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Development of an Emergency Radio Beacon for Small Unmanned Aerial Vehicles

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ABSTRACT Emergency locator transmitters (ELTs) used to locate manned aircrafts are not well suited to find and recover small crashed unmanned aerial vehicles (UAVs). ELTs utilize an international satellite system for search and rescue (Cospas-Sarsat System), which should leverage its expensive resources to save lives as a priority. Besides, ELTs are too big and heavy to be used within small UAVs. Some of the existing solutions for this problem are based on receivers that detect signal strength, which may be a long and tedious process not suitable for user needs. Others do not have enough range or require radio license and expensive amateur radio receivers. This paper presents an emergency radio beacon specifically designed to locate small UAVs. It is triggered automatically in the event of a crash and allows finding and recovering a crashed UAV in a fast and simple way. It meets not only the required specifications of user-friendliness, size and weight of this kind of application, but also it is a high precision and low cost device. Besides, it has enough range and endurance. The experiments carried out show the operation of the proposed system.

INDEX TERMS Aerospace electronics, emergency beacon, localization system, low cost, radio beacon, sensor systems, unmanned aerial vehicle.

I. INTRODUCTION

Although most of UAVs were initially developed for military purposes, in the last decade there has been a noticeable and rapid development of UAVs for civilian purposes. For example, the model aircraft UAVs have experienced an exponential demand among the ordinary consumers thanks to reduced cost and wide variety and range of UAV products that have emerged lately. The appealing possibilities that these UAVs offer to the consumers make them a desirable good for all ages. UAVs are here to stay, and in the next decade, these products will experience a commercial boom similar to that experienced by electronic devices such as smartphones or tablets: there will be one in each home. In fact, the Federal Aviation Administration (FAA) estimates that more than 7 million small UAVs are expected to be purchased by 2020 with 5.5 million sales forecasted for 2018 [1].

While the authorities are still deciding how to integrate public operations, civil operations, and model aircraft UAVs into the same airspace, it is expected that demand for small commercial UAVs will keep increasing, not only for leisure purposes, but also as a business tool. The evolution of these small UAVs will go in parallel with the consumer demand for high-tech on-board electronic equipment that will improve the performance of UAVs. Consumers will want a UAV to go faster and further than any other UAV just a decade ago. In order to cover these consumer demands, it will be necessary to develop lighter, smaller, more precise and more efficient electronic equipment that will be considered as mission payload (cameras, sensors, inertial measurement units, etc.).

Evolution and miniaturization of technology have made possible some payloads that were previously only available in manned aircrafts. Therefore, a user might be flying UAVs that would be worth thousands of dollars only on avionics and payloads.

The fact that UAVs are continuously exposed to events during flight that might cause a crash accident raises concerns among the users since they can lose their UAVs and their investments. For instance, a failure in on-board guidance systems or running out of electrical power could cause the UAV to collide with any obstacle (or just the ground) and it could become very arduous to recover it. In some cases, depending on the terrain on which the plane has fallen, it might be rather difficult.

One possible solution to locate UAVs in an emergency could be using the ELTs employed in manned aircrafts. They operate on 406 MHz to signal a distress and interact with the so-called Cospas-Sarsat System [2]–[4]. This is an international satellite system for search and rescue (SAR), operated and managed by forty-three countries and organizations. Its mission is to provide an accurate, fast and reliable distress alert and location data to help SAR authorities assist people in distress. Other types of emergency beacons that interact with the Cospas-Sarsat System are the Emergency Position-Indicating Radio Beacons (EPIRB), designed for maritime navigation, and the Personal Locator Beacons (PLB), beacons for personal use that are usually activated manually (alpinist, hikers, etc.).

All these 406 MHz radio beacons should be registered in the databases of the Cospas-Sarsat Secretariat to allow SAR authorities to retrieve crucial information about the aircraft, vessel or person in an emergency, and people who could provide additional details about aircraft/vessel characteristics, travel plans, emergency contacts, etc. Nowadays there are more than 1.5 million Cospas-Sarsat distress beacons in operation. The price of 406 MHz radio beacons vary form $500 up to $1,500, depending on their specifications. Both size and weight also depend on the model of radio beacon, but a common optimized ELT for a manned aircraft measures approximately 20 cm $\times$ 10 cm $\times$ 10 cm, and weighs 1 kg.

Since the Cospas-Sarsat System uses expensive technology and human infrastructures, it should be used only for important rescues concerning people's lives. It should not become saturated under not crucial demands and its resources should be not wasted. Besides, the ELTs required to use the Cospas-Sarsat System are too big and heavy to be installed in small UAVs. Therefore, these drawbacks make this solution not practical to locate small UAVs in an emergency.

In consequence, there is a need for developing radio localization systems especially suited to small UAVs (keeping in mind the associated weight, dimensions and cost constraints) in such a way that they can be on-boarded on these lightweight unmanned planes, enabling their localization on ground after a collision so that the airframe and the payload can be recovered. It is clear that some of the characteristics of UAVs such as weight, size and flying range will stablish requirements on weight, size and endurance of the radio beacons they can carry. In addition, the designed solution should be as inexpensive as possible.

Thus, the aim of this paper is to propose a radio beacon adequate to locate mini UAVs in distress after a crash accident meeting the desirable requirements of user-friendliness, small size and weight, long endurance, long range and reduced costs. To the authors' knowledge, this problem has not been yet addressed in the scientific literature.

Although localization has been an active area of research over the last few decades and, in fact, there is a growing need for positioning UAVs, the few localization systems for UAVs found in the literature are aimed to navigation, to control the UAV continuously, what is a different problem where precision and real-time operation are crucial, and so these systems end up being very complex and costly, with high power consumption, size and weight. Besides, none of them is intended for plane crash scenarios, that is, with the capability to detect an accident and activate the whole system just at that moment, which allows reducing power consumption considerably. Our design addresses this issue in a simple and practicable way: incorporating a low-cost micro-electro-mechanical accelerometer to detect collisions. Our design is also based on Global Positioning System (GPS) technology to obtain the precise location of the UAV. Thus, in case of collision, the user receives the location of the UAV, easing considerably the plane recovery (notice the difference respect to existing localization systems for small UAVs, which are based on receivers that detect signal strength or signal direction but they do not provide the exact location of the crashed airplane).

This paper is organized as follows: Section II exposes the system requirements for UAVs in general and for mini UAVs in particular, which is the context of this work. Despite not having found any emergency radio beacons designed for UAVs in the scientific literature, in section III we present the extensive literature review we have made to compare our work with others somehow related. Section IV describes the proposed emergency radio beacon. Section V presents the implementation details. In order to provide the reader a comprehensive understanding of the emergency radio beacon's performances, we have also made a comparison between our solution and some current commercial equipment that, although they are not emergency radio beacons, might be used to locate lost UAVs in some cases. The experimental results are discussed in Section VI. Finally, section VII presents the conclusions and future work.

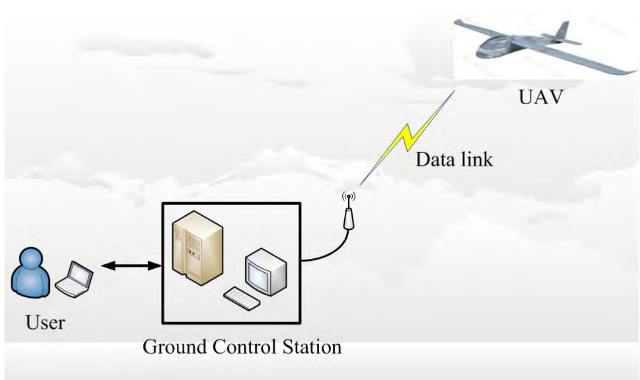


FIGURE 1. Unmanned Aerial System overview.

II. REQUIREMENTS FOR EMERGENCY RADIO BEACONS FOR UAVS

We have assumed that the UAV is part of the so-called unmanned aerial system (UAS). Fig. 1 shows an overview of a UAS, which is constituted by the UAV, the ground control station and any other element to enable flight, such as data link or launch and recovery system.

Some of the characteristics of UAVs such as weight, size and flying range will impose requirements on weight, size and endurance of the radio beacons they could carry. In fact, there is a great variety of UAV classifications depending on their characteristics. In this paper, we have adopted the classification presented by van Blyenburgh [5], where four UAVs main categories are identified according to mass, range, flight altitude and endurance: small UAVs, tactical UAVs, strategic UAVs and special task UAVs. Small UAVs (range less than 10 km and flight altitude around 250 m or 300 m) can be micro UAVs (mass less than 5 kg and 1 h endurance) or mini UAVs (mass less than 30 kg and endurance less than 2 h).

Some requirements for an emergency radio beacon according to the type of UAV in which it will be mounted could be:

- It must be light enough; we think a good design would have a weight less than 1% of the weight of the UAV.

- Its endurance must be enough to keep itself available during the maximum time of flight in addition to the extra time needed to locate the aircraft after a collision. This extra time will depend on the localization technique used and it is desirable to minimize it.

- Its range must be enough to allow the ground control station to receive the distress signal. Thus, it must be the maximum range of the UAV in addition to a clearance to take into account rebounds after impact. In fact, it is desirable to maximize it.

- It must be small enough to be mounted inside the UAV fuselage together with the payload. The maximum total volume of the system will depend strongly on the model of UAV to use.

- Information received by the pilot on the ground must be clear and accurate.

- It should provide user-friendly operation.

The radio beacon should also fulfil applicable regulation regarding aviation, radio signals, frequency, power, etc., which will depend on where the UAV is going to fly (in the internal space of a certain country, in the unsegregated airspace, etc.). Other requirements like flexibility, electromagnetic compatibility, robustness or functionality could be established but we have not considered them herein because they are not crucial.

In this paper we address the specific requirements of mini UAVs. These aircrafts have total prices which range up to several thousands of dollars, justifying the introduction of emergency radio beacons to recover the airplane (or its payload) in case of collision. As reference mission profile for this class of UAV, we consider a 30 kg MTOW (maximum take-off weight) airplane cruising at 300 m AGL (above ground level), with a maximum range of 10 km and 2 hours of endurance. Thus, considering the general requirements for radio beacons stated above, the proposed design should fulfil the following requirements: maximum weight of 0.3 kg, minimum endurance of 2 h, and minimum range of 10 km. Besides, since the variety of mini UAV fuselages existing nowadays, we estimate a maximum volume of the radio beacon of 6 cm $\times$ 6 cm $\times$ 12 cm. We also have assumed the UAV is going to fly outdoors, in open space areas, far from any great obstacles. Under these premises, if an UAV crash happens, the user must be able to find it rapidly and easily.

III. RELATED WORK

We have not found emergency radio beacons developed specifically for UAVs in the scientific literature. In fact, we have found only a few references related to emergency beacons and they are not valid or cannot be adapted to solve our problem. Some deal with EPIRBs, as [6], where the authors propose to use the system and equipment aboard a vessel to monitor the EPIRBs signal and reduce the false alarm rate of EPIRBs. In [7] the authors propose the design and development of a portable global system for mobile communications (GSM) base stations to locate a lost person with and active GSM cell phone. They propose to place it in a base vehicle (car, plane, UAV, etc.) to provide GSM coverage in extremely remote areas where accidents are more likely to happen. However, this costly and complex solution is not practicable for our case. In [8] the design and implementation of an infrared signal transmitting tongue-activated emergency beacon is reported. It is small, low-cost, and simple and it could help immobile patients communicate with the medical staff in the event of an emergency, but its range is only 12 meters. The radio beacon presented in [9] is designed to be incorporated into a picosatellite. It is mainly intended to find the picosatellite more easily above the horizon and send some basic data telemetry to the ground station. It also could be operated in an emergency autonomous operation mode in case of onboard computer failure. It is also small and light. Nevertheless, it presents some drawbacks that make this solution not viable for our application: it requires a radio amateur transceiver on the ground station (for example, the Icom IC-910H), which is quite expensive; the prototype needs at least one monopole antenna of 170 mm to transmit on the 435 MHz radio band (too long for our case); and it is dependent of the satellite power bus which distributes electrical power generated by solar panels.

We have also extended the literature review to localization systems for UAVs and we have found more references but the existing designs are neither well suited to be onboarded on this class of UAVs nor intended to report the localization of the collision scenario. Some of these references, as [10] and [11], propose indoors localization systems, where Global Positioning System (GPS) technologies do not perform correctly, but they have short range, which is not adequate for our purpose. Others make use of the visual information provided by one or two cameras for UAV indoor localization or UAV navigation, which is a different problem. For example, [12] proposes a UAV capable of navigating autonomously to geo-localize arbitrary ground target by using a camera. It captures images to calculate the 3D scene points of the environment, avoid obstacles and geo-reference those images to a known reference image with known coordinates system. Reference [13] presents the concept of aiding inertial navigation with vision-based simultaneous localization and mapping to compensate for inertial navigation divergence in UAVs. Reference [14] deals with control problems associated with various UAVs moving in formation, proposing to use two cameras, several inertial sensors and a new algorithm to get formation flight. In [15] visual odometry and localization of moving objects from aerial images embedded in a UAV are presented but this work does not accommodate our needs. In [16] a state-dependent Riccati equation navigation filter is proposed for UAV localization problem, using data from the on-board inertial navigation system and GPS. It is presented as an alternative to Extended Kalman Filter, which has been largely used in the literature. However, it is an approach oriented to precise navigation problem, which is crucial in order to achieve high-performance flight, but this is not the problem we are examining. The work in [17] presents a solution to the localization problem of micro UAVs: an on-board infrared tracking sensor with built-in vision processing is used to detect infrared markers and a point-based pose estimation algorithm is implemented to obtain six degrees of freedom localization at high rates. However, these vision-based localization approaches are focused on continuous UAV control, which is not the issue we are examining (providing localization in the event of a crash due to possible damage or failure of the systems being employed). Finally, a new localization and positioning system for aerial vehicles is presented in [18] as an alternative to GPS and other visual based positioning systems. Nevertheless, the proposed system architecture has only been simulated and it relies on using transmitting stations on the ground whose coordinates and characteristics of their propagated signals are known and stored in a database. The aerial vehicle would use multilateration to determine its position, measuring the difference in distance to three or more stations that broadcast signals at known times. One main drawback of this proposal is the need for a great infrastructure on the ground (multiple transmitters). Besides, no data about possible size, weight, price, power consumption or range of the localization system are reported.

Regarding localization techniques in general, we can say that the most important technologies to locate a mobile terminal are satellite positioning, cellular network-based positioning and indoor positioning. Reference [19] makes a comparative and analytic study of the various techniques for mobile positioning and presents the limitations of each method based on some performance indices. Some of these techniques are Time of Arrival (TOA), Angle of Arrival (AOA), Time Difference of Arrival (TDOA), Enhanced Observed Time Difference of Arrival (EOTD), Received Signal Strength (RSS) indication, and GPS systems. The work in [19] shows that AOA and GPS are the most appropriate techniques for outdoors and, in addition, GPS offers more accuracy than AOA. Although GPS method has some drawbacks over other competing techniques (high battery usage, long signal acquisition time, lack of indoor coverage and coverage in densely populated areas), they really do not represent a problem for our application. There are other methods for outdoors positioning (vision-based localization approaches, systems based on Wi-Fi infrastructures, location estimation with inertial sensors) but they offer rough location accuracy or their implementations are too complex for our system, which must be simple and inexpensive as well. So, we have chosen GPS technology to sense object location because it allows us to know the position of the downed UAV in a fast, easy and precise way. In fact, current differential GPS receivers can reach 1-3 meter accuracies 99 percent of the time.

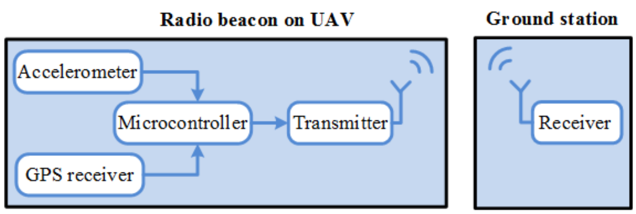


FIGURE 2. General structure of the proposed radio beacon system.

IV. PROPOSED EMERGENCY RADIO BEACON

Fig. 2 shows the proposed scheme for the emergency radio beacon system. It is simple and effective. The radio beacon consists of an accelerometer, a GPS receiver, a microcontroller, and a wireless transmitter. The accelerometer is used to detect strong impacts against obstacles like trees, birds, another UAV or just ground. It allows saving power significantly until the event occurs because before that, the system is in sleep mode (microcontroller, GPS, and transmitter). The GPS receiver is used to sense the beacon's location when the UAV has gone down. The wireless transmitter sends the position to the receiver. The operator on the ground will only need a simple wireless receiver.

This scheme has some advantages. One is that the radio beacon not only sends a distress signal on a specified radio frequency, but also provides directly the coordinates calculated by the GPS receiver. Another advantage is that the radio beacon can be in sleep mode during normal flight operation, reducing significantly power consumption (energy consumption of GPS receivers in normal operating mode can be considerable). The radio beacon is designed as an external element, with its own independent battery too, and its GPS receiver is independent of the GPS receiver used in the UAV for navigation.

Fig. 3 shows the flowchart of the main program of the microcontroller. The logic operation of the proposed radio beacon is as follows:

1) The system will be originally switched on when the UAV is going to take off. This start-up can be either manually (pilot on the ground) or automatically (by autopilot software).

2) After that, both the GPS and microcontroller will enter sleep mode until activated.

3) If the UAV crashes or lands abruptly, that event will be detected by the accelerometer. The accelerometer sends an interrupt signal to the microcontroller when it detects more than five G's, waking it up. The microcontroller checks if that acceleration higher than 5 G's corresponds to a real impact.

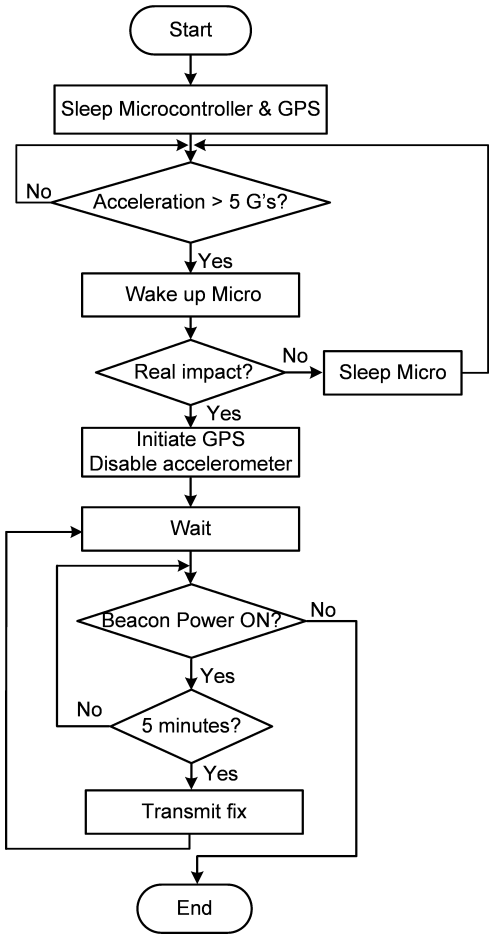


FIGURE 3. General structure flowchart of the main program of the microcontroller.

If there has been a real impact, the radio beacon is activated and it must transmit its location. If not, the microcontroller will go into sleep mode to save power.

4) When the radio beacon is activated, the microcontroller initializes the GPS and collects information from it (location, time, etc.). Then it sends this information to the wireless transmitter.

5) The wireless transmitter sends this information along with the identification of the radio beacon to the ground station or receiver. The transmitter will repeat this transmission periodically at certain established time interval with data from the GPS unit. In fact, it will remain transmitting its position until the user finds the UAV and turns off the radio beacon manually or until its battery runs out of energy.

On the ground station there will be a wireless receiver that will collect data from the radio beacon and will be able to send them to a handheld device (tablet, smartphone, etc.) via a serial port. This device, a laptop, for instance, will integrate an interface that receives the coordinates of the UAV down. Entering latitude and longitude coordinates in a map application, the location of the down UAV can be found.

One of the assumptions we have done for the operation of the radio beacon is considering 5 G's as level for the accelerometer to detect a strong impact and generate an interrupt. It is important to note that the level of the accelerometer that triggers the event is quite sensitive to the shape of the UAV, the materials used in its construction, and the velocity and nature of the impact or crash. Therefore, the 5 G's level is a value considered in the initial phase of development and will be susceptible of being adjusted once more data of flight tests are obtained.

Since data about UAV accidents are scarce, we have based our decision on some related studies [20], [21] and, as well, on some experiments we have done ourselves. The study in [20] of crashed cars fitted with on-board crash pulse recorders (CPR) presents differences in crash severity depending on collision partner. For the 544 real-world crashes included, average mean and peak acceleration, change of velocity and duration of the vehicle acceleration pulse have been measured and calculated. CPR has a trigger level of approximately 3 G's. Crash data are available principally for the car industry since they are an essential tool for its development and evolution. The study of the events that trigger distress situations has become an important source of information that has helped both the car industry and the auxiliary industry such insurers and on-road assistants (for example, the OnStar service) to develop their services and products. Some interesting data and conclusions regarding the crashes are presented in [20]:

- Acceleration is relatively low in collisions with deformable objects, compared with rigid objects or in two-vehicle crashes. The highest mean acceleration was found in collisions with trees and house walls. Collisions with poles had pulses with lower mean acceleration than collisions with other objects.

- The maximum mean acceleration of all crashes included in that study was found in a crash with a rigid roadside object, i.e. 23.10 G's.

- The maximum mean acceleration in frontal single vehicle crashes with a deformable guardrail was 8 G's. In over 23% of crashes with rigid objects and 21% of all two-vehicle crashes, the mean acceleration was higher than 8 G's.

- The mean acceleration was lower than 9 G's in all crashes with deformable objects and only in 8% of them, it was higher than the geometric average mean acceleration (5.8 G's) for rigid roadside objects.

- Average duration of a crash was in an approximate range of 60 ms to 110 ms depending on the type of crash.

In [21] analysis and testing have been conducted where a small UAV essentially impacts the surface of the water. Acceleration data were collected by means of 3-axis accelerometers positioned at five locations, including the wingtips. This allowed drawing conclusions with respect to the loads experienced on impact throughout the airframe. These data were also used to find loads corresponding to the maximum decelerations experienced during impact. We have checked the minimum and maximum values and duration of the acceleration pulse with different impacts in the acceleration tests presented in [21].

The impact response and the behavior of the UAV during a collision depends on many factors: relative velocity between the UAV and its collision partner, the mass and structure of the UAV and its collision partner, existence of damper system, the crash situation, including impact angle, overlap, etc. However, in our case, we only need to trigger an activation signal if a strong impact occurs. We think that in a mini UAV with the radio beacon inserted at the center of its structure, an acceleration in any axes of more than 5 G's during at least 10 ms shows a strong impact. The bigger the mini UAV, the longer the duration of a crash, and the radio beacon will operate properly too. In addition, we believe that this assumption is validated by some experiments we have done, as we will show in the experimental section of this paper, but we are also aware that this trigger flag of 5 G's can be adjusted and improved as more flight tests and crash experiments will be conducted in the future.

Another consideration we have done is that a 5-minute interval is adequate to comply with the transmission requirements since the GPS takes 2 or 3 minutes to get a fix. This will also help the transmitter to save power because it is not using a continuous transmission mode.

Our radio beacon is currently intended to give users UAV location only after a crash. Other situations, as non-crash safe landings handled by the flight controller, for example, after link loss, are not being considered here as emergencies. Nevertheless, in a future work, this functionality can be added if the microcontroller wakes up after receiving an interrupt signal from the accelerometer (in case of real impact) or from the flight controller (in case of safe landing).

In order to fulfil size and weight requirements, we must choose the elements of the system as integrated circuits with a high level of integration and low power consumption, and we must choose them properly among the full range of commercial solutions since the overall performance of the radio beacon will depend on this selection. Besides, it is necessary to choose a transmitter with enough range (more than 10 km) and with a power consumption as low as possible. We have chosen commercial off-the-shelf (COTS) components for our prototype because they allow building systems at reduced costs, within shorter development time, while maintaining their quality. We will present implementation details in the following section.

V. IMPLEMENTATION DETAILS AND PERFORMANCES

In order to implement the proposed radio beacon for mini UAVs, we have chosen the following components:

- A self-contained board based on a high performance 32-bit microcontroller (Atmel SAM3X8E ARM Cortex-M3 CPU). The operating voltage is 3.3 V. Its size is 101.52 mm × 53.3 mm × 10 mm (length × width × height). Its 3.3 V pin is able to give a DC current of 800 mA. It weighs 36 g.

- A low-cost low-power RF module (Xbee PRO 868) to transmit the localization with outdoor RF line-of-sight range up to 40 km with a 2.0 dBi dipole antenna. This range is important for the proposed radio beacon and its application. The operating frequency band is the SRD G3 Band (869.525 MHz), which is license free. The transmit power output can vary from 1 mW to 315 mW (0 dBm to +25 dBm). The supply voltage, given by a shield to adapt the RF module to the microcontroller board, is 3.3V and the operating current for a transmit power output of 25 dBm is 500 mA typically (and 800 mA as maximum). There will be a similar module in the receiver to receive the information. Other features are RF data rate of 24 kbps, receiver sensitivity of −112 dBm and receiver operating current of 65 mA typically. These modules use the IEEE 802.15.4 network protocol for fast peer-to-peer networking. We have configured this module by AT commands. Its size is 24.38 mm × 32.94 mm and weighs 4.5 g.

TABLE 1. Hardware cost data of the prototype emergency radio beacon.

Item	Typical cost ($)
Microcontroller board	27
RF module (Xbee PRO 868)	44
Adafruit Ultimate GPS breakout	43
Accelerometer module (ADXL345)	18
Li-po Battery (3.7 V, 2000 mAh)	2 x 21
Wireless Shield	18
TOTAL	192

- A high-quality GPS module (Adafruit Ultimate GPS Breakout). It has an excellent high-sensitivity receiver (−165 dB tracking), a built-in antenna and tracks up to 22 satellites on 66 channels. Its position accuracy is 1.8 m. It can be powered with 3.3-5 VDC in and power usage is only 20 mA during navigation. Its size is 25.5 mm × 35 mm × 6.5 mm. It weighs 8.5 g.

- A low power, 3-axis MEMS accelerometer module with I2C interface (ADXL345 with Adafruit breakout). It features four sensitivity ranges from +/− 2 G to +/− 16 G. Its V_{CC} pin takes up to 5 V in and regulates it to 3.3 V with an output pin, consuming 175 μA approximately in measurement mode. Its size is 25 mm × 19 mm × 3.14 mm. It weighs 1.27 g.

- A rechargeable Li-po battery of 7.4 V and 2000 mAh composed of two modules of 2000 mAh, 3.7 V, size of 53 mm × 51 mm × 8.5 mm and weight of 42 g.

We will mount the radio beacon in the UAV's tail section, where it is more likely to survive a severe crash, and we will locate the antenna outside of the aircraft. If the UAV crashes, there is no way of knowing in advance its direction relative to the user. Thus, a dipole antenna mounted vertically (dipole oriented along the z-axis) through the top of the fuselage is appropriate for our purposes. It has a vertical radiation pattern that looks like the number 8 and a horizontal radiation pattern omnidirectional (in fact, it has 2dB of gain compared to an isotropic radiator). It is true that the range will depend much on the receiving antenna and the final position of the aircraft, but it is highly probable that the UAV fells on its belly. In that case, the antenna will remain pointing to the sky and the user would only have to move the receiving antenna trying to orientate it adequately.

TABLE 2. Hardware comparison of commercial equipment and the proposed emergency radio beacon.

Device	(1) Locator kit (DMD)	(2) Tracking equipment (Marshall Radio Telemetry)	(3) Radio search system (1slon ltd)	(4) Tracker (BigRedBee)	Our prototype
Size of radio beacon (mm x mm x mm)	43 x 33 x 15	14 x 14 x 26	43 x 22 x 8	76.2 x 31.75 x 38	101.5 x 53.3 x 50
Weight of radio beacon (g)	18	3.5-9	12	Unknown	160
Price	Radio beacon: $62 Searcher: $148	Radio beacon: $235-$575 Tracking receiver: $1,295-$1,795	Radio beacon: $70 Complete system: $230	Complete system: $309	Radio beacon: $193 Receiver: $69
Range (km)	1-4	4.8-56 (LOS and directional Yagi antenna in receiver)	2.5 (8 if LOS and directional Yagi antenna in receiver)	9.6 (24 if directional Yagi antenna in receiver)	40 (outdoor RF LOS) (80 if directional antenna)
Accelerometer?	No	No	Motion sensor (anti-theft protection)	No	Yes
Transmitter architecture	Microcontroller + radio transmitter	Radio transmitter	Radio transmitter	GPS + radio transmitter	GPS + radio transmitter + accelerometer
Receiver architecture	Power detector with directional antenna	Direction finding receiver with directional Yagi antenna	Signal strength detector	RF receiver to monitor the GPS data in real-time	RF receiver to collect the GPS data (every 5 min)
Endurance	70 d	5-20 d	4 h@active search 2 months@standby	Unknown	15 h@trasnmitting 9 d@sleep mode
Working frequency (MHz)	869.9@Europe 903.9@EEUU	215-219 (or 233-237)	868 (915@EEUU)	900	869.525

We also have selected a wireless shield to connect the RF transmitter to the microcontroller board in a quick and easy way. Table 1 shows the prototype development cost taking into account hardware costs only. That total cost ($192, approximately) does not include packaging nor integration, assembly and test costs. However, we assume that production costs of a particular unit or lot will be much smaller than the cost of the prototype. In order to implement the receiver we would only need a second RF module ($44) and an Xbee USB adapter ($25) to connect it easily to a computer, for example. Thus, total cost of the receiver is $69, approximately.

In [22], a study on the actual step-down in hardware costs from the research and development phase to the production phase was presented. Historical costs in areas as general electronics and shipboard electronics were examined. The step-down factor was found to be typically in the range 0.47 to 0.67, proving a significant reduction in cost for the first unit production from its prototype development cost.

Bearing in mind that traditional ELTs used for manned aircrafts are too big (200 mm $\times$ 100 mm $\times$ 100 mm), heavy (1,000 g) and expensive ($500-$1,500), it must be said that there are a few commercial devices that, although they are not emergency radio beacons, could be used to locate downed UAVs. Nevertheless, most of these devices would not be suitable for searching and recovering a UAV that would have gone beyond 10 km. Moreover, most of them are based on receivers that detect signal direction or signal strength with big directional antennas, which may be rather tedious and take too much time. Table 2 shows a comparison of the performances among commercial locator equipment and our emergency radio beacon. We have only considered those locators with range above 2 km. We can see than most of them are much smaller, lighter and more inexpensive than ELTs. However, devices (1) and (3) are not suited for finding a UAV beyond 10 km. Besides, the searching method, by monitoring the signal strength of the beacon on a display, can be very tedious. The ground operator would have to be moving continuously in order to find the direction of maximum received power, handling a big and heavy directional antenna. This task could become very difficult and last many hours.

Some of the devices (2) can have a long range (up to 54 km line-of-sight), but at the expense of elevated costs. Moreover, they use a direction-finding receiver. This type of receiver is not only expensive (more than one thousand dollars) but also its use could be difficult (by pointing the integral directional antenna in the direction of the strongest signal and moving toward it until the target containing the transmitter is found).

Currently, there are also some commercial transponders that can be used to track mini UAVs, but we have not considered them because they are not focused on the problem we are facing (designing a simple, user-friendly, low cost emergency radio beacon) but they are designed to provide a response when they receive a RF interrogation or even broadcast information like position, speed, direction, height and identification of the UAV. They are used in navigation and because of their complexity and sophisticated functionality, they are typically high cost (several thousand dollars).

VI. EXPERIMENTAL RESULTS

We have implemented a proof-of-concept prototype of the proposed emergency radio beacon for mini UAVs to check its functionality. Fig. 4 shows that prototype.

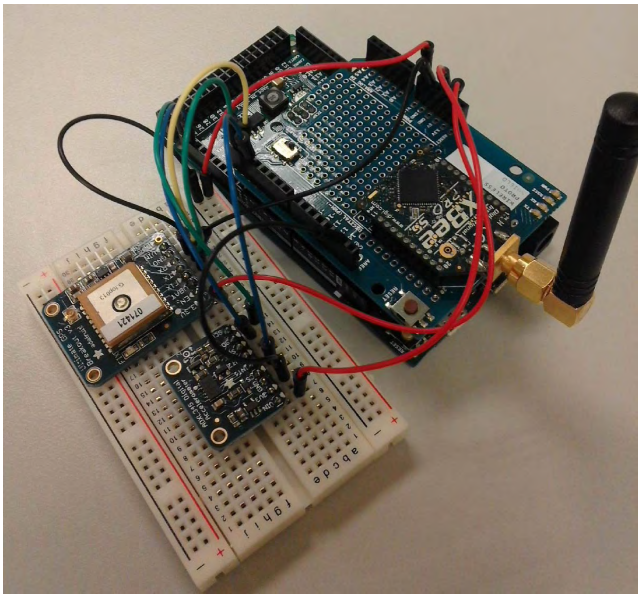


FIGURE 4. **The implementation of the proposed emergency radio beacon.**

Nevertheless, in a final product, all the components should be stacked and soldered appropriately in order to occupy the smallest possible volume. Besides, the radio beacon should be inserted in a shockproof container to withstand impacts.

It has been checked the operation of the radio beacon by several experimental setups. Firstly, we have tested each module separately and, afterwards, the whole system.

In a first step, we have checked the operation of the GPS. Radio beacon precision relies on GPS accuracy because it is the subsystem in charge of calculating its location. The selected Adafruit GPS breakout is said to offer a Circular Error Probability (CEP) of 1.8 m but, if it is indoors or surrounded by tall buildings, it is often only accurate to 5-10 m. However, it is built around the MTK3339 chipset, which is said to have a position accuracy of 3 m without aid and 2.5 m if differentially corrected (DGPS). We have made some measurements to check position accuracy in practice.

```
$GPGGA,083334.000,3724.6446,N,00600.0204,W,2,6,1.39,16.5,M,49.7,M,0000,0000*75
$GPGSA,A,3,14,02,25,29,31,21,,,,,,,2.10,1.39,1.58*0C
$GPGSV,2,1,07,29,79,041,47,31,59,312,36,25,47,066,44,39,35,135,43*7D
$GPGSV,2,2,07,14,27,216,44,21,22,167,35,02,09,039,32*4E
$GPRMC,083334.000,A,3724.6446,N,00600.0204,W,0.01,131.61,150914,,,D*79
$GPVTG,131.61,T,,M,0.01,N,0.02,K,D*3F
```

FIGURE 5. **Example of sequence of received NMEA sentences by the GPS and sent by the radio beacon.**

Fig. 5 shows an example of sequence of NMEA sentences (NMEA is the standard developed by the National Marine Electronics Association for GPS receivers) received from the GPS standing in the Higher Technical School of Engineering of Seville (Spain).

The basic information extracted of these sentences is:

- Time: 08. 33. 34 UTC
- Latitude: 37°, 24.6446' North
- Longitude: 6°, 0.0204' West
- Fix quality: 2 (GPS Differential Fix)
- Number of satellites being tracked: 5
- Altitude above mean sea level: 16.5 meters

In this experiment, the used map application has confirmed that these coordinates correspond to the Higher Technical School of Engineering of Seville.

In order to check the GPS precision, we have measured the position with the GPS in different locations, in both urban and rural environments, obtaining some pairs of coordinates and, as well, our "real" locations pointing them in Google Maps. Then we have calculated the difference in meters between GPS locations and locations according the map application. For example, at a certain point in urban area, outdoors, the GPS offered the location (latitude and longitude in degrees, minutes, seconds) 37° 24' 35.5'' N, 6° 0' 8.0'' W whereas the map application offered 37° 24' 35.654'' N, 6° 0' 7.783'' W, meaning a difference of 7.4 m. In another point, in rural area, the GPS offered the location 37° 23' 29.5'' N, 6° 3' 7.2'' W whereas the map application offered 37° 23' 29.569'' N, 6° 3' 7.39'' W, meaning a difference of 4.17 m. In all the measurements, the GPS got the fix in less than 5 minutes and showed quickly a Horizontal Dilution of Precision (HDOP) of approximately one or less than one. In general, we can say the results obtained confirm that, in the areas where the considered UAV is going to fly (rural areas, outdoors, far from any great obstacles), the accuracy of the GPS given by its manufacturer is valid and it is very good.

Secondly, we checked the response of the accelerometer to taps, double taps, vibrations and strong shocks to ensure that it was reading the data correctly, including when it was motionless. This helped us to define a series of events to discriminate possible false detections of crash events. After that, we programmed it to send an interrupt to the microcontroller when it detected an acceleration higher than 5 G's during at least 10 ms, but also considering the readings of the accelerations to discriminate against hard take-off and landings. Then, we did some impact tests in the laboratory to read the data when it was being dropped directly onto a table. As well, we moved it quickly in the air crashing into a rigid object and deformable object. In all the cases we checked that the interrupt was activated with an impact great enough and that the lectures were above 5 G's during 10 ms in any of the three axes x, y, z. We were also checking other levels of acceleration and crash duration to detect strong impacts and try to ensure the correct operation of the radio beacon. Furthermore, we supported our decision on trigger level and minimum crash duration with telemetry obtained from real flights of two different UAVs. Table 3 lists some characteristics of these two tested UAVs.

The first UAV (UAV '#1') corresponds to a prototype designed and developed for research at the Department of Aerospace Engineering at the University of Seville. Fig. 6 shows this mini UAV.

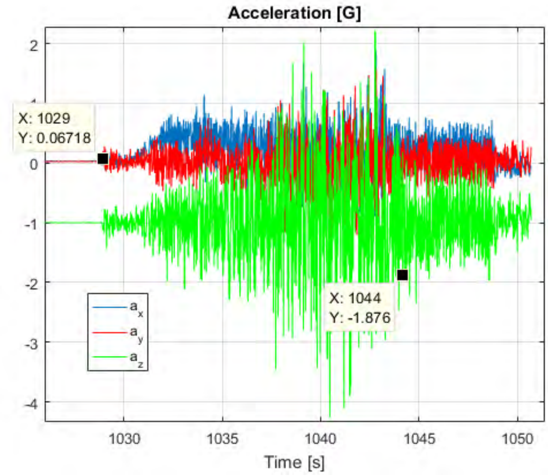
The mini UAV '#1' was tested first on ground and later, on the air. The telemetry system collected relevant flight

TABLE 3. Some characteristics of the tested UAVs.

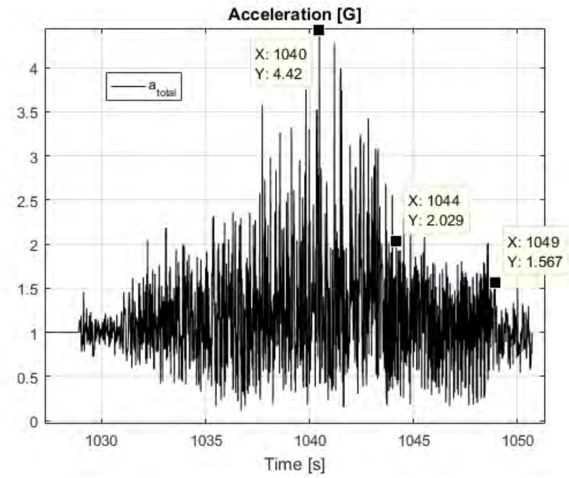
	UAV '#1'	UAV '#2'
Endurance	1.5 h	2 h
Cruise speed	90-140 km/h	32-72 km/h
Cruise altitude	500 m	100 m
Maximum Takeoff Weight (MTOW)	25 kg	3 kg
Fuselage length	1.5 m	1.04 m

(a) (b)

FIGURE 6. Mini UAV developed for research purpose: (a) motionless; (b) flying.



(a)



(b)

FIGURE 7. Acceleration data collected from the UAV '#1' during flight-testing: (a) X, Y and Z acceleration data; (b) total acceleration.

data as attitude, altitude, acceleration, throttle, voltage and current of motor's battery, motor speed, among many others. Fig. 7(a) and Fig. 7(b) show X, Y and Z acceleration, and total acceleration respectively for a portion of the flight data collected from a 3-axis accelerometer. In the interval time of 0 s to 1015 s, ground tests were done. In the interval time of 1015 s to 1030 s, the UAV was still. The take-off roll began at 1030 s and the UAV was ascending to 1044 s, where it reached the cruise speed of 90 km/h. Unfortunately, at 1049 s, a failure happened, throttle and motor speed fell dramatically, telemetry stopped working, and the UAV fell down. The mini UAV was not carrying an emergency radio beacon yet, and despite its size, since the crash site was a cornfield, it took us 60 minutes to identify its location. Despite not acquiring impact data, the previous data helped to identify the necessity to define robust logic that would help to eliminate the possibility of triggering the emergency radio beacon in non-crash situations. As it can be seen in Fig. 7(a) and Fig. 7(b), during the take-off the largest acceleration values are due to vibrations, as expected, but that peak total acceleration remains below 4.5 G's.

The second UAV '#2' was also tested first on ground and later, on the air. The take-off began at 2635 s, after ground tests. It was flying during 24 minutes approximately. The UAV did not suffered any accident but we can show acceleration data during an abrupt landing. The UAV was descending to land when it hit the runway (at 3999 s) and rebounded up. Then, it was suspended in the air and finally, it landed, being still since 4143 s. Fig. 8(a) shows the total acceleration data collected from a 3-axis accelerometer during the flight. In Fig. 8(b) we also show the Z acceleration because it was much bigger than X and Y accelerations and it shows the impact when landing clearly. In fact, that impact generated a peak of 4.994 G's, giving us somehow evidence of the adequate level to trigger an emergency radio beacon. Again, these results, despite not constituting a true trigger situation, have helped to define the logic to ensure that the emergency radio beacon is properly activated.

The first tests of the whole system were made in an urban area, more precisely in the city of Seville (Spain). Firstly, the radio beacon and the receiver were set only some meters away from each other, in an indoor area, and we checked that the whole system (radio beacon and receiver) worked properly. Once the radio beacon was activated, after hitting the accelerometer in a manual way, the GPS took less than 5 minutes to get a fix (there were some open windows) and the transmitter started to send data to the receiver. The receiver module was connected to a laptop computer. In the laptop, a freeware software was used to establish a connection with the receiver module via a serial port and monitor the received data. Therefore, we could read the location data of the emergency radio beacon easily. Fig. 9 shows the receiver and the laptop receiving the data transmitted by the radio beacon.

Afterward, we also carried out experiments in an outdoor urban area with many buildings and trees and we checked

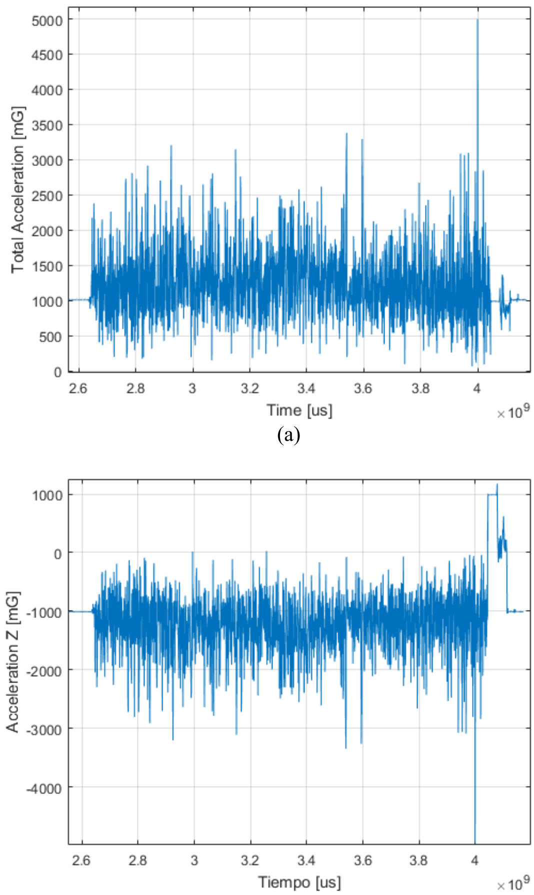


FIGURE 8. Acceleration data collected from the UAV '#2' during flight-testing: (a) total acceleration; (b) Z acceleration.

FIGURE 9. The receiver module receiving the location data of the radio beacon and sending them to a laptop.

over 1 km range. In any case, this is not the scenario where we have assumed that the UAV would fly, due to the current laws in many countries.

We made tests in a quasi-direct quasi-free-space path of over 2.5 km between the radio beacon and the receiver. Fig. 10(a) and Fig. 10(b) show the two types of terrains where we made these tests. We confirmed experimentally

(a) (b)

FIGURE 10. Terrains where some tests were made: (a) with some vegetation on the ground and in the LOS; (b) with vegetation on both sides of the LOS.

that the radio beacon and the receiver worked properly those 2.5 km away from each other. Because of the topographic features and vegetation of the terrain accessible for the authors, we could not do more RF line-of-sight range tests, but we must rely on the 40 km RF LOS range provided by the manufacturer in the datasheet of the transmitter.

Although basically for economic reasons, we have only been able to do limited tests, we can say that our design already fulfils most of requirements (maximum weight of 0.3 kg, minimum endurance of 2 h, maximum volume of the radio beacon of 6 cm × 6 cm × 12 cm, and minimum range of 10 km). In fact, our proof-of-concept prototype, whose size optimization is still pending, has the following characteristics:

- It has a weight of around 160 g.
- We have calculated that if the radio beacon is not activated, then it could be working continuously during nine days roughly with the chosen battery. Once the radio beacon is activated, it could transmit the distress signal almost during fifteen hours ensuring the required endurance.
- The overall volume of the proof-of-concept prototype is 10.15 cm × 5.33 cm × 5 cm, approximately.
- Regarding range, it is true that after a crash there can be problems of line-of-sight and Fresnel zone obstacles, but we think that if the transmitter has a 40 km RF LOS range according to the manufacturer, it is very probable that the radio beacon reaches more than 10 km as practical range.
- Location information provided to the receiver is clear and accurate.

Besides, the radio beacon is fast, inexpensive, simple, and user-friendly.

In addition to the need to activate the protocol when the acceleration in any axes is above 5 G's during a time interval of 10 ms at least, we have developed a series of algorithms that, using the measurements of the accelerometer, check if the UAV is still moving after the system is in alert mode. If the acceleration in any of the axis during the instants after the event that triggers the alert is different than zero, then the airplane is rolling (accelerating or decelerating), thus the emergency radio beacon should not be activated. These algorithms require improvement to adequately characterize the possible impacts of any UAV and guarantee the activation of the radio beacon in any emergency. For that purpose, it is necessary to develop a well-established testing program and crash a variety of UAVs on purpose with and without the radio beacon. Since the impact depends on many factors, it is required a series of destructive tests, but currently we have to discard it for economic reasons. These tests open a new line of research to characterize the different trigger levels according to the type of UAV and crash. For the scenario described in this article, we only need to trigger an activation signal if a severe impact occurs. In any case, for future needs, the level of activation of our radio beacon can be easily reconfigured.

Since the system being used is a wireless system, it has been identified the necessity of defining a real-time feature at least according to the time-scale being used in this type of events. Right after the event that triggers the activation of the emergency radio beacon, the transmitter would send data to the receiver more frequently taking into consideration the limit of its duty cycle. After the first 5 minutes, the transmitter can go back to a transmission rate of 5 minutes to extend the battery duration.

VII. CONCLUSION AND FUTURE WORK

Traditional Emergency Locator Transmitters (ELTs) used to locate manned aircrafts in an emergency are not suitable for finding small UAVs. Besides, the Cospas-Sarsat System used by ELTs utilizes expensive technology and human infrastructures that should be focused on saving people's lives. Moreover, ELTs are too big and heavy to be used within small UAVs. This paper has reviewed the existing solutions in the scientific literature and the market that could fulfil the requirements of user-friendliness, size, weight, range and costs needed to locate crashed small UAVs. We have not found emergency radio beacons developed specifically for UAVs in the scientific literature. In fact, we have found only a few references related to emergency beacons and they are not valid or cannot be adapted to solve our problem. We have also extended our literary search to localization systems for UAVs and we have found more references but they are not valid either to solve the problem addressed in this paper. In addition, none of these localizations systems for aerial vehicles is intended to crash emergency situations. A few commercial equipment could be used to locate downed UAVs. Some of these devices are based on receivers that detect signal strength, which may become a very long and tedious process. Others do not have enough range (more than 10 km is needed) or require radio license and expensive amateur radio receivers. In addition, none is designed to give the location of the UAV only after a crash.

In this paper, we have presented the design and implementation of an emergency radio beacon appropriate for finding and recovering small UAVs in a fast and simple way after an impact. It is user-friendly, its size and weight are quite reduced, and it has a high precision and low cost. Besides, its endurance is more than enough to find the UAV and it appears to have enough range (more exhaustive tests should be done to ensure it in every circumstance). We have carried experiments that show the operation of the proposed system.

In the future we intend to extend the number and coverage of the experiments to demonstrate the performances of the system. We also aspire to adapt the prototype to the current UAVs and achieve its full operation. For this, it is still necessary to develop some aspects. Firstly, it would be interesting to further reduce the size of the assembly, using a smaller microcontroller, welding the components optimizing the volume they occupy and encapsulating the entire electronic assembly in shockproof material. The transmitter antenna must also be prepared to receive impacts. Concerning the receiver set, it is also subject to changes. We could collect all the components in an ergonomic casing and add a small microcontroller to extract the information sent from the UAV in order to show the location on a screen. This system could be further sophisticated by adding another GPS to the receiver set that would allow calculating, by simple algorithms, the distance and the direction in which the user must look for the UAV. We also intend to add the functionality of activating the radio beacon if the UAV flight controller has handled a non-crash safe landing.

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