Drones to the Rescue!

Unmanned Aerial Search Missions Based on Thermal Imaging and Reliable Navigation

The use of unmanned aerial systems for civilian search-and-rescue operations or disaster management is not new. Predators drones, commonly associated with military operations, were used in the aftermath of the hurricane Katrina in the United States; rotary-wing vehicles equipped with radiation sensors, infrared thermometers and cameras helped out at Japan's post-tsunami Fukushima nuclear facility. These are just a couple examples of the cross-application potential of such platforms. This article explores the concept, development, and results of a project to develop an unmanned system on board an aircraft. Equipped with a thermal/optical camera and a multi-sensor navigation system benefiting from the European augmentation system EGNOS, the system is designed for a particular application: finding people lost in remote and rugged outdoor environments.

August 1994, early morning. Spain's Central Pyrenees Mountains still in darkness.

At the outset of an ascent to a 3,000-meter peak along the international border, one of the co-authors encounters a group of tourist hikers who have begun searching for a colleague who had left the camp the previous evening. In the pre-sunrise gloom, helicopters cannot yet operate.

A week later, the body of the hiker is found. The rescue efforts came, unfortunately, too late.

If you know a bit about GNSS, inertial navigation systems (INS), remote sensing, and maps, and if you have ever seen an unmanned aircraft in flight, you can only come to the same conclusion as we did when we defined, proposed, and won the CLOSE-SEARCH project to develop an unmanned aerial system (UAS) for search and rescue (SAR) applications. That is, if navigation can be performed accurately and reliably — and if elevation databases are accurate, up-to-date,

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The UAV during the project flight test

and available — then an unmanned aircraft with the appropriate payload can be sent to systematically search for a lost person as soon as that individual is discovered to be missing.

Indeed, light-weight, easily deployable platforms can quickly provide good quality imagery from the air or ground.

Sound like a good idea? It doesn't just "sound like," but is actually being confirmed by the increasing efforts among the remote-sensing industry and research institutions. The recent acquisition by Trimble of Gateway, a provider of lightweight unmanned aerial vehicles (UAVs) for photogrammetry and rapid terrain mapping applications, is only one of the many examples of related commercial moves with which many readers are familiar.

Until now, the lack of regulatory support has proved to be a show-stopper for achieving the final boost to UAV commercialization. However, the willingness of regulators seems finally to be turning positive. As reported in the Institute of Navigation's Winter 2011 newsletter, recent Congressional legislation directs the United States transportation secretary to "develop a comprehensive plan to safely accelerate the integration of civil UAS into the national airspace system as soon as practicable, but not later than September 30th, 2015." Hence, we are on the way to a future in which robots fly around, cooperating with humans – a future in which robots even *search for* humans.

The SAR Potential of Unmanned Technology

When a small plane crashes in a remote area, or a fishing boat is lost at sea, or a hurricane devastates a region, or a person simply gets lost while he or she is hiking, SAR teams must scan vast areas in search for evidence of victims or wreckage. For this purpose, UAVs equipped with remote-sensing devices can be programmed to fly predefined patterns, possibly at low altitudes — 30 to 150 meters — and produce various types of images (thermal, optical, and so forth) captured from their privileged point-of-view. Ideally, this imagery is transmitted real-time back to a ground control station via a data link.

The use of UAVs for the so-called "wilderness SAR" is rapidly evolving. See, for example, the discussion in the article by M. Goodrich *et alia* listed in the Additional Resources section near the end of this article. The navigation aspects related to the specific platforms operated in those particular missions leaves room for additional research.

CLOSE-SEARCH, a European 7th Framework project <www.close-search-project.eu>, addresses the previously described scenario: a person is lost outdoors, a distress message is generated (either by the person him- or herself or by the person's companions). In response, an alert is generated by the civil protection authority providing a rough estimation of the area in which the person may remain. That prompts an SAR team to move as close as possible to that area carrying a UAS, composed of a rotary-wing platform and its ground control station (GCS).

The airborne UAS is equipped with vision systems, say, thermal and optical cameras. The goal of the team is to fly the UAV around in search of the missing person and, in case of success, provide precise coordinates for his or her location. At that point, rescue is triggered and fingers are crossed. This operation may need to take place day or night, possibly in adverse weather conditions, and fast enough to minimize the lost person's anxiety or, ultimately, to safe a life.

When thinking about the key system requirements that enable a UAS to be used for SAR, one realizes that the degree of safety in navigation is crucial. Indeed, when moving from military and governmental applications to the commercial or mass-market level, safe navigation will be revealed as a "must."

The CLOSE-SEARCH Project

Within the CLOSE-SEARCH project, a hybrid multi-sensor navigation system has been developed, augmenting the standard baseline integrated INS and GPS. The hybrid system couples the INS/GPS with the European Geostationary Navigation Overlay Service (EGNOS) and other navigation sensors, such as barometric altimeters (BA) while also enabling us to explore the use of redundant inertial measurement units (RIMUs).

The project's goal was to assess the potential of a low-cost, highly redundant system and ultimately demonstrate EGNOS-based UAV control with an integrated EGNOS-GNSS/RIMU/BA solution. Details of the navigation system design can be found in the sidebar article, "Flight Control and Target Identification Requirements and Results with EGNOS and Multi-Constellation GNSS."

In relation to safety, a key metric was integrity. The project sought to benefit from the integrity monitoring potential brought by the EGNOS system to generate protection boundaries for the unmanned platform.

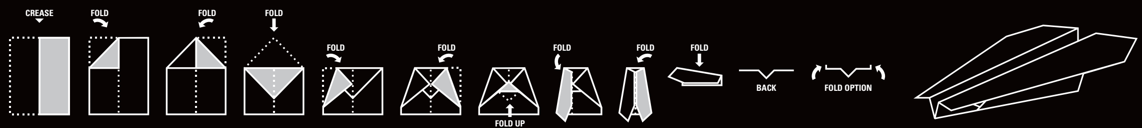
The idea of incorporating integrity in non-conventional

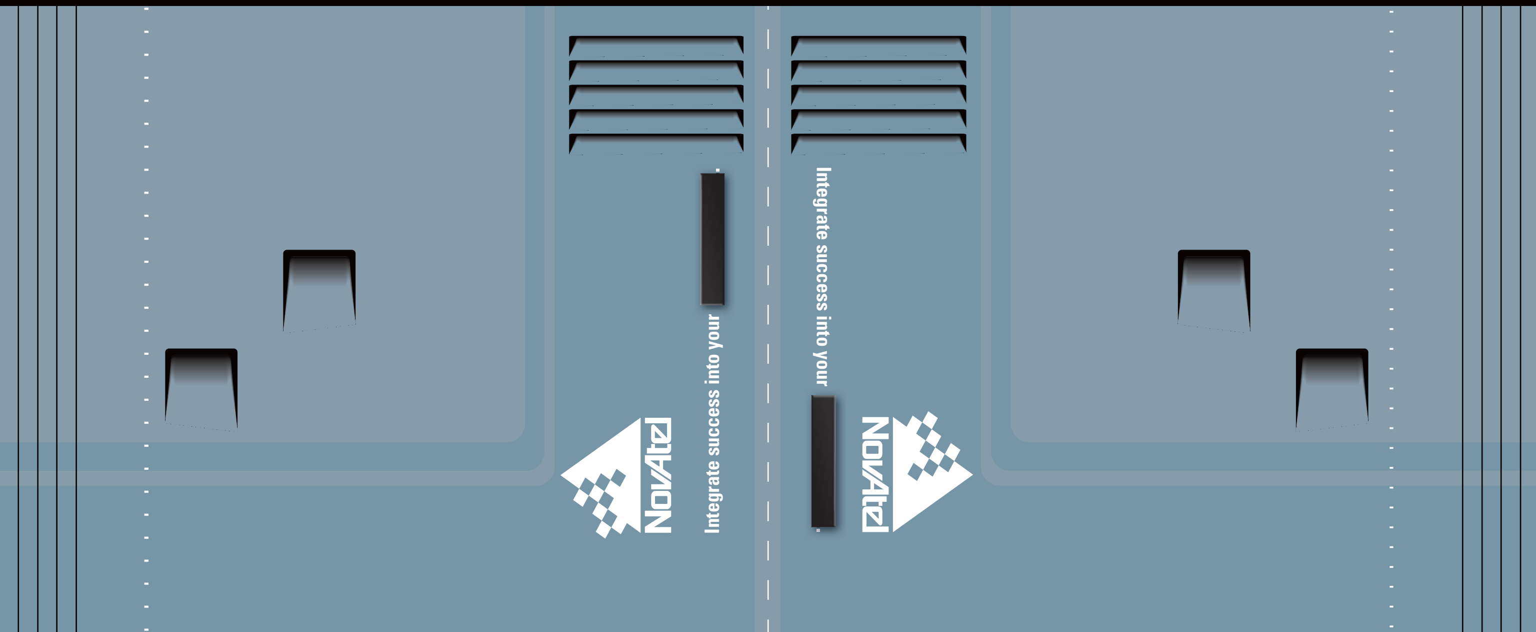
Take it for a test flight.

actual size

New SPAN-MEMS, small enough for any unmanned air or ground vehicle.

Our new SPAN products combine GNSS technology with a range of MEMS inertial measurement unit options to provide continuously available position, velocity and attitude – even when GNSS signals are blocked by barriers such as trees, canyons or buildings. It's ideal for UAVs or UGVs, tracking and mapping, or anyplace else you'd like to soar over the competition. To help imagine what it is like to hold the power of SPAN-MEMS in your hand, fold this page according to the instructions. Or, to integrate the real card into your own design, call you-know-who. Just remember, MEMS the word. For more info, visit novatel.com/span-mems.





Flight Control and Target Identification Requirements and Results with EGNOS and Multi-Constellation GNSS

Following a route defined by application requirements and remotely sensing the environment in order to analyze and interpret the outcome on- and off-line: this is the *axioma* of every aerial remote-sensing mission and, indeed, also for search missions. Yet, the specific requirements for navigation might vary according to the application.

Beyond endurance, size of on-board systems, sense-and-avoid and others, three levels of requirements must be considered: firstly, safety (keeping the platform far from the ground or known obstacles in order to avoid collisions); secondly, flight control (the navigation solution is stable enough for the platform to comfortably follow a pre-defined route); and thirdly, the application-specific performance (ranging from centimeter-grade accuracy for photogrammetric applications to a few meters for surveillance applications).

Indeed, SAR (but extensible to other fields) demands a high level of safety and flight control whilst looser requirements apply for georeferencing the target (i.e., a missing person), which is the application-related goal. Thus, as flying with a stand-alone GNSS-based solution would simply be too risky, the key role of GNSS augmentation is two-fold for UAV missions: improving the real-time horizontal and vertical accuracy — which reaches two and three meters (2σ), respectively, using EGNOS — and ensuring high levels of safety using the integrity mechanisms provided by EGNOS and the multi-sensor navigation concept.

Even if RTK would deliver much better positioning performance (yet without an integrity measure), its dependence on static GNSS setups and communication links may not be fully suitable for SAR missions. Such missions usually demand go-and-fly actions anywhere at anytime, which requires us to eventually assume medium-to-large communication dropouts. The economic savings on using EGNOS instead of RTK setups are also non-negligible.

The navigation system developed within the project consisted on an integration of the following set of sensors: a 36-channel GPS/GLONASS/Galileo receiver, a tactical-grade inertial measurement unit (IMU), and a high-precision barometer. Note that the redundant IMUs were studied as an off-line navigation solution. The integration scheme used the L1 code measurements from the GNSS receiver and the pressure measurements from the barometric altimeter (BA) in a Bayesian filter based on a weighted least-squares solution. The real-time acquisition and processing navigation system on-board has been developed at the Institute of Geomatics.

The integrated solution was delivered in real-time to the FCS in order to enable the platform control using the EGNOS-based solution,

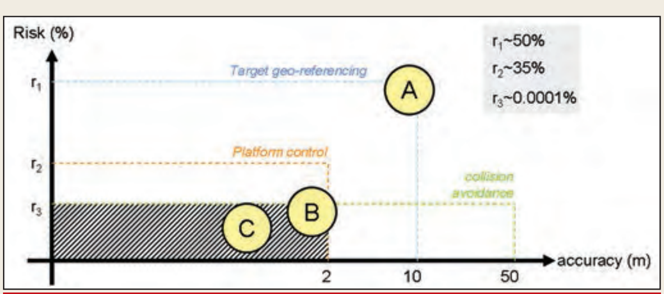


FIGURE S-1 Non-metric accuracy versus risk plot of flight control, target georeferencing and collision avoidance requirements in UAV-based SAR missions: A, standard IMU/GPS integration; B, the CLOSE-SEARCH system (EGNOS-GPS/IMU/BA); C, a future EGNOS-GPS + GLONASS + Galileo + Compass/redundant IMU/BA/++).

	Test 1 (6m 40 sec)			Test 2 (24m 26s)		
	East	North	Height	East	North	Height
Mean	-0.56	0.12	-0.62	-0.82	-0.24	1.35
Std Dev	1.07	1.34	0.71	1.06	1.72	1.46
RMSE	1.21	1.35	0.94	1.34	1.74	1.99

TABLE S-1. Accuracy results in two flight tests: comparison in easting, northing and height components between the reference RTK solution and the closely coupled EGNOS-GNSS/INS/BA

when convenient (Note that the RTK solution was also in place and used as a back-up.) **Table S-1** shows the performance of the proposed CLOSE-SEARCH navigation approach during two test flights compared to the reference RTK solution:

The study of GNSS multi-constellation in CLOSE-SEARCH was also carried out by means of simulations. Starting from a real UAV trajectory generated on one test, two realistic scenarios for present and future configurations were considered: GPS/IMU/BA data were simulated, as already available on the real-time system. Additionally, EGNOS-v3 (the future evolution of the EGNOS system) and Galileo data were simulated to finally re-process the solution in both cases.

The signal availability conditions were assumed to be those of a harsh environment: just four satellites for each constellation (GPS and Galileo) were considered to be visible. Under these conditions, preliminary results showed an improvement of the horizontal and vertical accuracy of around 30 and 35 percent, respectively, with multi-constellation GNSS and EGNOS augmentation together with inertial and baro-aiding. These results are in line with our expectations for the proposed approach: UAV navigation is accurate when using EGNOS and multi-constellations, and probably even a mandatory option in reduced-visibility conditions.

In summary, then, the navigation approaches described here are qualitatively positioned with respect to the UAV-based SAR operations' requirements shown in the **Figure S-1**, which deserves some preliminary definitions. Firstly, the horizontal axis represents the three accuracy requirements in UAV-based missions, and the vertical axis represents the associated tolerable risk level. Coherently, the platform control accuracy requirement is set around two meters (1σ), for both horizontal and vertical components.

The target georeferencing requirement varies between 10 and 30 meters in horizontal, setting the first as the 50 percent level, and the ground collision avoidance accuracy requirement for low-altitude missions can be set as 50 meters in height (considering operational heights from 50 to 150 meters) but with a low level of risk, which has been preliminarily established at 10^{-6}, that is, 0.0001 percent, in view of the system characteristics and mission considerations. (UAVs in SAR can afford higher risk than manned platforms.)

Further, the figure assesses three navigation approaches: A is a standard IMU/GPS integration, B is the CLOSE-SEARCH system (EGNOS-GPS/IMU/BA), and C is a future EGNOS-GPS + GLONASS + Galileo + Compass/redundant IMU/BA/++). Note that the CLOSE-SEARCH proposal reaches the highlighted area in which the three requirements are met, and also note that the assistance of future GNSS multi-constellation will definitely enable UAV-based SAR operations. IG

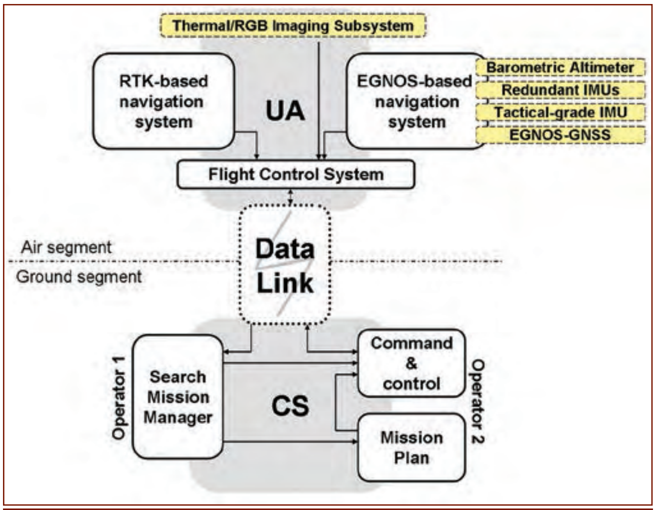


FIGURE 1 CLOSE-SEARCH system architecture

platforms is of increasing interest, and its implementation in unmanned platforms may be even necessary when facing the previously mentioned regulatory processes. It goes like this: you own a UAV that you want to fly around; so, you need to demonstrate that a navigation failure has a (very) low probability of happening, and that the consequences of a failure slipping into your aircraft control system is bounded by a certain predictable amount.

The question is: how far are those of us interested in operating UAVs from reaching that capability? The sidebars, "Requirements for Precision-Based Integrity and Geodetic Quality Control in UAV-Based SAR Missions," and "Safe Navigation from Hybrid, Redundant Navigation Sensor Systems" explore that question in greater detail based on experience from the CLOSE-SEARCH project.

The CLOSE-SEARCH Prototype

Figure 1 depicts the air and ground segments of our proposed system's architecture. As is common for UAS architectures, the prototype arises from efforts to integrate imaging, navigation, communications, and mission planning, that is, a system of systems. In the figure, yellow boxes are used to highlight imaging and navigation sensors, and white boxes are used to identify software components on the aerial platform and the ground. The following sections provide further details of the various components.

Aerial Platform, Ground Control Station and Communications. Three fundamental components comprise every UAS: the UAV or drone-, the GCS, and a communication data link between them. In CLOSE-SEARCH, these three components were brought by a project partner, the Asociación de la Industria Navarra (AIN), from Pamplona (Spain). Accompanying photos show the UAV performing during one of the project tests, and an outdoor and indoor view of the GCS.

The UAR-35 is a non-commercial, in-house rotary-wing platform of about three meters length, minimum take-off weight of 75 kilograms, and with an 18-horsepower engine.

Safe Navigation from Hybrid, Redundant Navigation Sensor Systems

Navigating safely is always necessary, and unmanned platforms especially need to do so, as they still must demonstrate to the general and technical public that flying without a pilot on board works and is safe (or as safe as piloted crafts). So, when asking ourselves what is the right approach to safe navigation in UAVs, one word steps immediately into the discussion: redundancy.

The use of redundant sensor configurations paves the way to achieving robust navigation. By providing redundant observations, the precision of the navigation parameters' estimation is significantly improved (as discussed in the article by A. Waegli *et alia*). Redundancy also enables detection and exclusion of eventual faulty measurements and therefore guarantees a higher continuity of operations in the presence of a fault.

This applies to GNSS systems, which are inherently redundant (usually more than four satellites in view to estimate four unknowns). Yet, redundancy is not exclusive to GNSS — the use of several low-cost IMUs in UAV navigation is definitely interesting from a cost-effectiveness perspective as long as acceptable performances would be achieved.

Referring to Equation (1) in the main article, if we think of the index as the number of navigation subsystems and we make explicit the dependency of the *operational risk* (OR) with respect to n, then we have $OR(n,AL) > IR(m, AL)$ for $n < m$. In other words, we claim that for an INS/GPS navigation system (that is, $n = 2$) the OR is higher than for the proposed navigation system in CLOSE-SEARCH (where $n \geq 7$) made of up of one GNSS receiver, four IMUs, one baro-altimeter, one magnetometer, and various close-range sensors.

We note that, while the probabilities p_i of the various failure types are only related to the instrument/system "intrinsic" properties (quality and age), the terms $a_0(AL)$ and $1 - \beta_{0i}(IR)$ depend on the navigation instruments' configuration. Indeed, this is how SBAS (WAAS or EGNOS) and GNSS multi-constellations contribute to the decrease of the IR. In the SBAS case, although the probability of a GPS failure, say p_1, purely depends on GPS satellites' failure rates, the probability of not detecting a system failure, say $1 - \beta_{0i}(IR)$, is smaller because of the additional SBAS infrastructure and mechanisms devoted to satellite monitoring and fault detection.

Analogously, in the case of additional GNSS constellations, the overall risk will decrease even if there are more contributors to the sum term, as both $a_0(AL)$ and $1 - \beta_{0i}(IR)$ will become smaller due to a better precision estimation and a better fault-detection capability in redundant conditions, respectively. New and better future signals, as provided by GPS modernization and Galileo among others, will simply lead us to more accurate and precise solutions.

In the case of CLOSE-SEARCH, starting from the base EGNOS performance and considering several IMUs and other navigation sensors, the risk of the baseline INS/GPS configuration,

$$OR(2,AL) = a_0(2, AL) + p_1 \bullet (1 - \beta_{01}(IR)) + p_2 \bullet (1 - \beta_{02}(IR)),$$

is transformed into

$$OR(7, AL) = a_0(7, AL) + \sum_{i=1}^{7} p_i \bullet (1 - \beta_{0i}(IR))$$

where having more contributors to the "integrity-related" sum —even using sensors of a cheaper quality — is compensated by a higher precision — smaller a_0, $a_0(2, AL) > a_0(7, AL)$ — and smaller probabilities of subsystem failures' misdetections, $1 - \beta_{0i}(AL)$. IG

The flight control system (FCS), responsible for the platform control, is also an in-house development, and the navigation solution input to the FCS is obtained through a real-time kinematic (RTK) GNSS system incorporating IMU and magnetometer measurements for the attitude determination. As RTK techniques are characterized by providing centimeter-level navigation accuracy, the described RTK-based navigation system was used as a reference for the validation of the EGNOS-based navigation system, with the latter being a specific CLOSE-SEARCH project development.

Due to its high payload capacity (up to 30 kilograms), the UAV that we used was an ideal platform to integrate remote sensing instruments or other navigation sensors.

On the ground, the GCS is mounted on a four-wheel-drive van outfitted with three computers and the appropriate ancillary electronics. A redundant power supply system is mounted in the cargo area.

At the software level, "command & control" software receives the platform telemetry and sends appropriate commands to the aerial platform. Also installed in the GCS vehi-

Requirements for Precision-Based Integrity and Geodetic Quality Control in UAV-Based SAR Missions

As this article points out, if one is willing to *safely* use UAVs, then a key indicator to account for is integrity. Commonly, UAV navigation is performed with differential GNSS processing, in the form of RTK, which lacks integrity measures. Hence, integrity is (or should be) of high interest for UAV platform operators, as it might even be mandated when demonstrating compliance with future safety regulations. In this regard, two key statements define integrity: *precision is below tolerances*, and *no faulty measurements are used*.

The first statement is inherently related to SBAS systems. The use of EGNOS enables the computation of protection thresholds in position, called *protection levels* (PLs), in the horizontal and vertical subspaces. These PLs are directly derived from the precision estimation and scaled up by a factor to account for a certain level of risk, the so-called *integrity risk* (IR) (See the paper by B. Roturier *et alia* in Additional Resources). Thus, by comparing the PLs against a set of 'tolerable' thresholds called *horizontal* and *vertical alert limits* (HALs, VALs), the user can measure the safety level achieved when navigating. Note that, because the PL concept is "precision-based," it can be fully applied to multi-sensor navigation solutions and not restricted to GNSS-only navigation.

The integrity frame defined by the IR and the ALs is well established for highly demanding applications such as civil aviation. However, analogous requirements for other applications have not been fully developed, and accomplishing this will not be a trivial exercise. Other platforms such as cars, trains, and pedestrians are likely to benefit from integrity concepts but have much looser safety requirements (see the paper by S. Pullen *et alia*).

UAVs also need to develop integrity requirements, which has been a motivation in CLOSE-SEARCH. The recent paper by P. Molina and I. Colomina (see Additional Resources) outlines a set of integrity requirements adapted to the needs of two flight phases in SAR missions employing UAVs. These requirements are presented in Table S-2. Civil aviation APV-I values are also provided merely for comparison, as they correspond to actual EGNOS certification requirements.

On one hand, the presented ALs are based on the mission requirements such as overlap of thermal images to seamlessly scan a certain area or minimum distance to ground to activate a UAV's landing sensors. On the other hand, the IR specification is a preliminary value, reflecting the idea that the risk in UAV missions can certainly be less restrictive than civil aviation.

	IR (- / approach)	HAL, VAL (m)
APV-I (EGNOS certification)	2×10^{-7}	40, 50
W2W (waypoint-to-waypoint)	2×10^{-6}	4, 7.5
GA/S (ground approach/separation)	2×10^{-6}	2.5, 4

TABLE S-2. Integrity risk and alert limits defined in CLOSE-SEARCH for two UAV flight phases, waypoint-to-waypoint and ground approach/separation. APV-I is also featured for comparison.

During the final test campaign of the project, protection levels were derived from the EGNOS-GNSS/INS/BA solution. The results showed that choosing an IR of 10^{-3} and HAL, VAL of 10 meters, the availability (that is, the percentage of time that PLs are below ALs) is around 95 percent. That is to say, a UAV can safely fly down to 10 meters above ground, with the risk of "something goes wrong and undetected" remaining lower than 1 over 1000 during the 95 percent of the time. Indeed, these results need further improvement, and the proposed integrity values need to be finally confirmed.

The latter statement regarding integrity values is related to the fact that precision might be an untruthful measure of accuracy when faults in the observations are present. Indeed, computing PLs using EGNOS information offers protection up to a certain level, accounting for orbit and satellite clock errors, ionosphere, and so on. Nonetheless, other errors may be present at a local scale (for example, receiver noise, multipath, and interference), and the fault list even increases when other sensors are added, such as IMUs, barometers, or magnetometers.

This consideration motivates the need for outlier detection capabilities to detect faults in the measurements and, if possible, to exclude them from the navigation solution computation. Classical geodesy offers well-established techniques to proceed with quality control in least-squares estimation, including outlier detection, estimation of marginally detectable errors, and fault impact on parameter estimation. These concepts were introduced by the Dutch geodesist W. Baarda in the 1960s.

Again, as in the precision-based integrity, the set of thresholds to be defined in the outlier detection and exclusion (basically, the probability of *false alarm* and *missed detection*) are still unclear for low-altitude UAV applications. In continuation with the work performed on defining suitable ALs and IRs for UAV navigation, the authors will further study the use of geodetic quality control techniques and work toward defining the frame of an outlier detection and exclusion method for such platforms.

Finally, GNSS multi-constellations are also safety enablers in UAV-based SAR operations. In rough terms, the more satellites in view (as will be the case in future GPS/Galileo, GLONASS/Compass . . .), the better the accuracy and precision (as already seen in the simulations presented earlier) of platforms using them to navigate. And more satellites also improve the chances of continuously operating in "obscured" environments (as those imposed by SAR missions, where flying below the peaks of steep mountains is a common situation). Indeed, further investigations need to follow on the potential benefits of future GNSS systems for unmanned platforms in SAR missions. IG cle's computers is the "Search Mission Manager" software, which receives, displays, and enables a photo-interpreter to interact with images from the UAV.

A minimum of two operators monitor and command the UAV to operate the search mission: a "safety remote pilot" and the image interpreter. The two-person crew also drives the GCS vehicle, mounts and dismounts the helicopter, and performs associated logistical tasks.

Mission planning is usually performed off-line and loaded into the GCS, but the same process can be done on-site. Modifications to the UAV waypoints and actions can also be implemented during the mission. Hence, if the operator has seen something of interest in an image, for instance, he can modify the route and re-visit that location — if for nothing else, just to discard false alerts. In order to generate the mission plan, LiDAR-based digital surface models (DSMs) with point density of 0.5 points/m^2 were used. These models are available now for the entire region of Catalonia from the Institute of Cartography of Catalonia (ICC).

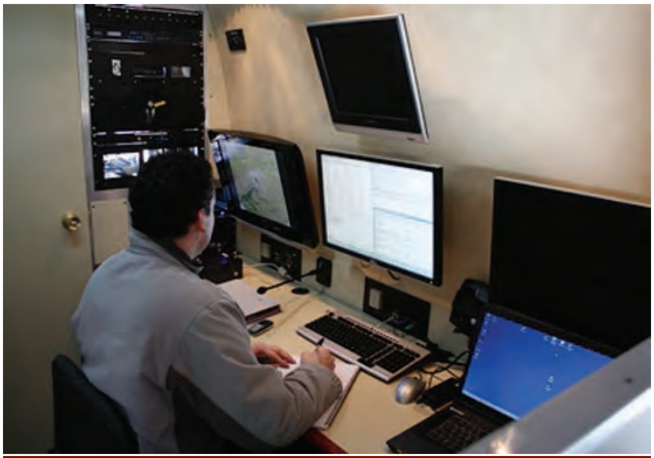
Two data links are established in the prototype: command & control, consisting of a downlink to transmit the telemetry data from the UAV to the GCS, and an uplink to send commands to the UA; and the payload data link, which provides a downlink to transmit real-time thermal and optical images captured by the aerial platform.

Design of these data links employed two communication architectures to address user requirements. The first and principal architecture was based on line-of-sight (LoS) communications. More precisely, WiFi technology was implemented to support both data links (command & control and payload) due to its suitable performance in terms of range and bandwidth. The particular drawbacks of this technology arise from performance degradation as a function of the UA-GCS distance (tested up to four kilometers with the current system) and also in presence of obstacles that block the wireless signals.

These drawbacks are quite in conflict with SAR missions' requirements: finding people in difficult-to-access areas where no road access is available often necessitates flying and scanning in mountainous areas in which direct LoS between the UAV and the GCS can be lost. Consequently, a beyond-line-of-sight (BLoS) architecture was also considered to fulfill the SAR mission in such situations.

The candidate technology to support the BLoS architecture was the so-called Worldwide Interoperability for Microwave Access (WiMAX). This technology, based on a wireless communications standard designed to provide 30 to 40 megabit-per-second data rates, has been tested and used in controlled UAV flights to assess its suitability for command & control and payload data transmission and reception. These tests yielded more than satisfactory results and demonstrated potential for future improvement. The interested reader is referred to <http://www.wimaxforum.org>.

Vision Systems to Detect Human Body Heat. Within a reasonable time after the notification that a person has gone missing, body heat is a key indicator when searching people from above. In addition, in human-unfriendly outdoor scenarios i.e., cold environments, darkness, and so forth, the heat of a person's body might be the only differentiator when searching for him/her.



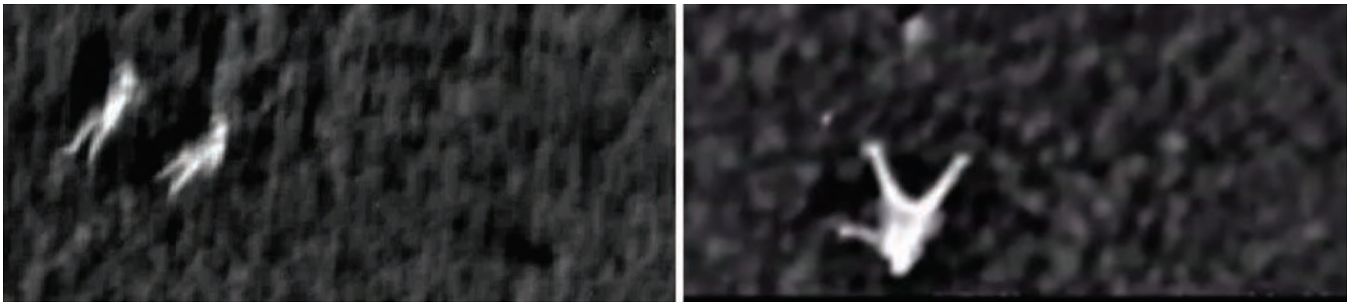
Inside view of the UAS ground control station

But besides thermal vision, being able to "see as humans see" was also requested by SAR operators, as sometimes a piece of clothing, a bag, or other human belongings might provide a crucial hint of a lost person's whereabouts. Thus, a good complement to thermal vision in search missions is optical vision. Previous work on combined thermal and color imagery in UAVs has pointed out the difficulty on identifying people in thermal images with trained algorithms due to low resolution of such cameras, blurring caused by halos around thermal targets, and so on. (For further discussion of these points, see the work by P. Rudol and P. Doherty in Additional Resources.)

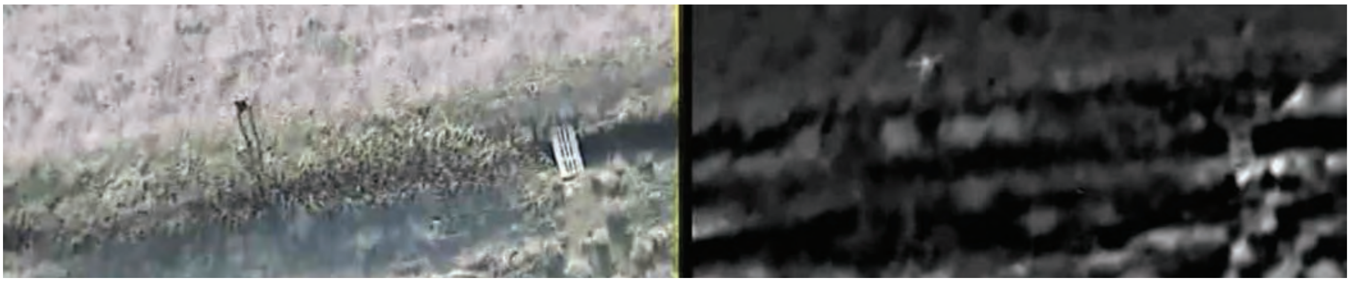
In our project, the ultimate analysis of images is done by the (human) operator in the GCS, who watches the images in real-time and decides whether a thermal spot and its corresponding colored image represent a lost person. In this, the operator is aided by an automatic feature-highlighting algorithm. If uncertain, the same waypoints can be re-flown just by modifying the mission plan *in situ*.

Two sensors comprise the remote sensing component integrated on the UAV: a thermal camera — 320 x 240 pixels, focal length of 25 millimeters, 33 x 25–degree field of view (FOV), sensitive in the 8-12 µm spectral range — and a 582 x 500–pixel color camera — accepting lenses of various focal lengths. In the absence of *a priori* geometric or radiometric calibration, both cameras were mounted downward-facing on a carbon fiber sheet attached to the payload frame using cup-style isolators. The latter provide vibration isolation for low frequencies down to 10 hertz and exhibit low transmissibility at resonance.

The accompanying thermal images were captured during the first (left) and second (right) campaign. On the left image, with a ground sampling distance (GSD) of 5.5 x 5.5 centimeters, two people lying down are perfectly distinguished against the floor (regular flat ground) during a day test in central Catalonia (November 25, 2011). On the right image, with a GSD of 3.7 cm x 3.7 cm, another person can be recog-



Left, thermal image of two persons lying on the ground captured during a day test (GSD = 5.5 cm x 5.5 cm); right, thermal image of a person lying on the ground captured during a night test (GSD = 3.7 cm x 3.7cm)



Optical (left) and thermal images of a person standing and waving arms (GSD = 7.3 cm x 7.3 cm)

nized against the same type of floor, but this time during a night mission in March, 2012.

A second set shows paired RGB (red, green, and blue) and thermal images captured on the last test campaign of the project. In that particular test, a person stood and waved his arms as though asking for help. These images were taken during daylight hours near Pamplona (February 28, 2012), and have a GSD of 7.3 x 7.3 centimeters for both the thermal and color images. The full video footage can be seen on the Internet at the project's YouTube channel, featured in the section, "About the CLOSE-SEARCH Project."

Safe Navigation for Low-Altitude Unmanned Aerial Missions

In an ideally well-organized and technologically advanced world, the integration of UAS into non-segregated airspace would be feasible. UAVs would coexist with manned platforms and cooperate seamlessly with ground teams. However, neither technology nor regulations — nor, probably, our own minds — are yet there. Among other factors, sense-and-avoid and safe navigation capabilities are needed for that.

In our context, safe navigation refers to real-time positioning with a low probability of failure and within spatial boundaries defined by low-altitude search requirements. In practice, this "low failure probability" should translate into a "navigation never fails" de facto reliability. Moreover, in an ideally technologically advanced world, a single perfect navigation instrument would suffice.

In practice, we approximate a perfect navigation instrument by extending our INS/GNSS low-redundant baseline system with a highly-redundant multi-sensor system. More specifically, redundancy can be added by using GNSS augmentation systems (EGNOS in the European region), using other available GNSSes (GLONASS) or planning to use future GNSSes (Galileo, Compass). We could also build redundancy by replacing high-end tactical-grade IMUs with four MEMS-based IMUs or by adding magnetometers and baro-altimeters.

These instruments are usually complemented with short-range sensors in support of specific UAV maneuvers, such as take-off and landing. Last but not least, we note that "safe" or "low failure probability" shall be quantified in the context of the CLOSE-SEARCH application requirements.

Generally speaking and in classical geodetic terms, "augmenting" a system or adding redundancy to it translates into higher precision and reliability. If the redundant measurements are correctly modeled, that will also result in higher accuracy. In the language of navigation, more redundancy translates into higher accuracy and a smaller *integrity risk* (IR).

We define the *operational risk* (OR) as the probability of occurrence of a situation by which safety is threatened for a particular operation. In other words, OR can be understood as the combination of navigation-related factors leading to unacceptable precision (or accuracy, in absence of model errors and measurement outliers) or to a loss of integrity. Note that OR is a combination of the precision-related risk, as precision is the metric of accuracy in nominal non-faulty conditions, and the integrity risk, which is the probability of missed detection of faults causing a hazardous error.

More specifically, we distinguish two situations contributing to the OR 1) under nominal conditions, the error of a navigation state (position, velocity, or time) exceeds some tolerance or alert limit (AL) that is regarded as hazardous for the particular application, or that 2) a failure event has occurred and gone undetected — misdetection — with an effect on the navigation solution that exceeds the AL. Mathematically, given an IR,

$$OR(AL) = a_0(AL) + \sum_{i=1}^{n} p_i \bullet (1 - \beta_{0i}(IR) \qquad (1)$$

where:

- $a_0(AL)$ is the probability that, under nominal fault-free conditions, the navigation state error hazardously exceeds the tolerable limits (related to the system's PVT precision),
- p_i is the probability of occurrence for each element e_i of the Failure Types set $F = \{e_1, ..., e_n\}$ (related to the navigation sensor or system's failure rates)
- $1 - \beta_{0i}(IR)$ is the probability of type II error (missed detection, related to the system's reliability)

For the given specification *AL* and *IR*, an ideal system verifies equation (1) at the lowest price, weight, electrical power consumption, and so forth.

Safe navigation in CLOSE-SEARCH can thus be regarded as an exercise to identify correct requirements and to design an ideal system accordingly, that is, to set integrity requirements — among others — for our SAR application domain and vehicle. The project has also sought to approximate the ideal system through a hybrid navigation system including redundant IMUs and other sensors, and, last but not least, to benefit from EGNOS and multi-constellation configurations for platform navigation and target identification tasks.

Lessons Learned about Use of Unmanned Platforms in SAR Operations

We thought we might compile our experiences on the use of unmanned platforms in search operations as a concluding section. These comments are a result of the close work with some SAR teams who would eventually need these platforms and who provided valuable inputs for the project. Of course, we also provide observations in case any interested reader is inclined to jump on this business opportunity.

1. The three famous words that describe the nature of UAV operations (dull, dirty and dangerous), especially hold true when describing SAR missions. SAR teams ask for autonomous machines operating continuously day and night, on long missions, and in adverse weather conditions. This is definitely a challenge for UAV manufacturers willing to explore the SAR field. Within the project, a short demonstration of a night flight was performed, which probably represents a case in which UAVs would provide service where others simply could not.
2. Nowadays, RTK is the most common GNSS processing scheme implemented in UAVs. But in SAR-like missions (navigating behind mountains, or at several hundreds of kilometers away, or using mobile control stations), LoS-dependent RTK systems would simply fail to meet the mission requirements. In contrast, satellite-based augmentation system (SBAS) solutions such as EGNOS or the U.S. Wide Area Augmentation System (WAAS), offer acceptable performances independent from local stationary setups or dedicated communication links, as required by RTK. In addition, the use of integrity may push the start-button for regulating safe operations in any open-air environment.
3. One of the issues related to certifying UAV operations is the sense-&-avoid capability. Without a human onboard, unmanned aircraft lack a built-in capability to avoid mid-air collisions, when radar coverage is absent or transponders are inoperable or not installed, and to avoid also ground obstacles (basically, manmade structures). Conceivably, this latter issue could be addressed by the use of LiDAR-based DSMs during the mission planning component of the system. Discussion was raised about the need of DSMs to contain updated information about existing infrastructures (powerlines, buildings, etc.) — thus, cartography providers shuold generate suitable updated products as a first step towards a complete reliability concept for UAVs (sense-&-avoid plus navigation integrity)
4. The trend is to go smaller and smaller — for technology, in general, and sensors in particular. This is in line with the miniaturization process that UAVs are also experiencing, as smaller payloads require smaller equipment and sensors. Vision sensors nowadays achieve centimeter-level GSDs shooting at acceptable frequencies (up to one hertz), enabling application into more demanding fields such as geomatics. Improvement is also present for generic infrared sensors (thermal, night vision) which is of interest for surveillance applications and extensive to SAR. This paper's results are just a starting point for further investigation of UAV-based thermal vision.
5. Many applications were pointed out by SAR users as possibly suitable for UAV-based systems, which might be interesting from a business perspective — a system operating transversally, i.e., in both SAR and non-SAR operations, could easily reach a satisfactory point of return on investment. Examples of these applications include agricultural management, detection and response to forest fires, aerial pollution monitoring, aerial road traffic control, and sea search missions, among others.
6. UAV motion is quite constrained in small- or medium-sized rotary-wing UAVs, especially in surveillance-type missions (low speeds, near-zero pitch and roll values, smooth transitions between flight phases). However, our platform's engine (one-cylinder, two-stroke, air-cooled) operating at full power proved to be a source of high-frequency, high-amplitude vibrations, which severely affected the IMU measurements. Efforts have been added to the project to carry out further IMU modeling for highly vibratory environments. Much work also still remains to achieve optimal sensor fusion performances.

About the CLOSE-SEARCH Project

The research leading to these results is framed on the CLOSE-SEARCH project website <www.close-search-project.eu> and has been funded by the European Community Seventh Framework Programme under grant agreement no. 248137, managed by the European GNSS Agency (GSA), in response to the call *"Use of EGNOS Services for Mass Market: Innovative Applications targeted to SMEs"*.

CLOSE-SEARCH has been carried out by a heterogeneous yet complementary consortium led by a research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center (Institute of Geomatics) and including a private non-profit technology center (Asociación de la Industria Navarra), the Geodetic Engineering Laboratory (TOPO) of the Ecole Polytechnique Fédérale of Lausanne (EPFL), an aerospace engineering company (DEIMOS Engenharia), a public research agency and geospatial data provider (Institute of Cartography of Catalonia) and an end user (the Catalan Civil Protection Authority).

Additionally, a User Advisory Board was created consisting of representatives from teams involved with real SAR operations. The board helped assessed the development of the project by providing their opinions and counsel. Within the board, various fields were represented, including mountain rescue, sea rescue, and firefighters. More information on the board and its members can be found on the project website.

The authors would like to specially thank all the people involved in developing the project. Finally, the reader is welcome to visit the CLOSE-SEARCH YouTube channel where some videos of the prototype testing and imaging results can be found at <www.youtube.com/closesearch>.

Manufacturers

The navigation system developed within the project consisted on an integration of the following set of sensors: a TR-G3T GNSS receiver from **Javad GNSS**, San Jose, California, USA; an LN-200 IMU from **Northrop Grumman**, Woodland Hills, California, USA; and a High Precision Barometer from **Honeywell Aerospace**, Plymouth, Minnesota, USA. The CLOSE-SEARCH remote sensing platform included a Thermal-Eye 2000B infrared camera from **L-3 Infrared Products** (formerly Raytheon Commercial Infrared) Dallas, Texas, USA; and a CCD CM-3120CDM color camera from **Sony Corporation**, Tokyo, Japan. Galileo observables (ranges) were simulated using a GRANADA simulator from with **DEIMOS Space**, Madrid, Spain.

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