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Design of UHF RFID Sensor-Tags for the Biomechanical Analysis of Human Body Movements

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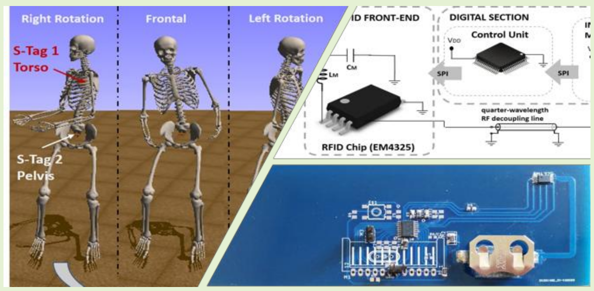
***Abstract*— This paper presents the design and the development of a Battery Assisted Passive Radio-Frequency IDentification (RFID) tag in the Ultra High-Frequency band integrated with inertial measurement unit (IMU) sensors tested for the biomechanical analysis of human body movements. Enhanced by a compact and efficient meandered Planar Inverted-F Antenna (PIFA), the device exploits a specific RFID chip having a dual-access —wired and wireless— to the memory. A properly decoupled cell battery is also foreseen to boost the chip sensitivity and to supply power to an ultra-low power microcontroller and to the sensors. The device has been realized using off-the-shelf low-cost discrete components on FR4 substrate, validated, and tested in capturing real human movements. Two sensor-tags have been applied on the pelvis and on the torso of an individual moving in front of the RFID Reader antenna. Afterward, sensor data have been collected, processed, and filtered with specific algorithms, and used to control a musculoskeletal virtual model in the OpenSense software tool. The results show that the whole system correctly reproduces the performed movements, demonstrating the appropriateness of the proposed RFID-sensor in wireless movement capture applications.**



***Index Terms*— Inertial sensors, Motion analysis, Planar Inverted-F Antenna, RFID Sensor-tag, UHF technology**

I. INTRODUCTION

Human movement analysis is a crucial task in many sectors including medicine, gaming, sport, and activities of daily living, as it allows to study the characteristics of both normal and pathological human actions [1]. Some approaches to acquire movement data are quite invasive, such as those based on stereo radiography [2], on single plane fluoroscopy [3], or in magnetic resonance imaging (MRI) [4]. Much less invasive tools are based on the placement of appropriate sensing devices —used as markers— to various body segments and the subsequent reconstruction of the movements elaborating the acquired data through a cinematic model which accounts the constrains among different rigid segments [5], [6]. It is worth observing that the sensors are not actually applied on the rigid segments, i.e. the bones, rather on the skin, and that consequently some artifacts due to skin movement can arise making the approach not suitable in some specific cases in which high precision is required and where marker-less solutions would be preferable [7]. Nevertheless, for most of the contexts, sensor-based human movement analysis is more than adequate and, in case of sensors provided with wireless interface, it becomes also easy to manage when natural patterns of movements need to be acquired. Moreover, wireless sensors have the advantage of being transportable, low-cost and low-power consuming if compared, for instance, with optical motion systems [8], [9].

As for the parameters to be sensed, inertial measurement units (IMUs) are commonly used both for movement measurement of a specific segment of the body, and for movement classification intended as gait analysis or gesture and activity recognition [8], [10].

IMUs measure and fuse the information obtained from the various kinds of sensors, such as accelerometers, gyroscopes, and magnetometers. Then, appropriate noise cancellation algorithms, such as a Mahony complementary filter [11], Kalman filter [12], frame rotation calculation, and integral operations [13], can be applied in order to estimate attitude and

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position of each sensor/segment. Even though the selection of the right sensors enables, de facto, the human movement data collection, aspects like data communication technology and usability must be considered [14]. Therefore, the individuation of the most adequate communication technology, the design of the related antenna capable of working properly despite the closeness to human skin, the optimization of the interface between sensors and radio front-end, as well as the minimization of the power consumption, represent crucial tasks. In this regard, many communication technologies are able to correctly transmit data for a few meters, including Wi-Fi, Bluetooth low energy (BLE), and ZigBee. For example, the BLE module is one of the most commonly used as it offers high spectral efficiency [10], [15], [16], whilst ZigBee technology guarantees robustness, longer ranges, and ease of use [15], [17], [18]. However, their main common drawback is the need of generating an active radio carrier with a related significant energy consumption [19], [20].

A wireless sensing device integrating a Battery Assisted Passive (BAP) Radio-Frequency IDentification (RFID) tag [21] in the Ultra High-Frequency (UHF) band with IMU sensors could solve the problem. Indeed, BAP RFID guarantees adequate working distances of the order of a few meters and, leveraging on the so-called *back-scattering modulation*, does not need the generation of a "power-hungry" radio carrier, thus allowing an extremely low-power data communication. It is worth highlighting that the use of RFID for movement recognition is not new, but at the Authors' knowledge none of the experiments reported in the literature so far is based on accurate and dedicated IMU sensors, but rather on the analysis of the signal backscattered by the tag to derive information on its position [22]–[25]. The benefit of the joint use of RFID and IMU in precise localization and movement recognition has been actually demonstrated from both the theoretical [26] and the applicative point of view [27]. Nevertheless, there is not yet evidence on the development of a single RFID-sensing device integrating IMUs and UHF RFID Tags. The closest examples are reported in [28], [29], where however a simpler sensor, i.e. a three-axis accelerometer, instead of an IMU is used. The application on the human movement reconstruction is hence unpracticable.

Specifically, in this work, a medium-range RFID sensor tag compliant with the EPC global Class-1 Generation-2 (Gen2 for short hereafter) standard and supporting IMU sensors has been designed, realized, and tested. The device exploits a proper RFID chip provided with a dual-access memory: the canonical UHF RFID wireless access for communication with GEN2 readers, and a wired serial peripheral interface (SPI) access managed by a microcontroller. To guarantee higher robustness, effectiveness, and working range, the proposed device derives power from an on-board battery to boost the chip sensitivity and to supply an ultra-low power microcontroller and the sensors. In such a context, specific electromagnetic aspects have been faced to insulate the battery from the radiofrequency (RF) circuitry and a Planar Inverted-F Antenna (PIFA) has been designed to match the RFID chip input impedance. The device has been realized using off-the-shelf low-cost discrete components on an FR4 substrate and then validated. Finally, an applicative use-case has been carried-out in which raw data coming from two novel RFID sensor-tags are collected, combined, and processed with inverse kinematics algorithms in OpenSense [30] environment to reconstruct a real biomechanical movement in terms of torso angular rotation and 3D spatial orientation.

II. Related Works

Several wireless communication technologies have been used in literature for the sensing system development. One of them is BLE which offers high spectral efficiency and moderately low power consumption [15]. Rajkumar *et al*. realized a BLE-based human movement sensing system of the upper extremity that consists of a mechatronic inertial unit including magnetometer, accelerometer, and gyroscope sensors mounted on the body with straps and a belt. This mechatronic inertial sensor for motion capture is useful in clinical applications to identify movement restrictions and to determine rehabilitative tailored treatments [16]. Another example of BLE system is presented in the paper of Liu *et al*. in which a human motion tracking device is developed. It is based on a built-in-lab micro flow sensor and a commercial inertial sensor unit (STMicroelectronics LSM9DS1). The device is validated in the detection of human limb posture [10]. Tosi *et al*. have designed a BLE-based sensor network leveraging on MEMS sensors and three different ST boards of the NUCLEO family for human motion tracking [31]. In a previous study, Qiu et al. developed three magnetic angular rate and gravity sensors to track lower limbs motion in daily activities, showing prospective of applicability in augmented and virtual reality, rehabilitation, and emergency responders [32].

ZigBee is another exploited wireless communication technology characterized by robustness and ease of use, although a limited data rate [15]. In the work of Kan *et al*. a ZigBee-based wireless inertial sensor node for body motion analysis is described. This system includes a 3-axis accelerometer, a 2-axis yaw rate gyroscope, and a modified printed inverted-F antenna [33]. Recently, Shull *et al*. used a custom-designed ZigBee-based wireless IMU sensor allowing for the estimation of trunk sway during walking and running gait [17].

RFID technology could offer several advantages in terms of cost and power consumption. Nevertheless, the experiments reported in the literature so far perform the movement analysis either through the direct processing of the signal backscattered by a standard RFID tag [22]-[25], or through simple accelerometers, instead of using accurate dedicated IMU sensors [28], [29]. In the study of Dang *et al.*, for instance, the RFID tags have been used to implement a system consisting of a 3-axis accelerometer for the detection of falling in aging population [34]. Ranasinghe *et al*. have developed a single kinematic sensor capable to identify the bed-exit and bed-entry posture transition of a patient [35]. House et al. have designed a system that tracks the location of individuals in smart-home environments using inertial navigation sensors and pedestrian dead reckoning fused with RFID tags [36]. RFID solutions have been also used by Manzari et al. to develop a system based on a motion inertial sensor; in particular, the prototype has been tested on a cashier working in a market, a person coughing, and

a pathological hands' tremor [37]. Again, Occhiuzzi et al. have developed a system based on RFID tags equipped with inertial switches to monitor limb movements during sleep [38]. Recently, a flexible UHF RFID tag with an inverted-H slot antenna geometry is proposed in [39] by Morais et al. in order to detect human body motion. The proposed geometry has a tuning capability through the variation of the slot dimensions, which allows the same overall shape of the antenna to be set for several frequencies of operation.
Concluding, none of the mentioned solutions integrates IMU and RFID tags to exploit the accuracy of the IMU sensors and ultra-low power consumption guaranteed by RFID.

III. Design of an Ultra-Low Power RFID Sensor-Tag for Biomechanical Analysis of Human Movements

As shown in Fig. 1, the core of the proposed RFID sensor-tag for biomechanical analysis of human body movement includes an UHF RF section and a digital section.

The UHF RF section is mainly designed around the EM4325 [21] augmented RFID chip. It is a BAP chip allowing a dual-access to the internal memory. On the one hand, a wireless access is guaranteed by means of a specific antenna connected to the chip RF port. On the other hand, a wired access is guaranteed by means of a Serial Peripheral Interface. The sensitivity of the chip assumes a different value depending on the use of the BAP mode rather than the fully-passive mode, in accordance with Table I. Since for this application the battery is essential in order to ensure the correct power supply to the IMU sensor, the BAP mode is to be preferred as it guarantees a sensitivity boost from -8.3 dBm to -31 dBm. Moreover, it is worth highlighting that in addition to sensitivity, the operating mode has an impact on the input impedance which varies from 23.3-j145 Ω in fully-passive mode to 7.4-j122 Ω in BAP mode. Consequently, once the conjugate matching has been designed for the BAP mode, any use in fully-passive mode would not be optimized.

From the operational point of view, the EM4325 RFID chip is provided with computational capabilities so, in addition to the typical stand-alone working mode, it can be configured to be interfaced with external digital devices, like sensors, actuators, or microcontrollers. As reported in Fig. 1, the digital section of the proposed RFID sensor-tag is composed of: a microcontroller, that manages and elaborates timing, data, thresholds; a LED for alerting purposes; and a 9-axis IMU unit for sensing the movement.

The selected microcontroller is the 16-bit MSP430G2553 from Texas Instruments [40]. This ultra-low power device can run up to 16 MHz with a supply-voltage range from 1.8 V to 3.6 V and a typical current consumption of only 230 μA in active mode. Moreover, the MSP430G2553 supports several digital interfaces (SPI, UART and I2C) useful to communicate with both RFID chip and external sensors. The considered IMU unit is the Bosh BMX160 chip which integrates a 16-bit accelerometer, a 16-bit gyroscope, and a 16-bit magnetometer. It only requires an average current lower than 1 mA to work with the considered 3V CR2032 cell battery (see Fig. 1).

In order to minimize the power consumption of the sensor-tag and to guarantee a battery lifetime of several months, advantages of the UHF RFID technology have been exploited

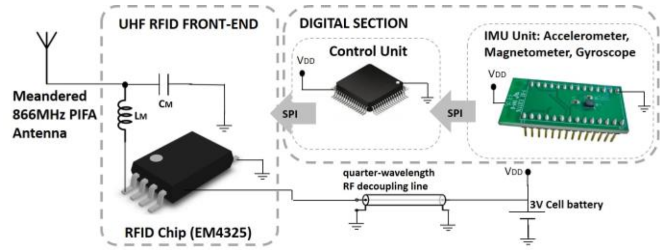

Fig. 1. Architecture of the proposed RFID sensor-tag

TABLE I.
SENSITIVITY AND IMPEDANCE IN FULLY PASSIVE AND BAP MODE OF THE EM4325 RFID CHIP

	fully-passive	BAP
Read Sensitivity $S_{chip,r}$ [dBm]	-8.3	-31
Write Sensitivity $S_{chip,w}$ [dBm]	-7	-31
Chip input Imped. Z_{chip} [Ω]	23.3-j145	7.4-j122

to develop an highly optimized firmware capable of smartly alternating active periods and stand-by periods according to a specific policy: 1) as default, the whole device is configured to be in stand-by mode (current consumption of a few microamps) with the EM4325 chip programmed to wake-up the MCU when, and only when, an RFID reader detects the sensor-tag and read the backscattered identification code; 2) if the tag is correctly detected and the reader electromagnetic signal is sufficiently "strong" (i.e., over the sensitivity threshold), the MCU is activated for a few milliseconds, just the time to acquire the 48-bit stream raw data from the IMU and write them into the volatile memory of the EM4325 RFID chip; 3) once in the memory, data are backscattered toward the RFID reader through the RF interface and the antenna; 4) the RFID reader receives the raw IMU data and the sensor-tag is automatically turned in stand-by mode with the wake-up mode activated, hence ready for the next transmission. More in general, the proposed operating mode allows for the RFID reader to fully control "on-demand" the sensor-tag by remotely setting reading time, data sampling, and then battery usage according to the specific sensing needs. Moreover, the use of this "reader-controlled" working mode along with the exploitation of the RFID backscattering modulation avoids frequent battery charging and/or replacement, typical of other conventional IoT wireless technologies, including BLE.
In addition to architecture, firmware, and working policy definition, an important effort is mandatory for carrying-out the electromagnetic design of the whole proposed solution. At this regard, an unbalanced meandered RFID PIFA, working in the RFID-dedicated European standardized band centered at 866.4 MHz, has been designed on a 13.3x6.8 cm^2 FR-4 substrate with thickness 1.6 mm. Moreover, an RF-DC decoupling circuit has been realized by adopting a quarter-wavelength microstrip impedance transformer [41]. This RF-DC separation is mandatory when augmented RFID BAP chips are powered through batteries, since power-supply tracks, once coupled with antenna and RF portions of the circuit, can seriously compromise the chip performance in terms of impedance variation, sensitivity, and ultimately, reading range. A correctly dimensioned decoupling circuit generates an hi-impedance condition in proximity of the RFID chip capable of suppressing the RF signal without impacting the DC one.

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Fig. 2 shows the CST Microwave Studio layout of both top and bottom sides of the novel RFID sensor-tag designed on a FR4 substrate (ε_r = 4.7, thickness of 1.52 mm) where both meandered PIFA antenna and quarter-wavelength transformer and digital circuit are clearly visible.

The final size of the prototype is 13.3 x 6.8 x 0.32 cm^3 (considering also the battery slot). In this regard, it is worth highlighting that, as clear from Fig. 2, the antenna groundplane is extended over the area occupied by the circuitry as a result of the CST simulation, but a further reduction is practicable by removing almost straightforwardly an area of almost 4.5 x 6.8 cm^2 without significantly affecting the radiation performance. Nevertheless, the obtained size is adequate for the validation phase described in this paper, after which a new version will be developed by deeply accounting miniaturization aspects and platform tolerance of the antenna.

Fig. 3 shows the details of the designed digital section including the RF-DC decoupling microstrip line. Finally, Fig. 4 shows the designed RFID PIFA antenna and Table II reports the related dimensional parameters obtained after a CST Microwave Studio simulation and optimization at 866.4 MHz.

Once designed, the proposed RFID sensor-tag has been preliminarily prototyped as a development board connected to the external BMX160 IMU board (Fig. 5) and then tested with the aim of validating electromagnetic antenna performance, other than sensing and reasoning capabilities in a realistic situation of biomechanical human body movements reconstruction.

IV. Results: RFID Sensing System Validation

In this Section, results related to the electromagnetic validation and testing of the proposed RFID sensor-tag for human movement sensing are reported. All the simulated outcomes have been performed by using *CST Microwaves studio*, whilst measurement results have been obtained with the dedicated measurement setup described in [42]–[44]. It is based

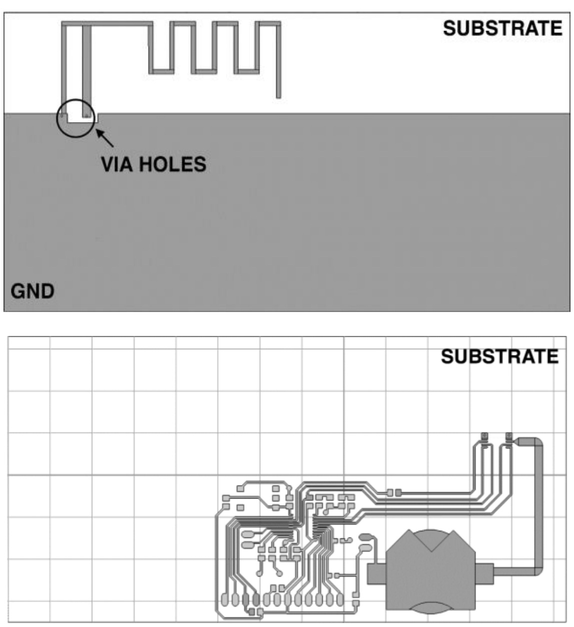

Fig. 2. Top (a) and bottom (b) layers of the proposed sensor-tag. Dimensions: 13.3 x 6.8 x 0.32 cm^3 (with battery-slot).

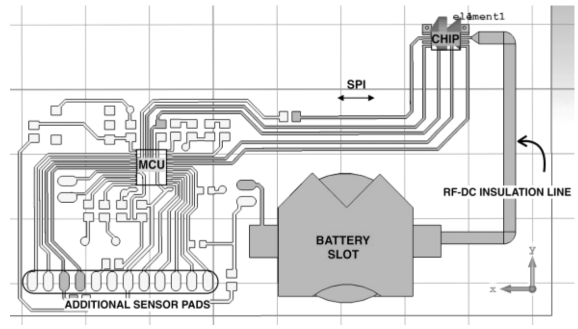

Fig. 3. Digital section of the novel RFID sensor-tag with the detail of the RF-DC insulation quarter-wavelength transmission line.

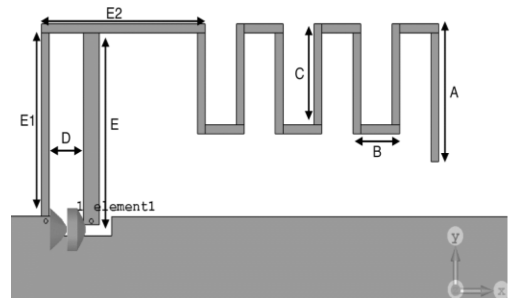

Fig. 4. Dimensions and parameters of the proposed meandered PIFA tag antenna

Table II.
Meandered PIFA Antenna Optimized Parameters

A [mm]	B [mm]	C [mm]	D [mm]	E [mm]	E1 [mm]	E2 [mm]
16.5	6	10	3.85	20.9	20	21

on a programmable RFID reader, the ThingMagic Mercury 6e (M6e) [45], which is connected to a circularly polarized antenna with known gain (5.1 dBi). The system can vary both emitted power (up to 31.5 dBm), frequency (in the range 860-928 MHz) and tag antenna angular position. In this way, for each selected frequency and/or tag angular position, the system automatically evaluates the power threshold at the reader stage, which is the minimum power emitted by the reader capable of switching on the tag placed at a certain and known distance. As discussed in [26], such a tag activation power threshold can be used to derive the frequency-dependent sensitivity of the tag, which accounts the sensitivity of the chip and the tag antenna radiation pattern. As for the simulated results, Fig. 6 shows the antenna return loss (Fig. 6a) and radiation pattern (Fig. 6b). A return loss lower than -45 dB has been obtained at 866 MHz with a bandwidth ranging between 855 MHz and 876 MHz.

The radiation pattern exhibits a -3 dB angular width of 102 degrees on the horizontal plane (x-y plane of the antenna reference system in Fig. 4) and of 90 degrees on the vertical plane (x-z plane of the antenna reference system in Fig. 4). Finally, an appreciable simulated antenna radiation efficiency of -1.2 dB has been obtained, as well as a maximum directivity of 2.72 dBi. Note that the radiation pattern is expressed in terms of realized gain normalized with respect to the maximum obtained gain of 1.52 dBi with the aim of making straightforward the graphical comparison with the measured radiation pattern, evaluated with the method reported in [26]. In this regard, Fig. 7 shows both the planes of the antenna

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measured radiation pattern considering the same reference system used for the simulated one. The very good agreement with the simulated radiation pattern of Fig. 6b can be appreciated, thus confirming that the realized antenna is actually well performing as desired. In addition, the tag sensitivity has been also evaluated. As clear from Fig. 8 (where the tag sensitivity is reported for both European and USA bands) a tag sensitivity of -24.38 dBm has been measured at 866MHz. This sensitivity value corresponds to an estimated maximum reading range of about 13 m when a power of 2 W ERP is used at the reader stage. It is worth highlighting that this working range is the maximum one when the tag is in free space and it is reduced at about 9 meters when the tag is close to the human body. However, the working range is suitable for indoor applications with reference to the one addressed in this work and related to the human movement sensing.

Besides the electromagnetic performance evaluation of the proposed sensor-tag, a further analysis has been performed to estimate the power consumption of the whole sensing solution. Since the tag is battery-assisted by a cell coin battery, a model estimating the tag battery lifetime in a realistic use case has been developed. This power consumption model considers the maximum power that a single component dissipates for each working profile: active mode and standby mode. Being the components powered by the same supply source, at a fixed voltage of 3 V, currents have been considered instead of powers. The current consumption has been measured for each component by using a low-value shunt resistor of 1 Ω (tolerance 0.5%), in series with the component under test, connected to the probe of the digital oscilloscope.

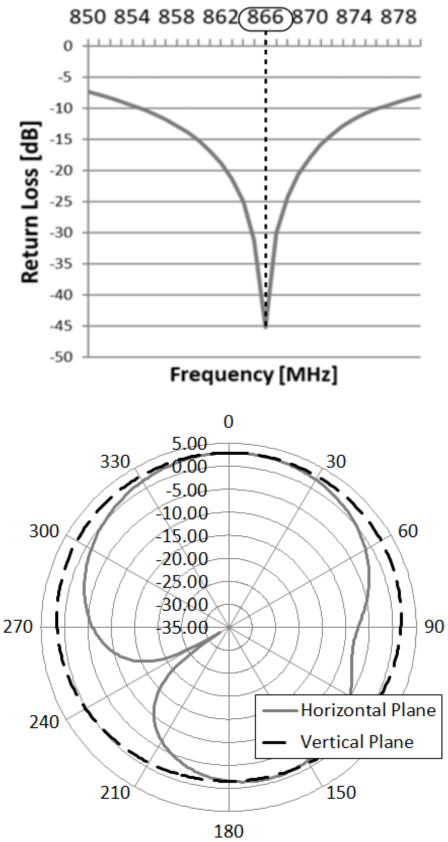
The results show that the EM4325 RFID chip drives an average current of 1.8 μA in sleep mode and of 6.2 μA in active mode.

a)

b)

c)

Fig. 5. Top a), bottom b), side c) view of the prototyped sensor-tag connected to the external BMX160 IMU board



a)

b)

Fig. 6. a) Meandered PIFA antenna return loss, b) simulated Meandered PIFA antenna radiation pattern on horizontal plane (x-y plane of the antenna reference system in Fig. 4) and vertical plane (x-z plane of the antenna reference system in Fig. 4).

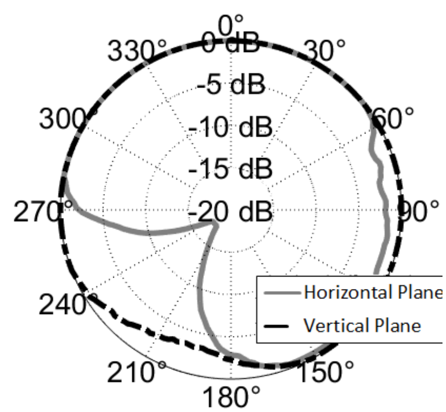
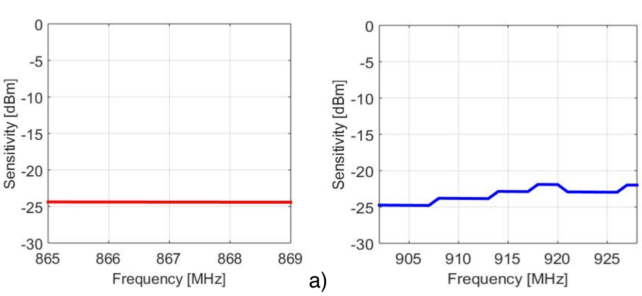


Fig. 7. Measured PIFA antenna radiation pattern on horizontal plane (x-y plane of the antenna reference system in Fig. 4) and vertical plane (x-z plane of the antenna reference system in Fig. 4).



a) b)

Fig. 8. Measured Tag Sensitivity in the European a) and USA b) RFID dedicated band.

The measurements confirm the good agreement with the data reported on the datasheet of the component, where 1.7 μA and 6 μA are declared for sleep and active mode, respectively. The MSP430G2553 MCU exhibits a measured current consumption of 362 μA at 1 MHz in active mode and of 0.55 μA in standby mode. Even in this case a good agreement with the related datasheet current values, of 330 μA at 1 MHz in active mode and of 0.5 μA in sleep mode, can be observed.
The obtained results are also useful to demonstrate the effectiveness of the RFID technology in terms power saving if compared with other wireless technologies based on active radio front-ends, such as BLE, Wi-Fi and ZigBee. Indeed, apart from the IMU consumption (which is in common), the active current consumption is almost 15 mA for BLE, reaches peaks of 50 mA for ZigBee and even of 230 mA for Wi-Fi, with a typical sleep current consumption of 10-100 μA. Consequently, in a typical scenario where a 225mA/h cell battery is used to transmit 10 sensor data per second, the battery lasts 2 days with Wi-Fi modules, a few months with ZigBee and BLE radios, and a couple of years with RFID BAP devices. In addition to the cost of the RFID BAP tags, which is almost ten times lower than other active devices, the reduced power consumption makes the RFID solution suitable for the specific application.

Once validated and tested in terms on power consumption, the novel RFID sensor-tag has been calibrated to sense real movements on the three axes. The calibration procedure has been performed at firmware level by using known reference positions and by tuning specific coefficients to compensate any possible deflection. Then, the tag has been placed in front of an active ThingMagic M6e Reader and a simple rotation movement of about 80 degrees toward the x axis has been performed and "registered" through a properly developed Matlab tool connected to the Reader application. For the sake of clearness, the same three-axis system of the BMX160 IMU board has been considered to perform this test [46]. Fig. 9 shows the raw data describing the performed movement as collected by the software system in terms of angular velocity, acceleration, and magnetic flux along the three axes, namely *X, Y, Z* in Fig. 9. It is worth highlighting that data reported in this figure demonstrate that each single sensor of the IMU unit measures and transmits the sensed raw value toward the RFID hardware and software infrastructure. If singularly considered, these values are not adequate to describe the physical movement of the sensor-tag in terms of three-dimensional rotation angles. A software elaboration in terms of data fusion is then mandatory. Fig. 10 shows a graph related to the rotation movement around a fixed axis in terms of Euler angles after the performed data fusion. Indeed, this result is obtained by elaborating in Matlab the raw IMU data of Fig. 9 through the Madgwick AHRS algorithm [47] and through an articulated procedure that takes into account mathematical transformations such as rotation matrixes and quaternions. In the graph of Fig. 10 it can be observed that, after almost ten seconds necessary to the Madgwick algorithm to reach the convergence, the tag position is kept constant for a few seconds (the three graphs are almost flat) and then it is turned of almost 80 degrees only along θ, with smaller variation along Ψ and Φ substantially due to the natural oscillations during the movement.

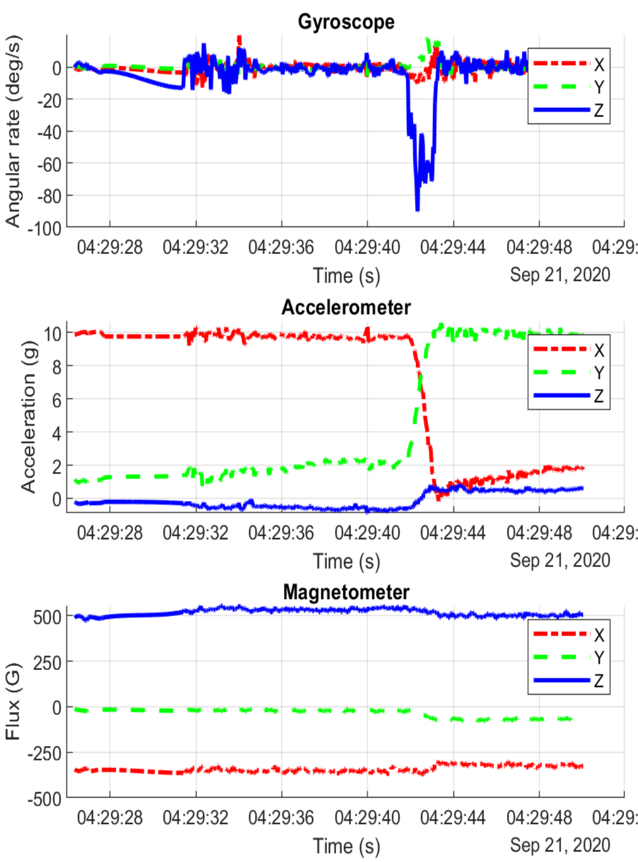


Fig. 9. Raw sensor data of angular velocity, acceleration and magnetic flux captured by the novel RFID sensor-tag for as simple rotation movement along the sensor x axis.

V. Test Case on Human Movement Reconstruction and Virtual Model Visualization

In a further test case, the sensor data received by the RFID reader have been processed and filtered with specific inverse kinematics algorithms and used to control a virtual subject in OpenSense platform to verify the adherence with the performed movements. OpenSense is a tool incorporated in OpenSim desktop application, an open-source software package with a robust application programming interface used for computational modeling and simulation of biomechanical systems [48]. In this context, Rajagopal et al. created a biomechanical model implemented in the OpenSim platform [49]. This model, derived from the lower body model developed by Arnold et al. [50] and the tracking upper body by Hamner et al. [51], is used in dynamic simulations of human movements. It is realized on healthy young individuals and includes bony

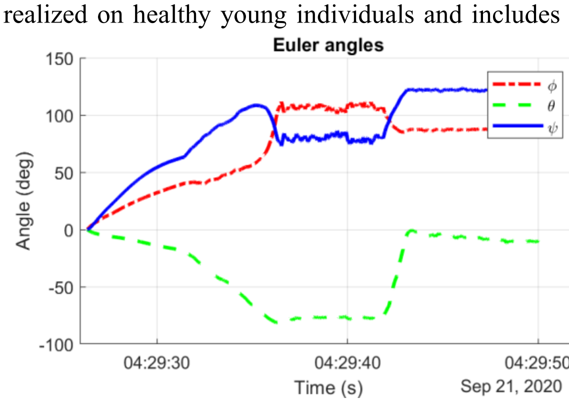


Fig. 10. Description of the RFID sensor-tag performed movement after data fusion.

geometry for the full body, 37 degrees of freedom to define joint kinematics, 80 muscle-tendon units actuating the lower limbs and 17 torque actuated upper bod. It can generate muscle-driven simulations of gait within a few minutes on a common PC [49]. The workflow of OpenSense can be summarized as follows:
1) collection of sensor data; 2) conversion of IMUs data into a format that can be read into OpenSim and processed with the OpenSense workflow; 3) calibration of the OpenSim model (as an IMU Frame); 4) computing inverse kinematics to track orientation data from IMU sensors; 5) visualization of the results of IMU tracking (model visualizer and motion) using the OpenSim application (GUI) visualizer [30].
Based on this workflow, a test-case aiming at virtualizing a biomechanical movement of the torso of an individual has been performed. In this regard, a specific setup has been implemented and reported in Fig. 11. First, two RFID IMU-equipped sensor tags have been applied on the pelvis in proximity to the sacrum (reference point) and on the torso of an individual by guaranteeing the adherence with the body. Second, at the system level the RFID M6e reader equipped with a 5.1 dBi-gain antenna has been physically connected to a PC to collect sensor data coming from the tags at an average data rate of about 25 samples per second (depending on the standard Gen2 protocol timing and collision avoiding mechanisms [52]). A properly designed Matlab tool has been used to retrieve Reader raw data, to interpolate them, and to perform oversampling at exactly 100 samples per second. The Matlab tool also implements data fusion by using the Madgwick AHRS algorithm and calculates the relative rotation angles for both tags. In addition, the tool is interfaced with the OpenSense libraries in order to control the human body inverse kinematic model (IK-model) and to animate the virtual musculoskeletal model (virtual subject) reported in Fig. 12. As for the test execution, the individual has been asked to rotate the torso from right to left in a way as natural as possible. This action has been then sensed, recorded, and elaborated by the system. Fig. 12 shows three of the about 500 generated frames describing the performed 5-second movement. As clear from the figure, the torso rotating movement is recorded, identified, and virtually reproduced by the novel developed RFID system. It can be noted, for instance, that the system is also able to recognize a displacement of the pelvis and a lowering of the right shoulder, which actually occurred during the execution of the movement.

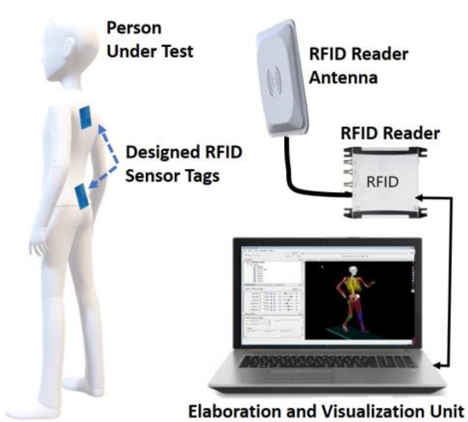


Fig. 11 Graphical configuration of the RFID system setup to reconstruct human movements through Matlab and OpenSense software tools.

Results confirm that the proposed approach offers a valid way to perform a reliable biomechanical analysis of human body movements based on novel ultra-low power RFID sensing devices. Besides the low power consumption, advantages of the system in tracking body movements are scalability, easiness of use, low functional interference with real movements (due to the possibility of future miniaturization), the opportunity to integrate additional sensors to measure health parameters or to compare some quantities measured on the body with the same quantities measured on the environment. Again, the possibility to capture natural gestures without any distraction for the subject open the ways to several applications fields (posture and movement analysis, exercise and position feedback), also remotely, in different fields, such as workplace posture and ergonomics, frail subjects monitoring, physiotherapy rehabilitation, sport training.
As a future work a systematic analysis of different biomechanical movements performed by different individuals is foreseen, including the exact 3D orientation evaluation and the comparison with the output data produced by vision systems recording the moving subject.

VI. Conclusion

In this paper, a medium-range RFID Battery-Assisted Passive sensor tag mounting a 9-axis IMU sensor and designed for sensing biomechanical movements of the human body is presented. This device exploits the EM4325 RFID chip having a wired SPI memory access, managed by a microcontroller, in addition to the canonical wireless access for communication with GEN2 readers. The device derives the power from an on-board battery to boost the chip sensitivity and to supply the power both to the ultra-low power microcontroller and the sensors. Furthermore, a meandered Planar Inverted-F Antenna has been designed in order to guarantee proper working and tag efficiency. Next, once the antenna is electromagnetically validated and the system capability of sensing and backscattering Inertial Measurement Unit (IMU) data is proven, two sensor-tags have been realized and applied on the pelvis

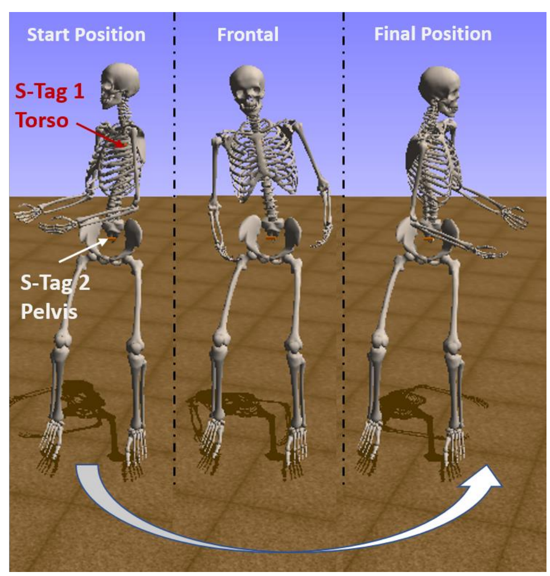


Fig. 12. Sequence of the reconstructed movements related the virtual subject implemented in OpenSense software tool.

and on the torso of an individual moving in front of an RFID reader antenna. These data have been "fused" and used to control a virtual subject in OpenSense platform to verify the adherence with the real movements. The obtained results show that the whole system correctly recognizes and reproduces the performed movements, demonstrating the appropriateness of the proposed RFID-sensors in wireless movement capture.

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