SAT406M. Physiological Status Determination of a Wrist-Worn Personal Locator Beacon User: Preliminary Results

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***Abstract*—This paper presents the concept, developments and preliminary results of the Horizon 2020 project named SAT406M. The goal of this project is to develop an application based on a wrist-worn device, conceived to be a maritime application, and the use of European Global Navigation Satellite Systems, particularly the Galileo system. It provides an end-to-end solution based on the Galileo Search and Rescue service, using its unique Return-Link-Message function, improving the mobility and safety of citizens. In particular for this paper, we focus on the development and the first testing results of a physiological monitoring component included in the device. This component will provide the Search and Rescue services with additional information about the SAT406M user's physiological status once the distress alarm is triggered. The algorithm implemented uses some stochastic techniques to deduce the SAT406M user's physiological status, encoded in two bits, from sensor inputs. The results here presented, which are still preliminary results from an intermediate stage of the project, show a good accuracy in most of the cases, but not all of them yet. The proposed improvements, clear and easy to implement in the algorithm, make us conclude that it has the potential to end up determining the SAT406M user's physiological status with a significantly higher accuracy, improving this way the user's safety.**

***Keywords*-Galileo; Personal Locator Beacon; Search and rescue; IMU.**

I. INTRODUCTION

Over the last few years, the market of the wearable smart devices, and in particular the smartwatches market, has experienced a huge growth. This has been possible, to a large extent, thanks to the development in sensor technology. Sensors are steadily becoming smaller, cheaper and more precise, driven in particular by the microelectromechanical systems (MEMS) technology. Inertial sensors, among others, have been miniaturized, resulting in small, wearable devices suitable for measuring the motion of its carrier. This has boosted research and development in various fields such as robotics [1], satellite technology [2], optics [3], human motion analysis [4], [5], [6], [7] and many more. Taking the market of smartwatches and smartbands as example, one can nowadays easily find wrist-worn devices that measure the user's heart rate [8], or track and analyse one's daily activity, [9].

One of the fields whose applications have the potential to take benefit from these technologies is Search and Rescue (SAR). In particular, the use of sensors in Personal Locator Beacons (PLB) can still be broadly enlarged. PLBs are devices carried by sailors, hikers and all kind of adventurers as a safety tool. If they are in a distress situation, the PLB can be activated, sending an alert via satellite communications. Once the alert is sent, the PLB provides periodically the user's position to a SAR team, whose goal is to rescue the person in distress as quickly and efficiently as possible. With the advent of the Galileo technology, some unique Global Navigation Satellite System (GNSS) features will be available for the use of PLBs, such as the Return-Link-Message (RLM) or the ability of sending some additional information, apart from the user's position.

Nowadays, PLBs are too expensive and bulky for mass market. Moreover, it is not easy to find a wearable PLB; the Breitling watches [10] are an example. Wearable PLBs do not only have the advantage to be attached to the user; they also have the possibility to include additional sensor technology. Therefore, there is a clear opportunity for the advent of smaller, wearable PLBs that may benefit from the miniaturization trend of technology. In addition, given the future multi-constellation GNSS panorama, PLBs are likely to feature world-wide coverage for positioning and distress message reporting. It is needless to say that this potential has a direct impact on the quality of SAR services and safety of distressed people.

In this paper, we present the SAT406M, a research and development project in progress that aims to develop a wrist-worn PLB. In particular, we focus on the PLB's physiological monitoring component. This component will consist of an algorithm deducing the PLB user's physiological status from Inertial Measurement Unit (IMU) and GNSS inputs. MEMS

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IMUs have already been used to analyse human motion in many contexts, that range from pedestrian dead reckoning using one several sensors attached to the body [5], [7], to qualitative motion analysis with the IMU placed in a pocket [4], [6]. However, the approach of using of an IMU to deduce the physiological status of a wearable-PLB user is new.

To present this research, we firstly explain the project in Section II, providing insights on its foundations and key innovative features. Secondly, in Section III, we describe one of the innovative components of the proposed PLB, the Physiological Monitoring component. In this same section, we also present and interpret the preliminary results obtained at the current stage of the project. Finally, some conclusions are drawn in Section IV.

II. The SAT406M concept

SAT406M is a Horizon 2020 project that aims at developing a wrist-worn PLB, specially targeting at marine environments and users. This beacon will be a 406MHz Cospas-Sarsat [11] compatible one, and will integrate a Digital Selective Calling (DSC) transceiver compatible with marine Very High Frequency (VHF) radios. This H2020 project started in February 2015 and is expected to finish in February 2018.

The SAT406M concept is based in Mobit Telecom's SAT406 [12] (Figure 1), the world's first affordable wrist-worn PLB. It will make use of Thales Alenia Space MEOLUT technology for SAR satellite solutions [13]. Even though it is conceived to be used mainly by boaters and sailors, it can also be a life-saving tool for travellers, pilots and all kind of adventurers that run a constant risk and can, at some point, be in need of the SAR services. If a SAT406M user considers that he or she is in a critical situation, the PLB alarm can be triggered. The alarm triggering procedure is complex enough to avoid false alarms, but also easy enough to be executed in a distress situation. Once this has been done, the distress alarm is sent with an Ultra High Frequency (UHF) 406 MHz Cospas-Sarsat compatible transmitter and a VHF DSC transceiver.

Figure 1. SAT406 PLB

Thanks to the VHF signal, the nearby boats will be aware of a potential distress situation notified by the user, providing them the means for assistance if necessary. Moreover, thanks to the UHF signal located on the 406MHz frequency for GNSS, such as Galileo, this alarm will be sent to the SAR services. Once received, a notification of acknowledgement will be sent to the PLB via the RLM service.

In the project, an innovative communication method is being developed that will enhance the standard communication between the PLB and the SAR/Galileo system, using an uplink solution compatible with the Cospas-Sarsat standards and the Galileo SAR downlink. In this way, the SAR data throughput between the beacon and the SAR/Galileo system will be increased.

One of the innovative features to be included in the upgraded PLB device is the capability of automatically interpret and notify distress situations. Since the PLB user may be in a situation in which no manual alarm triggering is possible (loss of consciousness, high stress, etc.), the goal of the physiological monitoring component is to autonomously provide information to the SAR services about the status of the person based on the PLB built-in sensors. This will be done automatically each five minutes once the alarm has been triggered for the first time.

III. Physiological monitoring

The physiological monitoring in SAT406M is based on motion and positioning sensor inputs. The current approach is to deduce the user's physiological status from IMU and GNSS data, and to encode it in a minimal data structure to be easily transmitted. The result of the physiological monitoring will be then reported to the SAR services, who can take profit of this additional information when executing the SAR operation. No other sensors are implemented due to design and power consumption limitations.

The selection of the physiological features to be monitored by the algorithm is one of the crucial steps. Many aspects define the potential distress of a person, ranging from vital signs or motion of the body, to environmental or weather conditions. Given the particular requirements gathered along the project, two status worlds are defined: the 'health status' and the 'qualitative positioning status'. These two categories set a clear distinction about the personal user condition and his/her whereabouts; in addition, many states can be defined for each of these categories. At this stage of the project development, we have defined two possible states for the 'health status', namely 'alive' and 'unknown', and two possible states for qualitative positioning, namely 'in water' and 'unknown'. Far from being exhaustive and complete for all the potential applications, this selection of states is derived from the SAT406M context and requirements. The definition of the health status world's states follows from trying to determine the probably most valuable information for the SAR services: knowing if the user is alive. Since the product is specifically thought to be a maritime application, it also makes sense to consider the states of the qualitative positioning status in the way proposed.

A. Input/Output

The input consists of IMU and GNSS measurements, acquired in a modality conditioned by the current PLB. During about 20 seconds each 5 minutes, these sensors will be turned on to collect measurements. The sensors cannot be constantly turned on because of the Cospas-Sarsat battery life requirements. Each 5 minutes, once the data has been collected by the sensors, they will be analysed by the physiological monitoring algorithm, and the user's physiological status will be deduced. This information will then be sent to the SAR services.

The specific IMU to be integrated in SAT406M is Bosch Sensortech's BMI160 [14]. Table I shows the specifications of this IMU. If some parameter accepts several options, only the one chosen for the project is specified. The measurements are collected at an output data rate of 25Hz from three accelerometers, measuring linear accelerations, and three gyroscopes, measuring angular velocities. Figures 2 and 3 show examples of accelerometer and gyroscope data respectively, collected by an IMU on different motion situations.

TABLE I. BIM160 specifications

	Accelerometer		Gyroscope	
Parameter	Value	Units	Value	Units
Resolution	16	bit	16	bit
Range	± 4	g	± 1000	°/s
Sensitivity	8192	LSB/g	32.8	LSB/°/s
Sens. temperature drift	± 0.03	%/K	± 0.02	%/K
Sens. change over voltage	± 0.01	%/V	± 0.01	%/V
Zero offset	± 150	mg	± 3	°/s
Nonlinearity	± 0.5	%FS	± 0.1	%FS
Output noise	180	$\mu g/\sqrt{Hz}$	0.007	$°/s/\sqrt{Hz}$

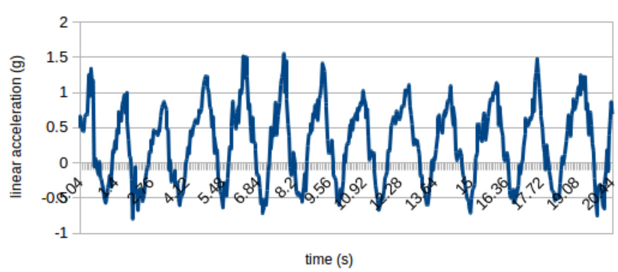

Figure 2. Accelerometer. User swimming

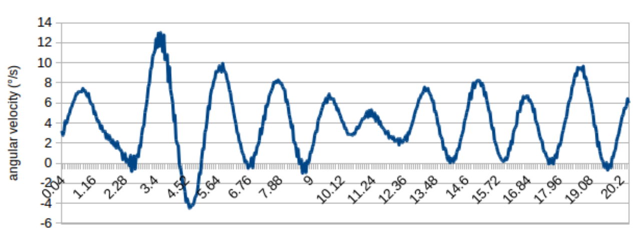

Figure 3. Gyroscope. IMU on a boat

Figure 2 corresponds to the measurements taken by an accelerometer placed on a person's wrist while swimming, breaststroke style. Figure 3 corresponds to the measurements taken by a gyroscope placed on a boat, while it was advancing at a speed of about 10 knots. In both cases, periodicity is a clear feature, but the signal's shape suggests that the periodicity is produced by different kinds of motion. With the information given by such features and other ones, also provided not only by an IMU but also a GNSS receiver, the goal is to determine the user's physiological status, in terms of the defined states.

Indeed, the IMU is the primary sensor used in SAT406M, and its measurements clearly provide meaningful information about the experienced motion. Parameters such as the magnitude of the measurements, the periodicity (if any) and its related frequency, or the amplitude of the observed signal, can be significantly distinct when acquired in various platforms (pedestrian, vehicle, etc.) and types of motion (standing, swimming, walking, etc.). Additionally, GNSS data might also be helpful to describe the context of the PLB user.

Regarding the output, it is a goal of the algorithm to generate a minimal data structure to express the target outputs describing the health and qualitative positioning status of the user. Actually, the amount of information given by the output is limited by the Cospas-Sarsat message standards, and it is only thanks to the innovative communication method developed by Mobit Telecom ltd. that we can send two bits encoding the user's physiological status. In line with this goal, the output of two bits encodes the states 'alive', 'unknown' and 'immersed in water', 'unknown'. This seems to be the most relevant information to be given to the SAR services about the user's status encoded in only two bits. One can easily deduce that there exist four possible outputs: 'Alive/In water' (A/W), 'Alive/Unknown' (A/?), 'Unknown/In water' (?/W) and 'Unknown/Unknown' (?/?).

In fact, since the number of defined states is finite, concretely set to four, one can think of the whole physiological status determination concept as a directed graph with four vertices. In this graph, each vertex represents one of the possible outputs, i.e. one of the states the user can be in. At each point in time, a probability is associated to each vertex, representing the probability of the user being in that state. The directed graph edges represent the possible transitions from a state to another one. This concept can be generalized to any number of states, and is known as "qualitative navigation" or "graph navigation".

B. Algorithm

The physiological monitoring algorithm's output is deduced from a set of four probabilities. In order to express this, a probability vector is defined:

$$v^t = \begin{pmatrix} v_1^t \\ v_2^t \\ v_3^t \\ v_4^t \end{pmatrix} = \begin{pmatrix} P_{A/W} \\ P_{A/?} \\ P_{?/W} \\ P_{?/?} \end{pmatrix}, \text{ where } \sum_i P_i = 1,\ P_i \geq 0. \quad (1)$$

Here, the t stands for a timestamp, meaning that this is the probability vector representing the user's state at time t. Hence, each element v_i^t represents the probability of the SAT406M user being in state i at time t.

In order to compute the final probability vector at time t, not only the sensors' data is considered, but also the user's state at time $t-1$. This is done by multiplying a stochastic transition matrix M^t by the probability vector at time $t-1$:

$$v^t = M^t v^{t-1} = \begin{pmatrix} \sum_{j=1}^4 m_{1j} v_j^{t-1} \\ \sum_{j=1}^4 m_{2j} v_j^{t-1} \\ \sum_{j=1}^4 m_{3j} v_j^{t-1} \\ \sum_{j=1}^4 m_{4j} v_j^{t-1} \end{pmatrix} = \begin{pmatrix} v_1^t \\ v_2^t \\ v_3^t \\ v_4^t \end{pmatrix}. \quad (2)$$

Here, the term 'stochastic matrix' refers to the fact that the conditions $\sum_{i=1}^4 m_{ij} = 1, \quad m_{ij} \geq 0$ hold for each j. It is apparent that each probability vector is conditioned by its estimation on a previous epoch, leading to an iterative process. Like the elements of the probability vector, the elements of the transition matrix also have a clear interpretation: the element m_{ij} represents the probability of transitioning from state j to state i.

The determination of each of these elements depends on a sensor-dependent contribution, determined by the values of the parameters deduced from the raw sensor data, and a sensor-independent contribution: a priori, if the user is in a given state, the probability of transitioning to a different (or the same) state may not be equal for each state.

This is expressed with the equation

$$m_{ij} = W\alpha_i + (1-W)\beta_{ij}. \quad (3)$$

In this equation,

- The α_i are the sensor-dependent coefficients. They change from time $t-1$ to time t, and represent the probability of the user being in state i according to the data acquired between these two times. Clearly, the equality $\sum_{i=1}^4 \alpha_i = 1$ must hold.
- The β_{ij} are the data-independent (and thus also time-independent) coefficients, and represent the probability of the user transitioning from state i to state j a priori. For these coefficients, the equality $\sum_{i=1}^4 \beta_{ij} = 1$ holds.
- W is a weight, a real number between 0 and 1, that allows to control the importance given to the information coming from the sensors' data.

C. Preliminary testing and results

Due to the restrictions related to the PLB's computational capacity, a light implementation of the algorithm described above has been written in C++. In the next stages of the project, this algorithm will be migrated to the final platform.

In order to validate this algorithm in realistic situations, some test cases have been performed involving a person in a marine environment and experiencing different situations. The platform used to acquire IMU measurements was an iPhone 6, which includes an InvenSense MP67B IMU. This IMU presents very similar specifications to the IMU to be integrated in the final version of SAT406M. A smartphone platform was selected due to the ease of use and the already available apps to acquire measurements from the built-in sensors. The smartphone was attached to the wrist of the person with a water-proof case.

We acquired data in a range of situations that basically include standing on a small boat and being immersed in water, either swimming, slightly moving or not moving at all. For the cases on the boat, we also collected data of the IMU not worn by the person, but steady on a table. With these tests, we target at the situations when the user is not wearing the device, is sleeping, dead or unconscious lying on the floor. Finally, we note that no GNSS data was considered at this stage of the project. Figure 4 shows a representative sample of the results obtained when running the algorithm with different sets of data. The green cells correspond to true positives, i.e. the output corresponds to the reality. For false positives, we highlight in red the algorithm output, and we use blue to indicate the truth. The initial probability vector has been set to (0.25, 0.25, 0.25, 0.25) in all cases here presented. These results correspond to one or more iterations of the algorithm considering IMU measurements during 20.48 seconds. Again, the algorithm will execute one iteration each 5 minutes.

	A/W	A/?	?/W	?/?
In water, moving arms to avoid sinking	0.144148	0.314897	0.122503	0.418452
Swimming breaststroke (it. 1)	0.359905	0.331564	0.064455	0.244076
(it. 2)	0.380773	0.343455	0.055093	0.22068
Swimming forward crawl	0.363996	0.337172	0.0740269	0.224805
In water, dead (it. 1)	0.130764	0.201391	0.239261	0.413584
(it. 2)	0.0918138	0.171366	0.24674	0.460305
IMU on a still boat (it. 1)	0.10358	0.143995	0.239326	0.498098
(it. 2)	0.119274	0.13207	0.178376	0.540505
IMU on a moving boat (it. 1)	0.090598	0.159977	0.171894	0.562531
(it. 2)	0.0945691	0.134524	0.134815	0.606317
(it. 3)	0.0788965	0.125106	0.128332	0.623337
User standing on a moving boat (it. 1)	0.152387	0.233552	0.197714	0.401347
(it. 2)	0.209262	0.323019	0.116418	0.336302

Figure 4. Preliminary results

We start analysing the correct preliminary results obtained during these tests. Looking at the table, it can be seen that the software clearly relates the situation of the IMU being motionless on a boat (that is, not worn by the user) to the state (?/?), which is the desired output. The software also correctly detects if the user is swimming. Actually, the outputs (A/W) and (A/?) feature high, almost equal probability leading to potential false positives -yet, the software yields a correct and necessary information, which is the user being alive.

On the other hand, in three situations the software output is (?/?), while the real output should be another one. Firstly, in the case in which the user is just moving arms to avoid sinking, some activity is clearly detected, but since the user is moving the arms slowly and the sea was calm, it is not clear which kind of activity it is. Secondly, in the case where the user simulated to be dead on water, the algorithm tends to the (?/?) state. Yet, it must be noticed that the probability corresponding to (?/W) is significantly higher than in the other cases. And finally, in the case where the user was standing on a moving boat, the software detects some activity, if we compare it to the other cases. But since the user was almost not moving, this small activity is still not detected by the software as (A/?). As we can see, the current algorithm outputs tend to the states with '?' if the contrary is not clear.

It is also to be noted that, in general, in the cases where there are more than a single iteration, each iteration reinforces the output given by the algorithm.

It must be remarked that determining the SAT406M user's physiological status is a challenging task. In particular, if the user is hardly moving, being able to discern between situations in which the user is immersed in water and situations where the user is on some kind of boat or platform can be considerably difficult. This is basically due to the effect of the waves, whose range of different signals that can generate is very large, and depends mainly on the sea conditions.

IV. Further Research and Conclusions

We have introduced the SAT406M project, which is one of the first approaches to this kind of technology. It makes use of the whole constellation of SAR-ready GNSS, including the in the future full operational Galileo, that has the RLM as remarkably useful feature.

We have focused on the algorithm determining the user's physiological status, information that will be sent to the SAR services for them to act as efficiently as possible. This, in addition to the fact that the PLB is wrist-worn, is a clear advantage for improving the user's safety with respect to other PLBs. On the other hand, the small size of the PLB restricts the memory and the computing capacity. Also, the amount of information given to the SAR services is restricted due to communication standards.

The algorithm for the physiological monitoring has been designed following a rigorous mathematical approach based in stochastic theory and state estimation techniques. Additionally, its implementation is modular and extensible, enabling other sources of information i.e. new sensors to be also included in the process with low effort and minimal modifications.

The software's performance is acceptable considering that it is a prototype version, but it still tends excessively to the output 'unknown' if the contrary is not clear. This indicates the need for fine tuning based on multiple sets of data, with high repeatability of the simulated situations, and varying the test person and the sea conditions.

Also, GNSS data, which is still not considered in the software's current version, will be considered in the future. This kind of data will contribute mostly to the determination of the qualitative status world. For example, if the user is moving at high speed on a boat, he or she will probably be alive, which might not be clearly detectable only with the IMU data. All this will yield the identification of further parameters, and the improvement of the currently considered ones, contributing to the determination of the PLB user's physiological status and the robustness of the system.

Next steps of the project also include testing, working and obtaining results with the final platform. In addition, dissemination and commercial activities will be executed, to launch this product to the mass market.

In conclusion, the product under development in the SAT406M project has the potential to improve significantly the safety of the PLB users, and might open the door to the implementation of other new technologies in such devices.

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References

[1] L. Ferranti and F. Cuomo, "Nano-wireless communication for microrobotics: Bridging the gap," in Proceedings of the Second Annual International Conference on Nanoscale Computing and Communication, ser. NANOCOM' 15. New York, NY, USA: ACM, 2015, pp. 31:1–31:6. [Online]. Available: http://doi.acm.org/10.1145/2800795.2800803 [accessed: 2016-06-13]

[2] D. Tithi and D. Ravishankar, "Role of MEMS Technology in Improving the Satellite and Space Communication System: A Review," in Proceedings of the Manipal International Conference on Technology Management, MiCTM 2015 March 25–26, 2015, Dubai, UAE.

[3] F. Chollet, "Devices based on co-integrated mems actuators and optical waveguide: A review," Micromachines, vol. 7, no. 2, 2016, p. 18. [Online]. Available: http://www.mdpi.com/2072-666X/7/2/18 [accessed: 2016-06-13]

[4] P. Molina, I. Colomina, M. Troger, B. Hofmann-Wellenhof, and C. Aguilar, "Non-conventional INS/GNSS integration for qualitative motion analysis in caregiving applications," in ION GNSS 2010. Portland, Oregon, USA., Sep. 2010, pp. 542–555.

[5] Y. Qilong and C. I-Ming, "Localization and velocity tracking of human via 3 imu sensors," Sensors and Actuators A: Physical, vol. 212, 2014, pp. 25–33.

[6] E. Lockhart, R. Soangra, J. Zhang, and X. Wu, "Wavelet based automated postural event detection and activity classification with single imu (tempo)," Biomed Sci Instrum, vol. 49, 2013, pp. 224–233.

[7] A. R. Jimnez, F. Seco, C. Prieto, and J. A. Guevara, "A comparison of Pedestrian Dead-Reckoning algorithms using a low-cost MEMS IMU," in Proceedings of the Intelligent Signal Processing 2009, WISP 2009 26-28 August 2009 Budapest, Hungary, pp. 37–42.

[8] "Apple Watch," URL: http://www.apple.com/watch/ [accessed: 2016-06-13].

[9] "Fitbit," URL: http://www.fitbit.com/ [accessed: 2016-06-13].

[10] "Breitling," URL: http://www.breitling.com/en/ [accessed: 2016-06-13].

[11] "Cospas-Sarsat," URL: http://cospas-sarsat.int/en/ [accessed: 2016-06-13].

[12] "SAT406," URL: http://www.sat406.com/ [accessed: 2016-06-13].

[13] "TAS MEOLUT," URL: https://www.thalesgroup.com/en/worldwide/space/news/meolut-next-breakthrough-technology-search-rescue-satellite-solutions [accessed: 2016-06-13].

[14] "Inertial Measurement Unit BMI160," URL: https://www.bosch-sensortec.com/bst/products/all_products/bmi160 [accessed: 2016-06-13].