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Mechanical Modul with Jack-Screw for SMILING Rehabilitation Shoe

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KEY WORDS
Elderly, Gait Training, Rehabilitation, Mechatronics, Chaotic Perturbations

ABSTRACT
The SMILING shoe developed within the international project SMILING is a complex mechatronical system that requires human-machine interactions. Optimization of its motor control unit during tuning and durability testing was provided on the mechanical unit based on jack-screw mechanism designed at the Technical University of Košice. We present the architecture of the main mechatronical unit that consists of a mechanical unit based on jack-screw mechanism driven by DC motor with embedded gearbox and the microcontroller based Motor Control Unit (MCU). Chaotic data are used for control of all 8 actuators that perform perturbations in the pair of rehabilitation shoes devoted to training of seniors' gait. The parameters of the chaotic signal were optimised using simulation model to approve efficient chaotic sets of data.

INTRODUCTION
A fall is one of the most common events that threaten the independence of older adults. Each year, up to a third of older adults living in the community suffers a fall. About half of all people in nursing homes fall each year. Most falls result in a minor injury of some type, most often bruises and scrapes. However, 10-15% of falls result in a broken bone or other serious injury. These falls can be serious for elderly people and influence their daily life. They cause physical problems, emotional trauma, avoid to move and be active. To improve movement capabilities the rehabilitation shall be applied. This may be achieved by training and rehabilitation programs focused on the process of recovery of the gait performance. Such research has been provided within the international project SMILING - Self Mobility Improvement in the eLderly by counteractING falls [1], where authors participate.
The main idea of the SMILING research project is to develop a special training device - SMILING shoe that changes unpredictably position of the users who wear that shoe on their daily used shoe. The SMILING shoe performs chaotic perturbations and in such way forces a user to react on changes in shoe inclination. That is influencing the motor learning process [8]. Technically it means that we have to generate the chaotic signal to be applied for driving of four SMILING shoe motors, 8 for 1 pair of shoes, during a user walk to make changes in ankle declinations (Fig. 1) in the sagital and frontal planes. Within a training program each task is associated to a set of perturbations to apply at each step and for each foot.

MATERIALS AND METHODS
SMILING shoe is a complex mechatronical system that requires interaction of various sensors data, mechanical components and human activity. The microcontroller based Motor Control Unit (MCU) is the electronic heart of the SMILING shoe. The MCU must store suitable set of perturbation patterns and drive motors according these perturbations. Driving of motors by MCU must be synchronized with a human walking activity that is detected by an external gyroscope (S-Sense) unit [4]. Motors can move only during swing phase of the actual leg. The architecture of MCU is optimized for acquisition and fast processing of relevant sensors data and control of mechanical actuators used in the SMILING shoe. Control algorithms embedded in the MCU firmware had to be tailored to the parameters and limitations of mechanical actuators used in the SMILING shoe [5]. Optimization of MCU firmware for tuning of mechanical parts after assembling and durability testing of complete SMILING shoe was also done in order to support integration of all SMILING shoe components.
The main concept of the SMILING shoes is described in (Fig. 1). Both left and right shoes are equipped with 4 mechanical units driven by DC motors. Two are in the front and two are in the back side. In generally, mechanisms change the height after each or several steps, and in such way they change inclinations of the shoe's sole in two planes - frontal and sagital. SMILING shoe is worn on a standard shoe used by user. User has to react

on changes of the shoe inclinations to keep balance during walk while providing specific tasks. The drawing in (Fig. 2) shows STRATH mechanism that was design used for final prototype.

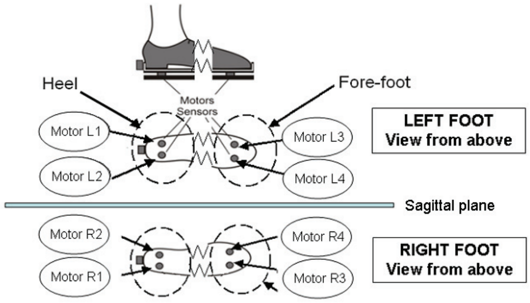

Fig. 1 *Position of the motors in the right and left SMILING shoes*

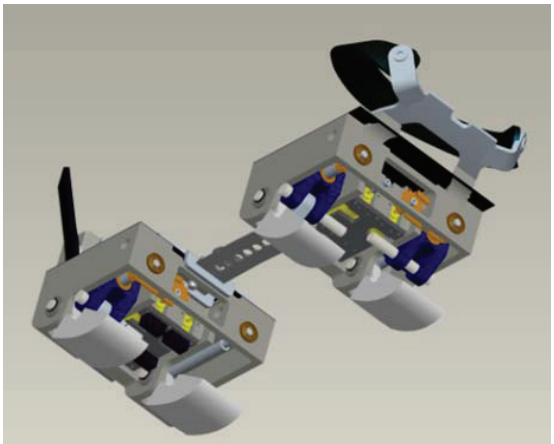

Fig. 2 *3D CAD drawing of the STRATH Shoe [5]*

Four prototypes were produced at the University of Strathclyde and used in validation trials with seniors at 4 clinics in different countries (Fig. 3).

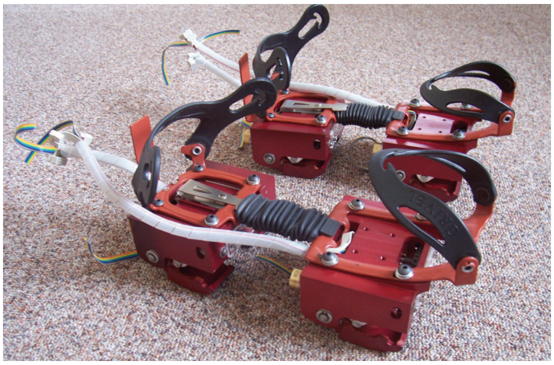

Fig. 3 *SMILING shoes mechanics developed at the University of Strathclyde*

TUKE MECHATRONICAL UNIT

In the early stage of the project there were proposed two different designs for the mechanical unit. For final prototypes used for shoe validation the STRATH design shown above [5] was selected. In this paper we describe mechanism that was used for the TUKE (Technical University of Košice) version of the mechanical unit. Design of the TUKE mechanical unit is based on jack-screw mechanism, but uses the same type of Fullhaber DC motor as the STRATH shoe (Fig. 4, 5). TUKE mechanical unit was used for the MCU development and tuning, which was provided by TUKE too, mainly as a single mechatronical unit. Limited tests were done also in the full configuration as integrated into the SMILING shoe (Fig. 6).

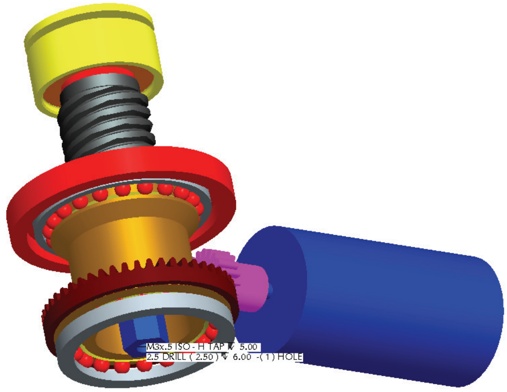

Fig. 4 *The concept of TUKE mechanical unit*

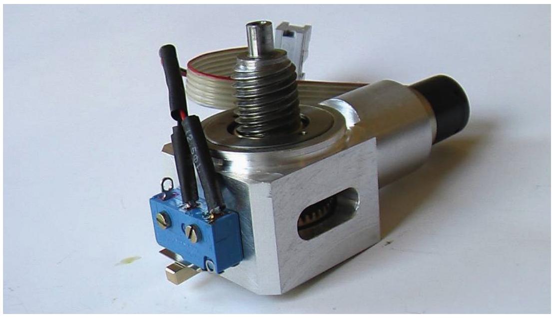

Fig. 5 *The complete TUKE mechanical unit with drive and end switch*

Drive of TUKE unit actuates front cogwheel, which actuates wheel-crown. Wheel crown is squeezed to screw female. Screw female is radially and axially stored in the friction-ball bearings. Screw female - nut is rotating and moving the screw, which is secured against rotation by six rimmed plug, which is fixed to the frame. The heel is attached to the bolt through the joint, which allows 10 degrees pitching motion. The pitch of the triple thread bolt is 5,25 mm, it means that it gives 5,25 mm of the vertical change in one revolution. Total height gain of the screw was 15 mm in 250 ms limit, and after first trials it was changed in the improved version to 20 mm.

FEM linear static stress analysis of the mechanical unit was performed using software Solid Works 2009. Simulation of all conditions was realized in two alternatives. First alternative was for extreme loads (800 N) that are normal to bottom surface of one foot (Fig. 7). Second alternative was for extreme loads applied with angle 45°. Simulations were made for extreme position of the screw (15 mm exsertion). Simulations with all conditions were realized by some assumptions and similarities of solvers. The simulations were done by means of commands Eurocode 3: Design of steel structures, Part 1.5: Plated structural elements, Annex C [informative] - Finite Element Methods of analysis (FEM). The geometry and structural imperfections were not taken into consideration.

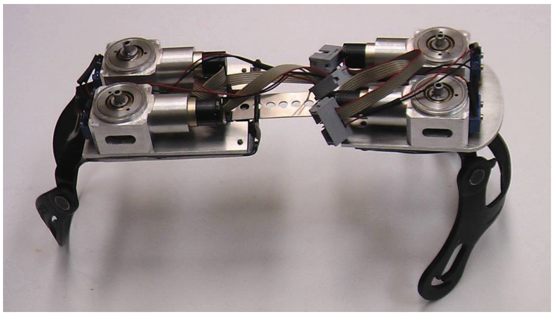

Fig. 6 *Layout of TUKE mechanical units on the shoe*

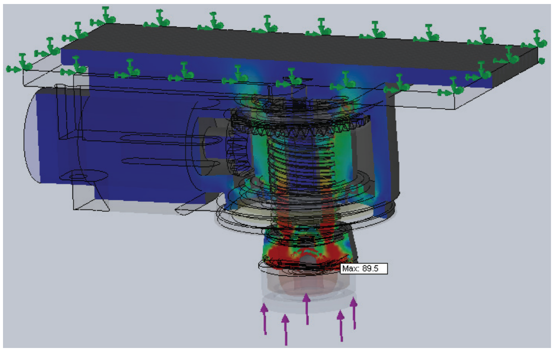

Fig. 7 *Situation for load applied in axial direction*

MOTOR CONTROL UNIT

The Motor Control Unit for the SMILING shoe (MCU) is a typical custom microcontroller system embedded in the motorised mechanics creating a complete mechatronical unit of the SMILING shoe. SMILING mechatronical units are interfaced to the MCU hardware by using 4 Faulhaber 1524E12SR DC-micromotors [7] with IE2-16 encoders and a set of microswitches for detection of reaching actuator terminal positions. The motor has embedded a gearbox. This clear definition for interface between MCU and the mechanical unit enabled us to apply a flexible approach with common features used for different design of mechanical units. It was important for continuous development of the complete MCU hardware without access to the final SMILING motorized shoe mechanism [5]. In the same time it enabled us to use different mechanical units in the same mechatronical concept. The MCU firmware and SMILING motorized shoe mechanism [5] were developing at different partner organizations in parallel; therefore it was an advantage to have available TUKE mechanical unit for the development of the MCU firmware. Development and tuning of the MCU was a long time process and without working mechatronical units would be very inefficient and time consuming. Parameters of mechatronical units were encoded into MCU firmware as a set of parameters that can be easily adapted to the actually used mechanical alternative module.

The MCU performs in each shoe the following basic hardware functionalities:

- *interfaces to the S-Sense unit [4],*
- *interfaces to the Power Supply Unit (PSU),*
- *interfaces to 4 incremental encoders monitoring actual motor (actuator) positions,*
- *drives 4 DC motors used for actuators movement,*
- *stores perturbation data pattern used in current training session,*
- *monitors reaching terminal positions of 4 mechanical actuators,*
- *monitors motor currents in order to detect non-expected conditions.*

The MCU performs the following software supported functionalities:

- *communicates with the User Control Unit (UCU) in order to support remote shoe control,*
- *communicates with the S-Sense in order to react on swing phase detected by S-sense,*
- *applies a suitable perturbation pattern (different*

levels of difficulty applied progressively during long term training) to motor control during standard shoe operation,

- *monitors and evaluates abnormal sensor data values (e.g. large driving currents and no actuators movement),*
- *provides telemetric data channel to the UCU for on-line monitoring of shoe state during normal operation but also during shoe testing and tuning.*

Chaotic perturbations data

It is known that human joints exhibit chaotic characteristics during gait. Nonlinear dynamics analysis methods have been developed to analyze such ambiguous dynamic signals. Matjaz [3] described that human gait possesses properties typical for a deterministic chaotic systems. For the same reason it was proposed to use the chaotic signal for perturbations applied to the shoes worn by a senior during gait training [9].

The perturbations module generates the sequence of chaotic data to be applied to the right and left motorised units during gait training. In chaos theory, there exist many algorithms which differ in complexity. Clinical tests based on the gait training of the seniors with the SMILING shoe shall give us the answers how efficient are selected perturbations data. It will be necessary to analyze the dynamics of the shoe using different algorithms and take into account limitations/restrictions for the range of movement and synchronization of right and left sides of the shoes. We selected for clinical trials the chaotic patterns defined by Lorenz attractor.

Lorenz attractor is generated by the following nonlinear differential equations:

$$\frac{dX}{dt} = -\sigma (X - Y)$$
$$\frac{dY}{dt} = rX - Y - XZ \qquad (1)$$
$$\frac{dZ}{dt} = XY - bZ$$

In the Fig. 8 we can see one possible representation of the dynamic behaviour of these differential equations in 3D phase space generated for the left and the right shoe with the following parameters r=28 and r=46,92 respectively (σ=10, b=8/3).

The relative simplicity of this model hides a wide range of dynamical behaviours for various values of one control parameter. The Lorenz system has either stable or unstable fixed points, globally attracting periodic or nonperiodic solutions, a homoclinic orbit embedded in a two-dimensional stable manifolds, bistability and hysteresis, and a variety of cascading bifurcations (Fig. 9). It is usual to represent stable solutions with a solid line and unstable solutions with a dotted line. In our case the bifurcation parameter is parameter r (initial conditions: x = -1; y = 0; z = 2 and σ = 10, b = 8/3, r = 1-240).

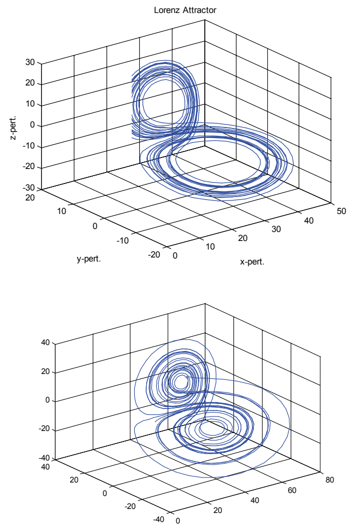

Fig. 8 *Two examples of the dynamics of the trajectory of Lorenz attractor*

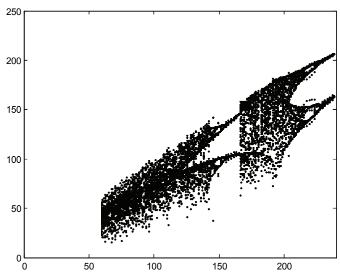

Fig. 9 *Bifurcation diagram for the Lorenz system*

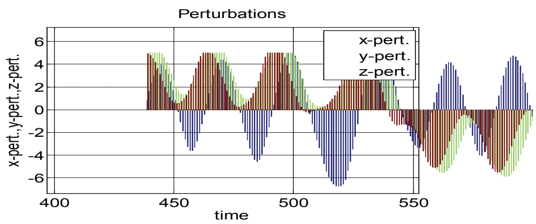

Fig. 10 *The chaotic perturbations as a function of time/steps*

The Lorenz system with unstable solution shall have chaotic behaviour and the purpose of this is to enable control of the shoe drives in an unpredictable way for user who has to react to changes in the shoe sole declinations in 2 planes - sagital and frontal.

The generation of the chaos data could be provided on-line or off-line; pre-generating by any computer or electronic module with central or stand alone processor. Each task within a gait training program is associated to a set of perturbations, defining the sequence to be applied at each step and for each foot.

Chaotic perturbations may be applied the same for several steps or be modified continuously in each step. They are stored in the MCU at the beginning of the training session and sequentially delivered to the SMILING shoes motors during the swing phase when there is no load applied on the mechanism. The input parameters for the generation of perturbation data are as follows:

- *perturbation max amplitude (z – mm, x, y – degrees)*
- perturbation frequency (number of steps after which change the perturbation)
- *the indication of the degree of performance difficulty (level 1, 2,…)*
- *the target task performance index (minimum number of steps to be accomplish to reach a satisfactory performance)*
- *the sequence of perturbations to be supplied at each step (perturbations may be null in case no perturbation is envisaged).*

Output values created by chaos algorithm for the training task define perturbations parameters that are used for shoe drives control. Shoes motors change the position during the swing phase. They include (Fig. 10) the degrees of rotations along two axes (x-pert and y-pert) and the vertical displacement of the sole (z-pert). The complete set of the chaotic perturbations generated in PC or in μ-controller are distributed between 4 drives in the right (motors R1 - R4) and the left shoe (motors L1 - L4) in the data form suitable for motor control (Fig. 11).

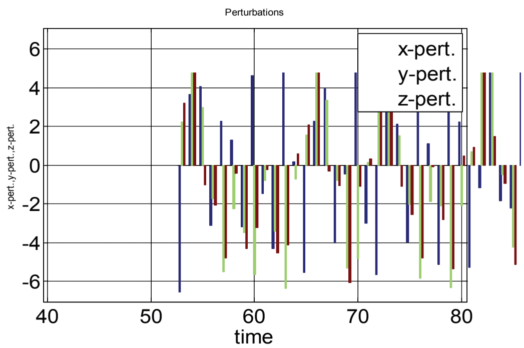

Fig. 11 *The chaotic perturbations as a function of time (every 10-th solution from Fig. 10 is taken)*

RESULTS

MCU FIRMWARE ADAPTATION TO THE MECHATRONICAL UNIT

We included several parameters for adaptation of MCU firmware to parameters of actually used mechatronical unit. The most challenging was setting of threshold for detection of actuator blocking (e.g. by early contact with floor or a failure of mechanical part) and it will be described as an example of used approach.

Early contact of SMILING shoe actuators with floor caused high current peaks required for driving motors. It was decided to detect such situation as soon as possible in order to decrease current consumption during these events in order to increase SMILING system battery lifetime and possibly also prevent activation of battery over-current protection circuits. Detection time depends also on mechanical parameters of actuators and tuning of time constants tailored to particular actuators was required. The detection of blocking state of actuators during unexpected shoe contact with floor is done by processing of incremental encoders signals in MCU. Currently MCU firmware uses CPLD (Complex Programming Logic Device) hardware for processing of incremental encoders signals. Internally, the CPLD process 8 incremental signals from 4 encoders with full resolution (64 pulses per one motor shaft rotation). CPLD passes to the analogue digital micro controller (ADuC) program only 4 pulses per revolution in order to limit all main program variables to 8 bits and save ADuC processing power. (Fig. 12) shows time evolution of accumulated number of pulses for TUKE #1 actuator visible in the main ADuC C program for running up of TUKE #1 actuator.

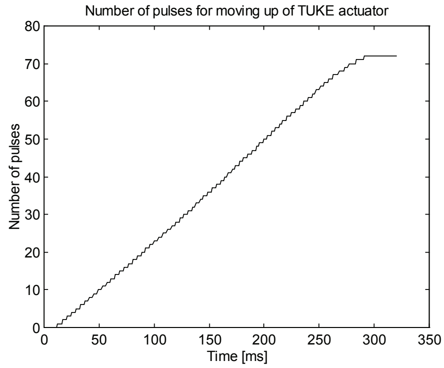

Fig. 12 *Time graph of accumulated number of pulses*

Fig. 13 *SMILING shoe with jack-screw TUKE testing mechanics*

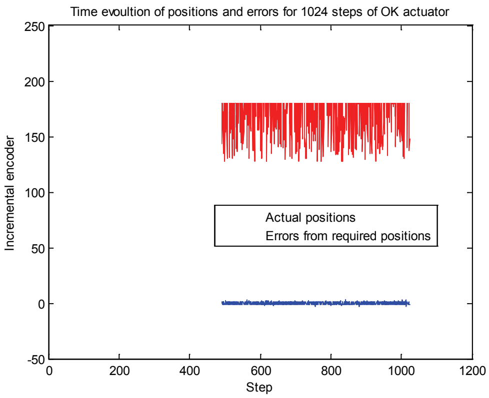

Fig. 14 *Time evolution of actual positions and errors of TUKE actuator for 1024 uniformly distributed random steps after total of 15,000 executed steps*

The start-up delay caused by mechanical inertial forces was less than 20 ms. We decided to evaluate the blocking state of actuators of TUKE mechanism by analyzing pulse increments after 20 ms delay. An increasing number of pulses detected during last 20ms lower than 2 indicate blocking of particular actuator. Similar measurements were performed with STRATH shoe during integration phase of complete Smiling system and adaptation was done only by changing thresholds in the final MCU firmware. The described approach using well defined parameters allowed us quickly adapt MCU firmware functionality to actually used mechatronical units.

In order to enable on-line monitoring of internal MCU and mechatronical units' states we added a background telemetric channel directly into implemented MCU firmware. This channel together with the user control unit (UCU) emulator was used also for durability testing of mechanical SMILING shoe parts during integration and optimization phases of SMILING shoe development to check functionality and precision setting of mechatronical unit after execution of tens thousands of steps. Precision of actuators setting was evaluated from LOG txt files automatically generated by the UCU emulator.

We provided testing under real load by user shown in (Fig. 13) with testing by using test bench and specially prepared testing artificial perturbation files downloaded to the MCU hardware. The second shoe was only the wooden dummy shoe. Similar approach was used also by other SMILING partners during integration and optimization phases of final SMILING shoes.

As testing perturbation pattern we used uniformly distributed random positions from 0 to 15 mm (maximum height gain of TUKE actuators) and constant 410 ms for swing phase generated automatically with the 500 ms gaps between swing phases. The MCU firmware uses a simple control algorithm and durability tests to evaluate if parameters of control algorithm are set correctly. Durability tests allowed us to detect also mechanical problems of mechatronic units in the first stages of development.

Precision of actuators settings is influenced also by inertial mechanical forces of given actuators. A performance of the implemented control algorithm had to be experimentally tested. We downloaded pattern of 1024 randomly distributed steps to the MCU and executed automatically under control of the UCU emulator. We evaluated errors by measuring of incremental encoder pulses. Current MCU firmware has resolution of ¼ of encoder shaft rotation so 15 mm height of TUKE actuator corresponds to 106 pulses and the 3 pulses error corresponds to approximately 0,2 mm error of the screw vertical change.

Figure 14 shows time evolution of actual encoder positions and corresponding errors of TUKE #1 shoe actuator after approximately 15,000 steps (only last 1024 steps shown). This performance demonstrates high durability of mechanical construction of TUKE actuators. Required encoder positions are from 128 to 233 for TUKE #1 shoe actuators. Zero shift to 128 is given by the MCU firmware requirements.

CONCLUSION

We described functions and testing of the MCU that is used in all currently used SMILING shoes developed within the international SMILING project. The complete laboratory testing and tuning was done using the TUKE mechanism with the jack-screw concept. As testing showed the TUKE mechanical unit may be an alternative solution for the SMILING shoe, but it needs some improvements - higher height gain and speed in screw motion to provide higher perturbations.

Finally, TUKE produced MCUs for all final versions of the SMILING shoes. They have been heavy tested during real trials at four different countries and provide a reliable embedded electronic platform for SMILING shoe control.

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