the proposal of several solutions instead of only one from the machine is suggested. However, the decision of which suggestion to be chosen or using manual mode is mainly affected by the ratio between human operator's trust in exoskeletons and self-confidence. It is well believed that even if the cooperative skills of the exoskeleton-type systems are very restricted, exoskeleton-type systems can at least help the human operators to perform the activities in better conditions than the current ones.

4.4 Man-in-the-loop control strategy

Some traditional man–machine intelligent systems are concerned that the intelligent machines are designed to increase their adaptability to the variety of environments, while they cannot equal operators in adaptive skills [**48**, **49**]. The main reason for these drawbacks is the lack of real-time feedback to its human operator when the machine is performing a task. This results in the well-known 'human-out-of-the-loop' syndrome and leads the human operators, when necessary, to

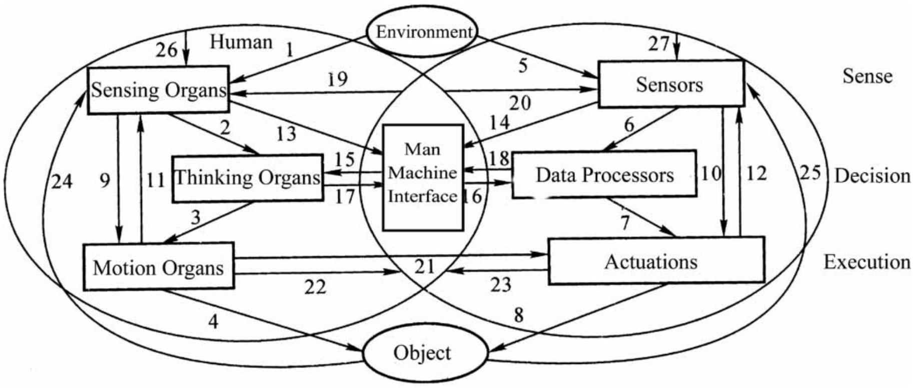


Fig. 11 The diagram of man–machine intelligent system structure. Specification: The system structure has three layers: sense, decision, and execution. In the sense layer, (1) the information from environment to human; (19) the human sensing of the machine; (26) the human self-sensing; (11) the human sensing of self-motion; (24) the feedback from the object to the human; (13) the data exchanging to man–machine interface; (5) the environment information measured by the machine; (20) the human state detected by the machine; (27) machine self-sensing; (12) the feedback from actuation; (25) feedback from the object; (14) data to the man–machine interface. In decision layer, (2) the information from sensing organs; (15) the machine sensing information and machine processed data from man–machine interface; (17) sending the thinking results to the man–machine interface; (6) sending the sensing information to the data processors; (16) the information of human sensing and thinking from the man–machine interface; (18) sending the data processing results to the man–machine interface. And in execution layer, (9) the human reflecting motion to the outside motivation; (3) the motion commands from thinking organs; (21) human operating the object through the machine; (4) human coping with the object in hand; (10) the active signals to the actuations directly from the sensors; (7) the control signals from the data processors; (8) machine working on the object; (22) the maintenance of the machine; (23) interaction from the machine

take control in hand without any clear situation awareness. Contrarily, in the exoskeleton-type system control architecture as shown in Fig. 1, the exoskeleton receives sequences of commands from the human operator or command generator of the system. In turn, the response of the environment is sensed and signals are fed to the exoskeleton. By means of visual, audio, and tactile feedback, the human can intuitively and dynamically execute the work. It is the core that is emphasized in the 'man-in-the-loop' control architecture [**50**]. However, it is not easy to fully or partly realize such an ideal control loop. It faces several difficulties including the above-mentioned cooperation and function allocation between the human operator and the exoskeleton, as well as the following discussed information perception and fusion of these two, real-time motion planning, safety control strategy with high-dependability, and so on. Dependability of the safety control strategy of the exoskeleton-type system calls for a modular and hierarchical architecture, which is also advantageous for testing the single components and isolating possible faults so as to achieve operating robustness. As known, exoskeleton-type systems are designed to assist the human operator to work in dynamical environments. Dynamic situations are uncertain since they are partially controlled. Unexpected factors can modify the dynamics of the process and lead to the errors whose cost can be very high in terms of accident and money. Hence, the human operators must manage the errors when implementing a decision. For them, the major risk is the loss of control in a certain situation, acting too late, although comprehension can reach a high level by this time. Due to the need for continuous monitoring, the response of the environment, exoskeleton operation and the human operator state, as well as for online changes in motion planning, the operation system of the control architecture on exoskeleton-type systems must run in 'real-time'. In many researchers' work, many methods for control in real-time could be found. The majority has involved tracking or flight-control tasks in which the operators were required to detect sudden failures in the dynamics of the controlled element [**51**]. Sheridan [**52**] proposed supervisory control of automated subsystems, primarily in monitoring, diagnosis, and planning activities. In the work of Moncada *et al.*, a multi-purpose man–machine interface for a control systems laboratory is presented [**53**]. It possesses capabilities for multiple real-time data acquisition, which is useful in practical

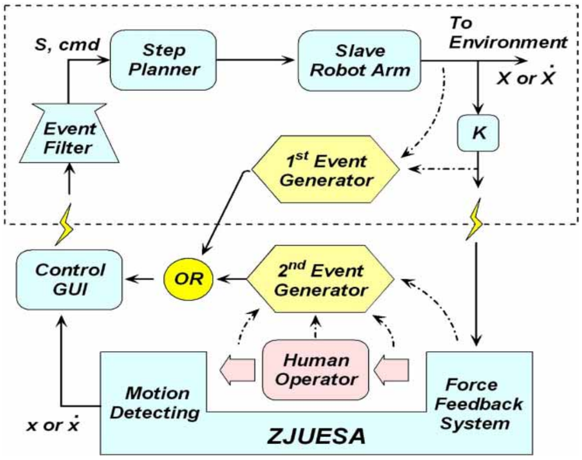


Fig. 12 The diagram of the event-based control architecture

process identification and control. Suzuki *et al.* [**54**] developed a novel man–machine interface, which took into account the mutual cooperation between the operator and an expert system in order to realize precise decision-making and operation. But too many factors may affect the control performance, especially the delay in the LAN, which connects each module of the system for data exchange. The event-based control architecture proposed by Kang *et al.* [**55**] and Tarn *et al.* [**56**] gives a new thought. It changes the continuous system into a discrete domain with event reference s instead of time reference t and it is proved to be effective in dealing with the real-time control and good synchronization in the overall modules or hierarchies in the control architecture [**57**].

Figure 12 shows the application of the event-based control architecture in the proposed exoskeleton-type master arm, ZJUESA, for the robot master–slave control. The upper part in the dashed rectangle represents the slave robot arm and the other part expresses the master system, namely exoskeleton-type system. These two sites over great distance are connected through LAN. Each control command or feedback information, for instance, the force feedback, is transmitted with a unique sequence s, which is a monotone increasing function of time t. Only the event containing the latest sequence can pass through the event filter, which promises only one event existing at any time, and ensures that one control command is corresponding to only one state feedback information. As a result, it leads the system to perform well in terms of good synchronization.

4.5 Information perception and data fusion

As mentioned above, in a man–machine system, the information interchange between the human operator and the intelligent machine is necessary. In order to achieve their bilateral natural communication, a universal expression or even a kind of standard language is required. The formulized computer language is a popular expression in the man–machine communication. Through this technology, the information can be easily input for controlling the behaviour of a machine, especially a computer, but there is a barrier in the inverse application. Because of its inconvenience to be translated into the natural human language, the feedback information from the machine becomes incomprehensive and may cause misinterpretation. Although the visual, acoustic, graphic, and even tactile information have been added to enrich the language, yet it is still far from satisfactory due to the limitation of relative researches. The human language is also widely proposed to be used in the man–machine communication. However, a few difficulties should be faced [**58**]. The arbitrariness of languages is the first problem. This means that there is no logical connection between meanings and sounds. This is a sign of sophistication and it makes it possible for languages to have an unlimited source of expressions. Second, languages are productive or creative in that it makes possible the construction and interpretation of new signals by its users. This is why an infinitely large number of sentences or messages can be produced, including much of what they have never heard before. Additionally, languages are rich. Sometimes for the same expression, a wide choice of words can be offered in one language. These natures of human languages block its application in the man–machine communication.

At present, some novel bio-chips and bio-sensors based on the EMG, which evaluates and records physiologic properties of muscles, electroencephalograph (EEG, which monitors brain waves), and electrooculograph (EOG, which monitors eye movement) can be found in other references to assist the exoskeleton-type systems to detect the motion of the human operator [**34**, **59–62**]. Nevertheless, most of these devices still stay in the labs for experiments rather than practice, in which top signal processing technologies and advanced prospecting algorithms are required. Certainly, these bio-techniques will be widely applied on exoskeletons in near future. For example, in neurotechnology, a biochip (DNA microarrays, protein chips, RNA chips) may be embedded in the human brain, which allows him/her to control a computer or a machine using his thoughts.

In fact, only the implementation of the information perception and interchange between the human operator and the machine in such a man–machine intelligent system is not enough. Depending on the multi-sensor system and network, the perception information should be processed and synthesized based on the knowledge in the expert database. As this work involves the data fusion between the human operator and the machine, some challenges

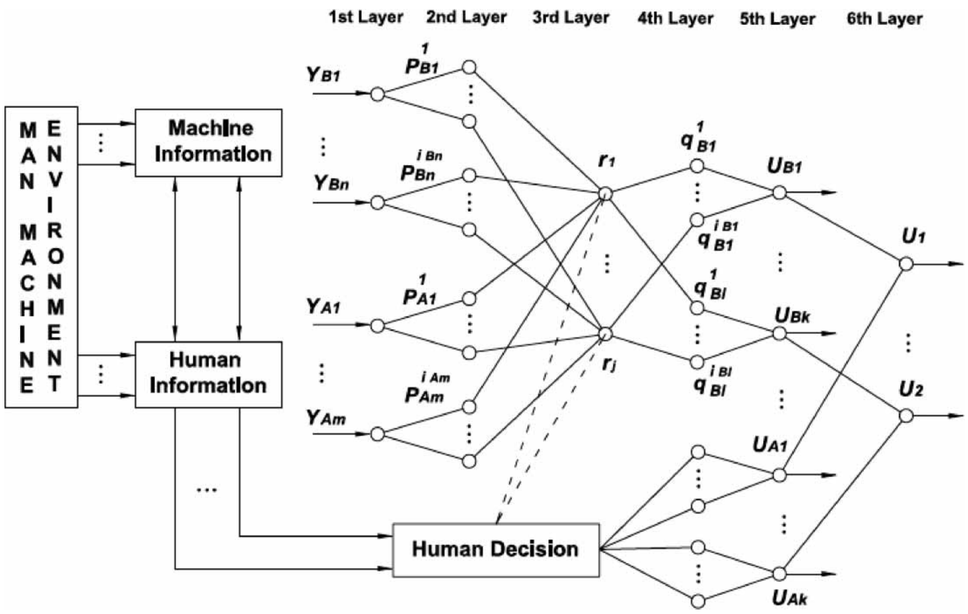


Fig. 13 The exoskeleton fuzzy neural-network control architecture for man–machine information perception

are encountered, for example, the information expression (how to express the information so that it can be comprehended by both human and machine), symbol meanings (how to define the symbols in the information), and information management (how to manage the information exchange and modify the experts database) [**63**]. Since humans evaluate input from their surroundings in a fuzzy manner, the fuzzy logic can be recognized as an ideal medium. In previous important work, the Mamdani fuzzy logic was introduced in the man-in-the-loop based information fusion for exoskeleton-type systems [**64, 65**]. Equation (1) expresses this concept in fuzzy implication

$$\text{if } x \text{ is } A_i \text{ and } y \text{ is } B_i, \text{ then } z \text{ is } C_i \tag{1}$$

It also can be represented in mathematics as

$$\mu A_i(x) \wedge \mu B_i(y) \to \mu C_i(z) \tag{2}$$

where A_i is the fuzzy information from the human, B_i the accurate information from the exoskeleton, and C_i the results of the information fusion and synthesis are the fuzzy sets associated with the universe of discourse X, Y, and Z, with membership function denoted $\mu_{A_i}(x)$, $\mu_{B_i}(y)$, and $\mu_{C_i}(z)$, which can be expressed as

$$A_i = \{(x, \mu_{A_i}(x)) : x \in X\} \quad B_i = \{(y, \mu_{B_i}(y)) : y \in Y\}$$
$$C_i = \{(z, \mu_{C_i}(z)) : z \in Z\} \quad i = 1, 2, \ldots, n \tag{3}$$

Note that after the fuzzification, the information fusion problem between the human and the machine becomes a routine fuzzy logic case. With an appropriate rule base, it is easy to get the results by defuzzification. Here, the neural-network control architecture is introduced to specify the rule base, as depicted in Fig. 13. It provides a formal methodology for representing and implementing a human's heuristic knowledge. It allows for the modification of parameters and learning fuzzy rules from input/output data pairs, incorporating prior knowledge of fuzzy rules, fine tuning the membership functions, and acting as a self-learning controller by automatically generating the fuzzy rules needed.

4.6 System safety and reliability

As mentioned, the exoskeleton-type systems always work around humans or even touch with them and the conventional safety strategies for industrial robots are not well fit to exoskeleton-type systems. Considering the impact force in a sudden collision, which is the possibility of injury to humans from exoskeleton-type systems, Ikuta *et al.* [**66**] proposed a general safety evaluation method by employing the critical impact force F_c as a minimal impact force that causes injury to humans and giving the definition of danger-index as the producible impact force F against F_c in equation (4)

$$\alpha = \frac{F}{F_c} \quad \alpha \geqslant 0 \tag{4}$$

By using this method, not only the impact force F but also many types of safety or dangerousness can be evaluated quantitatively. Definitely, minimizing the impact force by means of safe design, control strategy is the effective way to reduce the damage of the human from the collision.

4.6.1 *Reducing the weight and inertia of exoskeleton part*

According to Newton's law of motion, the relations between the danger index and the weight and inertia respectively, as shown in equation (5), can be obtained

$$\alpha = \begin{cases} ma/F_c & \text{linear motion} \\ I\ddot{\theta}/lF_c & \text{rotary motion} \end{cases} \tag{5}$$

where m and I are the mass and inertia of the exoskeleton part, respectively; a and $\ddot{\theta}$ are system acceleration and angular acceleration, respectively; and l the distance from joint to contact point.

4.6.2 *Distributed macro-mini actuation and joint compliance (DM2)*

Another approach to reduce the manipulator's arm inertia for safety, while preserving performance, is the methodology of distributed macro-mini actuation (DM2) [**67**]. Conventionally, in an exoskeleton-type, a pair of actuators is employed for each degree of freedom. The DM2 actuation approach is to divide the torque generation into separate low- and high-frequency actuators. The low-frequency actuations, where large actuators are required, are located at the base of the exoskeleton, while the high-frequency torque actuators, often small motors, are placed at the joints to ensure the control performance. This reduces the overall inertia to a certain degree while decreasing the overall weight of the motion part in the system.

Additionally, an effective strategy for enhancing the system safety by reducing the impact force in collision is to have compliance in each joint as shown in Fig. 14(b). With the rotary joint on exoskeletons, the impact force F in collision can be calculated as

$$F = \frac{I(\dot{\theta} - \dot{\theta}')}{l\,\mathrm{d}t} \tag{6}$$

And according to the collision dynamical equation of the system

$$I\ddot{\theta} + C\dot{\theta} + K\theta = 0 \tag{7}$$

The damage index of the system can be derived as

$$\alpha = \frac{I\dot{\theta}}{F_c\,\mathrm{d}t} \tag{8}$$

where $\mathrm{d}t = (\tan^{-1}(-\xi\omega_n/\omega_d) + \pi/2)/\omega_d$, and $\omega_n = \sqrt{K/l}, \omega_d = \omega_n\sqrt{1-\xi^2}, \xi = C/2\sqrt{IK}$.

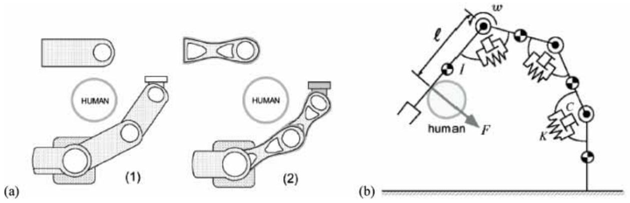


Fig. 14 Safety design of exoskeleton [**68**]: (a) with small mass and low inertia; (b) with compliant joints

4.6.3 *Mounting stop block*

For ensuring safety, the stop block is important to the system. The joint motion spaces on exoskeletons should be limited in those of human operator. Especially under the abnormal state, the exoskeleton cannot hurt the operator due to its over-scaled joint motion spaces. Generally the stop blocks on intelligent machines can be cataloged into soft and hard stop blocks, which are implemented in software and hardware, respectively. According to the definition of damager index, it can be concluded as equation (9)

$$\alpha = \begin{cases} 0 & \text{with stop block} \\ f/F_c & \text{without stop block and } f < F_c \\ 1 & \text{without stop block and } f \geqslant F_c \end{cases} \tag{9}$$

where f is the impact force to the human operator due to the over motion of the exoskeleton joint.

4.6.4 *Fault hanging*

To preserve the safety of humans interacting with exoskeletons, especially in occurrence of unexpected events, as failures or abrupt changes of the environment, fault handling and fault tolerant control have to be considered as fundamental functionalities. It requires the application of a sequence of activities for dealing with faults [**68, 69**]:

(a) fault prevention, to prevent the occurrence or introduction of faults;
(b) fault removal, to reduce the number and severity of faults;
(c) fault detection and isolation, to recognize the occurrence of a fault and characterize its type;
(d) fault tolerance, to avoid service failure in presence of faults;
(e) fault forecasting, to estimate the present number, the future incidence and the likely consequences of faults.

Fault prevention and fault removal are collectively referred to as fault avoidance. Fault detection and isolation are parts of fault diagnosis based on the existing analytical fault diagnosis techniques including observe-based approaches, parameter estimation techniques, and so on. Fault tolerance and fault forecasting are collectively referred to as fault acceptance that may guarantee that the effects of local faults remain internal to the modules, and also permits the reconfiguration of the system.

5 CONCLUSIONS

The exoskeleton-type system is designed as the 'human centered' man–machine system. It fully combines the merits of the human control system and robotic power. The potential exists for the exoskeleton-type system to establish a technology revolution that may exceed the impact of intelligent mechatronics and robotics on society. Its two prominent applications are teleoperation and power amplification. As the field of exoskeleton-type systems is adopted by many disciplines, various advantageous mechanical and control properties are exploited, the diversity and acceptance of exoskeleton-type system will grow. However, it is difficult to develop a quite excellent exoskeleton-type system due to several technological limitations and challenges.

Biomechanical design is a main research on the design method of exoskeleton based on the anatomy of human limb movement. Although, many structures of exoskeletons have been proposed, it has proved to be difficult to mechanically emulate the natural motion of the human. Thus, the structures of exoskeletons should be biomechanically investigated not only in shape but also in function, and in degrees of freedom distribution as well.

System structure modelling is severely concerned with the cooperation and function allocation between human operator and exoskeleton in the sense, decision, and execution layers. There must be some rules for building good cooperation between them, and allocating functions to the one or the other that is the most appropriate for the job. Definitely, it is well believed that even if the cooperative skills are very restricted by recent technology, exoskeletons can at least help the human operator to perform activities in better conditions than the current ones.

Control strategy also raises an important issue. Different from the autonomous robotics, the exoskeleton-type systems focus on the 'man-in-the-loop' control strategy. But it is not easy to fully or partly realize such an ideal control loop. Cooperation and function allocation, man–machine information exchange, real-time motion planning and safety control are the difficulties faced by building such a control strategy.

Safety evaluation of exoskeleton-type systems should also be considered carefully. Exoskeletons are closer to human and its security should be completely promised. However this point is rarely discussed in existing research. Few relative literature, design standards or specific law files could be found, that may lead to a fatal mistake.

Indeed, significant on-going efforts in advanced biomechanical and automatic engineering are improving the performances of exoskeleton-type systems. In the near future, exoskeleton-type systems may play a tremendously significant role in the never-ending development of the man–machine system.

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REFERENCES

1 **Lu, Y. X.** and **Chen, Y.** Foundation of the Humachine System (in Chinese). *Chin. J. Mech. Eng.*, 1994, **30**(6), 1–9.
2 **Yang, C. J., Chen, Y.,** and **Lu, Y. X.** Study on the humachine intelligent system and its application (in Chinese). *Chin. J. Mech. Eng.*, 2000, **36**(6), 42–47.
3 **Yang, C. J.** *Study on the theory of humachine intelligent system and its application*. PhD Thesis, Zhejiang University, Hangzhou, 1997.
4 Available from http://www.wired.com/wired/images.html? issue=13.01&topic=ironmen&img=1
5 **Li, X. M.** *Teleoperation of internet based robot using a human arm exoskeleton*. PhD Thesis, Zhejiang University, Hangzhou, 2004.
6 **Dreyfus, H. L.** *What computers can't do? the limitation of artificial intelligence*, 1979 (Harper & Row, HarperCollins, New York).
7 **Repperger, D. W., Remis, S. J.,** and **Merrill, G.** Performance measures of teleoperation using an exoskeleton device. In Proceedings of the IEEE International Conference on Robotics and Automation, Nice, France, 1990, vol. 27, pp. 552–557.
8 **Repperger, D. W.** and **Remis, S. J.** Use of a multi-axis Fitts' law paradigm to characterize total body motion-a study in teleoperation. In Proceedings of the IEEE Conference on System Engineering, Pittsburgh, PA, USA, 1990, pp. 105–108.
9 **Jau, B. M.** Anthropomorphic exoskeleton dual arm/hand telerobot controller. In Proceedings of the IEEE Workshop on Intelligent Robots and systems, Tokyo, Japan, 1988, pp. 715–718.
10 **Sala, R., Milanesi, S.,** and **Rovett, A.** Measurement of single phalanges positioin: a new fast and accurate solution. In Proceedings of the 20th International Conference on Industrial Electronics, Control and Instrumentation, Bologna, Italy, 1994, vol. 2, pp. 942–945.
11 **Wright, A. K.** and **Stanisic, M. M.** Kinematic mapping between the EXOS handmaster exoskeleton and the Utah/MiT dextrous hand. In Proceedings of the IEEE International Conference on System Engineering, Pittsburgh, PA, USA, 1990, pp. 101–104.

12 **Giuffrida, F., Piaggio, M.,** and **Guerrasio, C.** G-EXO, a modular exoskeleton as multi purpose multi media interface. In Proceedings of the IEEE International Workshop on Robot and Human Communication, Tsukuba, Japan, 1996, pp. 213–216.

13 **Brown, P., Jones, D., Singh, S. K.,** and **Rosen, J. M.** The exoskeleton glove for control of paralyzed hands. In Proceedings of the IEEE International Conference on Robotics and Automation, Atlanta, GA, USA, 1993, vol. 1, pp. 642–647.

14 **Lee, S., Agah, A.,** and **Bekey, G.** IROS: an intelligent rehabilitative orthotic system for cerebrovascular accident. In Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, Los Angeles, CA, USA, 1990, pp. 815–819.

15 **Rosen, J., Hannaford, B.,** and **Burns, S.** Neural control of an upper limb powered exoskeleton type system-grant report. In the First NSF Robotics and Computer Vision (RCV) Workshop, Las Vegas, Nevada, 26–27 October 2003, pp. 21–23.

16 **Turner, M. L., Findley, R. P., Griffin, W. B., Cutkosky, M.R.,** and **Gomez, D. H.** Development and testing of a telemanipulation system with arm and hand motion. In Proceedings of the ASME Dynamic Systems and Control Division, Orlando, FL, 2000, pp. 1057–1063.

17 **Koyamal, T., Yamano, I., Takemura, K.,** and **Maeno, T.** Multi-fingered exoskeleton haptic device using passive force feedback for dexterous teleoperation. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Lausannne, Switzerland, 2002, pp. 2905–2910.

18 **Kim, Y. S., Lee, J., Lee, S.,** and **Kim, M.** A force reflected exoskeleton-type masterarm for human–robot interaction. *IEEE Trans. Syst. Man Cybern. A, Syst. Humans*, 2005, **35**(2), 198–212.

19 **Park, J. O.** Virtual reality and teleoperation in robotics. In Proceedings of the 3rd IWAN, 1999, pp. 78–90.

20 **Jeong, Y. K., Lee, D. J., Kim, K. H.,** and **Park, J. O.** A wearable robotic arm with high force-reflection capability. In Proceedings of the IEEE International Workshop on Robot and Human Interactive Communication, 2000, pp. 411–416.

21 **Bouzit, M., Burdea, G., Popescu, G.,** and **Boian, R.** The Rutgers Master II-new design force-feedback glove. *IEEE/ASME Trans. Mechatronics*, 2002, **7**(2), 256–263.

22 **Zhang, J. F., Yang, C. J.,** and **Chen, Y.** Exoskeleton arm with force feedback for robot bilateral teleoperation. *Prog. Nat. Sci.*, 2007, **17**(9), 56–62.

23 **Zhang, T.** and **Nakamura, M.** Neural network-based hybrid human-in-the-loop control for meal assistance orthosis. *IEEE Trans. Neural Syst. Rehabil. Eng.*, 2006, **14**(1), 64–75.

24 **Chen, Y., Zhang, J. F., Yang, C. J.,** and **Niu, B.** The workspace mapping with deficient DOF space for the PUMA 560 robot and its exoskeleton-arm by using orthogonal experiment design method. *Robot. Comput.-Integr. Manuf.*, 2007, **23**(4), 478–487.

25 **Amat, J., Frigola, M.,** and **Casals, A.** Virtual exoskeleton for telemanipulation. Lecture notes in control and information sciences. In *Experimental Robotics VII* (Eds D. Rus and S. Singh), 2001, pp. 21–31 (Springer-Verlag, London, UK).

26 **Amat, J., Casals, A., Frigola, M.,** and **Martin, E.** Experimental. Bilateral control telemanipulation using a virtual exoskeleton. *Springer Trans. Adv. Robot.*, 2003, **5**, 350–361.

27 Available from http://www.me.berkeley.edu/hel/hydextender.htm

28 **Neuhaus, P. D., Sullivan, M. O., Eaton, D., Carff, J.,** and **Pratt, J. E.** Concept designs for underwater swimming exoskeletons. In Proceedings of the IEEE International Conference on Robotics and Automation, 2004, pp. 4893–4899.

29 **Gao, L., Noritsugu, T., Takaiwa, M., *et al.*** Development of wearable power assist device using curved pneumatic artificial rubber muscle. In Proceedings of the International Conference on Fluid Power Transmission and Control, Hangzhou, China, 2005, pp. 330–334.

30 **Naruse, K., Kawai, S., Yokoi, H.,** and **Kakazu, Y.** Development of wearable exoskeleton power assist system for lower back support. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Las Vegas, Nevada, USA, 2003, vol. 3, pp. 3630–3635.

31 **Zoss, A. B., Kazerooni, H.,** and **Chu, A.** Biomechanical design of the Berkeley lower extremity exoskeleton (BLEEX). *IEEE/ASME Trans. Mechatronics*, 2006, **11**(2), 128–138.

32 **Niu, B.** *Study on the design and control of a wearable exoskeleton leg for human's walking power augmentation*. MSc Thesis, Zhejiang University, Hangzhou, 2006.

33 **Vukobratovic, M., Borovac, B., Surla, D.,** and **Stokic, D.** *Biped locomotion: dynamics, stability, control, and application*, 1990 (Springer-Verlag, Berlin).

34 Available from http://sanlab.kz.tsukuba.ac.jp/HAL/indexE.html.

35 **Liu, X. P.** and **Low, K. H.** Development and preliminary study of the NTU lower extremity exoskeleton. In Proceedings of the IEEE Conference on Cybernetics and Intelligent Systems, Singapore, 2004, vol. 3, pp. 1243–1247.

36 **Yoshimitsu, T.** and **Yamamoto, K.** Development of a power assist suit for nursing work. In the SICE 2004 Annual Conference, Hokkaido, Japan, 2004, pp. 577–580.

37 **Yang, C. J., Niu, B.,** and **Chen, Y.** Adaptive neuro-fuzzy control based development of a wearable exoskeleton leg for human walking power augmentation. In Proceedings of the IEEE/ASME International Conference on Advanced Intelligent Mechatronics, United States, 2005, pp. 467–472.

38 **Colombo, G., Joerg, G., Schreier, R.,** and **Dietz, V.** Treadmill training of paraplegic patients using a robotic orthosis. *J. Rehabil. Res. Dev.*, 2000, **37**, 693–700.

39 **Riener, R., Luenenburger, L., Jezernik, S., Anderschitz, M., Columbo, G.,** and **Dietz, V.** Patient-coorperative strategies for robot-aided treadmill training: first experimental results. *IEEE Trans. Neural Syst. Rehabil. Eng.*, 2005, **13**(3), 380–394.

40 **Riener, R.** *Control of robots for rehabilitation*, 2005, pp. 33–36 (EUROCON, Belgrade, Serbia & Montenegro).

41 **Schmidt, H., Piorko, F., Bernhardt, R., Kruger, J.,** and **Hesse, S.** Synthesis of perturbations for gait rehabilitation robots. In Proceedings of the IEEE 9th International

Conference on Rehabilitation Robotics, Chicago, IL, USA, 2005, pp. 74–77.

42 **Tortora, G. J.** and **Grabowski, S. R.** *Principles of anatomy and physiology*, 9th edition, 2000 (John Wiley, New York).

43 **Premkumar, K.** The massage connection: anatomy and physiology, 2004, (Lippincott Williams & Wilkins, Maryland).

44 **Zoss, A. B., Kazerooni, H.,** and **Chu, A.** Biomechanical design of the Berkeley lower extremity exoskeleton (BLEEX). *IEEE/ASME Trans. Mechantronics*, 2006, **11**(2), 128–138.

45 **Fitts, P. M.** *Human engineering for an effective air navigation and traffic control system*, 1951 (National Research Council, Washington, DC).

46 **Older, M. T., Waterson, P. E.,** and **Clegg, C. W.** A critical assessment of task allocation methods and their applicability. *Ergonomics*, 1997, **40**(2), 151–171.

47 **Hoc, J. K.** From human-machine interface to human-machine cooperation. *Ergonomics*, 2000, **43**(7), 833–843.

48 **Mosier, K. L.** Myths of expert decision-making and automated decision aids. In *Naturalistic decision making*, pp. 319–330 (Lawrence Erlbaum Associates, Mahwah, NJ).

49 **Parasuraman, R.** Humans and automation: use, misuse, disuse, abuse. *Hum. Factors*, 1997, **39**, 230–253.

50 **Zhang, J. F., Yang, C. J.,** and **Chen, Y.** Use orthogonal experimental method to the optimal design for exoskeleton arm. *WSEAS Trans. Syst.*, 2007, **6**(6), 1095–1101.

51 **Kessel, C.** and **Wickens, C. D.** The transfer of failure detection skills between monitoring and controlling dynamic systems. *Hum. Factors*, 1982, **24**, 49–60.

52 **Sheridan, T. B.** On how often the supervisor should sample. *IEEE Trans. Syst. Sci. Cybernet.*, 1970, **SSC-6**, 140–145.

53 **Moncada, R. S. Ferrer, J. S., Pavone, C.,** and **Vera, M.** A multi-purpose real-time man-machine interface for control systems laboratory. *Comput. Ind. Eng.*, 1997, **33**(1), 425–428.

54 **Suzuki, T., Sakino, Y., Nakajima, M., Asama, H., Fujii, T., Sato, K., Kaetsu, H.,** and **Endo, I.** A novel man-machine interface for a bioprocess expert system constructed for cooperative decision making and operation. *J. Biotechnol.*, **52**(3), 277–282.

55 **Kang, W., Xi, N.** and **Tan, J. D.** Analysis and design of non-time based motion controller for mobile robots. In Proceedings of the 1999 IEEE International Conference on Robotics and Automation, Detroit, Michigan, USA, 1999, pp. 2964–2969.

56 **Tarn, T. J., Song, M.,** and **Xi, N.** Intelligent planning and control for hybrid system. In Proceedings of the 1998 IEEE/RSJ International Conference on Intelligent Robots and Systems, Victoria, BC, Canada, 1998, pp. 972–977.

57 **Li, X. M., Yang, C. J., Chen, Y.,** and **Hu, X. D.** Hybrid event based control architecture for tele-robotic systems controlled through Internet. *J. Zhejiang Univ. (Sci.)*, 2004, **5**(3), 296–302.

58 **Wyard, P.** *Representational issues for context-free grammar induction using genetic algorithms*, 1994 (Springer-verlag, Berlin).

59 **Vogel, G.** Part man, part computer: research tests the limits. *Science*, 2002, **295**(5), 10–20.

60 **Fleischer, C., Wege, A., Kondak, K.,** and **Hommel, G.** Application of EMG signals for controlling exoskeleton robots. *Biomed. Tech.*, 2006, **51**, 314–319.

61 **Ji, J., Yu, M. S., Zhou, Y. B.,** and **Jin, Z. R.** A wireless EEG sensors system for computer assisted detection of alpha wave in sleep. In Proceedings of the 2005 IEEE Engineering in Medicine and Biology 27th Annual Conference, Shanghai, China, 2005, pp. 5351–5353.

62 **Kiguchi, K., Esaki, R., Tsuruta, T., Watanabe, K.,** and **Fukuda, T.** An exoskeleton for human elbow and forearm motion assist. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots Systems, Las Vegas, Nevada, USA, 2003, vol. 3, pp. 3600–3605.

63 **Lambert, D. A.** Grand challenges of information fusion. In Proceedings of the 6th International Conference of Information Fusion, Cairns, Queensland, Australia, 2003, vol. 1, pp. 213–220.

64 **Yang, C. J.** and **Chen, Y.** Study the model of the comprehensive perception of humachined intelligent system (in Chinese). *Control Theory Appl.*, 2000, **17**(2), 220–224.

65 **Passino, K. M.** and **Yurkovich, S.** *Fuzzy control*, 1998 (Addison-Wesley Longman, California).

66 **Ikuta, K.** and **Nokata, M.** Safety evaluation method of design and control for human-care robots. *Int. J. Robot. Res.*, 2003, **22**, 281–297.

67 **Zinn, M., Khatib, O., Roth, B.,** and **Salisbury, J. K.** A new actuation approach for human-friendly robot design. In Proceedings of the International Symposium on Experimental Robotics, S. Angelo d'Ischia, Italy, July 2002, pp. 379–398.

68 **Avizienis, A., Laprie, J. C., Randell, B.,** and **Landwehr, C.** Basic concepts and taxonomy of dependable and secure computing. *IEEE Trans. Dependable Secur. Comput.*, 2004, **1**(1), 11–33.

69 **De Santis, A., Siciliano, B., De Luca, A.,** and **Bicchi, A.** An atlas of physical human–robot interaction. *Mech. Mach. Theory*, 2008, **43**(3), 253–270.