FrailWear: A Wearable IoT Device for Daily Activity Monitoring of Elderly Patients

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***Abstract*— This paper introduces an IoT *wearable*, specifically designed for the analysis of the physical activity of elderly people, in order to provide objective information to the healthcare staff to assess the frailty in these patients. The device, called FrailWear, is based on a STM32 low cost, low power and high-performance microcontroller. It is a multisensory system that includes an IMU and atmospheric pressure sensor for collecting data. In addition, it is possible to obtain the centimetric-accuracy position of the patient, if the infrastructure includes an external ultrasonic local positioning system. The *wearable* also includes a LoRaWAN based architecture, to communicate the system and the cloud, where the acquired data will be stored for a later analysis. Both physical activity and localization information are obtained, able to be analysed in real time or to be requested on demand by the carers. First test results of FrailWear are very promising and show its feasibility for this application.**

Keywords—STM32, IoT, LoRaWAN, Frailty

I. Introduction

In recent years there has been an increased interest in monitoring people of all ages. This increase has been particularly noticeable in the use of *wearable* devices, such as smart watches or activity bracelets, which provide information on steps, distance travelled, calories consumed, etc. With the increasing age of the population, the need to design devices and applications for monitoring the health of these populations emerges with different objectives, as to provide telecare assistance, to improve their quality of life as well as to keep their independence.

Frailty is a multifaceted condition that decrease functional reserve capacity in different organ systems, leading to a number of adverse health outcomes, including disability, falls, hospitalization and death. This situation has a direct influence on their level of dependence. In other words, an independent person who can lead a normal life can become dependent by reaching a state of frailty. With the increase in life expectancy, it is considered a priority to develop systems that allow older adults to prolong their level of independence, since in addition to improving their quality of life, social expenses are reduced. Therefore, early detection of a person state of frailty is important and studies [1] show that following certain behaviour patterns and healthy habits (related to their physical activity) can improve or even reverse this state of frailty.

Currently, most of studies propose to perform physical tests of elderly people using inertial sensors located in different parts of the body [2][3], in order to provide information for the frailty assessment. A previous work shows that placing an inertial system on the patient's ankle provides accurate information about distance travelled and walking speed, that are valuable data for frailty assessment [4]. Some recent studies try to find the relationship between frailty and the patients location routine (time in different rooms such as the kitchen, bedroom, dining room, etc.). They conclude that there is high correlation between localization and frailty [5].

Then, it is not only important to measure the patient physical activity, but also to get patient routines related to localization. People spend most of their time indoors, so technologies for tracking or locating them indoors are emerging, as GNSS signals have limitations in these spaces. The main technologies for indoor location are UWB, ultrasound, cameras, ... [6]. There are works that show the use of these technologies applied to the location of elderly people, but mainly based on obtaining a symbolic position at room level using WiFi or Bluetooth [7][8].

As far as we know, there is not a *wearable* that can simultaneously provide information about physical activity and accurate positioning of the person, to correlate both types of information with the person daily activities. This work introduces a *wearable* designed by the authors, the FrailWear, that provides very useful information for the objective assessment of frailty and can be used either by individuals living alone or in elderly homes. The goal is for the system to be part of a community of "things".

The rest of the paper is organized as follows: Section II introduces the global required system for the activity monitoring; the hardware of the FrailWear device is described in-depth in Section III; Section IV shows the preliminary results; and finally, conclusions and future work are derived in Section V.

II. Global System Overview

The global system consists of an external infrastructure and the FrailWear device. The external infrastructure is an ultrasonic indoor local positioning (ULPS) system for providing absolute localization. All the information is stored on the cloud through a LoRaWAN Network architecture (Gateway 868MHz). Fig. 1 shows an overview of the global system. Next subsections introduce each subsystem.

A. FrailWear device

The FrailWear device is a wearable multi-sensory system as it will be described in next section. One of the sensors it integrates is an inertial measurement unit (IMU) that enables to record physical activity data of the person that carries the

978-1-7281-9132-4/20/$31.00 ©2020 IEEE

device and provides relative localization. Thanks to these data, through the appropriate processing, it can be obtained relevant information about the level of frailty of the patient [1]. In order to obtain the best results, it should be placed on the patient's ankle[4], although other positions are feasible. In addition to collect sensor data, FrailWear is able to do a pre-processing and to send the data to the cloud for an in-depth further analysis.

In summary the FrailWear consists of three blocks: the main board where the microcontroller and most of the components are located, a second board based on an IMU for relative localization and for measuring patient's physical activity, and finally a third board with an ultrasound receiver that can be freely allocated on a different body part, and it is used to get indoor absolute localization.

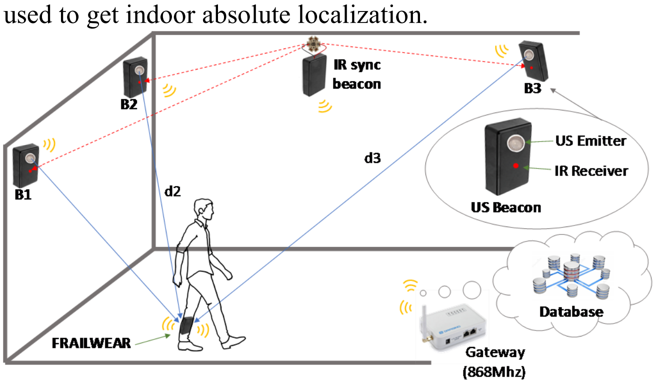

Fig. 1. Diagram of global system, including an ultrasonic local positioning system.

B. *Indoor Local Positioning System Infrastructure.*

In addition to the inertial measurements that can collect the FrailWear device, it is able to perform accurate or symbolic location of the person through a local positioning system that should be installed in the environment. We have developed an acoustic local positioning system based on encoded ultrasound emitting beacons (ULPS) [9]. As ULPSs are restricted to a room, a synchronization beacon must be installed per room. In this case an IR (Infrared) link marks the start of emission of the ultrasound beacons, as well as the start of acquisition of the ultrasonic signal received that integrates FrailWear. This synchronization enables the system to provide a very accurate positioning, both room level or centimetric accuracy. This positioning can be very useful to provide additional information about activity daily routines [1].

Fig. 2 depicts the block diagram of the designed ultrasonic encoded beacon (based on *Kasami* encoding codes and a Cortex-M3 microcontroller) with IR link for synchronization. Fig. 3 shows one of the beacons that is used in the ULPS.

C. *LoRaWAN Network Architecture.*

For transmitting the data to the cloud, we have proposed the use of LoRa. In the environment it is necessary to install a LoRaWAN gateway, in this particular case the Lorix One model is used [10], with a wide coverage, from 2km in urban scenarios to 12km in rural ones. The FrailWear requires the software Lora packet forwarder [11], to send or receive data and thus connect it to the ChirpStack Network Server that is installed in a virtual machine hosted in AWS (Amazon Web Services) [12]. The data is stored in InfluxDB, a time series database optimized for the IoT. Fig. 4 shows the scheme of the implemented LoRaWAN network architecture.

This work has been supported by the Projects: FrailCheck (SBPLY/17/180501/000392), MICROCEBUS (RTI2018-095168-B-C51) and PUILPOS (CM/JIN/2019-038).

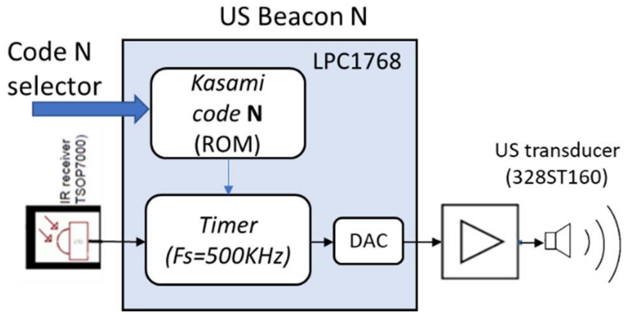

Fig. 2. Block diagram of an encoded ultrasonic beacon with infrared synchronized emissions.

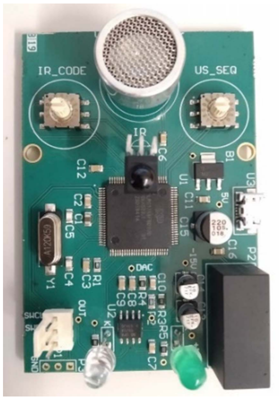

Fig. 3. Aspect of encoded ultrasonic synchronized beacon.

D. *LoRaWAN Network Architecture.*

For transmitting the data to the cloud, we have proposed the use of LoRa. In the environment it is necessary to install a LoRaWAN gateway, in this particular case the Lorix One model is used [10], with a wide coverage, from 2km in urban scenarios to 12km in rural ones. The FrailWear requires the software Lora packet forwarder [11], to send or receive data and thus connect it to the ChirpStack Network Server that is installed in a virtual machine hosted in AWS (Amazon Web Services) [12]. The data is stored in InfluxDB, a time series database optimized for the IoT. Fig. 4 shows the scheme of the implemented LoRaWAN network architecture.

III. Hardware FrailWear Description

The selection of the components that integrate the FrailWear device constitutes an important aspect of the design phase, as they have to meet a set of characteristics necessary to measure the parameters associated with physical activity: computation capacity, wireless communication and low power consumption.

Fig. 5 shows the block diagram of the FrailWear device and Fig. 6 the real prototype implemented. The main core of the device is a Cortex-M4 processor. It reads through I2C and SPI buses the information of digital sensors. It is particularly distinct its capability to acquire the ultrasonic signals from the beacons through a microphone, to decode the information and to process it to autonomously provide 3D positioning. At the same time, it is continuously recording a log of all the parameters obtained on a microSD memory card for further analysis. LoRa technology allows long-range, low-power wireless communication with a central station through a gateway under the LoRaWAN standard, in the 868 MHz band. Next subsections describe the main components that have been integrated in the design.

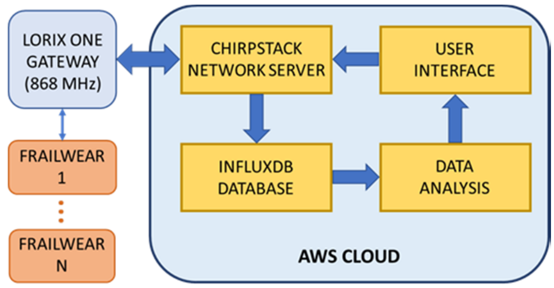

Fig. 4. LoRaWAN network architecture implemented.

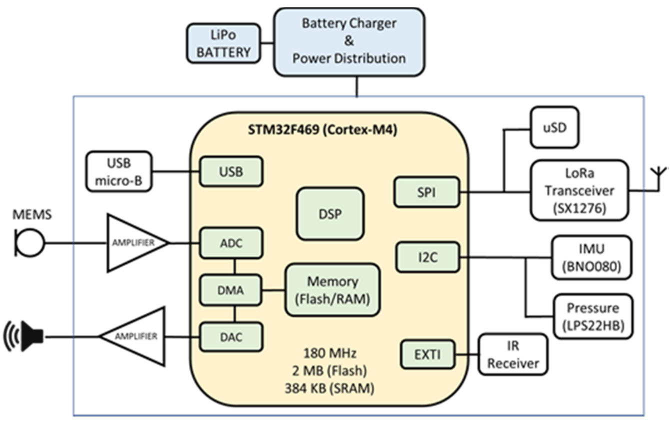

Fig. 5. Block diagram of FrailWear.

Fig. 6. Real prototype.

A. Microcontroller Unit.

The main processing unit of FrailWear is a 32-bit STM32F469 [13] microcontroller of *STMicroelectronics*. It is based on ARM Cortex-M4 core and provides a good trade-off between power consumption, performance and cost. This device is operating at up to 180 MHz, using a High-Speed External (HSE) crystal of 8 MHz. Also, a 32.867 kHz Low Speed External (LSE) crystal is used to generate a 1 Hz signal internally to feed the RTC (Real Time Clock). Although it has different peripherals, we have only used for this application the SPI, I2C, Timers, ADC, DMA, DAC and RTC.

Due to the task of decoding the ultrasonic emissions and generating localization information, the application requires memory to work with large floating-point buffers. The selected microcontroller has 2 Mbyte Flash memory and 384 Kbyte SRAM memory.

In addition, the core integrates DSP (Digital Signal Processor) and FPU (Floating-Point Unit) capabilities to execute high performance instructions, as some mathematical operations. The programming is based on function library provided by CMSIS (ARM Cortex Microcontroller Software Interface Standard) [14].

B. Power System.

The power system includes a 1-cell LiPo (Lithium Polymer) battery, a battery charger and a low-dropout (LDO) regulator. All chips are powered by SPX3819 [15] LDO output at 3.3V.The battery has a capacity of 2000 mAh and has a built-in protection circuit to prevent damage to the battery. It includes over charge and over discharge protections. The circuit stops the charging process if the battery voltage reaches 4.2 volts and cuts off the voltage output if the battery voltage drops below 2.4 volts. The TP4056 [16] chip is used to charge the battery as the input voltage is provided by the microB USB port. The maximum charging current is set with an external resistor, and in this case, it is selected to charge the battery up to 1 A. To estimate the remaining battery capacity, a resistive divider is implemented whose output is digitalized by an ADC of the microcontroller.

C. Pressure Sensor.

The barometer is used to provide information about the floor changes of the patient. It is based on the LPS22HB [17] from *STMicroelectronics*. It is a high-resolution MEMS nano pressure sensor with absolute digital output. The sensor can measure pressure variations in the range of 260 hPa to 1260 hPa. It has an accuracy of ±0.1 hPa, which is equivalent to about 10 cm in vertical resolution. The power consumption is 1 μA in the low power state and when operational about 12 μA. It communicates with the microcontroller through the I2C bus in the 400 kHz fast mode although it is also compliant with the normal 100 kHz mode.

The atmospheric pressure reading is obtained with a resolution of 24 bits. The data output rate can be configured at different frequencies, which are 1, 10, 25, 50 and 75 Hz, also a single shot measurement can be made. Internally it has a low-pass filtering and oversampling can be selected to obtain a better quality in the measurement. In addition, a 12-bit resolution temperature sensor with an is integrated in the chip, providing an accuracy of 1.5 ºC. This temperature value is used later to have a better accuracy when calculating the ToF (Time of Flight) of the ultrasonic signals.

D. Inertial Measurement Unit.

The BNO080 [18] is a System in Package (SiP) developed by *Bosch* and *Hillcrest Labs* that is used as the Inertial Measurement Unit of FrailWear. It integrates an accelerometer, gyroscope and magnetometer, all with three axes. Furthermore, it features a low-power 32-bit ARM Cortex M0+ microcontroller that implements high-level algorithms in a way to reduce the computation load of the main microcontroller. This information is relevant since it can be used as a classification system for the physical activity of the patients without the need of specific software.

It autonomously provides a step detector, a step counter and an activity classifier, that allows to have information about the activity status of the patient. It is possible to distinguish among different states: standing, walking and running. Another feature when programming the activity classifier is that it is possible to choose different sensor fusion schemes to provide better results of the detection of the activities.

Finally, it is important to mention that the IMU subsystem has been implemented on a dedicated board, that communicates with the core at 400 kHz through I2C. This allows it to be placed at anywhere but following the manufacturer reference for getting correct results with the algorithms.

E. *Ultrasonic Acquisition System.*

To estimate the absolute position, it is necessary to acquire the ultrasonic signals emitted by the beacons. For this purpose, a MEMS microphone is used which transforms the mechanical variations of the air into voltage magnitude. SPU0414HR5H-SB [19] is a miniature, high-performance and omnidirectional microphone. It has a built-in amplification and high-pass filtering stage, whose parameters are set with an external resistor and capacitor. The configured values are a gain of 20 dB and a cut-off frequency of 19.77 kHz. The microphone is mounted on an external board in order to place it on a location where the best ultrasonic coverage is achieved.

As the output voltage of the microphone is in the millivolt range, we use an amplification stage based on the operational amplifier OP184 [20], with a high bandwidth. It is used with a programmable gain modified by software, with a maximum gain of 500 V/V. The system gain is controlled by a software programmable resistor MCP4161 [21]. The purpose of the amplifier stage is to adjust the signal amplitude to the dynamic range of the microcontroller ADC.

F. *Radiofrequency Section.*

In order to provide external communications, the device integrates LoRa technology (see Fig. 7). For this purpose, the SX1276 [22] chip is used, a series of passive components to implement filters and impedance matching and a radio frequency switch. The design is based on the SX1276MB1MAS [23] board provided by Semtech.

The PE4259 [24] RF switch is controlled by a microcontroller digital output to allow input to the SX1276 or output from it.

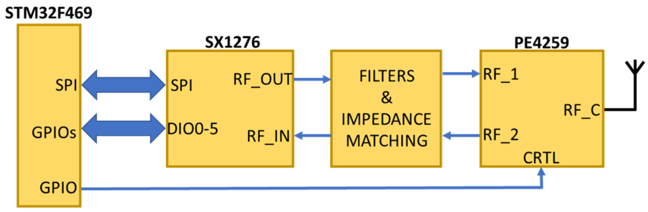

Fig. 7. Block diagram of the radio frequency section.

It is used an external helicoidal antenna adapted to the frequency of 868 MHz, which is connected to the PCB with a UFL connector. This allows it to be placed in the desired location in the case. The complete radio frequency system must be adapted to an impedance of 50 Ω.

The software that requires the LoRa module is based on the libraries provided by *STMicroelectronics* in the I-CUBE-LRWAN [25] software package. With these libraries all types of LoRa classes (A, B and C) can be implemented, although in this work only class C is used. Only class C allows to interrogate the receiver at any time to request data.

G. *Audio Messaging System.*

The system has the functionality of reproducing pre-recorded messages with the purpose of alerting the patient of events that may occur, such as excessive sitting time. Additionally, the supervisor may request the reproduction of a message, for example in an elderly care home, to request the patient to come to a certain room.

A series of messages are recorded at a sampling frequency of 8 kHz, digitalized into 8-bit samples and stored in Flash memory. These samples are sent via DAC and DMA to the input of audio amplifier. TPA301 [26] amplifier has been chosen because it has a BTL (Bridge-Tied Load) architecture which reduces the number of external components. It delivers 250 mW continuous power into a 8 Ω load with less than 1.3 % THD (Total Harmonic Distortion) while operating from a single 3.3 V supply. In addition, it has a pin to set the device to a low consumption state that is controlled by a digital output of the microcontroller, reducing current consumption to 0.15 µA.

H. *Infrared Module.*

TSOP7000 [27] infrared receiver from *Vishay* and works at a 455 kHz frequency. It is used to synchronize the whole ultrasonic positioning system. To obtain a symbolic location at a room level accuracy, the signal emitted by the synchronization beacon is encoded with an 8-bit code. This allows the room where the patient is located to be uniquely differentiated as the infrared signal is confined within the walls.

I. *Data Storage.*

The system includes a slot for a micro SD memory card. A FAT32 file system has been implemented with the aim of storing information for a later analysis. The reading/writing operations are performed through the SPI interface. To do this, a protocol specified in [28] must be followed, where an initialization at a low frequency (400 kHz) must be done and then data transfers can be made at the SPI bus clock signal of 25 MHz. Although the memory capacity is limited to 32 Gb, it is enough to continuously store the generated data for several days.

IV. Implementation and Experimental Results.

This section introduces a series of practical tests carried out to evaluate the performance of the device sensors. It also explains the configuration and the steps to be followed to obtain the information. The tests are realized in a delimited environment, where the ground truth for positioning is known.

A. *Pressure sensor tests.*

The atmospheric pressure sensor is configured with a data output rate of 25 Hz. In addition, the low pass filter is activated with the highest order and the oversampling factor is also configured with the highest order. In this way, a more precise measurement of atmospheric pressure can be achieved in which less variations are obtained when the device is in the same floor. It is important to note that the atmospheric pressure value depends on several parameters, including temperature, humidity, gravity, air density, etc.; it provokes variations in the measurements although there are no floor changes. Fig. 7 shows a test carried out when a person is wearing the FrailWear and walks among floors. As the figure shows, there are pressure variations even if the person walks on a plane surface. To mitigate these variations, a moving average filter has been implemented on the microcontroller. It is possible to distinguish the floor on which the patient is located and also whether he or she is walking upstairs or downstairs.

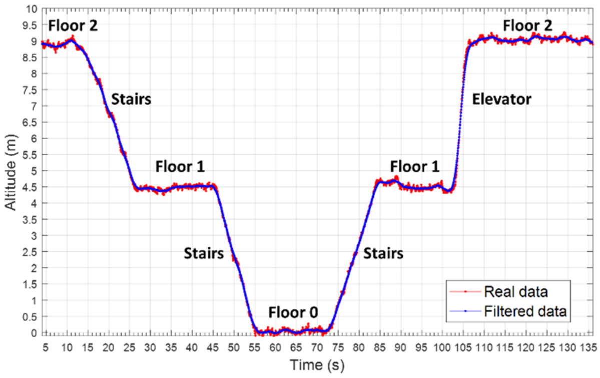

Fig. 8. Atmospheric pressure sensor for a 2-minute test walking indoors on a plane surface and walking upstairs and downstairs (three floors).

B. IMU tests.

The tests performed with the IMU are based on obtaining information about the physical activity by using the high-level algorithms implemented in the microcontroller. For this purpose, the IMU is configured to provide the step number and the output of the activity classifier. The number of steps provided by the IMU can be obtained with a configured sample rate. The number of steps increases and produces a roll over when it reaches the limit of the range of a 16-bit unsigned data. The output provides the total steps given. The activity classifier is configured with the default parameters specified in the datasheet. This allows to distinguish between several activities of interest with a confidence level, such as: standing, walking, running or walking stairs.

The evaluation of the step detector is more critical because it has to adapt the internal parameters of the algorithm to each patient. Three tests have been performed and the results are shown in TABLE I. In the first test, steps are performed with a normal step width of approximately 0.8 meters. Subsequently, the step width is reduced to half of the previous step width. And finally, a mix is performed between the two previous tests.

TABLE I. EVALUATION THE NUMBER OF STEPS.

BNO Output	*Test 1*	*Test 2*	*Test 3*	*Mean error (%)*
Normal Steps	99	95	96	3.34
Small Steps	92	94	90	8
Mixed Steps	92	90	89	9.66

Fig. 11 shows a real test when a person wears the FrailWear device (please see next page). The person has performed a trajectory in two floors walking at different speeds. With the information provided by the IMU and the pressure sensor is noticeable when the person changes the walking speed (pitch angle, see graph in the top), orientation (yaw angle, graph in the middle) and the floor (atmospheric pressure, graph in the bottom). The last part of the test shows when the person lies in bed (notice the change in pressure and the value of the pitch angle).

C. Ultrasonic Indoor Positioning System.

Finally, the position estimation system has been tested using a robot (that carries FrailWear) to follow a known path, which serves as a ground truth to compare the positions calculated by the implemented positioning algorithm on FrailWear.

The test environment is approximately 50 m^2, with ULPS installed (four beacons and one IR synchronism beacon) as Fig. 9 shows. The path to validate the positioning system is approximately 2.5 x 3.5 square meters.

Fig. 9. Image of the ULPS installation for evaluating its performance.

To determine the time of arrival (ToF) of each encoded emission, the receiver performs the correlation between the acquired signal and the codes associated with each beacon. This process is performed in the frequency domain to reduce computing time using the CMSIS libraries provided by *STMicroelectronics* for the Cortex-M4 family. The distances between the receiver and each of the ultrasound beacons are obtained by multiplying ToF by the speed of sound. A spherical trilateration algorithm [9] is used to estimate the position of the FrailWear, since the system is synchronous. Specifically, the Gauss-Newton algorithm is used, which is based on an iterative process to estimate the position using the distances to each beacon and the position of each beacon.

Fig. 10 shows the results of a known trajectory obtained by FrailWear when a robot carries it following a known path. The errors in position estimation are less than 5 centimetres in 90% of the measurements along the path, not exceeding 20 centimetres in the worst case, which is precise enough for providing a person position. These errors can be reduced by installing a higher number of beacons in the environment to provide redundancy.

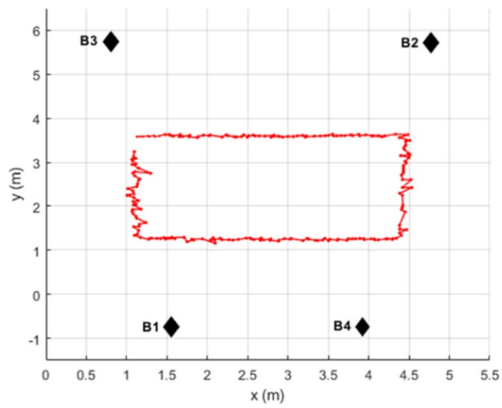

Fig. 10. Real results of a trajectory obtained by FrailWear when a robot carries it following a known path.

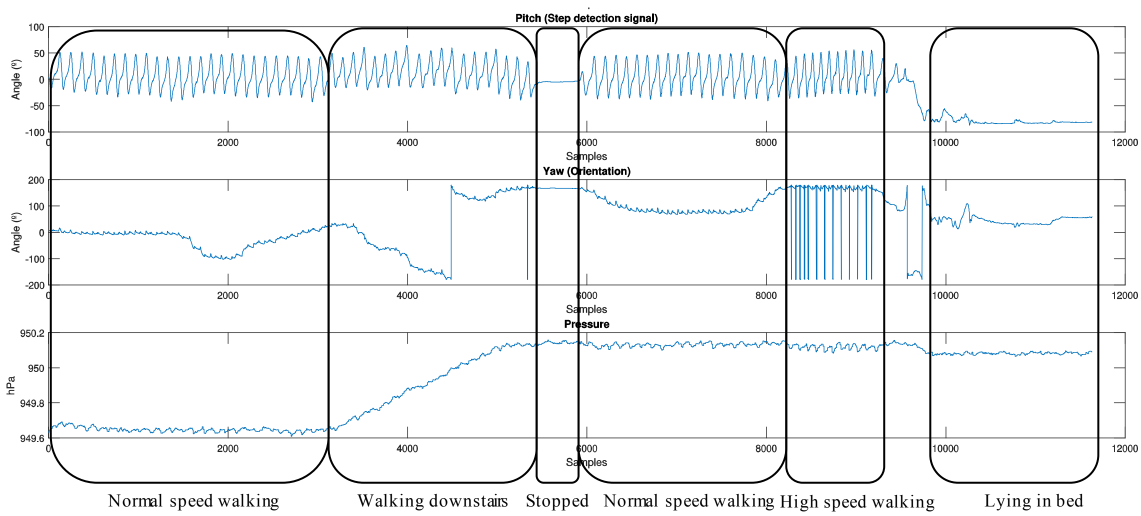

Fig. 11. Real IMU results when a person wears the FrailWear at different speeds (Top: step detection; middle: orientation; bottom: change of floors).

V. CONCLUSIONS

In this work, the FrailWear device and its functionality for the analysis of the daily activity of patients have been described. The development of the system hardware has been described and the correct operation of all sensors has been verified. It is possible to distinguish correctly on which floor the patient is located by using the atmospheric pressure sensor. It has been verified that the high-level algorithms executed by the IMU BNO080 have a good performance in terms of physical activity detection and step detection. Besides, the symbolic location using infrared signal coding has been implemented, as well as a precise ultrasonic localization system, obtaining a good accuracy, with all the algorithms performed by the FrailWear microcontroller.

Unfortunately, due the health emergency (COVID-19), we have not been able to provide real results with patients. As a future work, we will test the FrailWear in an elderly care home to obtain objective data of the physical activity and localization of the patients, for contributing to evaluate their level of frailty.

REFERENCES

[1] Haider, S., Grabovac, I. and Dorner, T.E., “Effects of physical activity interventions in frail and prefrail community-dwelling people on frailty status, muscle strength, physical performance and muscle mass-a narrative review”, Wiener Klin Wochenschr vol. 131, pp. 244-254, 2019.

[2] G. R. H. Regterschot, W. Zhang, H. Baldus, M. Stevens, and W. Zijlstra, “Sensor-based monitoring of sit-to-stand performance is indicative of objective and self-reported aspects of functional status in older adults”, Gait & Posture, vol. 41, no. 4, pp. 935–940, 2015.

[3] H. Zhou, J. Razjouyan, D. Halder, A. D. Naik, M. E. Kunik, and B. Najafi, “Instrumented Trail-Making Task: Application of Wearable Sensor to Determine Physical Frailty Phenotypes”, Gerontology, pp. 1–12, 2018.

[4] D. Gualda, J. J. García, A. Jiménez, D. Bousdar, E. Munoz, “Contribution to Frailty Diagnosis based on Activity and Behaviour Recognition using an IMU”, International Conference on Indoor Positioning and Indoor Navigation (IPIN), 2018.

[5] N. Goonawardene, H.-P. Tan, and L. B. Tan, “Unobtrusive Detection of Frailty in Older Adults”, Lecture Notes in Computer Science, pp. 290–302, 2018.

[6] M. A. Al-Ammar, S. Alhadhrami, A. Al-Salman et al., “Comparative survey of indoor positioning technologies, techniques, and algorithms”, Proceedings of the International Conference on Cyberworlds, pp. 245–252, 2014.

[7] M. G. Tsipouras, N. Giannakeas, T. Tegou, I. Kalamaras, K. Votis and D. Tzovaras, "Assessing the Frailty of Older People using Bluetooth Beacons Data", 14th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Limassol, pp. 5-11, 2018.

[8] Tegou T, Kalamaras I, Tsipouras M, Giannakeas N, Votis K, Tzovaras D., “A Low-Cost Indoor Activity Monitoring System for Detecting Frailty in Older Adults”, Sensors, 2019.

[9] Ureña J., Hernández, A., García, J. J., Villadangos, J. M., Pérez, M. C., Gualda, D., Álvarez, F., Aguilera, T., “Acoustic Local Positioning with Encoded Emission Beacons”, Proceedings of the IEEE 106(6), pp. 1042–1062, 2018.

[10] Wifx, “Lorix One”, 2020. [Online]. Available: https://www.lorixone.io/. [Accesed: 21/04/2020].

[11] Lora-net, “Lora packet forwarder”, 2020. [Online]. Available: https://github.com/Lora-net/packet_forwarder. [Accesed: 21/04/2020].

[12] Amazon, “Amazon Elastic Compute Cloud (Amazon EC2)”, 2020. [Online]. Available: https://aws.amazon.com/ec2/. [Accesed: 21/02/2020].

[13] STMicroelectronics, “STM32F469xx Product Datasheet”, pp. 1-219, 2018.

[14] ARM CMSIS, “ARM Cortex Microcontroller Software Interface Estándar Software Library”, 2020. [Online]. Available: https://armsoftware.github.io/CMSIS_5/DSP/html/index.html. [Accesed: 21/02/2020].

[15] MaxLinear, “SPX3819 Product Datasheet”, pp. 1-13, 2019.

[16] NanJing Top Power ASIC, “TP4056 Product Datasheet”, pp. 1-3, 2019.

[17] STMicroelectronics, “LPS22HB Product Datasheet,” pp. 1-49, 2017.

[18] Hillcrest Laboratories, “BNO080 Product Datasheet,” pp. 1-57, 2017.

[19] Knowles, “SPU0414HR5H-SB Product Datasheet”, pp. 1-11, 2012.

[20] Analog Devices, “OP184/OP284/OP484 Product Datasheet”, pp. 1-11, 2011.

[21] Microchip, “MCP414X/416X/424X/426X Product Datasheet”, pp. 1-88, 2007.

[22] Semtech, “SX127x Product Datasheet”, pp. 1-133, 2016.

[23] Semtech, “SX1276MB1MAS”, 2020. [Online]. Available: https://www.semtech.com/products/wireless-rf/lora-transceivers/sx1276mb1mas. [Accesed: 21/02/2020].

[24] Peregrine Semiconductor, “PE4259 Product Datasheet”, pp. 1-10, 2016.

[25] STMicroelectronics, “LoRaWAN software expansion for STM32Cube”, 2020. [Online]. Available: https://www.st.com/en/embedded-software/i-cube-lrwan.html. [Accesed: 21/02/2020].

[26] Texas Instruments, “TPA301 Product Datasheet”, pp. 1-34, 2004.

[27] Vishay, “TSOP7000 Product Datasheet”, pp. 1-8, 2003.

[28] SD Association, “SD Specifications Part 1, Physical Layer Simplified Specifications, Version 6.00”, 2018.