Design and Development of Low-cost Smart Training Pants (STants)

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***Abstract*—This paper presents the design and development of STants, a low-cost, wearable system for monitoring lower body movements in long-term training sessions. Multiple miniaturized inertial measurement units (IMUs) are integrated into a pair of pants and socks using textile cables. This results in a light-weight and easy to use platform providing comfortableness and maximal movement flexibility for the user. A customized firmware for energy-efficient data acquisition, in addition to a selection of low-power components extends the autonomous operation time compared to traditional approaches. Power consumption and data quality (in terms of estimated joint angles) are assessed in different experiments, showing the potential use of the proposed platform within personal training scenarios.**

Keywords*—*Wearable system, Smart Training, IMU, Joint angles.

I. INTRODUCTION

Wearable systems have been applied in various studies as a convenient and efficient solution for sport activity monitoring [1]–[4]. These systems typically consist of one or more sensing units, which are attached to the body segments. By fusing and filtering the measurements and extracting higher level information, such as joint angles, kinetics and kinematics analysis of the body movements can be performed. This provides useful information for monitoring performance levels and giving suitable feedback to help users improve their technique and avoid injuries during exercising [5], [6]. Most of these systems are specifically designed for intense elite training while results of research in [7]–[9] show that non-professionals can also suffer from injuries in their everyday workout exercises. Therefore, in addition to providing precise and reliable data during training, a wearable system should be an affordable, comfortable and easy to use platform for different types of users and operate autonomously over extensive periods of time in different training situations. These requirements result in many challenges in the design of such a system. For instance, in order to estimate the joint angles accurately, multiple sensing units should be mounted on the body and connected to a controller unit for data collection and processing. This increases the overall weight and power consumption, which consequently reduces user comfortableness and system operational lifetime. Moreover, wiring complexity and large dimensions of the sensing units can negatively affect the system cost and aesthetics, and, as a result, the user acceptance. Therefore we address three important aspects in the design of a wearable training system: sensing, connectivity and power consumption.

In contrast to technologies such as laser, (infrared) cameras, UWB or RFID, IMU based motion trackers are self-contained, unobtrusive and potentially inexpensive solutions, which provide reliable measurements for motion tracking. In most of the commercial IMUs extra modules such as transceiver and battery are added to the sensing unit in order to achieve high mobility through wireless networking. However, this increases the power consumption and results in bulky packages, which can hinder the user movements during training. Moreover, such units are not suitable for integration into clothes. On the other hand, a wired networking approach, which is commonly based on star topology, adds other problems such as high complexity of connections in body area networks and low movement flexibility [10], [11].

To increase the flexibility, an alternative is to use textile cables [12]. This, in addition, facilitates the integration of connections into clothing. As another solution for more feasible integration into clothing, the use of smart textiles is evaluated in [13] and

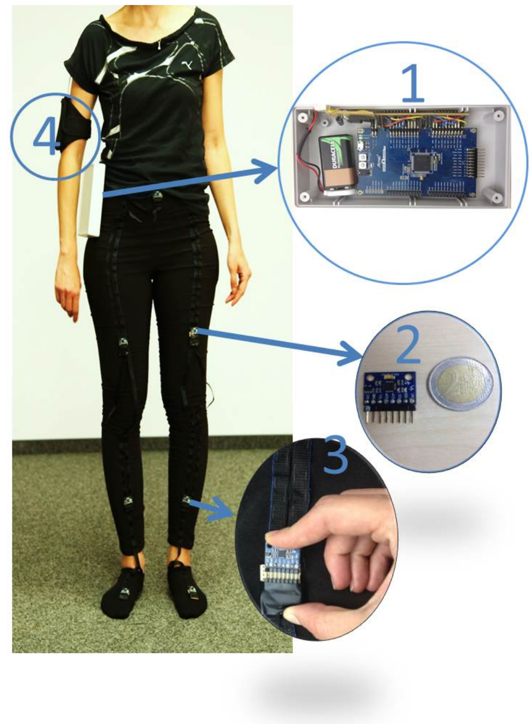

Fig. 1: STants harware components: (1) controller unit powered either by a battery or a smartphone through an OTG adapter; (2) IMU board; (3) textile cable connectors; (4) smartphone to store and/or process data.

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[14] for different types of applications including gait analysis. However, their level of accuracy is not yet meeting the high demands of sport monitoring applications. Moreover, each sensing unit needs to be sized differently for different body areas of different users [15].

Thanks to the advances in MEMs technology and embedded systems, low-power sensing and controller units are nowadays available. However, power consumption is still the main concern in the design of wearable systems, particularly portable and continuous monitoring systems. In order to reduce the power consumption an efficient approach is Dynamic Power Management (DPM) [16] in which a controller switches a module from active to sleep mode when it is unused.

There is a large number of commercial products in the growing market of wearable systems for health and fitness monitoring. These can be worn as wristbands [17], clasps [18], or in the form of clothing [19]. However, these systems provide only general information regarding the intensity and possibly the type of user activity. They do not provide the biomechanical details of body movements, due to their limited number of sensing units or the sensing technology.

In this work we present STants, a low cost, energy-efficient and unobtrusive wearable system, designed for the monitoring and support of everyday users during their daily workout. The system uses miniature IMUs, which combine inertial and magnetic sensors in a very small package. The IMUs are all connected to and powered by a central controller unit via textile cables. A low-power microcontroller is utilized, which supports different operating modes with a very low wake up time. An efficient interrupt driven data acquisition method is developed using Direct Memory Access (DMA). This highly reduces the CPU load and increases the system throughput. In order to reduce the wiring complexity, a cascaded method based on our previous work in [20] is deployed. This also reduces the CPU load by controlling the sampling of slave IMUs through master IMUs.

The paper is organized as follows: The design and implementation of the hardware and firmware are detailed in Sections II and III. The methods for data processing including joint angle estimation are summarized in Section IV. The system evaluation in terms of power consumption, weight, cost and accuracy of estimated joint angles is presented in Sections V and Section VI concludes the paper.

II. Hardware

The hardware platform uses a small-size (20 x 15 x 3 mm) and light-weight (2g) sensing unit containing an MPU9150 IMU from Invensense [21]. The controller unit is a SAM4N microcontroller from Atmel with a maximum clock frequency of 100MHz. Featuring a variety of serial interfaces, this microcontroller supports further system expansion in order to deploy different types of sensors and communication interfaces. We use an evaluation board of the microcontroller, SAM4N Xplained Pro, which includes an embedded debugger for fascilitating programming. The IMUs interface with the microcontroller via the I2C bus and the microcontroller receives interrupts from the IMUs through the GPIO pins.

The IMUs are connected to each other and to the controller using 6-wire textile cables. To reduce the effects of cross talk and high capacitance of the I2C bus, the data lines are distributed over multiple cables. The connectors for the textile cables are designed based on standard 2.54 mm pin headers for easy plugging and unplugging of the IMUs. These connectors together with the textile cables are then sewed and fixed on a pair of stretch pants and socks, making sure that the connectors provide a suitable placement of the IMUs for lower body motion capturing. The data transfer to an external processing device such as a smartphone or a portable computer, uses the microcontroller's UART interface and is currently realized via Virtual COM port and a USB cable. Figure 1 shows the hardware components of STants.

III. Firmware

The firmware consists of two main modules: initialization and data acquisition.

The initialization module detects and configures the available IMUs. For efficiently reading the measurements of multiple IMUs without adding extra components, our previously proposed cascaded approach is used [20]. This allows us to cascade two IMUs, a master and a slave IMU, and to connect two cascaded pairs with different master IMU addresses to one I2C bus. Since the used IMU provides an I2C interface with only two different configurable addresses and only two I2C buses are accessible in the current controller board, the system can support up to eight IMUs.

The data acquisition module sets the CPU to sleep mode via a Wait For Interrupt function. The firmware enables I2C data transfer on a DMA channel, when a Data Ready interrupt is received from a master IMU. Thus, measurements are transferred from the IMU to the memory while the CPU is switched back to sleep mode waiting for a Transfer Complete interrupt. This process is sequentially executed for all available master IMUs. Once the I2C transfer is complete, the UART data transfer is enabled on a DMA channel in order to transfer the data from the memory to the external device. A SysTick timer is used to prevent deadlock situations by checking the blocked data transfer processes and restarting them. A user interface has been developed for selecting among the available IMUs. This is beneficial since it enables a user to customize the system for different types of exercises.

IV. Data Processing

Assuming the IMUs to be internally calibrated, the above described platform provides 3D acceleration, angular velocity and magnetic field measurements from key positions on the body in physical units. At the same time, the targeted exercise monitoring applications typically require higher-level information such as joint angles and kinematics. Hence, we utilize a previously developed recursive filter, more precisely a set of cascaded extended Kalman filters, which deduces this information from the measurements assuming (1) a simple biomechanical body model with rigid segments connected via frictionless joints, (2) at least one IMU sitting on each rigid segment that should be tracked, (3) forward kinematics equations [20], [22]. The method has been implemented on a laptop and applied to the data acquired from the sensor platform. It is currently restricted to a lower body model comprising five rigid segments (pelvis, upper legs, lower legs) connected via three joints (hips, knees). Consequently, only five IMUs have been used for the initial evaluation results presented in Section V. However, with a maximum support of

TABLE I: Effect of using DMA and cascaded approach on the CPU processing time.

	1 IMU no DMA	1 IMU with DMA	2 IMUs with DMA	2 IMUs with DMA, cascaded
Time [us]	2646	7.77	15.4	7.84

eight IMUs and a respective extension of the method, STants enables capturing the movement of the complete lower body and torso, including ankle and chest angles. This makes it a suitable platform for monitoring and supporting various lower-body exercises, such as squats as one of the most popular.

V. Experimental results

The proposed system has been evaluated in terms of power consumption, weight and cost. Initial results concerning the precision of the joint angle estimation are also provided using an optical reference system.

A. Power consumption

In order to assess the performance of the proposed data acquisition method in reducing the power consumption, the CPU processing time and the current drain were measured in two experiments and compared with direct reading subsequently referred to as traditional method. Both the proposed and the traditional method are interrupt-driven and use the sleep mode. However, in the traditional method, at each sampling, the IMU measurements are directly read through I2C and written on the UART interface.

In the first experiment, the processing time, as one of the major factors in increasing the power consumption, was measured by counting the CPU cycles in read/write mode and dividing those through the clock speed. The results in Table I show that using DMA reduces the CPU load by 99 percent during sampling. Moreover, with the cascaded approach, one more IMU can be added without increasing the processing time by avoiding the need for switching between different I2C addresses.

For a more practical evaluation, the second experiment measures the current drain while sampling the maximum number of IMUs which the current system can support without using extra components, i.e. four IMUs using the traditional and eight IMUs using the proposed method. The results in Table IIshow that using the proposed method reduces the power consumption by 58 percent. During initialization, both methods have almost comparable power consumption. The value is slightly less for the proposed method, since it establishes connection to four IMUs on a single I2C bus, while the traditional method requires two I2C buses. The result for sampling eight IMUs implies that by using the proposed method, when extending the system capacity to support twice the number of IMUs, the power consumption is still optimized. Adding this result to the current sink of powering all IMUs (73 mA), the total power consumption of the system with 5V power supply is 414 mW. Powering the system with a fully charged iPhone 4S battery provides an autonomous run-time of four hours when sampling eight IMUs at 50Hz.

B. Weight and cost

The weight of the proposed system is compared with two commercially available inertial motion capturing systems in

TABLE II: Comparison of the CPU current drain.

	4 IMUs, sampling	4 IMUs, init.	8 IMUs, sampling
traditional method [mA]	22.6	13.2	not supported
proposed method [mA]	9.5	12.7	9.8

TABLE III: Weight comparison.

	XSENS [23]	Animazoo [24]	STants
IMU weight [g]	30	11.2	2
controller weight [g]	200	45	164
suit weight (total) [g]	965	750	453

Table III. Since the commercial systems cover the full body, the respective weights have been halved for easier comparison. The table shows that the weight of the IMUs used in STants is significantly lower than those used in other products. Moreover, the total cost of the components used in STance, including controller, eight IMUs, the required amount of textile cables and the pants, is less than 200 €, which can result in an affordable final product.

C. Joint angle estimation

The precision of the joint angle estimation method described in Section IV as applied to the measurements acquired from STants was evaluated using an optical tracking system [25]. This initial experiment was carried out with one subject performing a knee flexion and extension task over a period of two minutes. With the setup shown in Figure 3, estimates of the knee joint angles were recorded by both optical and proposed systems, while the subject performed left and right knee flexion and extension. The results are evaluated in the sagittal plane and shown in Figure 2. The root mean square error and standard deviation for the right and left knee are 6.65 ± 6.26 and 4.46 ± 3.93 degrees, respectively. The correlation coefficients are 0.987 and 0.991, respectively. The observed errors are in the range of previously proposed systems using the same type of IMUs under comparable conditions [26], however, leave room for improvement. The higher errors observed for the right joint resulted from unwanted sensor movement with respect to the body. This will be further investigated as part of our future work.

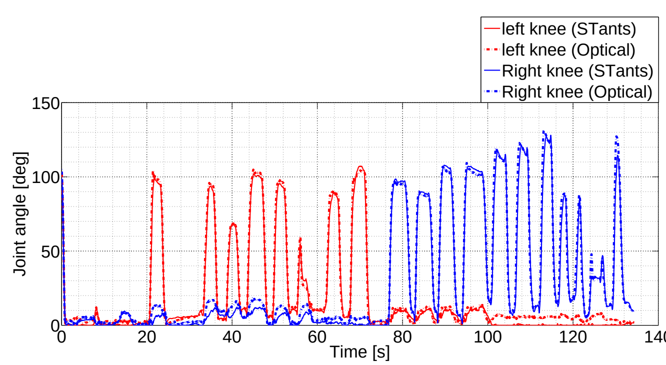

Fig. 2: Comparison of the estimated knee joint angles with an optical reference system.

Fig. 3: Setup for evaluating the knee joint angle estimation during knee flexion and extension using an optical reference system. Pairs of optical marker targets on both upper and lower legs allow for estimation of the knee angle in the sagittal plane.

VI. Conclusion

This paper presents the design and development of STants, a low-cost and unobtrusive wearable system for lower body motion capturing, designed for long-term monitoring and support of everyday users during their daily workout. The current platform combines miniaturized and energy-efficient electronic components connected via flexible textile cables and standard connectors with an energy-efficient firmware design. The result is a light-weight, configurable platform with high wearing comfort.

While the focus of this paper was on the hardware and firmware, initial experiments concerning the precision of estimated joint angles showed satisfactory results.

Besides a further miniaturization of the controller board for increased wearing comfort and the addition of a Bluetooth transceiver for wireless transmission to an external device, future work will focus on the extension, improvement and evaluation of the joint angle estimation as basis for the development of actual monitoring applications for different lower body training exercises on a smartphone.

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