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Embedded microcontroller unit for gait rehabilitation shoes

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Abstract— **The SMILING shoe developed within the international project SMILING is a complex mechatronical system that requires interaction of various sensors data, mechanical components and human activity. We present an architecture overview of main microcontroller based Motor Control Unit (MCU) that is the heart of the SMILING shoe. 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. Downloaded chaotic data are used for control of all 8 actuators that perform perturbations in the pair of training SMILING shoes. Their parameters were optimized using simulation model to generate the approved efficient chaotic sets of data. Development and optimization of the MCU during tuning and durability testing was done by using the mechanical unit based on jack-screw mechanism designed at our Faculty.**

I. 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, cause physical problems, emotional trauma, avoid to move and be active. To be able to eliminate the number of falling, the effective way to counteract falls is to improve movement capabilities. 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], contract number 215493, where authors participate.

Variability is an important characteristic attribute of human movements. The most common interpretation of this variability is a random process (noise). However, sources from several related scientific fields have shown that many apparently noisy phenomena are the result of nonlinear interactions and have deterministic origins [2]. As such, the ‘‘noisy’’ component of the measured signal may reveal important information about the system that produced it. Methods based on nonlinear dynamics may be beneficial in describing and understanding variability and subsequently identifying health status.

It is well known that human joints exhibit chaotic characteristics during gait. Nonlinear dynamics analysis methods have been developed to analyze such ambiguous dynamic signals. In [3] was documented that the human gait possesses properties typical for deterministic chaotic systems.

The main idea of the SMILING research project is to change unpredictably position of the motorised shoe (SMILING shoe developed within SMILING project) worn by user during his/her walk, and in such way to influence the motor learning processes [11], [12]. Technically it means that we have to generate the perturbations to be applied for driving of four SMILING shoe motors, 8 for 1 pair of shoes, during a user walk to make changes in shoe declinations (Fig. 1). Perturbations have chaotic behavior and the purpose of that chaotic signal is to enable control of the shoe drives in such way that a user has to react to changes in the shoe sole declinations in a 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.

SMILING shoe is a complex mechatronical system that requires interaction of various sensors data, mechanical components and human activity. A microcontroller based Motor Control Unit (MCU) is an electronic hart of 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 processing (S-Sense) unit [4][19]. 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 must 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 paper is organized as follows. First the MCU architecture and functions are described. Then, we describe the software for ADuC microconverter and Complex Programmable Logic Device (CPLD) processing,

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responsible for monitoring and motors driving. Further we describe mechanical unit used during development process and tuning of the MCU firmware with its adaptations and enhancement of functionalities for the integration and optimization of the complete SMILING shoe system. Main results of durability testing are included.

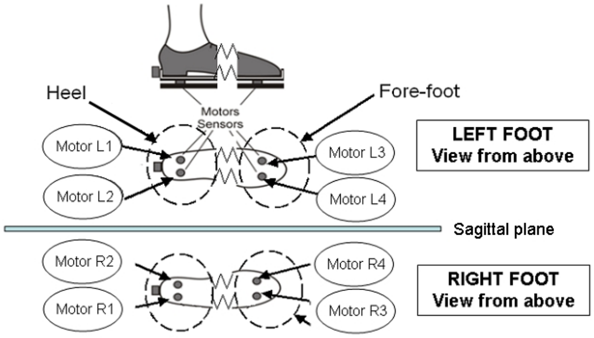


Fig. 1. Position of the motors in the right and left SMILING shoes

II. MCU ARCHITECTURE, FEATURES AND FUNCTIONALITY

The MCU is a typical custom microcontroller system embedded in each SMILING shoe that is part of complete SMILING system shown in Fig.2.

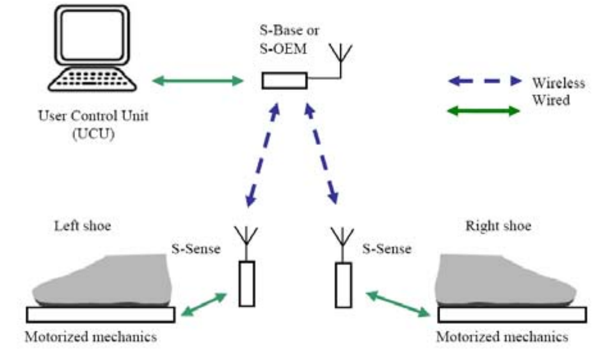


Fig. 2. Complete SMILING system

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

- interfaces to the S-Sense unit [4],
- interfaces to the Power Supply Unit (PSU),
- interfaces to 4 incremental encoders [13] monitoring actual motor (actuator) positions,
- drives 4 DC motors [10] 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 out of expected conditions,

and performs the following software supported functionality:

- communicates with the User Control Unit (UCU) [18] 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 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.

A. *MCU BLOCK DIAGRAM*

A block diagram of the final MCU version that we used in SMILING project is shown in Fig.3. We build-up the MCU as a complete custom based design around two main electronic components – the 8-bit Analog Devices ADuC848 microconverter [6] and Altera CPLD EPM240GT100CN [7].

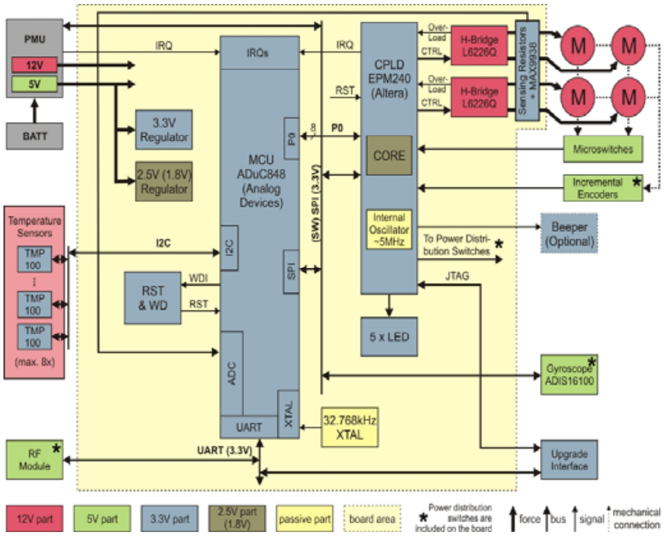


Fig. 3. Block diagram of the SMILING MCU

ADuC is interfaced to the PSU by using standard Serial Peripheral Interface (SPI), RF module of S-Sense by using standard Universal Asynchronous Receiver/Transmitter (UART) channel, TMP100 [14] based temperature sensors network by I2C bus and experimental 1D gyroscope ADIS16100 [8] by using a software based SPI. Not all mentioned components are included in the final MCU hardware setup but all were used in the development phase. We removed temperature sensor networks and ADIS1600 from the final setup during the MCU hardware optimization phase as we got the required functionality by using alternative SMILING components (S-Sense) or data processing of signals from other sensors (MAX9938 [15] current monitors). By using of ADuC with low frequency 32.768 kHz crystal XTAL and additional external watchdog we increased reliability of the MCU operation in harsh environments.

We used the EPM240 CPLD for efficient hardware interface of two H-bridges L6226Q [9] that are used for control of high performance DC-micromotors [10] with integrated incremental magnetic encoders [13]. Interface of incremental encoders signals trough CPLD and fast pre-processing in CPLD significantly increases reliability of actuator positions monitoring. We replaced software based pre-processing of incremental encoders' signals by hardware (CPLD) pre-processing in the MCU hardware optimization phase after deep timing analysis of the first SMILING MCU prototype. A possibility to upgrade ADuC software and CPLD configuration by using an upgrade interface (shown in Fig.3 as a connection to UART and JTAG interfaces) allows us to optimize the final MCU performance by upgrading the MCU firmware (ADuC software code and CPLD configuration) only. After fixing the MCU hardware functionality we performed all required optimization by firmware development and upgrading.

B. MCU PRINTED CIRCUIT BOARD

We adapted layout of MCU Printed Circuit Board (PCB) to the requirements defined by the mechanical construction of SMILING shoe taking into account also limitations of electronic components used in the MCU design, PSU electronics and battery sizes. We developed the 6-layer PCB with dimensions shown in Fig.4.

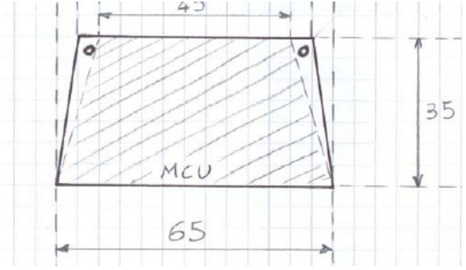


Fig. 4. Dimensions of 6-layer PCB of the SMILING MCU

We used as much as possible Surface Mount Devices (SMD) in order to minimize size of the MCU electronic. The layouts of assembled final MCU board are shown in Fig. 5 and Fig. 6. This board is a part of SMILING shoe electronic block [11] used in all currently deployed SMILING shoes.

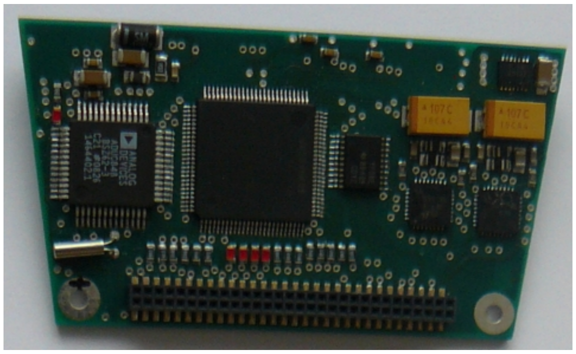


Fig. 5. MCU electronic layout – top view

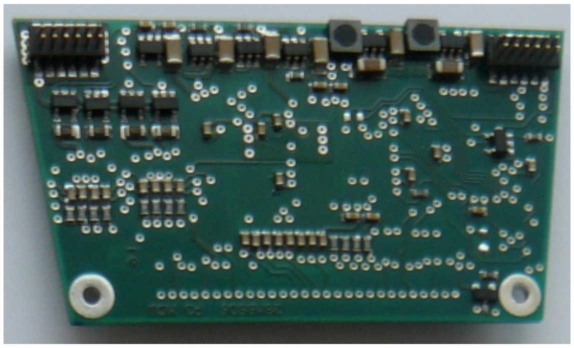


Fig. 6. MCU electronic layout – bottom view

C. ADuC SOFTWARE PROCESSING

For the ADuC software development we used Keil development tools [16]. All code used in the final MCU is written in C. We removed a highly optimized hand-coded assembly code used for software based decoding of incremental encoders signals used in the first MCU prototype (based on a less advanced hardware). It required over 50% of total ADuC processing power and it was not possible to add some more advanced MCU features. Main part of the time-critical low-level decoding of incremental encoders was moved to the hardware based CPLD processing described in next subsection.

Releasing ADuC from time intensive processing allowed us to include the following advanced functionality defined by the SMILING shoe requirements:

- decreasing motors current peaks during start-up phase of motor movements by an appropriate delaying of particular motor movements,
- detection of blocking state of actuators during unexpected shoe contact with floor by processing of incremental encoders signals,
- separation of system parameters for all used mechanical actuators described in [5], as well for the experimental TUKE mechanical unit described in next section, by conditional compilation for particular configuration,
- added a possibility to measure actual individual motor currents to detect potential high temperature conditions,
- faster on-line detection of motor malfunction,
- on-line detection of dangerous angles,
- extension of potential storage capacity for perturbation patterns up to 10000 steps (currently 1024 steps are used),
- additional on-line checking of critical data structures (e.g. CRC checks of the perturbation patterns) and communication commands (e.g. critical commands from the PSU),
- increasing capacity of background telemetric channel for on-line monitoring of internal SMILING shoe states.

Software for ADuC follows standard approaches typically used in embedded microprocessor systems as processing critical data in interrupt routines, software buffering of communication channels, testing and monitoring of critical data structures, usage of 2 independent watchdog systems, low power monitoring, etc. The most challenging task in the MCU firmware development was monitoring and proper driving of mechanical actuators described in the next sections.

D. CPLD DATA PROCESSING

All SMILING actuators use four Faulhaber 1524E12SR DC-micromotors [10] with integrated IE2-16 encoders with 6.3:1 gearhead [13]. The incremental shaft encoders in combination with the Faulhaber DC-micromotors are used for indication and control of both, shaft velocity and direction of rotation as well as for positioning. The encoder is integrated in the DC-micromotors of SR-Series and extends the overall motor length by only 1,4 mm. Solid state Hall sensors and a low inertia magnetic disc provide two channels with 90° phase shift shown in Fig. 7. Magnetic encoders provide 16 lines per revolution and two digital output channels shown in Fig. 8.

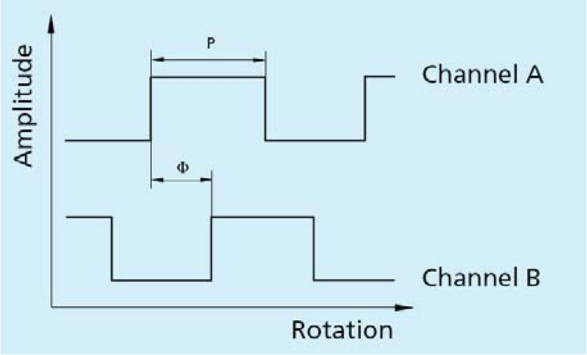


Fig. 7. Output signals of magnetic incremental encoder

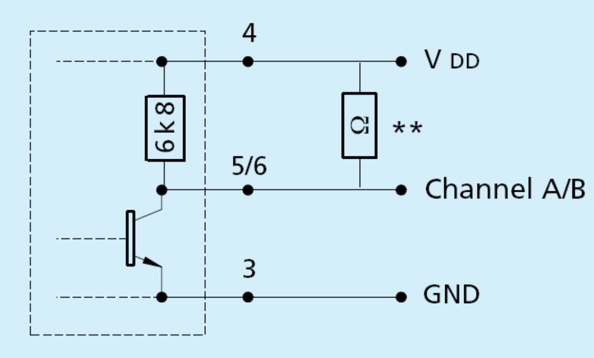


Fig. 8. Output circuit of magnetic incremental encoder

We connected 5V digital encoder signals to CPLD with 3.3V supply by using voltage translator circuit and process all fast encoders' signals directly in CPLD. The CPLD is visible by ADuC as a specialized external peripheral with 8-bit data bus interface connected to the ADuC by P0 port shown in Fig. 3. Moving time critical parts of signal processing to CPLD significantly increases overall reliability of embedded MCU hardware. The CPLD provides the following functionality:

- processing of all 8 incremental signals (2 per motor) in parallel,
- decoding of fast incremental signals directly in CPLD hardware,
- filtration of short glitch encoder signals,
- accumulation of incremental positions directly in the CPLD hardware,
- increased precision of position information by processing more bits than in software only based decoding,
- synchronous clock generated by the internal CPLD oscillator,
- motor overload detection and motor switch off in terminal positions directly by CPLD hardware without ADuC intervention,
- indication of reaching terminal positions by forcing ADuC interrupt,
- control of all 4 motors by forcing proper H-bridges signals according to high-level ADuC commands,
- LEDs signalization for indication of internal MCU states.

The top entity of the final CPLD configuration is shown in Fig. 9. It contains also new blocks OSC, DIVIDER and OVERLOAD that we added in order to improve functionality of the final CPLD firmware. The CPLD firmware is written in VHDL by using Altera Quartus II design entry and synthesis software [17]. We can easily adapt CPLD functionality by selecting appropriate parameters in the top level Quartus II graphical interface. This allows adaptation of CPLD functionality according to the actual performance and types of mechanical actuators.

OSC block provides internal 3.33-5.56 MHz clock signal for all synchronous logic used in the CPLD. Internal OSC improves reliability of the CPLD design as it uses only internal CPLD resources that are less susceptible to external interferences.

DIVIDER block provides 1 ms time base signal for motor driving protection circuits in the OVERLOAD block.

OVERLOAD block autonomously switches off H-bridges after a long over-current condition. Reaction time is configurable in the range of several tens of milliseconds. A possibility to detect high current peaks (after proper selection of analog components around H-bridges) during start-up phase was added as a potential possibility to decrease number of required battery packs in the final SMILING shoe prototypes. This block can ensure that no more than one motor will be active during relatively short startup phase. Priority encoding and different relaxation time can be encoded into this block.

SHOE block contains main processing hardware for decoding incremental encoder signals of all 4 motors. The block diagram of implemented CPLD hardware for

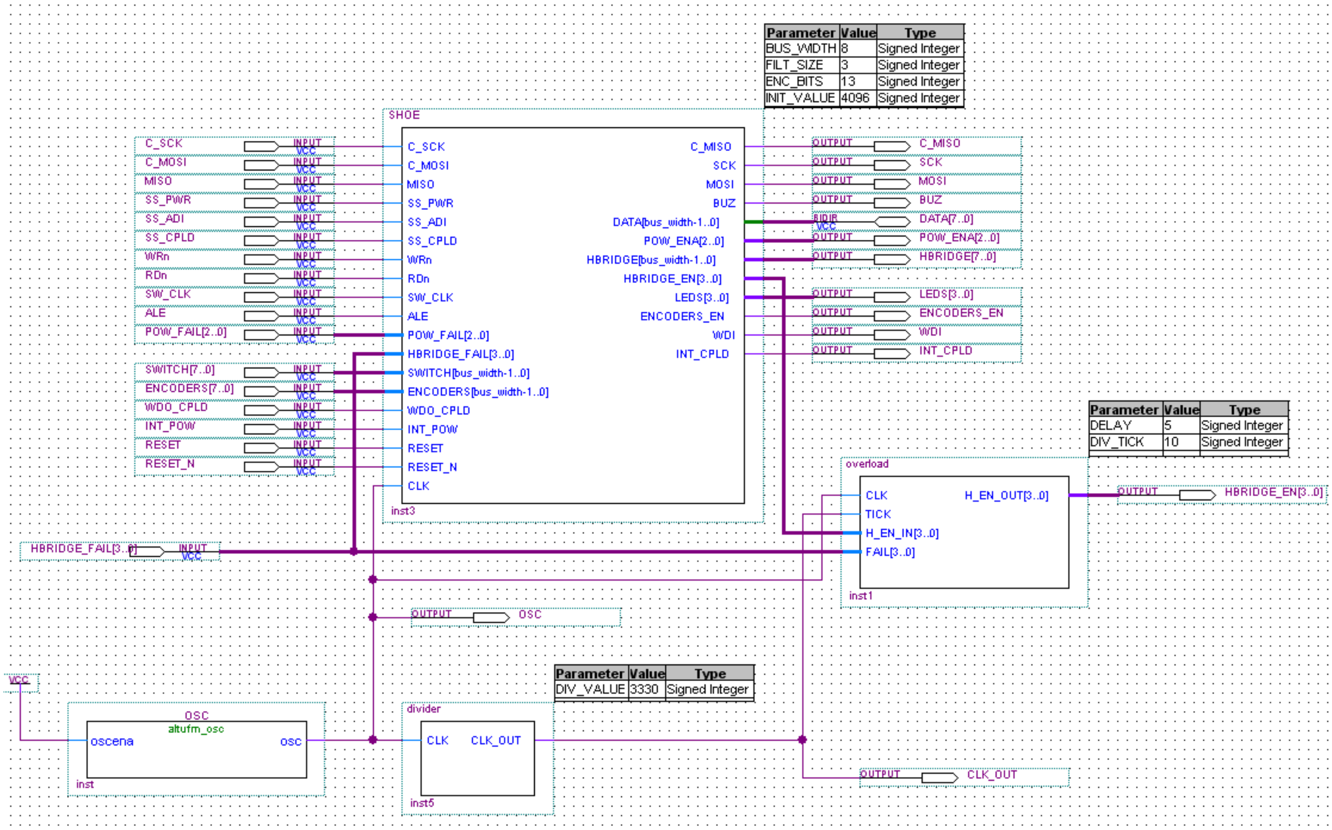


Fig. 9. Quartus II top level diagram of the CPLD configuration

processing of one incremental encoder signals CHA, CHB is shown in Fig. 10.

In contrast with former pure software based ADuC decoding, the CPLD configuration uses additional digital filtration in order to eliminate possible noise or glitch signals. Decoder logic is implemented as a Finite State Machine (FSM) and accumulation of incremental pulses is performed by 13-bit Position Counter (PoC). 8-bit Position Latch and Bus I/F Logic transfer 8 (hardware rounded from 9-th bit) MSB bits of PoC to ADuC for further high-level processing. Internal FSM based decoding of incremental signals provides resolution of 1/64 of the motor shaft rotation. Hardware based CPLD decoding provides resolution of 1/4 (with additional resolution gained from hardware based rounding from bit corresponding to 1/8 rotation) while maintaining fully compatible 8-bit interface used in the ADuC software layer.

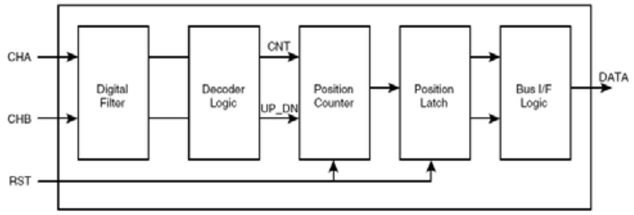


Fig. 10. Block diagram of CPLD hardware based decoding of incremental encoder signals

I. SUPPORT FOR ACTUATORS CONTROL AND TUNING

The MCU firmware and SMILING motorized shoe mechanism [5] were developed at different partner organizations in parallel work. SMILING mechatronical units are interfaced to the MCU hardware by using four Faulhaber 1524E12SR DC-micromotors [10] with IE2-16 encoders and a set of microswitches for detection of reaching actuator terminal positions. This clear interface definition available at the beginning of SMILING project enabled us to develop complete MCU hardware without access to the final SMILING motorized shoe mechanism [5]. It was a long time process and development of the MCU firmware without working mechatronical units would be very inefficient and time consuming. Parameters of mechatronical units were encoded into the MCU firmware as a set of parameters that can be easily adapted to the actually used one.

A. *TUKE MECHANICAL UNIT*

We decided to develop and produce own mechatronical units to be available in early stage of the MCU development. Design of the TUKE mechanical unit is different from the main version used for the final mechanical solution in the SMILING shoe described in [5] and is based on jack-screw mechanism, but uses the same type of DC motor and encoder for the mechatronical concept (Fig. 11), and will be referred as TUKE mechanical unit in the rest of the paper. TUKE mechanical unit was used mainly for MCU development and tuning as a single mechatronical unit of the SMILING shoe. Limited tests were done also in the full configuration as integrated into the SMILING shoe.

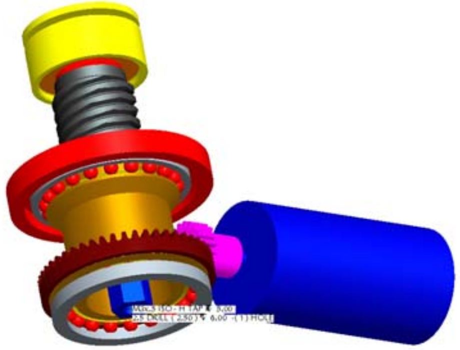


Fig. 11. Mechatronical concept of TUKE unit

DC motor actuates front cogwheel, which actuates wheel-crown. Wheel crown is squeezed to screw female. Screw female is radially and axially supported 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 that gives vertical change in one revolution. Total height gain of the screw is 15 mm.

TUKE mechanical unit is potentially an alternative solution for the SMILING shoe. It has light construction but needs to enlarge range of screw motion to be able to provide higher perturbations. We evaluated its functions in experimental testing with young subjects in our lab. The main requirements defined on the basis of testing were:

- To improve ergonomic properties of the shoe.
- To improve reliability of the mechanical unit.
- To continue on the integration work to optimize the complete system of the intelligent shoe – mechanics, motor control, user control, power unit, S-sense unit for gait data capturing.

Fig. 12. The complete TUKE driving unit

Fig. 13. Layout of TUKE driving units on the shoe

B. FIRMWARE ADAPTATION TO THE FEATURES OF MECAHTRONICAL UNIT

We included several parameters for adaptation of the MCU firmware to the 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 a 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 the 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. Current MCU firmware uses CPLD 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 ADuC program only 4 pulses per revolution in order to limit all main program variables to 8 bits and save ADuC processing power. Fig. 14 shows time evolution of accumulated number of pulses for TUKE #1 actuator visible in the main ADuC C program for running up of the TUKE #1 actuator.

As we can see from Fig. 14 and from a closer pulse record analysis of Tab.1, there is no detectable pulse change during the first 10 ms (startup delay caused by mechanical inertial forces), the first detected pulse is visible in the 12th millisecond, the second one in the 17th millisecond. We decided to evaluate actuators blocking of TUKE actuator by analyzing pulse increments after 20 ms delay. An increasing in the number of pulses detected during last 20 ms lower than 2 indicates blocking of particular actuator.

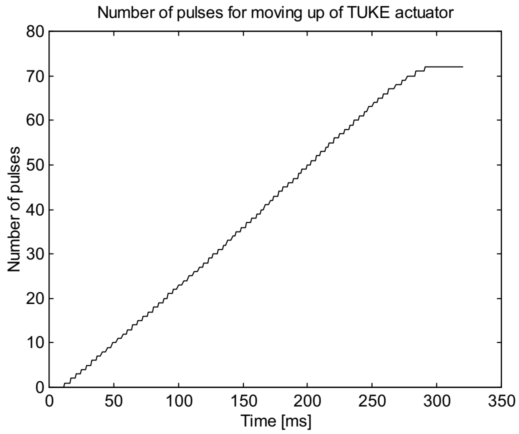
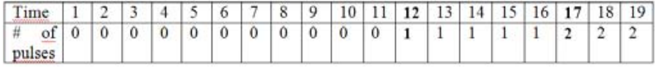


Fig. 14. Time evolution of accumulated number of pulses for the TUKE #1 actuator

Table. 1. Time evolution of accumulated number of pulses for the TUKE #1 actuator during start up



Time	1	2	3	4	5	6	7	8	9	10	11	**12**	13	14	15	16	**17**	18	19
# of pulses	0	0	0	0	0	0	0	0	0	0	0	**1**	1	1	1	1	**2**	2	2

Similar measurements were performed with STRATH mechanical unit, developed at University of Strathclyde [5], during integration phase of complete SMILING system and adaptation was done only by changing thresholds in the final MCU firmware. The above described approach, based on using well defined parameters, allowed us quickly adapt the MCU firmware functionality to the actually used mechatronical units.

II. MCU FIRMWARE ENHANCEMENT FOR DURABILITY TESTING

We started development of basic MCU firmware based on S-Sense to MCU and UCU to MCU software protocols that were defined at the beginning of SMILING shoe development. After finalization of hardware and software interfaces to the S-Sense module, we concentrated to the implementation of software UCU to MCU protocol. The UCU hardware was developed in parallel with the MCU. We developed a testing PC software program – the UCU emulator that enabled us to develop and test complete communication interface without a direct access to the real UCU hardware. Correct functionality of implemented MCU firmware was confirmed in the later stage of development by testing correct functionality of complete UCU – S-Sense – MCU chain operation.

During MCU development we extended functionality of the UCU emulator in order to simplify tuning and testing of mechatronical units used within SMILING project. In order to enable on-line monitoring of internal MCU and mechatronical units states we added a background telemetric channel directly into the implemented MCU firmware. This channel together with the UCU emulator was used also for durability testing of mechanical SMILING shoe parts during integration and optimization phases of SMILING shoe development. The purpose of durability tests was to check functionality and precision setting of mechatronical units after execution of at least 10,000 steps. Steps were executed under direct control of the UCU emulator Precision of actuators setting was evaluated from LOG txt files automatically generated by the UCU emulator.

As an example we present results of testing of TUKE actuators used in the MCU development phase. We typically mixed TUKE unit testing under real load shown in Fig. 15 with testing by using test bench and specially prepared testing artificial perturbation files downloaded to the MCU hardware. Similar approach was used also by other SMILING partners during integration and optimization phases of final SMILING shoes.

Fig. 15. SMILING shoes with jack-screw TUKE testing mechanics

For testing perturbation pattern, we used uniformly distributed random positions from 0 to 15 mm (maximum height gain of TUKE actuators) and constant 410 ms artificial swing phase generated automatically with the 500 ms gaps between swing phases. The MCU firmware uses a simple control algorithm and durability tests evaluated if parameters of control algorithm are set correctly. Durability tests allowed us to detect also mechanical problems of mechatronical 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. Fig. 16 shows distribution of errors for of TUKE actuator #1. We evaluated errors by measuring of incremental encoder pulses. Current MCU firmware has resolution of ¼ of encoder shaft rotation, so 15 mm range of motion of TUKE screw corresponds to 106 pulses and the 3 pulses error corresponds to approximately 0.2 mm error in the position of the screw.

Fig. 17 shows time evolution of actual encoder positions[1]

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[1] Required encoder positions are from 128 to 233 for TUKE #1 shoe actuators. Zero shift to 128 is given by the MCU firmware requirements.

and corresponding errors of TUKE #1 shoe actuator after approximately 15,000 steps (only last 1024 steps shown).

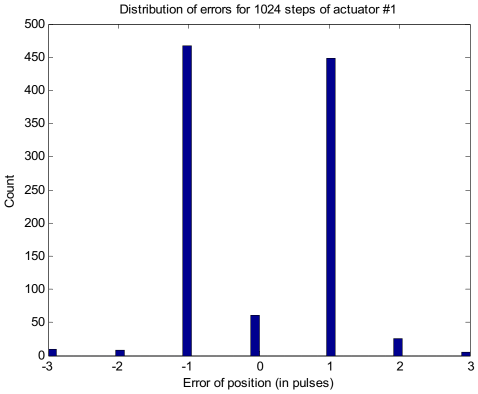

Fig. 16. Histogram of TUKE actuator #1 errors for 1024 uniformly distributed random steps

This performance demonstrates repeatability and high durability of mechanical construction of TUKE actuators.

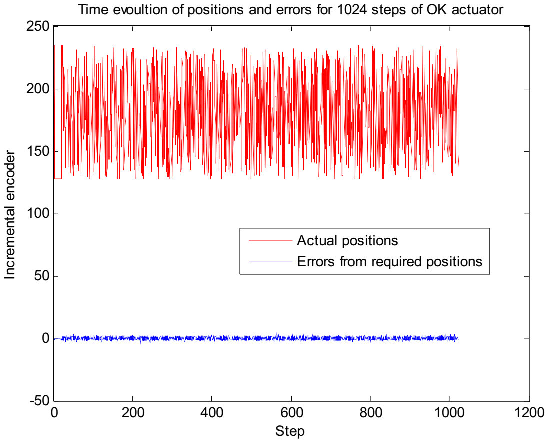

Fig. 17. Time evolution of actual positions and errors of TUKE actuator for 1024 uniformly distributed random steps after total of 15,000 executed steps

III. CONCLUSION

We described block diagram 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 testing mechanism with the alternative mechanical concept. The complete pair of shoes with TUKE mechanics was produced and laboratory tests were done for the integration and optimization of the MCU into the SMILING shoe system.

Finally, TUKE produced MCUs for all final versions of the SMILING shoes used for gait training of elderly at several clinics. They have been heavy tested during real trials and provide a reliable embedded electronic platform for SMILING shoe control.

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