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S-sense: a wireless 6D inertial measurement platform for ambulatory gait monitoring

Julien Penders, Jef van de Molengraft, Fabien Masse, Benoit Mariani and Kamiar Aminian

Abstract—**The SMILING system is a complete system for gait training and rehabilitation. Motorized shoes are used to apply perturbation during gait training. The SMILING Sense (S-sense) modules monitor inertial data from the two feet, wirelessly and in real-time. This paper reports the development of the S-sense module. Each module features a 3D-gyroscope and a 3D-accelerometer, and carries enough processing power to extract relevant information in real-time. Each module is equipped with a radio transceiver, antenna, local data memory and a rechargeable Li-ion battery. An algorithm for real-time walking phase detection has been developed and embedded in the S-sense micro-processor unit. When connected to the Smiling shoes, detection of swing-stance phase is used to control the motorized actuators, such that perturbations are applied during swing phase only. The S-sense modules can also be used independently of the shoes to monitor gait in ambulatory conditions. In this setting, the data is wirelessly transmitted to a receiving unit within 10m range, or may be stored in local memory. Wireless, miniaturized and wearable, the proposed system opens new perspectives for gait monitoring and training, outside the lab environment.**

I. Introduction

THE SMILING project aims at developing a comprehensive system for gait assessment and training in the elderly. The approach builds on new trends in neuro-motor rehabilitation, suggesting that challenging the brain with walking perturbations improves neural plasticity and allows the natural recovery of a normal gait pattern [1][2]. The SMILING system consists of a pair of motorized shoes, two wireless sensor units (S-sense), a user control unit and a PC software suite for gait analysis [3]. The motorized shoes are used to apply chaotic perturbations during gait training [3]. Control of the four motors of each shoe is achieved by a micro-controller unit [5] embedded in the shoe structure. Two wireless sensor units, the SMILING-sense (S-Sense), located at the back of each shoe monitor inertial data. The data is processed in real-time to detect swing and stance phase. This information is then passed to the shoe micro-controller to control the activation of the shoe motors. In addition, the S-sense can be used independently from the shoes, allowing wireless and real-time gait analysis. This paper reports the development of the S-sense modules: a wireless 6D inertial measurement platform for ambulatory gait monitoring.

Recently, an increasing number of papers have demonstrated new gait monitoring methods based on body attached sensors. Important spatio-temporal gait parameters such as walking speed, step length and frequency, duration of swing and stance phases can be determined using sensors attached to leg or trunk segments [6][7]. The advantages of these wearable technologies compared to traditional approaches are mainly their practical usefulness outside a laboratory, where longer walking distance in a natural setting can be performed. Systems that provide both spatial and temporal parameters are often attached on lower limbs (i.e. foot, shank or thigh) [6], and requires several sensors (accelerometers, gyroscopes). Furthermore, most of current studies monitor gait "off-line", using recorded kinematic signals and dedicated algorithms. On-line Gait phase detection has been addressed for the control of drop-foot stimulator using accelerometers [8], but such real-time applications remain rare, and lack implementation in wearable solutions, or testing in real conditions. Real-time detection of the swing phase is required in the SMILING system, to achieve timely activation of the motors.

The rest of the paper will be organized as follows. First the list of requirements for the S-sense system is presented. Then we describe the S-sense platform, the hardware and the communication protocol allowing several units to work within a same network. Finally, we describe the embedded implementation of an algorithm for real-time walking phase detection.

II. S-sense System Requirements

This section defines the set of functional requirements as derived in the context of the European project SMILING. An overview of the system is shown in Fig. 1. Two SMILING Sense (S-sense) modules are attached to the back of each foot. These two modules communicate wirelessly with a third wireless node connected to a PC or the user control unit. The three nodes make the SMILING body area network (S-BAN). The third node is managing the network and the communication flow, and is referred as the SMILING base-station or S-base.

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J. Penders, J. van de Molengraft and F. Masse are with imec at the Holst Centre, High Tech Campus 31, 5656 AE Eindhoven.

B. Mariani and K. Aminian are with Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory of Movement Analysis and Measurement, 1015 Lausanne, Switzerland.

Corresponding author is Julien Penders. Tel: +31-40-277.4073; email: Julien.Penders@imec-nl.nl

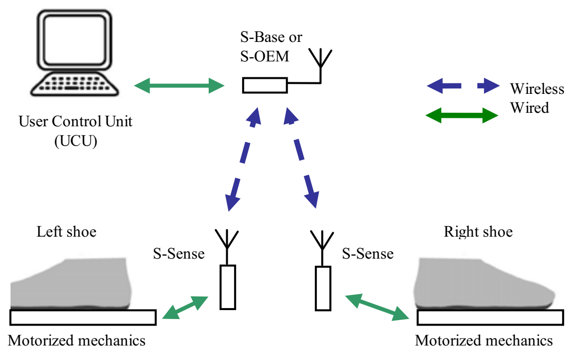

Fig. 1. Smiling system architecture

First, each S-sense module should measure 3D acceleration and 3D rate of turn (using a gyroscope). An operator (physician, gait analysis expert) must be able to get captured gyroscope and accelerometer data from the S-Sense modules to analyze the gait of the user. It must be possible to capture at least a period of half an hour of data. The data should be either streamed wirelessly from the S-Sense module through the S-Base to a PC, or it should be possible to store it locally on the S-Sense module. The user control unit consists of a PC or a portable system, and provides the user with an interface to the system.

Second, the S-sense modules should be battery powered. The user must be able to switch the modules on and off, and to know in which state the module is (on/off). The user should be able to charge the battery. When connected to the Smiling shoes, power should be drawn from the shoe battery, not from the S-sense battery.

Next, the system shall provide a configuration mode, in which parameters of the system can be set. In this mode, the system shall implement a wireless exchange of information between operator/user control unit and S-sense modules.

During usage of the system, the smiling network must be able to pass system control and status information to the control unit. The system shall also provide means to send commands to the S-sense modules from the control unit, such as start/stop function for instance. Synchronization between the wireless units in the network is required.

When used in combination with the shoe, the S-sense shall detect swing and stance phases, in real-time, and pass this information to the shoe electronics. Accurate detection is crucial as the swing/stance phase signal is used to drive the activation of the motors when the foot is in the air.

III. The S-Sense Platform

A. S-Sense module

The S-Sense module is composed of seven blocks: microcontroller, radio, SD-card, three-axis accelerometer, three-axis gyroscope, USB/UART switch and a power supply unit.

The S-Sense module features a MSP430 series 16bit RISC ultra low power microcontroller from Texas Instruments, chosen for its low power consumption in active and low power modes. The specific MSP430F1611 is mainly selected for its relatively large (10kbyte) SRAM memory, relatively large (48kbyte) flash memory, DMA (direct memory access) module and 12 bit ADC. The Nordic nRF24L01 2.4Ghz radio transceiver is selected for its high air data rate of 2Mbps maximum and low power consumption. The S-Sense module has an internal antenna.

The serial mode (USB or UART) is controlled by the microcontroller. Due to the limited amount of serial interface modules available in the MCU, the radio and micro SD-Card share the same serial peripheral interface (SPI) bus. A block schematic is shown in Fig. 2. A picture of the assembled printed circuit board is shown in Fig. 3.

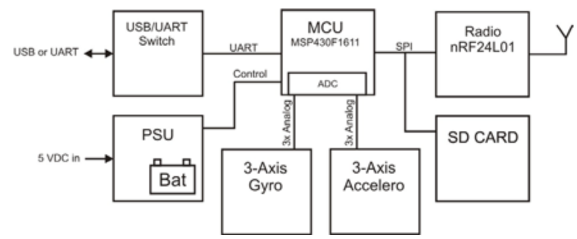

Fig. 2. S-sense block schematic

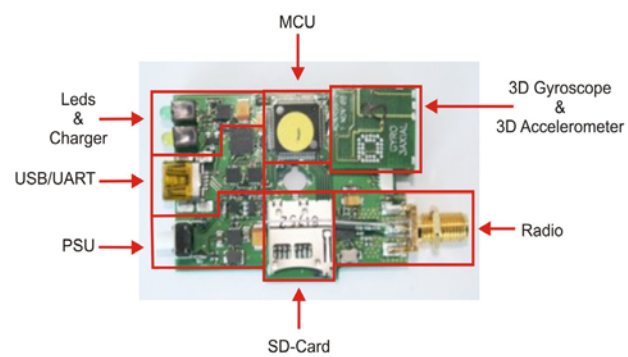

Fig. 3. S-sense printed circuit board

The S-Sense module features a small, thin, low power, complete 3-axis accelerometer with signal conditioned voltage outputs from Analog Devices (ADXL330), measuring acceleration with a minimum full-scale range of ±3 *g*. The S-sense also contains a module with three Analog Devices ADXRS610 gyroscopes mounted in the three perpendicular planes. Roll and Yaw are set to a sensitivity of 300deg/s and pitch is set to a sensitivity of 800deg/s. A table of the sensors and ranges is given in Table I. All sensors are sampled at 200Hz, to provide satisfactory time accuracy in detecting walking phases.

TABLE I
S-Sense Sensors

Sensor	**Range**
X, Y, Z 3-Axis Accelerometer	+- 3g
Pitch Gyroscope	800 deg/s
Roll Gyroscope	300 deg/s
Yaw Gyroscope	300 deg/s

The power can either be supplied at the 5 volt power input or by a Lithium-Ion battery (660 mAh). The battery is charged through USB. Average power consumption of the module is 18.5 mA at 3.6V, including power consumption of the 3D-gyro module (10mA at 5.0V).

The S-sense module and battery are packaged in a plastic casing (Fig. 4) which can easily be attached to any body parts. Total size of the packaged module is 57 x 41 x 19.5 mm^3.

Fig. 4. S-sense module in its package. Total size is 57 x 41 x 19.5 mm^3

B. S-Base module

The S-Base has the same blocks than the S-Sense except for the gyroscope module. The micro SD-Card and accelerometers are left unused. The serial interface of the S-Base is configured to USB and the module is USB powered. A block schematic is shown in Fig. 5.

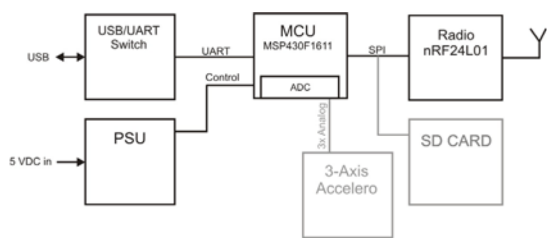

Fig. 5. S-base block schematic

C. Wireless Communication protocol

A breakdown of the total data rate for the S-BAN system is given in TABLE II. The wireless communication protocol enables the transmission of the data in real-time to the control unit and supports transfer of configuration parameters from base station to nodes (eg. Calibration parameters).

TABLE II
BREAKDOWN OF TOTAL DATA RATE FOR S-BAN SYSTEM

Node ID	Sensor	# of channels	Freq (Hz)	Resolution	Data Rate
LSN	Gyroscope	3	200	12	7.2
	Accelerometer	3	200	12	7.2
RSN	Gyroscope	3	200	12	7.2
	Accelerometer	3	200	12	7.2
				Total	28.8

A static Time Division Multiple Access (TDMA) is chosen as the Medium Access Control (MAC) protocol. The maximum data that can be transferred over the network with the implemented MAC protocol and radio is 625 kbps. The duration of a TDMA cycle is 100ms. A beacon is sent by the base-station to the nodes at the beginning of each cycle. All nodes are synchronized to the beacons, ensuring network and time synchronization. Beacons can also carry commands/configuration information specific to one node or to all nodes at the same time. In a TDMA cycle, a guaranteed time period is allocated to each node, during which the node can transmit its 6D IMU data.

The MAC layer also provides the network clock as a software clock to the application layer where data sampling takes place. This ensures synchronous data sampling across all nodes. As there can also be some control information exchange between a single node and base station, the data can be received asynchronously from different nodes. To be able to resynchronize signals acquired by different nodes, all the data frames are time stamped using the beacon ID and time slot ID of the first sample in the MAC frame.

IV. EMBEDDED REAL-TIME WALKING PHASE DETECTION

Each S-sense module is equipped with a walking phase detection (WPD) algorithm, which detects swing and stance phases of gait in real-time. The input of the algorithm is the foot angular velocity (pitch) measured by one of the gyroscope embedded in S-Sense, and the output is a binary on/off signal corresponding to Swing/stance phases. The swing/stance signal is then passed to the shoe electronics, where action is taken accordingly to control the motors. The swing/stance phase signal is also streamed online from S-Sense to S-Base and PC for visualization.

The choice to use gyroscopes instead of accelerometers was motivated by a better signal/noise ratio, and an easiest interpretability (no gravity influence requiring additional processing). Furthermore, walking phase detection algorithms were previously developed on angular velocity signals from gyroscopes placed on shank using wavelets [6] or digital filters [9], with good results in terms of precision, accuracy, sensitivity and specificity. However those methods are not suitable for an embedded real-time implementation due to their high complexity. More recently, Pappas et al. have presented a reliable real-time gait detection sensor based on gyroscope [10]. The algorithm presented here is designed using a heuristic approach based on simple features from patterns of angular velocity in sagital plane (around pitch axis of foot) during gait. The corresponding low complexity is particularly suitable for implementation in the S-sense micro-controller, achieving a complete and functional embedded real-time solution for walking phase detection.

A. Algorithmic Method

From previous experience and reference motion capture systems, we could identify periods of Mid-swing, Heel strike, foot flat and toe-off events on pitch angular velocity pattern of foot (Fig. 7).

The algorithm detects swing and stance phases from heel-strike and toe-off events, with threshold based comparisons and simple peak detection methods. Code has been optimized to rely on a small number of buffered values (to minimized detection delay) and low CPU-power consuming operators (addition and logical comparison). Mid Swing event is also detected as an additional condition to confirm or reject swing detection. The use of per-subject thresholds allows improving the robustness of the detection method. These thresholds are obtained by performing a preliminary measure of the subject's gait pattern with the same system, and by measuring its statistical properties (mean, range and standard deviation). Per-subject thresholds can be updated wirelessly in the S-sense modules, facilitating configuration of the system.

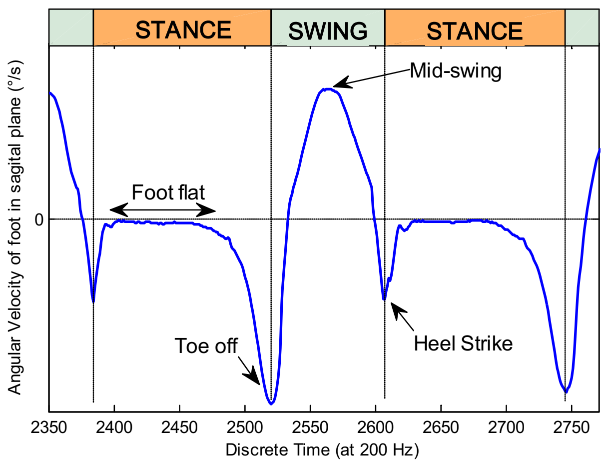

Fig. 6 Gait phases on angular velocity of foot during a normal gait cycle

B. *Experimental Results*

The algorithm was validated against a pressure insole system (Pedar) used as gold standard. Using pressure measure, we calculate vertical force. Swing phase is defined for vertical force bellow 5% of body mass. Gyroscope is attached to subject's foot and synchronized with Pedar system. Validation study was achieved with a clinical protocol involving 17 elderly volunteers (age >60), who were ask to perform a normal gait trial of approximately 50. A total of 3469 gait cycles were recorded with both systems at the same time. Overall, a sensitivity of 100% and specificity of 92% have been reported in detecting the swing phase. It is important to note that almost 50% of the cycles that were not detected by WPD correspond to either first or last steps of gait trial (transition cycles between standing and walking). This could be explained by the fact that such transition cycles are slightly different from steady-state gait cycles.

V. Conclusion

This paper reported the development of the SMILING-Sense (S-sense) system: a wireless 6D inertial measurement platform for ambulatory gait monitoring. The S-sense is one component of the overall SMILING system. It monitors and processes inertial data from the foot. When used in combination with the SMILING shoe, it provides the swing/stance signal required to control the shoe motors. The S-sense can also be used independently as a stand-alone system, providing a platform for wireless, ambulatory, gait analysis.

System requirements were discussed. The design and architecture of the S-sense and S-base modules were presented, and the wireless communication protocol was described. Finally, the embedded algorithm for real-time walking phase detection was described. Validated against a pressure insole system used as gold standard, and on a population of 17 elderly subjects, it achieves a specificity of 100% and a sensitivity of 93.2%.

The S-sense system has been validated on young and elderly volunteers for the purpose of ambulatory gait analysis [11]. Overall, the system is well received by patients and professionals, enhancing comfort and ease of use compared to existing systems. The system is currently in used by several hospitals as part of the clinical validation phase in the SMILING project.

Acknowledgment

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