

IROS: AN INTELLIGENT REHABILITATIVE ORTHOTIC SYSTEM FOR CEREBROVASCULAR ACCIDENT

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Abstract

Intelligent robotic systems can help improve the rehabilitation process of cerebrovascular accident (stroke) patients. In this paper, we discuss an intelligent externally powered orthotic system (exoskeleton) to be used for the treatment of the motor dysfunctions of the upper extremities of such patients. This system combines the needed skills of professional therapists (physical therapists and occupational therapists) with a sensor-integrated orthosis and a real-time graphics system to ensure proper interaction and cooperation with the patient in order to achieve the goals of therapy. The system employs the expertise of the therapists that is incorporated into its knowledge system while monitoring the sensory information from the patient, including the force, the motion, and the electromyogram signals (EMG). The treatment related tasks are displayed on the real-time graphic system to increase the interest and enhance the motivation of the patient. Such system can be used in order to improve the rehabilitation process of stroke patients.

Introduction

This paper describes the *Intelligent Rehabilitative Orthotic System (IROS)* developed for use in the treatment process of cerebrovascular accident (stroke) patients [12]. The objective of IROS is design, implementation and application of a sensor integrated, upper extremity, externally powered, robotic orthosis, equipped with a real-time graphics system, controlled by intelligent control, for the purpose of the rehabilitation of the stroke patients. The IROS is intended to help the stroke patient elicit muscle activity and to train the activity control for the specific tasks. Contractures and deformities resulted from loss of movement, spasticity, and improper positioning of the stroke patients are all preventable by the usage of IROS. In the case of dysfunctions affecting the proper usage of the upper and lower limbs, the problem could be of two different natures. One possible disorder is when the Central Nervous System (CNS) is intact and the actual limb is problematic (functional controller, malfunctional mechanics). The other possibility is the case of an intact limb with disorders in the CNS (functional mechanics, malfunctional controller). It is the latter that is the case for the stroke patients and is therefore addressed by the IROS. It should be noted that the design of the system is currently in the simulation phase. The IROS system incorporates the therapeutic knowledge of the therapists in a robotic orthosis which allows the training of the stroke patients in a game like environment. This paper is organized into three sections, including the *human* part of the system, the *machine* part of the system, and the *human-machine* system.

Human

The human involved in the human-machine system is a stroke patient. The incidence of strokes is approximately 1.8 to 2.0 per 1000 population per year and about 50 to 70% of the survivors will learn to function independently. Rehabilitation in order to improve the independence of such patients must be done during the early stages after the onset of stroke since the limbs that are not used a few weeks after

the stroke are unlikely to regain useful function. The rehabilitation of a stroke patient should result in regaining the ability to perform the activities of the daily life. Such activities require the upper extremities under the control of the CNS to do the following: grasping and releasing different objects in different arm configurations, transporting of objects to different locations, manipulations of the objects or tools, reaching in all directions, and using of the two hands together. IROS can be used to ensure the on time and accurate treatment of such patients.

Biomechanics

The shoulder, the elbow, and the wrist are the joints of the upper extremities involved in the positioning of the hand. The shoulder is the group of structures connecting the arm to the thorax [16]. The range of motion of the shoulder includes shoulder elevation: movement of the humerus away from the side of the thorax, forward flexion: shoulder elevation in the sagittal plane, abduction: elevation in the frontal plane, forward elevation: elevation in the plane of scapula, rotation about the axis of humerus, and other motions such as backward elevation or extension. It should be noted that the shoulder complex involves many more functions than required for the daily life. Several muscles are involved in the movements of the shoulder and due to the multiple linkage, a single muscle may span several joints and also muscle functions vary depending on the arm position.

The elbow is the area that joins the arm with the forearm, allowing the adjustment of the height and the length of the upper extremity. The elbow provides two degrees of freedom, namely flexion/extension and pronation/supination. Studies of the elbow motions required for performing daily activities are available and should be incorporated in the design of the orthotic system. For instance, from about 140 to 146 degree range of flexion/extension and the 142 degree range of pronation/supination of the elbow, only about 100 degrees of rotations are used in order to perform routine tasks such as using a telephone, pouring from a pitcher, etc. The configuration of the elbow joint unlike the shoulder possesses considerable stability.

The wrist (carpus) is the collection of bones connecting the forearm to the hand, allowing changes in the position and orientation of the hand. Motions of the wrist include flexion/extension in the sagittal plane and radial/ulnar deviation in the frontal plane. The normal range of motion of the wrist is from about 85 to 90 degrees of flexion to 75 to 80 degrees of extension, and from 15 to 20 degrees of radial deviation to 35 to 37 degrees of ulnar deviation. It should be noted that a significant loss of wrist motion may not affect the performance of daily routines due to the compensatory motion of joints proximal to the wrist, namely the elbow and the shoulder. The wrist also possesses inherent stability because of its double-hinged system of joint. It is the mobility of the shoulder, elbow, and the wrist, operating in different planes that allows the hand to operate in a large volume in space.

Electromyography studies of muscles involved in the movements of the upper extremity joints classifies the muscles into three categories based on their involvement in the motion, (1) Muscles which are responsible for the movement with increasing EMG, (2) Muscles which stabilize the motion with constant EMG, and (3) Muscles with-

out activity with no EMG. EMG readings of the patients are compared with the predetermined average values to allow further studies of the patient's improvements. The forces produced by the muscles to enable the movements are also studied and calculations are done assuming a simplified version in which the equilibrium equations of physics can be applied.

Cerebrovascular Accident (stroke)

Cerebrovascular accident (stroke) is the disturbance of the cerebral function due to a vascular cause [20]. Cerebral haemorrhage: rupture of abnormal blood vessels, cerebral embolism: blocking of vessels by embolus broken away from a vessel wall, and cerebral thrombosis: occlusion of artery due to blocking by thrombus formation are some of the causes of cerebrovascular accident (CVA). In these cases the portion of the brain tissues that is deprived from its blood supply becomes infarcted, hence resulting in motor and sensory disorders in the right side of the body if the CVA is in the left hemisphere of the brain and vice versa. Some of the possible disorders associated with stroke are as follows: Anosognosia, which is the lack of recognition and delusions concerning the affected limb. Agnosia, which is the inability to organize sensory information into a recognizable form. Disorders of visuospatial perception, which is the difficulty with drawing and figure-background discrimination. Dysphasia, which is the partial or complete loss of language ability. Dyspraxia, which is the inability to utilize the oral musculature movement for speech production or the impossibility of such voluntary movement and Dysarthria, which is difficulty in speaking clearly. Impairment of memory, loss of orientation in place and time, loss of emotional control, and loss of postural or position sense (proprioception) are other such disorders. These losses can deprive the hand from its useful functionality and therefore require appropriate treatments. One disorder that is treated by the rehabilitative orthotic system is Apraxia, which can be described as the inability to perform a specific movement pattern that was previously learned. In this case there is no loss of mechanical power, in other words the actual limb is unaffected but its control mechanism is damaged. It can be classified into ideomotor apraxia that is the loss of connection between the idea of the action and its execution and gait apraxia that is the inability to walk and correct postural errors. Note that in these cases there is no loss of motor power, comprehension, coordination, or sensation that is essential to the movement. The aim of the treatment using IROS can be categorized as follows:

- Prevention of deformity due to spasticity.
- Encouragement of correct patterns of movement.
- Discouragement of incorrect patterns of movement.

Such treatments as part of the overall rehabilitation process would result in the reestablishment of social, recreational and work roles of the patient. It should be noted that such treatments using IROS could also be incorporated in rehabilitation of patients suffering from illnesses with disorders similar to stroke, namely open or closed head injuries.

Therapy

The therapy process of the stroke consists of a complete assessment of the patient followed by the treatment [5, 17, 19]. Some components of the assessment that are related to the usage of IROS include mobility, motor control and functional abilities. Mobility includes range of motion, joint play, skin condition, compliance of muscle and connective tissue, and edema, while motor control includes muscle tone, strength, abnormal reflexes, voluntary movement patterns, motor planning ability, coordination, static/dynamic balance, developmental sequence, and automatic postural and equilibrium reactions. Range of motion exercises, motor control training, and tone reduction are the significant components of the treatment phase, and such goals can all be achieved by IROS. The motor relearning of the stroke patient is based on the brain's capacity to reorganize and adapt, and therefore encouragement of correct movement patterns

and discouragement of incorrect movement patterns, while closely linked to the normal performance can result in the recovery of the patient.

Different treatment programs for stroke are proposed and practiced by the therapist, having more similarities than differences. Rood approach, Bobath Neurodevelopmental approach, Brunnstrom movement therapy approach, Proprioceptive neuromuscular facilitation approach, and Carr/Shepherd approach are examples of such techniques. The aforementioned programs similarly emphasize the importance of sensation to movement and the importance of repetition to learning. One major difference between the approaches is the issue of whether attention should be directed toward the movement itself or toward the goal of the movement.

In development of the knowledge system for IROS, the encapsulation of the expertise of the therapists includes the development of a treatment approach based on the rationale of neurophysiology, motor learning, and motor development. The approach taken could include different parts of the different programs, with more emphasis given to the methodologies in the common intersection of the available techniques.

Machine

The Machine involved in the human-machine system is an intelligent upper extremity orthotic device that incorporates the design of orthoses with the principles of robotics and artificial intelligence.

Orthotics

An orthosis is a force system that acts on a body segment [2, 18]. It differs from a prosthesis in that it does not actually replace parts of the human limbs but adds on to them. The forces which an orthosis can generate are limited by the tolerance level of the skin and the subcutaneous tissues. Orthoses can be classified into two groups, static orthoses which prevent the movement of the specific joints and dynamic ones that allow such movements. A dynamic orthosis can be powered by other segments of the body that are capable of exerting ample forces for the task or it can be externally powered, namely elastic, pneumatic, or electric. The basis for selection of an orthosis for a patient includes a detailed study of the disorder or illness, an accurate biomechanical analysis of the patient, selection of appropriate components and finally the construction of the orthosis using the selected components.

The primary purposes of orthoses include one or more of the following:

- Relief of pain by limiting motion or weight bearing.
- Immobilization and protection of weak, painful, or healing musculoskeletal segments.
- Reduction of axial load.
- Prevention and correction of deformity.
- Improvement of function.

In the case of the stroke patients, orthoses are mainly used to position the upper extremity, aid in the prevention of contractures, and to support the shoulder.

Robotics

The integration of robotics with the design of orthoses has resulted in exoskeletons for the support and movements of the patient's arm. The first of such devices was developed at Case Institute of Technology in the 1960's. The orthosis (exoskeleton) had 4 degrees of freedom, was externally powered, and was used to carry the patient's paralyzed arm through a predetermined sequence of motion. In one version of the system, the motion sequence was taught to the system by an assistant who took the exoskeleton through the movements, allowing the device to later produce the preprogrammed motion. The other version incorporated a minicomputer to perform the coordinate transformation and used EMG signals for specification of velocities.

The next major development of such robotic orthosis was the Rancho Los Amigos Manipulator with 7 degrees of freedom and direct control of each joint by various switches, a tongue actuated one for example. The control of the arm was later computerized.

The research in application of robotic technology to rehabilitation took a different direction since it was determined that there was no practical usage in designing of an exoskeleton for carrying a patient's arm which possesses no functionality or sensation [15]. There was also the issue of injuries due to the potential ability of the robotic orthosis (robosis) to apply excessive force to the patient's arm beyond its normal range of motion. Such problems are dealt with in the IROS system since the system is not simply carrying a nonfunctional arm, but it is indeed taking part in the rehabilitation process of a patient with an intact arm who requires relearning of the movement patterns. Regarding the safety issues, the system does include a safety mechanism which prevents application of force by the exoskeleton to the arm beyond a certain threshold.

The current rehabilitative robots are robotic arms that are detached from the patient's arm and assist them in daily activities. Such applications require a highly structured work environment to ensure the proper functionality of the assistive robotic arm. Robotic systems at John Hopkins University, Veterans Administration Rehabilitation Engineering Center, Jet Propulsion Laboratory, University of California at Santa Barbara, the Spartacus project in France, and Stanford University's Robotic Aid are examples of such devices.

IROS: An Interactive and Cooperative Human-Machine System

The interaction and cooperation of the Human and the Machine is done by Intelligent Rehabilitative Orthotic System (IROS), composed of a robotic orthosis (robosis), a number of sensors, a real-time graphics system, and a knowledge system, all under the intelligent, structured control of the system. The overall structure of IROS is illustrated in Figure 1.

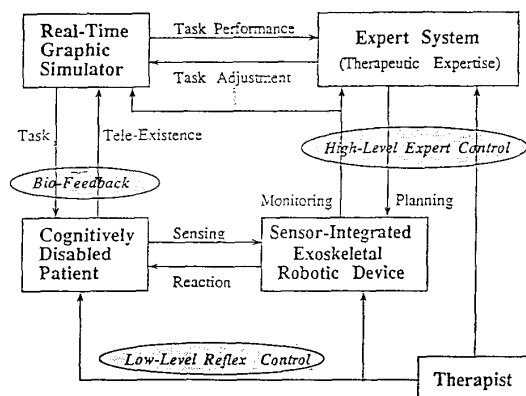


Figure 1: Intelligent Rehabilitative Orthotic System (IROS)

The therapist, the patient, the orthosis, and the graphics components of the system are shown under the main control. The boxes between the components represent the actual interactions and cooperations while the dashed lines represent the information links that were replaced by the controller. The therapist to controller connection allows the transfer of expertise and performing of the supervision. The patient to controller connection is a physical connection for sensing of the patient and reacting of the controller. The orthosis to controller connection is for the actual control of the device allowing planning and monitoring. And the graphics to controller connection is for the purpose of task adjustments and task performance. Combination of these connections allow the IROS to perform therapeutic techniques including eliciting the activity in the position of greatest advantage

to the muscle, not holding the limb too firmly, varying the conditions in a particular set when the muscles do not contract, not encouraging the muscles to contract incorrectly, clearly identifying the goal of movement, selecting goals that the patient will know whether they were achieved, and performing of a particular task passively.

Robotic Orthosis

The robotic orthosis (robosis) or sometimes called exoskeletal robotic device, is a dexterous mechanical arm allowing anthropomorphic motions of the human upper limb. It is of low weight, with adjustable links for the upper arm and the forearm to allow its usage for patients with different size arms. The robosis is equipped with a safety mechanism which is capable of shutting itself off in the case of excessive force sensing. The robosis is configured into 5 joints, with 3 degrees of freedom for the upper arm and 2 degrees of freedom for the lower arm motions. The structure of the robosis is illustrated in Figure 2.

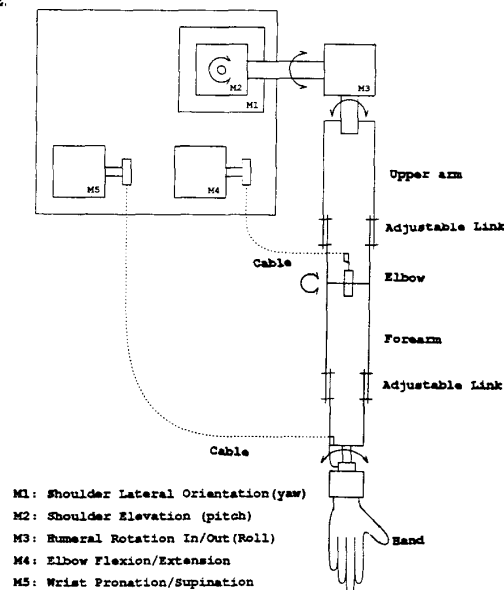


Figure 2: Robotic Orthosis of IROS

Motors *M1*, *M2*, and *M3* coupled with individual harmonic drives contribute to the upper arm motion, with motor *M1* for shoulder lateral orientation, motor *M2* for shoulder elevation, and motor *M3* for humeral rotation in/out. Motors *M4* and *M5* contribute to the motions of the lower arm using cables and pulleys to minimize the weight of the orthosis on the patient's arm. Motor *M4* is for the elbow flexion/extension, and motor *M5* is for the wrist pronation/supination.

Sensors

The sensory information used by the IROS includes joint angles, joint velocities, forces, torques and Electromyogram signals (EMG):

- Encoders to determine the joint angles of the wrist, the elbow, and the shoulder.
- Tachometers to measure the angular velocities of such joints.
- Force sensors to measure the interacting forces between the arm and the robosis
- Current sensors to measure the torques applied to the individual joints.
- EMG surface electrodes to measure the individual muscle activities associated with the movement. EMG signals are detected by the electrodes placed over the skin at proper locations, amplified, filtered, and then by using an analog to digital converter, it becomes available for processing by the controller [21]. The controller processes the signal to gain detailed information about the patient's intent, performance, and improvement.

The overall sensor fusion of the IROS is accomplished by the intelligent controller.

Graphics & Knowledge System

The real-time graphics system supplements the IROS system with an interactive environment that can increase the patient's interest in the treatment by allowing of a variety of tasks to be displayed for the patient. Patients can choose from a number of different graphic environments based on their individual interest. Displaying of the patient's arm and the orthosis while performing the task, in addition to the initial and goal configurations can greatly enhance the performance of the patient. In addition to displaying of the motions, the system can communicate with the patient by giving feedback using appropriate messages. The patient is not the only user of the graphics system, it is also intended for use by the therapists. The system can illustrate the past history of the patient, allow comparative studies of the performance over time, and be reconfigured for different patients.

The knowledge system encapsulates the expertise of the therapists, in order to be used by the structured controller of IROS. The information incorporated in the knowledge system includes the general principle of therapy, the typical trajectories of a normal person in performing the selected tasks, the typical correlation between the physical condition of the muscles and the movement patterns, and the methodology by which the reaction to the patient's move is determined. The knowledge system is used to identify the movement patterns of the patient, monitor the progress of learning, adjust current goal trajectory, and suggest appropriate control modes.

Control Structure

In order to achieve the goals of IROS, a hierarchically intelligent controller is designed for the system, structured by a high-level (symbolic) expert controller and a low-level (numeric) reflex controller, as illustrated in Figure 3. The high-level expert control monitors the progress of the patient, issues appropriate guidance to the exoskeleton robotic device for its low-level reflex control, learns the movement pattern of the patient to identify the nature of defects, and sets up intermediate goals accordingly with therapeutic expertise. The low-level reflex control applies a corrective force to the imperfect controller or the patient for the achievement of the given goal trajectory, responds reflexively to the sensor readings to control impedance (the ratio between force and velocity), and implements a guarded move against excessive resistance.

The intelligent controller consists of an imperfect controller representing the patient, a therapeutic controller representing the exoskeletal device attached to the patient, and an expert controller representing the high-level decision-maker based on the expertise of a therapist.

The therapeutic controller generates the force needed to correct the discrepancy between the trajectory made by the patient and the goal trajectory from the goal generator. Multiple task point control is therefore necessary, in order to adjust the Cartesian position and orientation of both the wrist and the elbow. Furthermore, it performs impedance control and guarded move under the existence of the resistive force, based on feedback provided by the force sensors and joint current sensors.

Once a resistive force greater than the threshold is detected, a partially constrained task (in a virtual sense) is formed in the direction of the excessive resistance, while the wrist or the elbow is allowed to slide on the surface of the partially constrained task. This is to release the tension of the muscle group experiencing high spasticity by changing the arm configuration. The therapeutic controller is capable of shutting itself down upon the presence of malicious symptoms such as spasm or vibration detected by the EMG surface electrodes and the force/current sensors. Note that IROS is also equipped with an override capability for the therapist.

The monitor estimates the trajectory that would result from the patient alone, based on the actual trajectory and the history of the corrective force made by the exoskeleton. This is to identify the movement pattern of the patient. The monitor analyzes the EMG signal and the resistance recordings to detect the physical condition

of the individual muscle groups. The correlation between the EMG signals of the individual muscle groups and the actual trajectory of the exoskeletal device also made. From the accumulated records of the actual trajectories, movement patterns, and muscle conditions, the progress of the patient can be evaluated.

The expert controller modifies the current plan, defined as a sequence of tasks or training goals, by analyzing the symbolic information provided by the monitor, such as the patient's progress, the current movement pattern, and the physical condition of the individual muscle groups, based on the system knowledge. The goal generator generates detailed trajectory of wrist and elbow based on the information provided by the expert controller.

The plan modification includes the symbolic description of how to modify the current trajectory, the choice of the system control mode that is adapted, and how the parameters (such as the threshold for the excessive resistance) of the therapeutic controller should be adjusted. The following system control modes are defined:

1. Passive mode. In this situation, the robosis is the master, and the patient is the slave. The patient passively follows the robosis as it performs the task. In this mode the patient experiences the performance of the task without actually trying to do it.
2. Assistive mode. In this situation, the robosis assists the patient performing the task. This is the normal mode of operation for training.
3. Observation mode. In this situation, the patient is the master, and the robosis is the slave. The orthosis is now following the patient, who is performing the task. This mode is for the observation of the patient's performance.
4. Testing mode. In this situation, the patient is challenged to direct the robosis into the correct path or range of movement. That is, the robosis is demonstrating an incorrect action for the patient to correct, making possible further testing and training.

The interaction and cooperation between components of IROS goes on continuously and autonomously as the treatment process of the stroke patient. The structured control of IROS achieves self-organized interaction and cooperation between the patient and the robosis toward a common goal: the rehabilitation of the stroke patient.

Conclusion

In conclusion, the Intelligent Rehabilitative Orthotic System is the incorporation of the therapeutic knowledge of therapists in a robotic orthosis (robosis) for the purpose of rehabilitation of motor functionalities of upper extremities of stroke patients. The real-time graphic system adds a game like feeling to the therapy, increasing the patient's interest and motivation. The control of such system is done in a hierarchical, intelligent fashion, structured into a high-level, symbolic controller and a low-level, numeric controller. IROS is an interactive and cooperative human-machine system, with both controlling the human arm. Initially the machine is the main controller of the arm. As the patient improves, the human control of the arm increases and the machine control of the arm decreases. Eventually the human is the controller of the arm, i.e. successful therapy.

References

- [1] Adrian, M.J. and Cooper, J.M., *Biomechanics of Human Movement*, Benchmark Press, Inc., Indianapolis, IN, 1989.
- [2] American Academy of Orthopaedic Surgeons, *Atlas of Orthotics, Biomechanical Principles and Application*, 2nd ed., The C.V. Mosby Company, St. Louis, Missouri, 1985.
- [3] Anderson, M.H., *Upper Extremities Orthotics*, Charles C. Thomas, Springfield, IL, 1965.

- [4] Asada, H. and Slotine, J.-J.E., *Robot Analysis And Control*, John Wiley & Sons, Inc., New York, NY, 1986.
- [5] Carr, J.H. and Shepherd, R.B., *A Motor Relearning Programme for Stroke*, 2nd ed., Aspen Publishers, Inc., Rockville, MD, 1987.
- [6] Fu, K.S., "Learning Control Systems - Review and Outlook", *IEEE Transactions on Automatic Control*, April 1970.
- [7] Glantz, S.A., *Mathematics for Biomedical Applications*, University of California Press, Berkeley, CA, 1979.
- [8] Glass, G. and Wong, C., "A Knowledge-Based Approach to Identification and Adaptation in Dynamical Systems Control", in *Proceedings of the 27th Conference on Decision and Control*, pp. 881-886, 1988.
- [9] Goldenberg, A.A., "Implementation of Force and Impedance Control in Robot Manipulators", in *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 1626-1632, 1988.
- [10] Hogan, N., "Impedance Control: An Approach to Manipulation, Part I-Theory, Part II-Implementation, Part III-Applications", *Journal of Dynamic Systems, Measurement, and Control*, March 1985, vol. 107, pp. 1-24.
- [11] James, J.R. and Suski, G.J., "A Survey of some Implementations of Knowledge-Based Systems for Real-Time Control", in *Proceedings of the 27th Conference on Decision and Control*, pp. 580-585, 1988.
- [12] Lee, S., "Man/Robot Interactive and Cooperative System for the Cognitively Disabled", in *Proceedings of the 1990 IEEE Engineering in Medicine and Biology Society*, to be published.
- [13] Lee, S., and Kim, M.H., "Cognitive Control of Dynamic Systems", in *Proceedings of IEEE International Symposium on Intelligent Control*, 1987.
- [14] Lee, S., and Saridis, G.N., "The Control of Prosthetic Arm by EMG Pattern Classification", *IEEE Transactions on Automatic Control*, Vol. AC-29, No. 4, 1984, pp. 290-320.
- [15] Leifer, L.J., "Rehabilitative Robots", *Robotics Age*, May/June 1981, pp. 4-15.
- [16] Nordin, M., *Basic Biomechanics of the Musculoskeletal System*, 2nd ed., Lea & Febiger, Philadelphia, PA, 1989.
- [17] O'Sullivan, S.B. and Schmitz, T.J., *Physical Rehabilitation: Assessment and Treatment*, 2nd ed., F.A. Davis Company, Philadelphia, PA, 1988.
- [18] Redford, J.B., *Orthotics Etcetera*, 3rd ed., Williams & Wilkins, Baltimore, MD, 1986.
- [19] Trombly, C.A., *Occupational Therapy for Physical Dysfunction*, 3rd ed., Williams & Wilkins, Baltimore, MD, 1989.
- [20] Turner, A., *The Practice of Occupational Therapy*, 2nd ed., Churchill Livingstone, New York, NY, 1987.
- [21] Webster, J.G. et al., *Electronic Devices for Rehabilitation*, John Wiley & Sons, Inc., New York, NY, 1985.

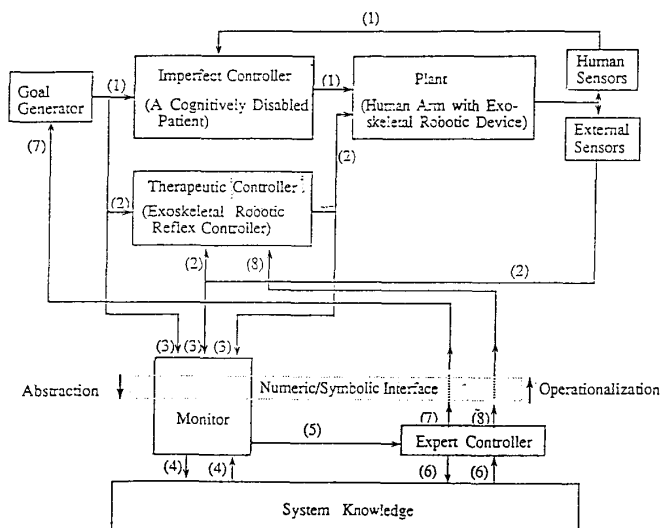


Figure 3: Intelligent Control of IROS