Wireless 6D inertial measurement platform for ambulatory gait monitoring

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***Abstract*— This paper reports the development and evaluation of a wireless six-dimensional inertial measurement platform for ambulatory gait monitoring. Each wireless 6D-IMU module (S-Sense) features a 3D-gyroscope and a 3D-accelerometer, and carries enough processing power to extract relevant information in real-time. The data is wirelessly transmitted to a receiving unit within 10m range, or may be stored in local memory. An algorithm for real-time walking phase detection has been developed and embedded in the processing unit of the wireless module. Validated against a gold standard system on a population of 17 elderly subjects, the algorithm shows a specificity of 100% and a sensitivity of 93.2%. The proposed wireless platform is evaluated in a clinical gait study involving 20 subjects. Wireless, miniaturized and wearable, the proposed system opens new perspectives for gait monitoring beyond the lab environment.**

I. INTRODUCTION

It is expected that micro and nano-system technology will soon enable people to carry their personal body area network (BAN) that provides medical, lifestyle and assisted living functions to the user [1]. Such a body area network comprises a series of miniature sensor/actuator nodes each of which has its own energy supply, consisting of storage and energy scavenging devices. Each node has enough intelligence to carry out its task. Each node is able to communicate with other sensor nodes or with a central node worn on the body. The central node communicates with the outside world using a standard telecommunication infrastructure such as a wireless local area or cellular phone network. Experts might then provide services to the individual wearing the BAN, such as management of chronic disease, medical diagnostic, home monitoring, biometrics, and sport and fitness tracking.

Recent years have seen the multiplication of body sensor network platforms and one can today find a panel of wireless sensor nodes for the monitoring of various biological and physiological signals [2]. These sensor nodes differ by their form-factor, their autonomy, the inherent building-blocks (micro-controller, radio, sensors) and their portability. Recent studies have demonstrated their successful implementation for various applications such as activity monitoring [3], sleep monitoring [4] or, more recently, emotion monitoring [5][6][7].

An increasing number of papers also demonstrate 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 [8][9]. 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) [8], and requires several sensors (accelerometers, gyroscopes). Reducing the number of sensors required to compute gait parameters has several advantages: decrease the total weight of the system, reduce the power consumption and memory size, improve the physical integration of the sensors and conditioning electronics with garments and attachment tools, and increase the reliability of the system (by reducing the number of the components of the system). 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 [10], but such real-time applications remain rare, and lack implementation in wearable solutions, or testing in real conditions.

In this paper, we apply the concept of body area network to the field of gait monitoring, and report the development and validation of a wireless six-dimensional inertial measurement platform. First we describe the platform, including the wireless 6D-IMU hardware module and the communication protocol allowing several units to work within the same network. Next we describe the embedded implementation of an algorithm for real-time walking phase detection in the wireless modules. Finally, we conclude with the results from the evaluation of the proposed platform for wireless gait monitoring.

II. WIRELESS 6D-IMU PLATFORM

A. Naming convention

This work was performed in the context of the European project SMILING. The following name convention will be used throughout the paper. The wireless 6D-IMU module will be referred as the S-Sense (SMILING-Sense) module, the base station as the S-Base (SMILING-Base station) and the network of wireless 6D-IMU modules as the S-BAN (SMILING-Body Area Network). The user control unit will be referred as UCU.

B. System requirements

This section defines the set of functional requirements as derived in the context of the European project Smiling, assumed to be representative of generic requirements for gait analysis applications. First 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 (next generations), and provide 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.

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 placed at the back of the foot, the unit shall also detect swing and stance phases, in real-time. In the case of the European project Smiling, accurate detection is crucial as the swing/stance phase signal is used to drive the activation of a motorized system when the feet is in the air.

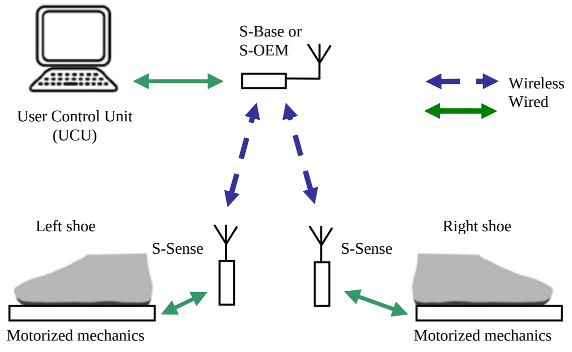

Fig. 1. Example of network configuration (European project Smiling)

Finally, an overview of the network configuration (S-BAN) for the case of the Smiling project is show in Fig. 1. In its minimal configuration, the network consists of two S-sense modules, attached to the back of each foot. A third module may be attached to the trunk, providing additional information on gait and balance of the wearer. The S-base is connected to a PC, where a user interface is implemented.

C. 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 nRF24L012.4Ghz 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.

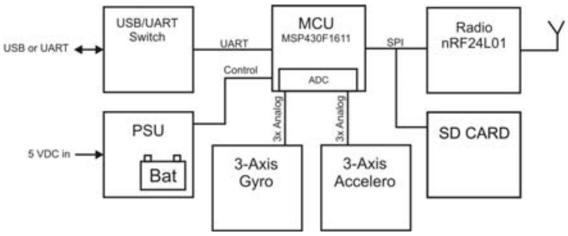

Fig. 2. S-sense block schematic

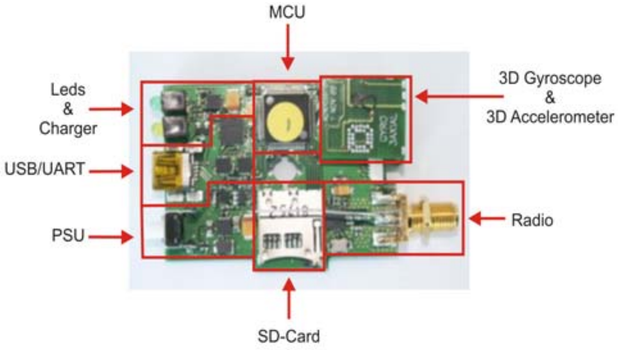

Fig. 3. S-sense printed circuit board

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.

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 which can easily be attached to any body parts. Total size of the packaged module is 57 x 41 x 19.5 mm^3.

D. 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. 4.

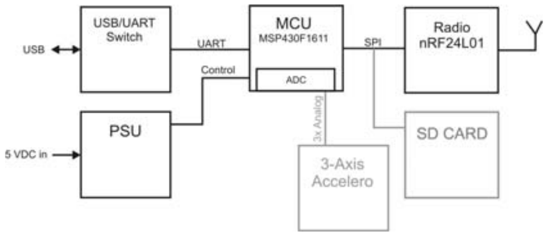

Fig. 4. S-base block schematic

E. 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
Trunk Node	Gyroscope	3	200	12	7.2
	Accelerometer	3	200	12	7.2
				Total	43.2

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. Fig. 5 shows one TDMA cycle. 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.

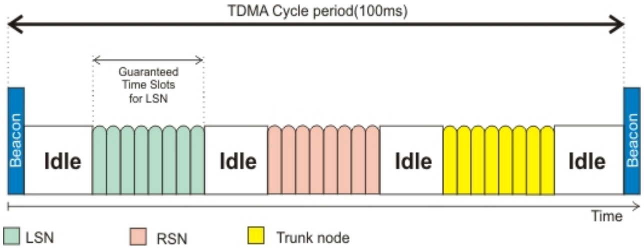

Fig. 5. TDMA Cycle

III. 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. This provides real-time access to a parameter of clinical relevance, in addition to the raw kinematic data. Information on walking phase detection can then be used as an input to an actuating device, such as a motorized system in the context of the Smiling project.

The input of the algorithm is 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, which is 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 [8] or digital filters [11], 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 [12]. 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. 6).

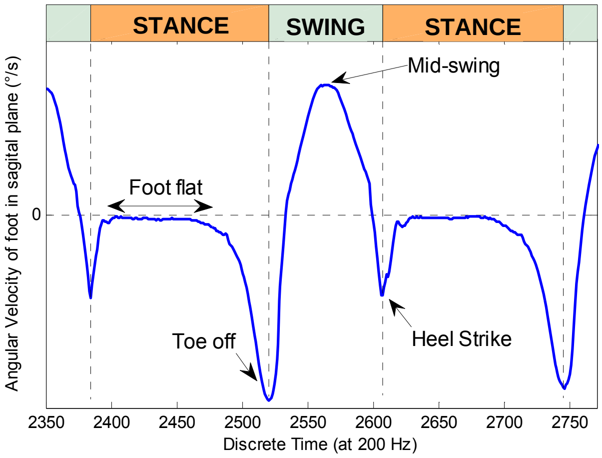

Fig. 6 Gait phases on angular velocity of foot during a normal gait cycle

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.

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. Detection results for swing phases (thus stance phases) are reported in TABLE III.

TABLE III
EXPERIMENTAL RESULTS FOR REAL-TIME WALKING PHASE DETECTION ALGORITHM AGAINST GOLD STANDARD

	Absolute Number	**Relative percentage**
Swing phases detected by gold standard	3469	100 %
Swing phases detected by WPD	3232	93.2 %
False detection by WPD	0	0 %
Swing phases undetected by WPD	237	6.8 %
… thereof at first step	57	
… thereof at last step	42	

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. Although using only a small part of the sensing possibility of S-Sense module, this application shows good performances with no false detection (specificity of 100%) and a sensitivity of more than 93.2%.

IV. PLATFORM EVALUATION

A. Evaluation Protocol

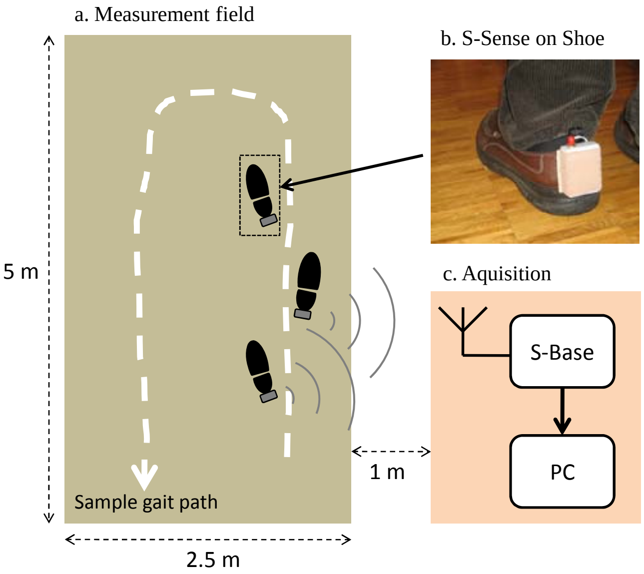

Fig. 7 Evaluation Protocol for Platform evaluation in task 1 to 3

The wireless 6D-IMU platform has been tested during a real clinical gait study involving two S-Senses and one S-Base module. Fig. 7 gives an overview of the full setup used in platform evaluation. 10 young healthy volunteers, as well as 10 fit elderly volunteers were recruited to perform various gait tasks while wearing the system attached to their own shoes (Fig. 7.b). The clinical gait study uses 6D kinematic data acquire by S-Sense modules on each foot. That protocol allows evaluating platform in its practical use, as well as its performance in streaming correctly data to the PC via wireless communication protocol for further offline processing.

Acquisition is done using receiving module (S-Base) connected via USB to a PC (Fig. 7.c). The S-Base is either placed on a fixed position on the floor at approximately 1m of the measurement field as in Fig. 7.a (task 1 to 3), or carried in order to follow subject while walking and performing a 6min gait task (task 4). Measurements were carried out in hospital environment with collaboration of CHUV in Lausanne.

B. *Experimental results*

Platform performances are evaluated in terms of loss of signal frames. Results for each task are presented in TABLE IV.

TABLE IV
LOSS OF SIGNAL FRAMES MEASURED DURING CLINICAL PROTOCOL (MEAN FOR 20 SUBJECTS)

task	**Description of task**	**S-Base**	**Frame loss (at 200Hz)**
1	side walking (S-Sense is oriented in front of S-Base)	Fixed on the floor	0.3 %
2	forward gait (S-Sense is oriented ~90° relative to S-Base)	Fixed on the floor	1.2 %
3	gait with curved path (mixed S-Sense to S-Base orientations)	Fixed on the floor	2.5 %
4	Long-term 6 min forward gait (S-Sense facing S-Base)	Following subject	0.8 %
All			**1.2 %**

Experimental results show that Platform guaranty a good overall performance to acquire 6D kinematic data (1.2 % of frame loss). Performances are even better in favourable condition (0.3 % of frame lost observed in task 1) when S-Sense is directly facing S-Base. Hardly lower performances are observed in task 3, which seems mostly due to body occlusion, as well as internal battery occlusion between S-Sense and S-Base antennas. That occurs when subject is walking toward S-Base. Another issue to consider is that frame losses can be grouped, meaning that successive frames are lost. In such case it could be difficult to interpolate the signal at instant where too much successive information is missing. This issue will be further palliated by local storage of the data in the module. In practical use, S-Sense appeared to be well accepted by patient as they are lightweight, small, and no cables are running. We have also received positive feedbacks from clinicians about the convenience of the platform (2 S-Sense + 1 S-Base) compare to already existing systems.

V. CONCLUSION

This paper reported the development and evaluation of a wireless 6D inertial measurement platform for ambulatory gait monitoring. The platform consists of a network of several S-sense wireless modules attached to different body parts, measuring, processing and sending data wirelessly to a S-base module connected to a PC or control unit. Each S-Sense module measures acceleration and rate of turn in three dimensions. System requirements, design and architecture of the S-sense and S-base modules were presented, and the wireless communication protocol was described.

An algorithm for real-time walking phase detection was developed and embedded in the S-sense module. The algorithm uses a heuristic approach based on simple features from patterns of angular velocity in sagital plane during gait. It was validated against a pressure insole system used as gold standard, on a population of 17 elderly subjects, showing a specificity of 100% and a sensitivity of 93.2%.

Finally, the proposed platform was evaluated in a real clinical gait study involving 20 subjects, to evaluate its practical use and its performance in monitoring wirelessly kinematic data from two feet. In average, the system achieved 1.2% frame losses, which is considered as satisfactory to perform off-line analysis of the data. Overall, the system was well received by patients and professionals, enhancing comfort and ease of use compared to existing systems.

ACKNOWLEDGMENT

This work was partially funded by the European Commission, under grant agreement n. 215493 (European project SMILING, 7th Framework Program).

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