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User Control Unit for the Smiling System: Design and Functionalities

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Abstract—**The SMILING project is aimed at providing a technological solution to motor problems, particularly related to gait and balance such as the risk of falling, occurring in the elderly population. The contribution of the present paper is to provide an insight on the SMILING system prototype with a particular focus on the User Control Unit, that is a portable, wireless device designed to assist the user during training and to control the interaction with the different parts of the system. Furthermore, integration aspects are introduced and preliminary tests of the system with young healthy subjects are described.**

Keywords: gait rehabilitation, wireless body area network, microelectronics

I. Introduction

RECENT advances in wireless and embedded technologies enabled a set of new opportunities for wearable electronics and body area networks in many field of applications [1]. In particular, the health sector is beneficiary of an increase in new solutions [2][3][4] to monitor, diagnose and provide assistance to patients with different pathologies. Among pervasive healthcare outcomes and products, rehabilitation systems have the interesting peculiarity to provide a direct mean of intervention. In fact, devices used for rehabilitation combine sensing and actuation since they should provide an appropriate stimulus to the user to generate a behavior towards heals [5]. In this field, the interdisciplinary nature of solutions is getting more and more importance, since rehabilitation involves not only functional and physiological state of the user but also her/his mental and cognitive state.

The SMILING project targets elderly population addressing in particular gait and balance problems. Rehabilitation is aimed at minimizing risk of falling by training patients with the SMILING system. The SMILING system consists of a body area network including three “nodes”: the user control unit and two mechatronic shoes to be worn as a complement to common shoes. Specific small perturbations are applied to the position of 4 motors per shoe to alter the height and slope of the surface where the feet land in each step, challenging the patient to solve a motor problem in real time.

As far as we know this is a unique example of a mechatronic training shoe, which changes configuration “online” according to a preprogrammed pattern, thanks to identification of gait phases.

Gait and gait phases identification and monitoring are widely studied [6][7][8]. Examples of sensorized shoes have been developed both for research [9] and for the market (e.g. Nike, Adidas). However no example exists of mechatronic shoes to train the abilities to perform gait and to find strategies to face unexpected ground conditions. The closest example is the one presented by Frey [10] in a different application field, which is assistance to pedestrian navigation.

The complete system consists of 3 modules: i) a complete gait analysis system; ii) a pair of motorized training shoes; iii) the user friendly portable control unit, already mentioned. The result is a complex prototype that mix together wireless technologies, sensing capabilities, motor control functionalities and user interaction. System integration is therefore a challenging task. The contribution presented in this work focus both on system integration and on part of the embedded electronics involved in the system and in particular in the User Control Unit (UCU).

In fact, the design and development of the UCU hardware and software followed specific requirements, such as:

- being part of the intelligence of the entire system
- interacting with the user and clinical assistant
- integrate the different part of the system that necessitate to communicate with the UCU (the wireless communication modules, the shoes’ motor control unit…)

This last issue has been particularly demanding, for the different technologies and protocols used, and for the geographic spread of the various technology providers within the SMILING consortium. However, we finally came to a valuable solution, thanks also to the different experiments and trials that were performed on the user, following a design and implementation model that considers the “user in the loop”. Such approach enabled to carefully consider safety and usability aspects, which we will discuss in this paper. We will also presentsolutions studied to assist safely the user and preliminary functional tests on users

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wearing the SMILING system.

The present paper is organized as follows: we start providing a brief system overview (section II) to introduce afterwards (section III) the user control unit as key building block of the system; then we present results from test conducted on user (section IV) and we end with conclusion.

II. SMILING SYSTEM OVERVIEW

The SMILING system is a dedicated rehabilitation and training system designed to challenge the user's motor abilities in facing problem arising from walking on a irregular and unexpected ground surface.

The system consists of a **pair of mechatronic shoes** that enable the change in height and inclination of the feet contact surface, while walking. Movement of the bottom part of the shoes are quite limited, since each shoe can achieve a combined movement of +/- 4.5 degrees for ankle flexion /extension and +/-4.5 degrees for foot internal/ external rotation in one or two steps made by a user [11]. The motor-based system determining the changes of the shoe are controlled by dedicated electronics (the motor control unit – MCU [12]).

The user interacts with the shoes by means of the **User Control Unit (UCU)**, worn on the belt or carried on while exercising. The motors are moved only during the swing phase of gait (the shoe is unloaded and motors can move easily). **Detection of the swing phase** is performed using a real time algorithm developed by EPFL running in the shoe electronics, that processes the inertial sensors signals. The inertial sensors and the wireless capabilities of the shoes are embedded in the IMEC S-sense device.

To implement the concepts of the project, the SMILING system is thought to be used in two different phases, referred here after as **Preparation Phase** and **Training Phase**. In each phase different components of the system are used or same components are exploited for a different purpose.

The Preparation Phase deals with the user gait analysis, collection and processing of parameters to define the kind of rehabilitation, the preparation of the chaotic pattern to determine motor movements during training. The main components of this phase are the Operator Control Unit, the IMEC S-sense wireless sensor modules, the algorithms to enable gait analysis [13], user profiling and chaotic pattern generation. Details regarding the preparation phase are not described in this work, which instead focuses on the Training Phase.

During the Training Phase, the SMILING users undergo a sequence of different perturbations (by means of sole movements) altering their own walking schema. According to the basic concept of the SMILING project, the sequence of perturbations applied to the two shoes must be chaotic both in height and inclinations. The sequence of perturbations is downloaded to the shoe electronics before the start of the training session by the UCU, which is afterwards used to handle the user interaction with the system during the training session (e.g. start, stop tasks). For each foreseen training task, the control unit supplies the main instructions and monitors the user's performance. A scheme of the entire system is shown in Fig. 1

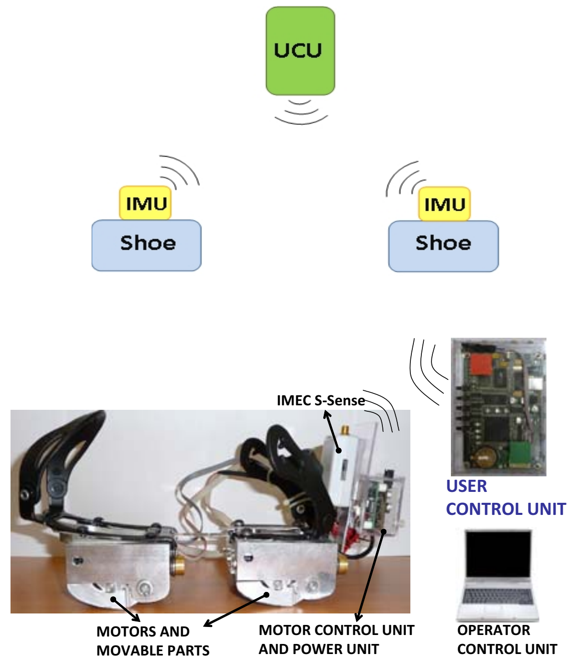

Fig. 1 SMILING system overview

III. THE USER CONTROL UNIT (UCU)

A. UCU general description

The UCU is a wearable programmable device designed to interact with the user and to control the entire SMILING system during the training session (Fig. 2).

1) Hardware components

The UCU was designed and developed based on the following hardware components: an ARM7 RISC Microprocessor, 4Mbyte Flash memory and 8Mbyte SDRAM memory; it includes a USB port, SD-card reader, audio interface plus speaker and microphone. The UCU includes a S-EOM transceiver developed by IMEC and a Bluetooth transceiver (as a second option) to enable wireless communication. Interface with the user is allowed by two operation buttons (*OK* and *Stop*) and one *Reset* button, six LEDs used to provide diagnostic information, two expansion connectors and one JTAG connector. The hardware was designed to obtain a low cost device with enough computational power to manage in real time the SMILING Training Session. The fully programmable architecture was chosen to allow the development of the system addressing the need of the patient and clinician. In particular, we took great advantages from hardware programmability to tune and improve the system taking into account the feedbacks coming from the first experiments and trials.

2) The user interface

The interface was designed to minimize the user interaction and at the same time to enable him/her to control the system in the easiest way possible.

Minimization of the user interface was included in the system design as a key aspect both for Ergonomics (usability) and for Safety (low risk of undesired actions).

The UCU interface consists in fact of only two buttons (*Ok* and *Stop)* and a speaker. The *Ok button* provides to the user the capability to decide when he/she is ready to start the task. The purpose of the *Stop button* is specifically to stop the system during each training task for safety reasons. The speaker provides the description and feedback of each operation performed during a smiling training session.

3) Data storage

The UCU is also equipped with an SD-Card for data storage. All the data acquired from the SMILING system during a training session are saved there. Clinicians are required to upload in the SD card the configuration data to perform the subject specific training session.

4) Diagnostic

The UCU has six LEDs, used to describe the internal status in real time, to test and debug the system.

5) Case

The device is housed in a robust, light and wearable box.

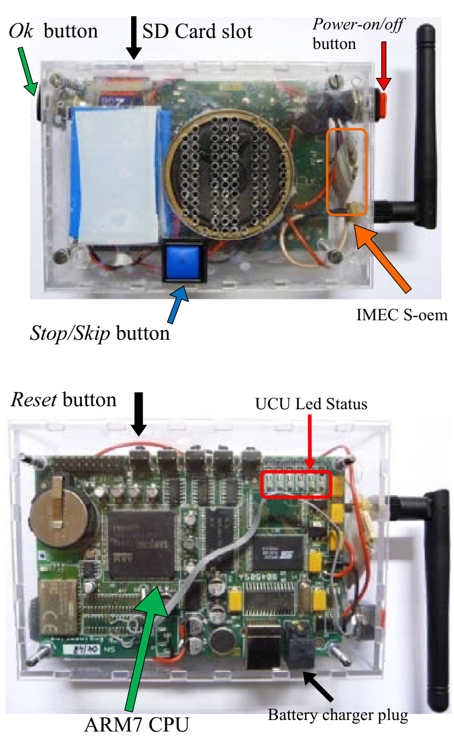

Fig. 2 Front and rear view of the User Control Unit of the SMILING system

B. UCU functionalities

The UCU was developed with the aims of providing:

a) System programmability for personalized training session;

b) Wireless communication with the shoe-subsystem;

c) User guidance and feedback for training-task execution;

d) Data storage: sensor and motor behavior data logging

e) Online data analysis for training adaptation

Such functionalities are described in details in the following paragraphs.

a) *System programmability for personalized training session.*

Clinicians can program the system to perform subject specific training sessions, by uploading personalized configuration files, perturbation patterns and audio message files in the SD-Card. The aim of this functionality is to provide the appropriate training session to each user, considering user's state, rehabilitation progresses and previous gait analysis results.

b) *Wireless communication with the shoes system*.

The UCU software coordinates the communication flow and the user interaction with the system. Therefore it manages the communication protocol responsible for synchronization, reception of data from the shoes, error handling, re-transmission in case of failing reception of a message.

The wireless nature of the system augments its usability. Since the user walks for several meters during trials, it is essential that he is able to bring with her/him the control unit to interact with the shoes (e.g. start and stop tasks and sessions). The UCU can be worn by the user in a very comfortable manner, e.g. just connected to the belt or to the trousers (just like a mobile phone).

Fig. 3 A user wearing the system

c) *User guidance and feedback for training-task execution*.

A vocal message at the beginning of each task explains to the user the corresponding goal of the task (e.g. "walk normally for 2 minutes"). Messages were found to be a suitable way to guide subjects under rehabilitation, since they are usually accustomed to physiotherapist's instructions.

Details of messages were defined together with the definition of tasks and of perturbation patterns. The messages were translated into the native languages of users (in our case: English, Italian, French, Hebrew and Slovak).

d) *Data storage*

During the training task, the data coming from the inertial sensors embedded in the shoes are stored in the SD-Card included in the UCU. This functionality was implemented to have raw data available for off-line analysis of kinematic data. The information saved includes details to be used for debug purpose in case of possible unexpected behavior (e.g. block of motors).

e) *Online data analysis for training adaptation*

After the end of each task the **Task Performance Index** (TPI) is computed from the inertial data stored to the UCU and acquired during the task. TPI is a binary index: success/ not-success. The computation of the TPI is task-oriented, i.e. it depends on the goal of the specific task (e.g. number of step performed, time necessary to complete the task, etc.). At the end of the session (consisting of a set of tasks) the total TPI will be considered automatically by the UCU and will be computed as the percentage of successful tasks within the session. It is used to determine the next session to be proposed to the user.

C. *UCU working states*

UCU is designed to have three consecutive working states: ***Perturbations Pattern Download*** state, ***Shoes Calibration*** state and ***Training Session*** state. Each state is reached either performing or skipping the previous state as shown in the graph in Fig. 4.

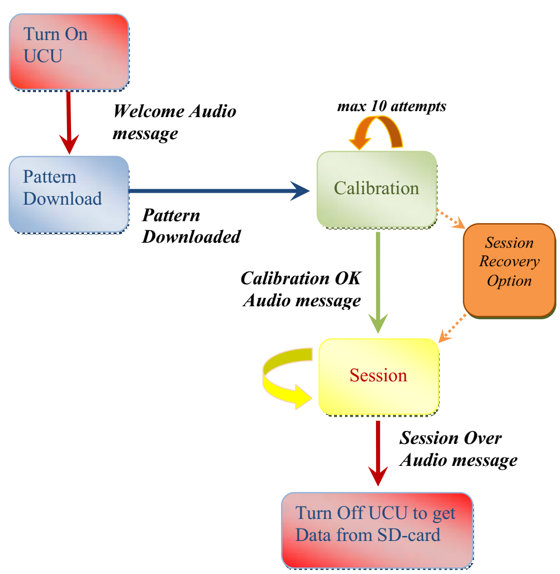

Fig. 4 Working states of the User Control Unit

Before performing each state the user is guided by an audio message describing the operation already performed and the next one available: for example, after the UCU is turned on a *"welcome"* audio message is played to inform the user about the availability of the system to start the pattern download procedure. The user can go to or skip the next state just pressing the *OK button* or the *Stop button* respectively.

At the end of the session the procedure is finalized (a *"Session finished"* audio message is played) and any interaction with the user is prevented to avoid corruption of the acquired data.

A detailed description of the UCU Working states follows.

Perturbation Pattern Download. The perturbation pattern is the dataset of shoe-motor positions that are used to obtain the chaotic small perturbations beneath the foot. The perturbation patterns are performed by means of a movement of the shoes extremities during the swing phase of gait, by means of small alterations of the height and slope of weight-bearing surfaces. Perturbation Patterns are stored on UCU SD-card and their integrity is checked, using CRC hash function, before and after sending it to the shoes. Before each pattern is downloaded, the wireless network availability is checked in order to have the two communication modules of the shoes and the UCU properly connected.

Shoes calibration. To correctly perform the perturbation pattern the shoes motor positions should be reset by means of a *Calibration* procedure. The UCU sends a calibration command to the motor control unit of the shoes and the motor calibration is performed on both left and right shoe at the same time. A retransmission policy is implemented in case of problems with reception (up to ten times). Before the beginning of the session, the calibration process must be performed at least one time per shoe. The calibration procedure is repeated until success.

Training session. After the shoes have been calibrated an audio message informs the user about the possibility to start the training session. Before each session starts, wireless network availability is checked and then the *start* command is sent to enable the shoes to execute the perturbation pattern downloaded in the previous phase. During task execution, UCU collects all the inertial data (3D accelerometer and 3D gyroscope) and all the status information coming from the shoes system. Status messages are used to detect possible problems on the shoes: in case of a critical condition the control unit handles the stop of the session. Feedback is provided to assist the user to in verifying the system to solve the problem occurred. When the shoes are restored the user can start again the session by the UCU ***session recovery*** procedure.

The UCU provides the session recovery procedure in case of possible session break due to unexpected UCU, shoes behavior or patient need. Before each session starts, the UCU will check if the previous session was completed or not: in case of session not yet finished, the UCU will ask if the user wants to recover the old session or start a new one.

D. UCU additional functionalities: Setting of the Swing Detection Threshold

In order to have subject-specific swing detection thresholds, UCU provides the ability to configure an "option.txt" file present in the SD-card, by changing a parameter. To obtain the correct threshold values for each subject the Operator Control Unit (OCU) software is needed [14]. The OCU is used to tune and test appropriate threshold values that are afterwards stored in the SMILING system to be used during training. The personalization of such values facilitates the correct activation of the motors, which must occur only during the swing phase. The UCU is the device that downloads the thresholds in the shoes for each session.

E. Safety and Security Issues

The different parts of the SMILING system UCU/communication modules on the shoes/ motor control unit have the needs to have reliable communication. To this aim a handshake protocol and CRC control with re-transmission were implemented. The handshake protocol requires acknowledgement each time a command or a data packet is sent. Moreover, data packet integrity is checked using the CRC. The procedure that manages exceptions in handshake and CRC control will repeat the operation until a successful transmission is achieved or up to ten attempts. In case of failure, an audio message is played to warn the user. However, no major issues for user safety are envisaged in case of transmission failure, since in case of lack of communication between the UCU and shoes, the following situations can occur:

• the pattern download does not succeed: the user is not at risk since the only consequence is that no training is present on the shoes, which also means that nothing happens and motors do not move. The UCU warn the user and provides the capability to perform again the pattern download.

• Calibration control command is not received by the shoes: again no calibration is done. Since the UCU waits for an acknowledgement from the shoes, which is obviously not sent, an audio message advises the user of the failure and the UCU provides the capability to perform again the calibration.

• Start, stop task is not received: in the worst case the user will experience a longer or shorter training, moreover the UCU will advice the user of the failure.

• The data streaming fails: this failure affects only the further data analysis and TPI processing.

IV. User in the Loop

Almost all the development of the system was achieved using a "user in the loop" strategy, i.e. by means of continuous tuning, definition, and improvement thanks to trials and experiments on the different parts and different prototype of the system. In fact, after a framework definition of the system (hardware platform, main functions and software), several sections were modulated according to needs presented during trials, or corrected, according to problems arisen during trials, not detectable on the testing bench. This method was particularly challenging and demanding, but it was necessary since the projects also included an important part in which a validation procedure was requested in field, i.e. with the system employed by clinicians in a clinical environment on elderly subjects, with a minimum of technical assistance on site. Thus, even if the system is still a preliminary prototype, it includes several peculiarities, in terms of reliability and usability, already characteristic of a quasi-final product.

A. Preliminary trials for usability

To test the usability of the system, a preliminary validation (five healthy young subjects) was undertaken, with a provisional prototype of the system, for testing the complete data-flow necessary for the system to work, and to evaluate (1) ergonomics, (2) adaptation and (3) safety, by means of a camera-based motion analysis system.

Subjects walked normally, wearing their normal shoes, in a laboratory provided with a camera-based system for movement analysis (Smart, BTS), in the following conditions (5 repetitions for each condition):

- Baseline: walking just with normal shoes
- Walking with SMILING shoes just worn;
- Walking with SMILING shoes worn for at least 20 minutes;
- Perturbed walks: Shoe inclination in the frontal plane ranged from approximately 5 to 15 degrees

The CAST protocol [15] for marker positioning was implemented.

Ergonomics. The system was found to change some of the gait patterns: knee and ankle movements in the sagittal plane are reduced (Fig. 5). In fact these joints are more rigid, due to the weight and height of the SMILING shoes. Such changes, however did not affect the ability to walk quite normally and usage of the shoes did not become uncomfortable for the subject.

Adaptation. A period for the subjects to get used to the shoes resulted essential: subjects confirmed much more confidence on the systems after wearing it for some time (about 20'), and measures of gait patterns moved toward baseline after having worn the shoes.

Safety during perturbation. Our preliminary experiments included exaggerated perturbation compared to the ones in the real SMILING protocol. The only important changes in users biomechanics during gait was seen for angle at 15 degrees on the frontal plane, when the ankle angle pattern in the frontal plane did change, mostly during the stance and the strike phases. For 15 degrees plane a subject claimed fear of falling in one of the last trial. Such angle can be considered as the limit for lateral perturbation.

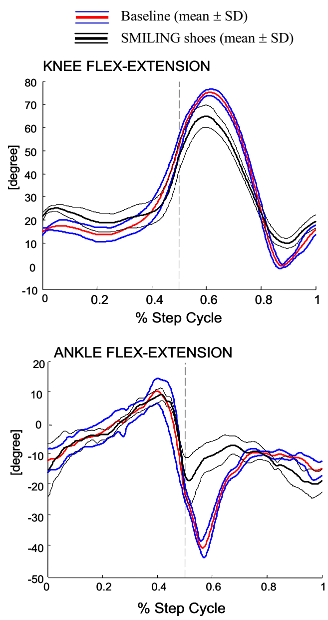

Fig. 5 Ankle and Knee flex extension

B. Simulation of rehabilitation sessions and training of clinical personnel

In addition different training sessions were performed for 7 healthy young subjects to simulate real training sessions and to train clinical personnel in the use and management of the SMILING system. Some cautions needs to be used during training, such as attention to fatigue, needs of adaptation to the system by the user.

V. Conclusion

The present paper described some of the building blocks of the SMILING system with particular emphasis on a crucial component: the User Control Unit. The UCU has been proved to be reliable, easy to use, and able to properly control the SMILING system and different events occurring during "on-field" trials. This last aspect was tested both on young healthy subjects, and it is now under validation, in older subjects in several clinical centers. Despite of its prototypal nature, it has been already possible to successfully conclude some of the planned validation trials with reasoinable technical assistance. Future use of the system could be extended to different scenarios and,e.g., be combined with additional technologies such as virtual reality environments, sensorized garments, both for rehabilitation and for basic research on the motor control system.

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