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EXPERIMENTAL STUDY ON THE FUZZY-PID HYBRID CONTROL ALGORITHM FOR UNLOADING SYSTEM IN MECHATRONIC DEVICE FOR GAIT RE-EDUCATION

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Abstract. *In the article, the control system dedicated to the unit responsible for the patient unloading, which is one of the components of the mechatronic device for gait reeducation will be discussed and experimentally verified. The control algorithm of the unloading system should guarantee an expected constant value of the unloading force, regardless of the position and direction of the patient movement.*

The article presents a solutions in which the hybrid control algorithm based on fuzzy logic coupled with PID controller has been implemented. The optimization of parameters for regulators was conducted based on numerical simulations in which the walk of a patient through a step was analyzed. The experimental results show that the proposed control algorithm realized the primary goal (rapid reaction to the changes of the unloading force values) very well.

1 INTRODUCTION

Modern mechatronic devices find an increasing number of applications aimed at aiding the activities performed by humans. Advanced mechatronic systems are used both in common household devices as well as in various industries. One of the more interesting applications of modern mechatronic technologies is found in medicine and rehabilitation. This might be exemplified by surgical robots such as Vinci or Robin Heart. These robots are required to allow for a precise positioning of surgical instruments as well as to provide a precise view of the surgical field [1,2,3].

The use of automated devices is beneficial in the process of rehabilitation - especially of the upper and lower limbs. Devices such as Lokomat, zeroG or exoskeletons allow to increase the intensity of the training and perform a larger number of repetitions, which – as reported by numerous studies – translates into a significant improvement in rehabilitation effects. Moreover, the devices also support the work of physical therapists, allowing them to concentrate on observing the patient's technique in performing the exercises [4,5].

Rehabilitation devices are also required to adjust the resistance to motion in a manner adequate to the strength of the patient's muscles and to minimize the excessive loads. These goals are reached by means of biofeedback or with the use of mechanical solutions [6].

One of the innovative projects in the field of rehabilitation equipment is the mechatronic device dedicated to the gait re-education, developed in the Institute of Theoretical and Applied Mechanics at Silesian University of Technology.

2 MECHATRONIC DEVICE FOR GAIT RE-EDUCATION

The structure of the device resembles a single-girder overhead travelling crane which perform a keeping up the movement behind the patient. In addition, the dedicated special purpose winch relieves the patient with a constant force in the vertical direction.

Each of the device's axes is driven by servo drives with permanent magnet excited synchronous motors. Due to the use of dedicated servo inverters, it is possible to adjust the dynamics of the device, e.g. by limiting the acceleration of individual elements. Moreover, all motors have been equipped with measuring encoders.

The designed control system has been created in MATLAB/Simulink and the transmission of control signals between the PC Computer and the device control unit is conducted by means of two RT-DAC4/PCI real time boards. A signal conditioning interface has also been developed that is used for the measurement of the rope inclination angle, the value of unloading force and the pressure of the patient's feet against the ground. The correlation between the components in the mechatronic device for gait re-education has been presented in figures 4 [7,8].

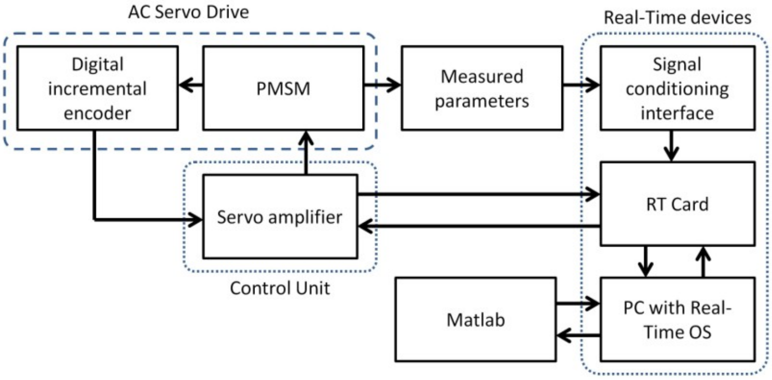

Figure 1: Block diagram of the of the components cooperation in mechatronic device for locomotor training.

The hoist assembly is of a special significance – it should rapidly react to the changes of the unloading force and simultaneously protect the patient against excessive loads. It is also important that sufficient vertical movement is provided as it is necessary e.g. for the training of climbing the stairs. To satisfy these requirements, two separately operating drive systems were installed in the unloading device. In the first of these (Z1), the drive motor drives the winding drum of the hoist by means of a planetary gear, which allows to control the vertical position of the sling. The second one has been coupled with a screw drive responsible for the movement of the travelling element which is separated from the pulley with elastic elements (Z2 drive). It is responsible for the dynamic compensation of the patient's body weight. Such an electromechanical system acts as a "Series Elastic Actuator", dedicated for rehabilitation devices or walking robots. The structure of the unloading system has been presented in fig. 2.

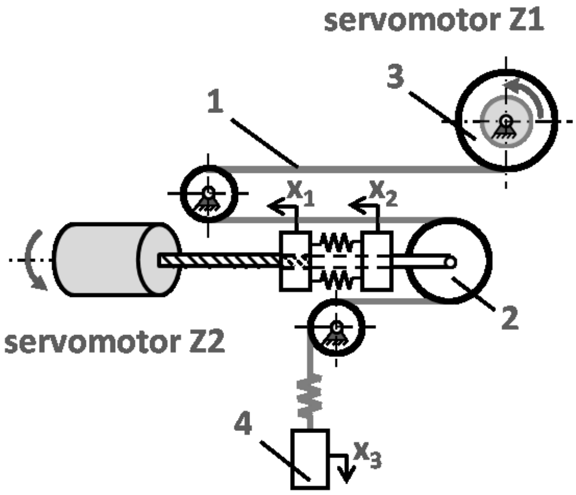

Figure 2: Scheme of unloading system.

The mathematical model of the presented device has been developed. The motion of the system has been described using the generalized displacement variables and the numerical calculations for this model were performed using the MATLAB/Simulink software [9].

Stiffness of the springs in the Z2 actuator and the stiffness of the rope were determined experimentally with the testing machine.

3 CONTROL ALGORITHM FOR UNLOADING SYSTEM

The development of an optimal control of the unloading system constitutes an interesting engineering problem. From the point of view of rehabilitation centres, it is desirable that the control is performed by means of a single, universal system, that would not be dependent on the type of exercises.

Experiments have shown, however, that in case of walking on a horizontal and flat surface it is best to only use the Z2 drive. The use of the PID controller allowed to maintain the unloading force with the precision of approximately 30 N. The movement of this actuator is limited by limiting switches and its range of movement is approximately 10 cm. To give consideration to the tests that have been completed, a solution was proposed in which the PID controller's operation was coupled with a fuzzy logic controller [10,11,12]. The idea of study control algorithm is shown in Fig. 3.

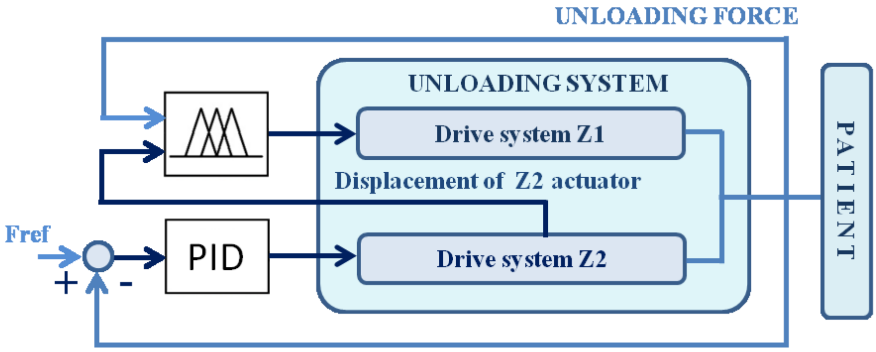

Figure 3: Block diagram of the proposed control system.

The developed set of controlling rules has been presented in table 1. The DZ_2 symbol denotes the displacement of the actuator in the Z2 drive, while UF relates to the unloading force misalignment value. The characters from “---“ to “+++” represent the values in an increasing order. The “nom” index means that the value of the variable equals the nominal value.

		Displacement of actuator in Z2 drive system						
		D_{Z2}---	D_{Z2}--	D_{Z2} -	D_{Z2nom}	D_{Z2}+	D_{Z2}++	D_{Z2}+++
Unloading force	UF - - -	Z1++	Z1++	Z1+++	Z1+++	Z1+++	Z1+++	Z1+++
	UF - -	Z1++	Z1++	Z1+++	Z1++	Z1++	Z1+++	Z1+++
	UF-	Z1+	Z1+	Z1+	Z1+	Z1+	Z1++	Z1++
	UF_{nom}	Z1--	Z1-	0	0	0	Z1+	Z1++
	UF +	Z1--	Z1--	Z1-	Z1-	Z1-	Z1-	Z1-
	UF ++	Z1---	Z1---	Z1--	Z1--	Z1---	Z1--	Z1--
	UF +++	Z1---	Z1---	Z1---	Z1---	Z1---	Z1--	Z1--

Table 1: Applied rules as a table.

The ranges of the membership functions have been determined in the process of optimization that was conducted using the numerical model of the device. During the numerical calculations the walk of a patient through a 10 cm high step was analyzed. And the optimization was done using genetic algorithm. The settings of the PID controller have been selected independently for the case in which the patient moves on a flat surface and only the Z2 drive is active. This allowed to tune the fuzzy controller to the existing control system and largely facilitated the numerical computations by reducing the number of variables in the optimization process.

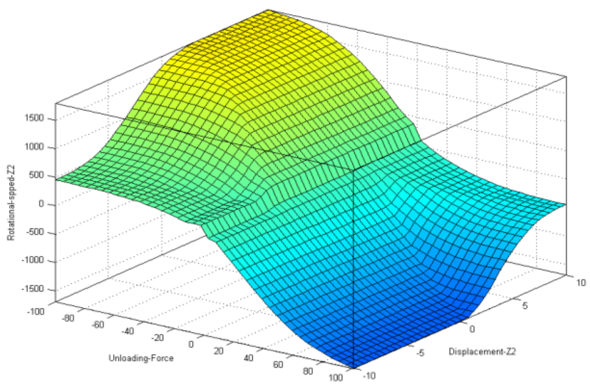

Figure 4: The output signal controlling the motor rotational speed in Z1 drive presented as a surface.

4 EXPERIMENTAL RESEARCH OF THE CONTROL SYSTEM

A series of experiments was conducted for the developed algorithm controlling the drives of the unloading system. In the experiments, the operation of the device was tested during walking on a flat surface and in case of climbing a stair that was approximately 10 cm high. During the study, the unloaded person moved with different speeds. Special attention was given to the operation of the motor driving the winding drum. The attached graphs exhibit the registered values of shifts of the centre of gravity of the unloaded person in vertical axis (fig. 5), the value of the unloading force (fig. 6), the displacement of the regulating unit in the Z2 drive system (fig. 7), the linear displacement of the end of the cable resulting from the operation of the winding drum (fig. 8) and the value of the control signal of the engine speed in the Z1 drive (fig. 9).

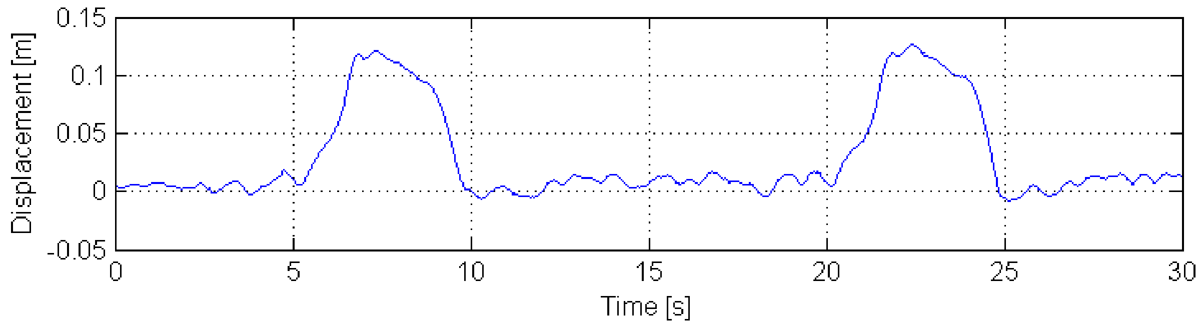

Figure 5: Registered displacement of the centre of gravity of the unloaded person in vertical axis as a function of time.

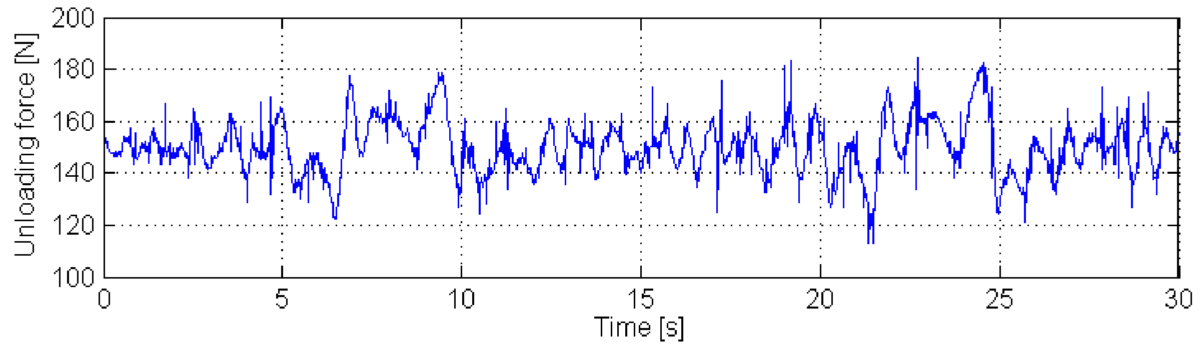

Figure 6: Registered value of the unloading force as a function of time.

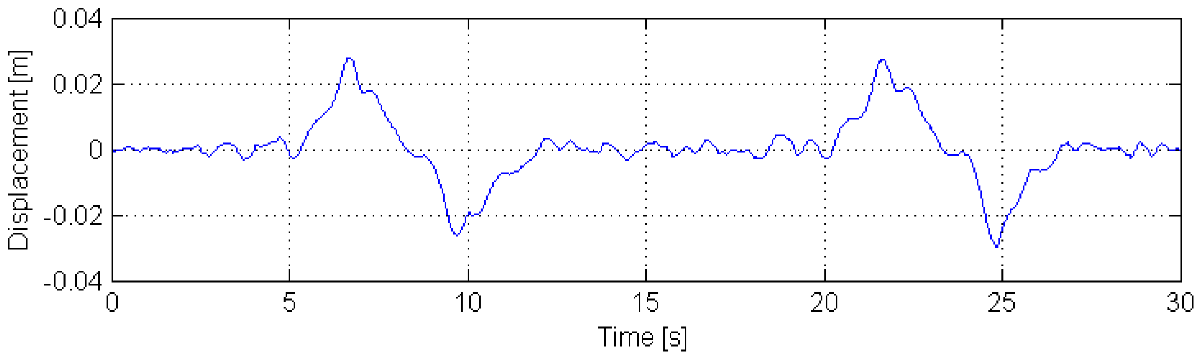

Figure 7: Registered displacement of the regulating unit in the Z2 drive system as a function of time.

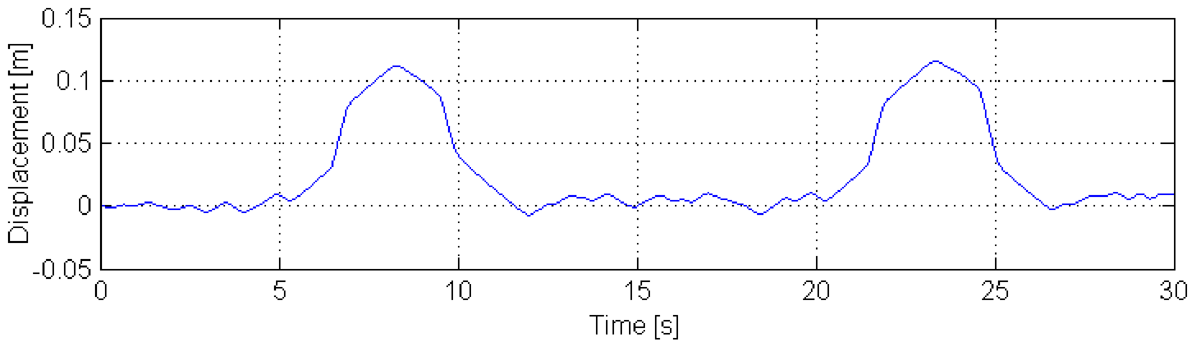

Figure 8: Registered linear displacement of the end of the cable resulting from the operation of the winding drum as a function of time.

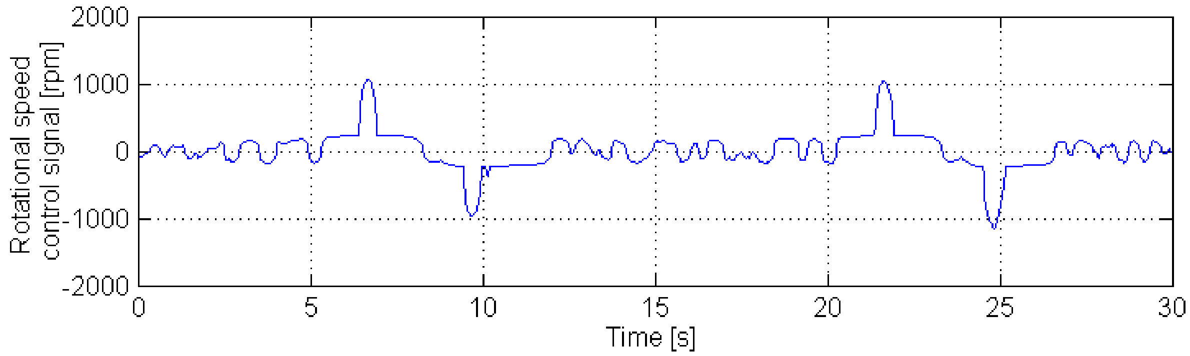

Figure 9: Registered value of the control signal of the engine rotational speed in the Z1 drive as a function of time.

5 CONCLUSIONS

- The work describes an innovative device used for the re-education of walk. Special attention was given to the structure and operation of the unloading system which requires the coordination of two independent drives for proper operation.
- A hybrid Fuzzy-PID control system was proposed, in which the PID controls the operation of the drive responsible for dynamic compensation of the patient's weight. The fuzzy controller controls the operation of the winding drum.
- A set of control rules has been developed for the presented fuzzy controller as well as membership functions have been defined for all input and output signals. The ranges of these functions have been selected in an optimization process with the use of the numerical model of the device.
- Experiments have confirmed the proper operation of the developed algorithm. The application of fuzzy control along a classic PID controller guaranteed the maintenance of the unloading force with the precision of 30N, notwithstanding the type of the exercises performed by the unloaded person. The experiments have also confirmed that one of the basic goals has been reached – during a walk on a flat surface the misalignment of the unloading force is regulated primarily by the dynamic compensation system. Moreover, the winding drum starts operating at high speeds only when the patient performs exercises requiring large vertical displacements.

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