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## REHABILITATION ROBOT PROTOTYPES DEVELOPED BY THE ITAM ZABRZE

Limb physical movements disability is the result of illnesses or serious injuries, impaired execution of daily activities and limitations or even inability to perform working activity. Restoration of fitness in such cases is possible through rehabilitation that requires arduous repetition of appropriate exercises with participation of an experienced physiotherapist. Exercises using the robot to repeat movements would speed up the process of rehabilitation. The paper presents the concept of rehabilitation robot control system realizing a specified purpose.

### 1. Introduction

In the world, the population of patients who need to improve movement of upper or lower limb is rapidly increasing. This is due to many reasons, including aging of the population, and civilizational changes in lifestyle that lead to many mobility debilitating diseases. Disabilities occurring after such diseases impede performance of daily living activities, bring pain, deteriorate quality of life and reduce the possibility of working [1, 2]. Treatment of this types of disorders and eliminating disabilities caused by them is long-lasting,

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expensive process that involves many people. Nowadays, it is impossible to imagine modern medical treatment without rehabilitation. One of the frequently used methods of physiotherapy is the method of PNF (Proprioceptive Neuromuscular Facilitation). It involves recreating complex multifaceted sequences of limb movements, called movement patterns. Doing an exercise with this method requires a great physiotherapist's commitment consisting in performing repetitive movement patterns with the patient. This limits the availability of frequent rehabilitation sessions needed for the patients [3, 4, 5].

Nowadays, increasingly assistive devices are applied in the rehabilitation of upper and lower limbs. Generally, they perform simple single-faceted movements, used in the rehabilitation of single joints [6, 7, 8]. For example, in the rehabilitation of upper limb one uses a device that allows for rehabilitation of the shoulder joint – Kinetec Centura Shoulder CPM. At the University of Zurich, in cooperation with Hocoma Company and a physician therapist from the Zurich clinic in Balgrist, the Armin device had been developed for multifaceted upper limb rehabilitation. Originally, it was characterized by six levels of latitude, from which four were propelled, while the other two were passive. The next version adds two more levels of latitude to allow movements of the forearm and wrist [9]. Other available sources show that, in many research centers, there are developed robotic devices to assist in the rehabilitation of the upper limbs [10] and lower limbs [11].

The solution that allows for increasing the access to rehabilitation is the usage of a robot that assists the patient to repeat patterns reflecting multifaceted movements, without a direct participation of the physiotherapist [12, 13]. The physiotherapist's participation would be limited to inputting movement pattern to the robot's memory, connected the robot to the patient's rehabilitated limb, and then programming the speed and number of repetitions. This solution would enable a highly qualified physiotherapist to perform simultaneous rehabilitation sessions with several patients.

## 2. Assumptions of the control system

The rehabilitation robot is a mechatronic system, where the patient's limb is fixed for recording rehabilitation movements and reproducing them many times in the next stage of rehabilitation session. The basic problem to solve is the combination of the robot's control system with the robot's mechanical system. The assumption made here consists in dividing the system into autonomic nodes controlling the individual robot's drives. The node operating a single drive is connected with one force sensor or two force sensors, so that the force acting on the limb by a specific drive could be

measured by a proper node controller (Fig. 1). The node is understood here as a system that implements a simple movement against one axis for a selected joint. Dividing the control system into individual nodes allows for realization of the autonomic operating process of the selected drive. Such solution would simplify the control of force exerted by a limb, both in the case when the limb is making passive and active movement (reproducing and forcing the movement) [14]. A very important problem to solve is also the appropriate location of the force sensors on the robot's individual structural elements to achieve required sensitivity and selectivity of the force measurements.

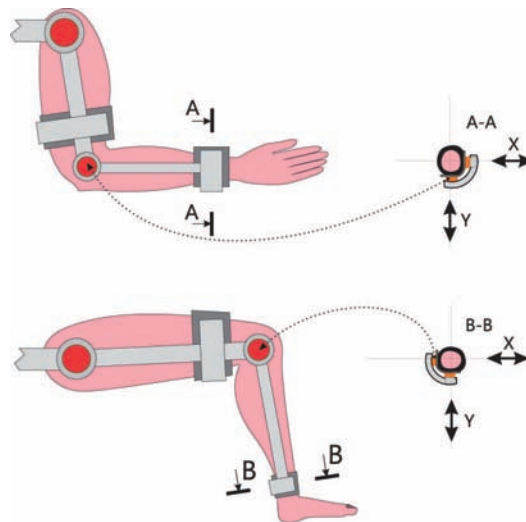


Fig. 1. The general conception of operating the rehabilitation robot in which motor drives are related to force sensors

### 3. Construction of the robot's control system

The control system of the rehabilitation robot consists of three components: measuring and executing node modules, communication module and the PC computer with the control software (Fig. 2). The idea of the system operation is based on cyclical information exchange between the control program on the PC and measuring and executing modules. In the current system, the time of full information exchange between the PC and all operating nodes was set to 100ms. The interface connecting the communication module with the PC computer is the USB interface. To connect all the nodes with the control system we used the RS-485 bus and a simple question-answer method of information exchange. In each cycle of data exchange, the PC sends new operating parameters to measuring and executing modules, which include information about mode of work of the node and its working parameters. In

response, node modules send information about working parameters, such as angular position, velocity, factors of PWM padding, temperature and supply currents.

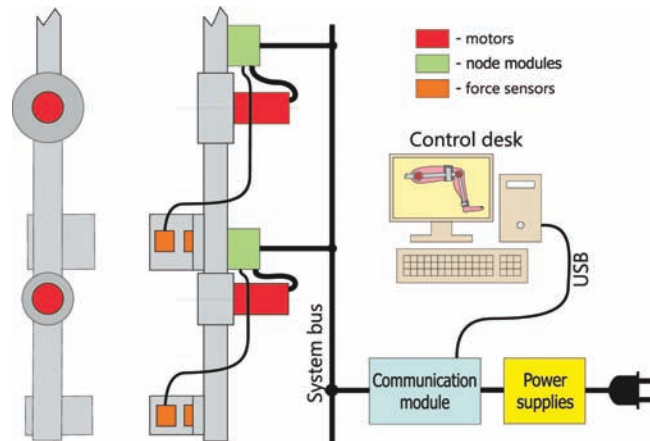


Fig. 2. The construction the of the robot control system

The PC computer with the operating program allows one to store the movement trajectory of the rehabilitated limb as a training program and makes it possible to recreate the saved training program controlling the measuring and executing operation nodes. During the training session, the person that operates the system starts to record the calibrated trajectory trace and, after finishing it, the operator starts the reconstruction of the trajectory trace. The program is a kind of a movement recorder. Each of the saved trajectories can be stored on the hard drive for later assessment of the rehabilitation progress.

One should also note the additional role of the communication module which is emergency voltage disconnection. In addition, almost every drive has been equipped with a magnetic brake, which blocks movement in the case of power failure or emergency. Disconnecting brakes supply is realized by the independent operating circuit. Such a solution gives the certainty that, after pressing the emergency button, the robot's motors will be stopped.

#### 4. The construction of node controlling system

To integrate and miniaturize all sensors and achieve appropriate functions in a specified node that operates the drive, we decided not to purchase ready-made solutions and instead we made own drive controllers cooperating with the BLDC motor [15, 16]. This allowed for an autonomous node protection in advance to a situation dangerous for the rehabilitated person

or the operated drive. It also allowed for controlling additional elements, such as linear actuators, which make it possible to adapt the robot to the length of the rehabilitated limb. The configuration of the measuring and executing node module is flexible and can be changed from the level of the operating program on the PC computer. The example of this flexibility is the measurement of the force realized by the use of the node controller. The controller has two analog measurement inputs, of which only one is equipped with a differentiated measurement amplifier for direct connection of an extensometer bar. The node controller allows one to choose whether the controlled node is connected to the strength measurement input 1 or 2, to negate or set the selected value which is the sum or the differences of the measured power inputs – Fig. 3.

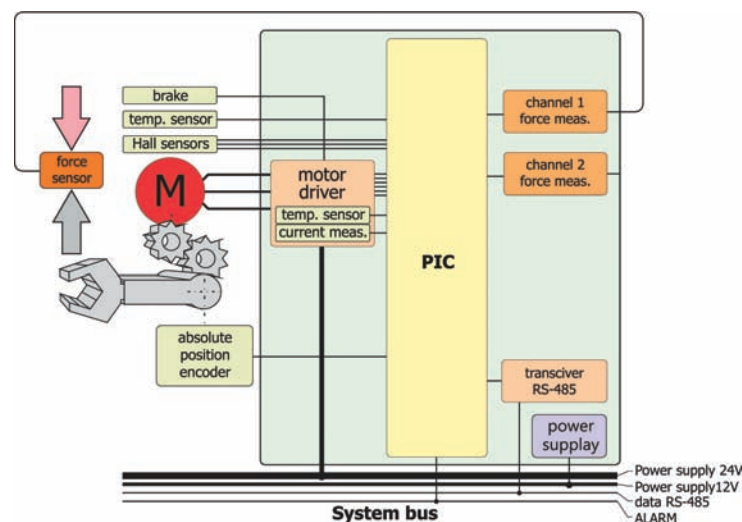


Fig. 3. The scheme of measuring and executing node for ARM-100

In most cases, the work algorithm of node is implemented using only one force sensor. In more complex cases, the work algorithm of node needs signals from two force sensors. In this cases the node's module controllers can be coupled in pairs, and in this configuration signals amplified by the amplifiers in each node controllers are exchanged between controllers. This solution allows us to control two drives connected in a pair, where one drive is controlled by the sum of forces and the second by the difference. Such a solution was used to operate the wrist drives – Fig. 4.

In addition, the node controller allows for setting gain of an individual measuring channel and, in the sensitive zone, for reducing the hysteresis influence of the sensor system on movement tracking based on the sensors strength.

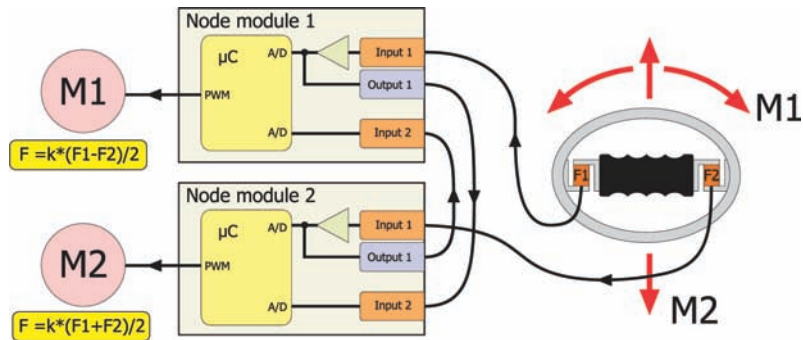


Fig. 4. Scheme of connecting nodes into pairs on the example of the handgrip

Each node can operate in a power supporting mode or the mode of position stabilization. The power supporting mode is mainly used for programming the trajectory of rehabilitation, but it also allows for an active exercise by setting an appropriate insensitivity threshold of force measurement circuit. The mode of position stabilization enables the implementation of passive training, in which the robot replays the previously saved rehabilitation movement, by moving the robot arm through the recorded previously points. Properly frequent flow of data determining the new position allows for smooth movement that accurately reproduces the movement inputted by the physiotherapist.

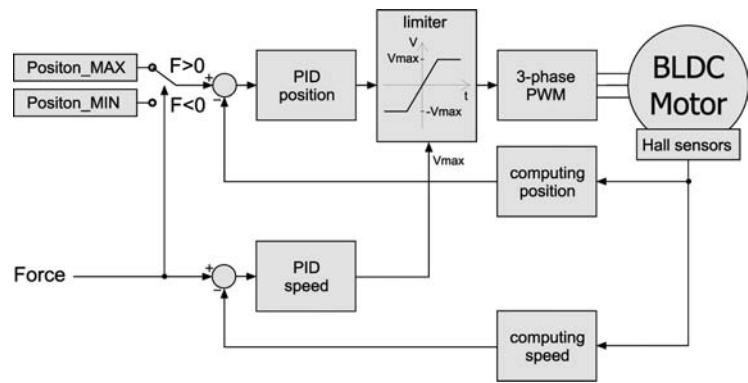


Fig. 5. Simplified block diagram of force supporting algorithm for ARM-100

A simplified action algorithm of the measuring and executing module in the working mode with force supporting is shown in Fig. 5. The basic elements of this system are two PI control units [17, 18]. The first controller stabilizes the speed of drive rotation, which is directly proportional to the applied force. The second one stabilizes the position, and provides the reduction of range motion in a given node. The direction of power performance switches the regulator position between two states: changing the position

for MAX position or MIN position. However, the displacement of given element occurs only when an adequate force is applied, such that exceeds the assumed threshold of insensitivity of the measurement mode. The speed of displacement is directly proportional to the applied force, provided that the system is in the allowed range of motion. The position regulator provides automatic speed reduction to zero value when the moved element reaches the limits of the range of motion.

Based on the assumptions of the control system described above, were created two constructions of rehabilitation robots for upper and lower limbs.

### 5. Rehabilitation robot ARM-100

The first robot, which was developed at the Institute of Medical Technology and Equipment, was a robot for upper limb rehabilitation ARM-100. The robot has seven degrees of freedom (N1-N7) shown in Fig. 6a. In addition,

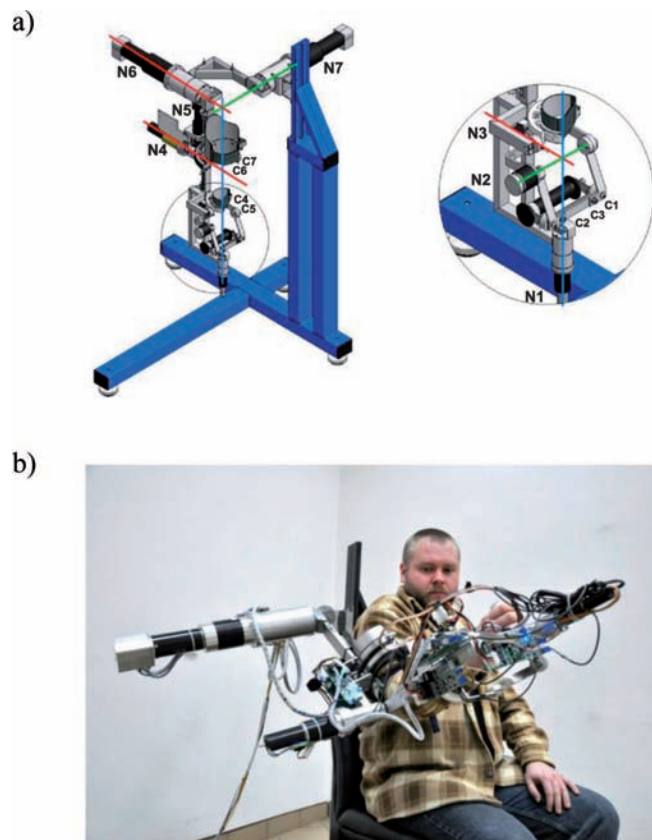


Fig. 6. The prototype of robot ARM-100: a) virtual model, b) photograph of actual robot prototype

Fig. 6a shows places where force sensors are located (C1-C7) giving possibilities of programming movements and protecting the rehabilitated person. The robot drives are seven Maxon Motor's BLDC motors. The most of used gears are the planetary gears, only two smallest drives are equipped with spur gears.

The node control system is based on 8-bit microcontroller PIC18F4431 [19], the hardware prepared for control of BLDC motors. All elements of the node are shown in Fig. 7.

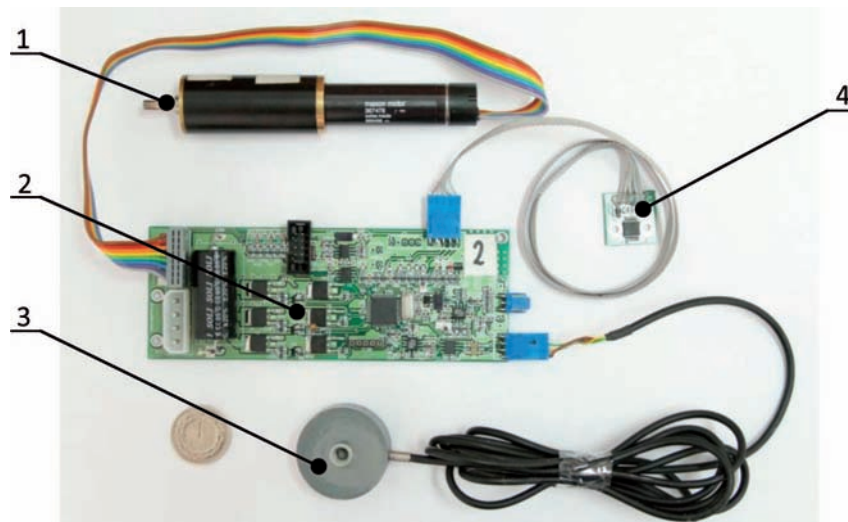


Fig. 7. Picture of ARM-100 node elements: 1 – BLDC motor-gearbox, 2 – node controller, 3 – force sensor, 4 – absolute position encoder

## 6. Rehabilitation robot LEG-100

The second robot, shown in Fig. 8, is a rehabilitation robot called LEG-100, which has 5 degrees of freedom (N1-N5). This construction uses motors from several companies. Drives that are transmitting the greatest loads are the hip joint drives from HARMONIC DRIVE company. The drives consist of synchronous motors with permanent magnets (SMPM) and harmonic gears. The BLDC engine from the Dunkermotoren company with a harmonic gear from the HARMONIC DRIVE company were used to move the knee joint. The smallest drives were used for moving the ankle joint. These consist of BLDC engines from FLAT series and spur gears from MAXON MOTOR. The use of different drives from many different companies was motivated by the need for finding an optimal solution in terms of quality and price. The optimization will be particularly important in the future implementation of this device into production.



In the project of LEG-100, the heart of each operating node system is a 16-bit microcontroller dsPIC33EP512MU810 [20] with hardware support system for operating BLDC engines and SMPM, additionally equipped with signal commands enabling, for example, realization of saturation arithmetic. The elements of the LEG-100 node are shown in Fig. 9. Additionally to the ARM-100's, the node controller in LEG-100 is equipped with a linear actuator driver, which makes it possible to quickly adjust selected dimensions of mechanical elements of the robot to adapt them for different patients.

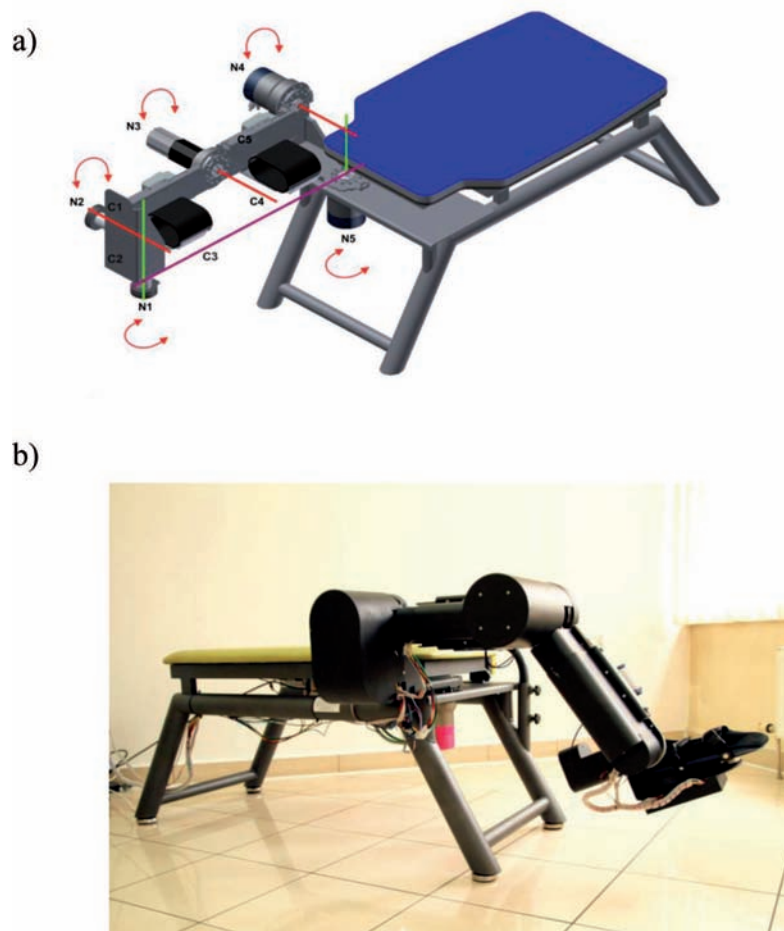


Fig. 8. The prototype of LEG-100 robot: a) virtual model, b) photograph of actual prototype

## 7. Verification of results

Verification of accuracy of the trajectory mapping was conducted by comparing a sample rehabilitation trajectory recorded during the learning

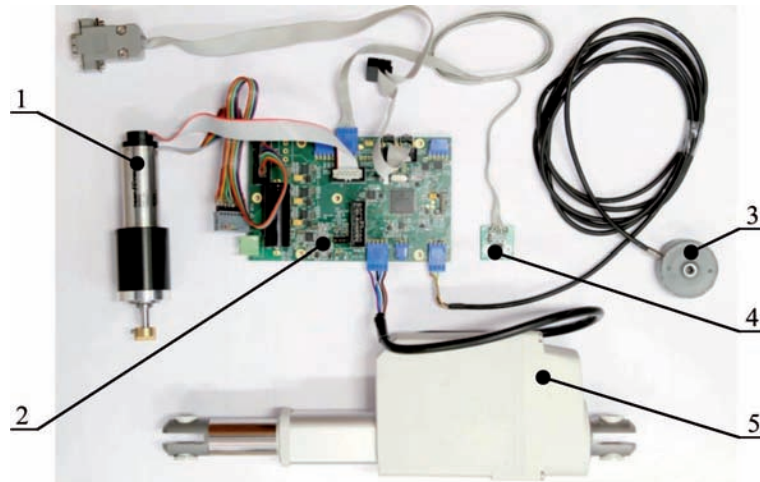


Fig. 9. Picture of LEG-100 node elements: 1 – BLDC motor-gearbox, 2 – node controller, 3 – force sensor, 4 – absolute position encoder, 5 – linear actuator

process with the same moving trajectory played from memory after learning. Figure 10 shows the comparative graphs of trajectory of chosen markers located on the arm of the ARM-100 prototype for upper limb rehabilitation. To conduct the verification, we applied the optical motion analysis system APAS to trace passive markers placed on the arm by means of a set of four cameras.

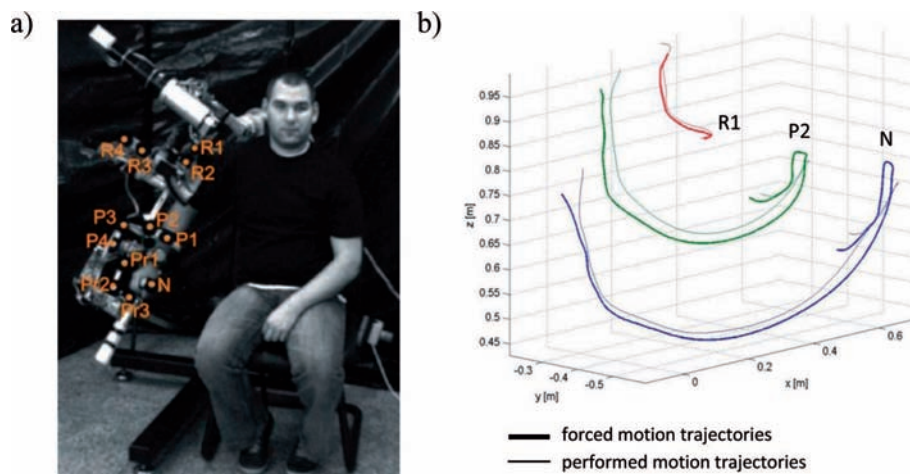


Fig. 10. Verification of accuracy of trajectory mapping by the rehabilitation robot ARM-100: a) the picture illustrating location of markers, b) sample trajectories of marker movements

In the verified prototype of the ARM-100 robot, the movement trajectory recorded from the memory of the control system differed from the actual movement maximally by up to 5 cm in extreme cases. The average value of

the difference between the assumed trajectory and the trajectory reconstructed during the studies did not exceed 2 cm. The main reason for the difference between the assumed and reconstructed trajectory was backlash in gears and coupling elements. However, it has been significantly improved in mechanical construction of the robot's lower limbs.

## 8. Summary

Rehabilitation robot for lower limbs LEG-100 is based on the experience gained during the construction of the first robot ARM-100. The severe problem of the first robot was backlash in gears and clutches, so that the robot LEG-100 was based on harmonic gears in which the backlash doesn't appear. An additional advantage of these gears is simplification of the mechanical construction, because the coupling elements are not required there. This solution ensures improvement of robot's stiffness and compactness of its mechanical construction.

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### **System sterowania rodziny robotów rehabilitacyjnych**

#### **Streszczenie**

Niepełnosprawność ruchowa kończyn powstała w wyniku przebytych chorób lub doznanych urazów, upośledza wykonywanie czynności codziennych i ogranicza a czasem uniemożliwia aktywność zawodową. Przywracanie sprawności w takich przypadkach polega między innymi na przeprowadzeniu rehabilitacji wymagającej żmudnego powtarzania odpowiednich ćwiczeń przy udziale doświadczonego fizjoterapeuty. Ćwiczenia z zastosowaniem robota do powtarzania ruchów rehabilitacyjnych pozwoliłyby ułatwić proces rehabilitacji. Praca przedstawia koncepcję systemu sterowania robota rehabilitacyjnego realizującego wymieniony cel.