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Research Article

# Design of Sensors' Technical Specifications for Airborne Surveillance at Borders

***Giorgos Kampas*** [a]***, Aggelos Vasileiou*** [a]***, Marios Antonakakis*** [b]***, Michalis Zervakis*** [b]***, Emmanouil G. Spanakis*** [c]***, Vangelis Sakkalis*** [c]***, Peter Leškovský*** [d]***, Sergio Sanchez Carballido*** [d]***, Razvan Gliga*** [e]***, Dejan Vinković*** [f]***, Bojan Pečnik*** [f]

[a] *Center for Security Studies, P. Kanellopoulou 4, Athens 101 77, Greece*
*http://www.kemea.gr/en/*

[b] *Technical University of Crete, Akrotiri Campus, Chania 731 00, Greece*
*https://www.tuc.gr/index.php?id=5397*

[c] *Foundation for Research & Technology – Hellas, Nikolaou Plastira 100, Heraklion 700 13, Greece*
*https://www.forth.gr/*

[d] *Vicomtech, Mikeletegi Pasealekua 57, Donostia 20009, Spain*
*https://www.vicomtech.org/en/*

[e] *Software Imagination & Vision, Șos. București-Ploiești, București 013685, Romania*
*https://www.simavi.ro/en*

[f] *Hipersfera Ltd., Ilica 36, 10000 Zagreb, Croatia*
*https://hipersfera.hr/*

## ABSTRACT

The need for fast and precise information in combination with the huge technological developments concerning drone, information and sensor technologies, over the last few years, promoted the use of Unmanned Aerial Systems (UAS) in several domains ranging from agriculture to surveillance applications. The unique opportunity that UAVs and the accompanied payloads offer for acquisition of real time and precise data, make them a valuable asset especially for Law Enforcement Agencies that benefit from UAV's capabilities,

✉ Corresponding Author: Tel.: +30 210 7710805    E-mail: g.kampas@kemea-research.gr

preventing or efficiently responding to several cases. Focusing on border external security, the continuous reports on cross border illegal activities apply constant pressure to Border Guard Authorities that aim to safeguard European borders, highlighting in this way, the need of new technologies and ways that will guarantee efficient border surveillance. In this framework, this paper analyses the methodological steps followed and the outcomes derived in the process of requirements identification up to the extraction of specifications, concerning an unmanned aerial system and its payload meaning the respective sensors for border surveillance that are capable of supporting border guard authorities on surveillance and search and rescue missions.

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UAS: Unmanned Aerial Systems, UAV: Unmanned Aerial Vehicle, LEA: Law Enforcement Agency, CAGR: Compound Annual Growth Rate, LADAR: Laser Detection and Ranging, LIDAR: Light Detection and Ranging, SAR: Synthetic Aperture Radar, SWIR: ShortWave InfraRed, LWIR: LongWave InfraRed, EU: European Union, BCP: Border Crossing Point, CBRN: Chemical, Biological, Radiological, Nuclear, SaR: Search and Rescue, RF: Radio Frequency, GPS: Global Positioning System, LoS: Line of Sight, HIT: Health Information Technologies, ROI: Region of Interest, FoV: Field of View



## I. OVERVIEW

The developments in the Unmanned Aerial Vehicles technological sector have been immense [1] with their market currently valuing 13.44 billion USD and it is expected to expand at a compound annual growth rate (CAGR) of 57.5% from 2021 to 2028 [2]. At the same time their technical attributes are constantly improving both in performance as well as in variety with new technologies being added to the already extended list. Due to this proliferation, UAVs are being extensively used in several industries such as, agriculture, transportation and logistics, energy, construction and engineering, real estate, forestry, media and safety. They are also being used in applications of supporting disaster [3] and environmental management [4].
A sector that is particularly benefited from the use of UAVs is the security sector and especially the border surveillance operations where unmanned aerial systems can operate at various altitudes providing real time situational picture to the command-and-control centres through a variety of available sensors. Border surveillance is one of the central operations that ensures a state's internal security.

Being such, it usually involves having a clear view of remote and hard-to-reach locations, operating day and night, under all weather conditions. UAVs in their many variations, came to facilitate the surveillance tasks by undertaking many of the previously hard and additional workload. This can be proven by the coordinated efforts in research aiming to improve border surveillance utilizing drone technology [5].

UAVs can carry many of the land fixed or mobile sensors such as high-resolution daylight and thermal cameras, LiDAR sensors and multispectral cameras. Being able to reach the desired altitude at any location under surveillance the provide high-quality video data, target acquisition and tracking targets, UAVs have become a valuable asset in border security.

Following the increasingly high rate of testing and using UAVs in border and cross border operations, considering in parallel the drone technology evolution, the EU funded project BorderUAS aims to introduce an airship (multi-role lighter-than-air (LTA) unmanned aerial vehicle) by combining different types of ultra-high resolution (cm-scale) sensors using technology such as synthetic aperture radar (SAR), laser detection and ranging (LADAR) and shortwave/longwave infrared (SWIR/LWIR). The actual BorderUAS rigid airship has significant “real estate” to support remote sensing instruments, enabling novel larger sensor array configurations. It can operate in almost complete silence, providing unparalleled opportunities for acoustic surveillance. It has a robust control over position and attitude at low relative air-speeds, enabling stable slow or stationary flight capabilities. Its semi-autonomous operations, long endurance and modular design result in modest workforce requirements, providing favourable system scalability and significant cost effectiveness for fleet operations over large ground areas. Through the continuous engagement of Law Enforcement Agencies (LEAs) in the definition of the requirements, pilot cases and in providing feedback throughout the system development and assets integration, BorderUAS will test and deploy a combined solution that will be dedicated to the current extended needs and will provide high coverage, resolution and revisit time with a lower cost than satellites or other aerial surveillance means, such as helicopters, and higher endurance than drones. The project focuses on an end-user-centred system design that addresses effectively border guard surveillance needs and as such the current paper presents the initial step for the design and layout of the BorderUAS system which includes the identification of end user requirements that are aligned with all operational challenges in the EU border region, as well as the definition of sensor specifications.

The current paper is divided into the following sections: Section II provides indicative incidents and background information regarding the illegal activities in the EU external borders, as well as a brief overview of the UAVs, their capabilities and limitations in border surveillance, Section III introduces the methodological approach followed under the scope of BorderUAS project, Section IV includes the analysis and the outcomes derived from the aforementioned implemented methodology, focusing on the specifications of airborne sensors, Section V presents the future steps that should be followed to extend the scope and the work of the current study and concludes with the outcomes.

## II. BACKGROUND ANALYSIS

According to FRONTEX's report [6], the number of illegal border-crossings at Europe's external borders for the first five months of 2021 saw almost a 50% increase in comparison with the previous year events where numbers dropped due to travel limitations linked to the outbreak of COVID-19. One year back FRONTEX's annual Risk Analysis for 2020, reported 141.846 attempts of illegal border-crossings between BCPs had been detected on entry in 2019. It is worth mentioning that 307.256 detections of illegal stay were made inland, indicating that a great number of persons cross the EU external borders between BCPs without being detected in time. According to the risk analysis [7], the current routes, being exploited by smugglers and facilitators to transfer people illegally to the EU countries, are through all parts of the Mediterranean Sea, western, central and eastern, through the Western Balkan route and the Eastern Borders route. As it has been also reported, there is an alternative and circular route being used to cross the borders from Albania to Greece. Further from detecting illegal border crossings, border guards and coast guards are also addressing crime related border activity such as drugs, firearms or any kind of illegal goods smuggling. In total, 356 tons of drugs were seized during surveillance activities at external borders of the EU. The analysis also highlights the need of effective and efficient border surveillance in order to prevent any threat to the internal security and public policy of the Member States from criminals and terrorists.

Europe's external borders face continuous challenges dealing with diverse types of illegal activities from smuggling of goods to human trafficking and illegal border crossing. The surveillance strategies and the systems being deployed in border areas are constantly under stress addressing the increased needs of operational readiness and efficiency. There are several examples that prove the pressure applied on border guards; some indicative and recent examples of illegal border incidents that took place in 2020 across the EU external borders are according to public media sources [8] [9] [10] [11].

### *A. UAVs, payloads and remote sensing*

UAVs are airborne and mobile platforms able to navigate in 3D environments, covering significantly large distances comparing their size and weight and fulfilling any type of mission assigned to them and able to carry one or two payloads from an exhaustive list [12] [13]. Airborne monitoring or airborne remote sensing is one of the most efficient tools in natural disasters, border surveillance or even environmental monitoring where large territories need to be scanned and analysed in a short timeframe [14]. The only suspending factor could be considered the high cost of the acquisition and usage of airborne means. Although, the cost comparison between unmanned and manned aircrafts that are used for border surveillance, such as the helicopters, could be a very complex calculation as there are different ways to calculate the various existing metrics; however, it is highly dependent on each mission's characteristics and objectives. In general UAVs, they are less expensive to procure and operate, offering high quality and more precise data, without risking human operators to any kind of danger [15], but covering small areas in contrast with the helicopters. As the drone technology and industry are evolving, Law Enforcement Agencies tilt the balance in favour of UAV instead of manned solutions. All these characteristics turn the UAV into a reliable and efficient system for mobile, aerial surveillance especially at the harsh and inaccessible for human border areas.

In the context of providing services for surveillance and monitoring activities [16], UAVs usually utilise a variety of payloads, in particular sensors including among others visual and thermal cameras, CBRN or SAR [17], etc, offering situational awareness in emergency incidents, ad hoc monitoring of specific area including detection of illegal border crossings or other relevant activities, capable of providing even under foliage detections with the proper payload. UAVs are considered as the ideal solution for aerial surveillance missions [18] [19] [12], tracking [20], as well as data capturing for SaR [21]. The selection of the most suitable payload depends on mission's parameters including the objectives, the environment and the light conditions, the target -if any-, etc. Different types of UAVs are able to carry a plethora of sensors to acquire a variety of information according to pilot's needs, including but not limited to the below indicative list:

- Visual sensor captures a large quantity of information from the environment around them to determine presence and orientation of objects of interest. Data acquired by this kind of sensors are high-resolution RGB colour images or videos [22].
- Thermal sensor indirectly measures the relative temperature of the objects of interest without any contact [23].
- RADAR, Radio Detection and Ranging sensor detects and tracks the distance, angle, or velocity of objects of interest, using radio waves [24].
- LiDAR, Light Detection and Ranging sensor is a method for determining ranges by targeting an object of interest, using light in the form of a pulsed laser [25].
- SAR, Synthetic Aperture Radar sensor is another type of imaging radar usually mounted on a moving platform, providing high-resolution, day-and-night and weather-independent images [26].
- Multispectral sensor acquires red, blue, green, near infrared, and short-wave infrared images in several broad wavelength bands [27].

- Hyperspectral, capture hundreds or thousands of narrow and contiguous wave-length bands providing a high level of performance in spectral and radiometric accuracy [28].
- Acoustic sensors, detects the acoustic wave energy produced by some oscillating body; the most common form used is microphones that detect pressure fluctuations created during wave transmission [29].
- CBRN sensors include a multi-gas detector able to distinguish CO, $Cl_2$, $O_2$, $NO_2$, $H_2S$, $SO_2$, LEL and provides information about the presence of Chemical, Biological, Radiological and Nuclear agents/compounds in the air [30].
- Radiofrequency analysers that are used to capture and analyse a sample of RF signal measurement data [31].

### *B. UAV capabilities and limitations in border surveillance*

According to European Commission [32], the EU external land borders exceed the 7,400 kilometres, while almost 57,800 kilometres constitute the external maritime borders and coastline. To successfully prevent and respond to all the challenges that Law Enforcement Agencies (LEAs) face across the EU border line, including illegal border crossings, contraband or even human smuggling, search and rescue operations, or marine pollution, the deployment of innovative surveillance solutions that would increase situational awareness is of utmost importance. Unmanned airborne platforms greatly extend the situational picture of the border environment by allowing the operators of the UAV to monitor remote and inaccessible areas without jeopardising human capital and assets in contract with all land-based platforms e.g. patrolling vehicles and vessels. This section discusses the capabilities and limitations of UAVs in border surveillance missions.

Based on a consensus of UAV capabilities [33] for a wide set of missions it was concluded that for a surveillance mission of maritime traffic the needed capabilities to meet the mission's objective were the ability to redirect a flight for adjusting to unplanned phenomena of interest, and for steering around obstacles, long range and endurance, precision trajectories, autonomous mission management, sophisticated contingency management, collision avoidance, intelligent system health monitoring, reliable flight systems and Over-the-Horizon communications.

Each one of these identified requirements is met from the majority of unmanned aerial platforms to a certain extent. As the various types of platforms e.g. fixed wing, multirotor, aerostats, employ different physical principles and technologies they perform quite differently on the field. Depending on a prioritization of the needs a compromise must be made on which UAV is the most appropriate for a specific task.

Nevertheless, most UAVs provide the following high-level standard capabilities that make them stand out from other surveillance solutions. Further from the fact that UAVs can be fully controlled remotely from the ground-based station without the need for an onboard operator, current UAV platforms offer a variety of flight modes to choose from, depending on the specific mission i.e real-time manual navigation, pre-programmed GPS-based autonomous flight through specific waypoints or fully autonomous flight without transmitting or receiving any kind of radio signal. Additionally, UAVs can be designed to carry specific or not payload, offering the opportunity to be used for a wide variety of different missions or be fine-tuned for a certain task [34].

When discussing the capabilities of UAVs and their exploitation to a surveillance mission, one should not omit to consider the limitations of UAV technologies. These limitations presented in the following paragraphs should be taken into account when purchasing a UAV platform as well as in mission planning. Endurance or flight time is one of the basic limiting factors and is mostly related to the ability to provide power to the aircraft along with the range of flight which is the ability of a UAV to cover an extended distance. The way that a UAV can be launched and recovered is another crucial factor that must be considered when planning an operation with small sized UAVs capable of hand launching while larger UAVs may utilize catapults, runways and parachutes. Further from the above, depending on dimensions and the complexity of the system, logistic support of the UAV platform should be also considered as well as data storage capabilities as the data collected from the aerial platform is of is of high importance [35].

The versatility, mobility and advanced remote applications offered extensively by the UAV platforms are based in a great extent on the wireless communication capabilities that are being utilised in these systems. Further from the completely autonomous UAV flight where the system does not receive or transmits any kind of data, the common situation is that there are one or more links between the ground station and the UAV allowing for control and video transmission and a satellite connection for GNSS information. The four main enabling communication technologies that are being used for these tasks are:

- The direct link communication which is point-to-point communication with the ground station that maybe a simple and low-cost setup, nevertheless, offers limited range, low data rate, is susceptible to interference and non-scalable.
- Satellite links for UAV control and data exchange offer global coverage but increases the costs of the operations significantly and suffers from high latency and signal attenuation.
- Cellular networks have been also utilized to provide UAV related communications offering cost-effective extensive accessibility while sparsely available to remote areas.
- Another communications’ option is being offered by a-hoc networks which are dynamically self-organizing and infrastructure-free networks, robust adaptable providing high mobility, still being costly and complex setups with intermittent connectivity [36].

## III. METHODOLOGICAL APPROACH

BorderUAS project aims to tackle the aforementioned limitations, offering a solution for a beyond the state-of-the-art border monitoring. The solution that is being developed and will be tested throughout the course of the project is an end-user-based solution as the technical specifications derived from the collected end-user requirements. In this context all the mentioned capabilities, limitations and the potential compromises that have to be taken into account regarding a UAV platform deployment were put forward to the stakeholders through the questionnaires and dedicated workshops as presented in the following sections. To successfully respond to the operational needs of border guard authorities, a specific methodology was designed under the scope of BorderUAS project which was based on the well-known *Waterfall* methodology [37] dedicated to airborne surveillance for border security. Under the scope of the current paper the first two stages of Waterfall method, meaning "*Requirements*" and "*Design*" phases, are presented and detailed to several sub steps focusing on concluding with the sensor specifications that will shape the payload of the unmanned BorderUAS platform. Additionally, it has to be highlighted that in the frame of the project, a parallel task within the presented methodology, was the definition of the scenarios, i.e. real-life stories, that would be used to evaluate the final solution during the 'Demonstration' phase. Indeed, it is considered by the authors that user requirements, technical specification and scenarios are closely related. Initially, scenarios can be drafted by analysing the user requirements. By this analysis some key story components can be found. An example could be that from the requirement where it is mentioned that "the platform should be able to operate in remote/inaccessible for border guard units areas" it can be easily deduced that part of the story should unfold in an exceptionally large distance from the base station. Furthermore, as scenarios depict the user necessities, they are also a basic component of the validation and evaluation methodology. Demonstrations of the system are based in predefined scenarios where the solution will be tested against the technical specifications and user operational needs. Scenarios' definition is thus, a procedure that ultimately flows along to the transition from end-users' needs to technical specifications.

The collection of border guards' requirements and the definition of scenarios, as well as the verification of them, form the initial methodological stage "Analysis & Requirement Gathering". The main objective is to identify the end-user requirements and scenarios of interest for border surveillance that are highly dependent on border guard authorities. To further facilitate the procedure of requirements and scenarios extraction, several techniques were used that are considered as sub steps which are also depicted in Figure 1. Specifically, the first sub step includes the design of a questionnaire and the analysis of the gathered responses, as well as the literature review that was an additional source of gathering needs and challenges in border areas. The definition of the initial requirements and scenarios was the subsequent step. These draft lists were validated and refined by border guard authorities through specifically designed workshops (sub step 3) that led the consortium to conclude with the final list of end user requirements and scenarios that constitutes the final sub step. The detailed description of this stage is available in Sections III.A and III.B.

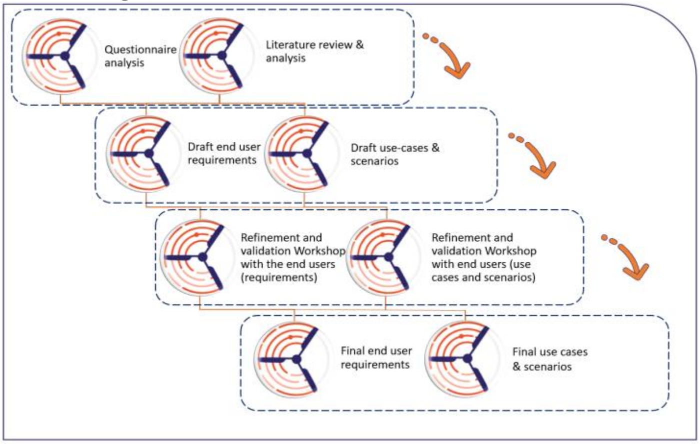


**Figure 1: Analysis & Requirement Gathering stage – detailed sub steps**

The final list of requirements and scenarios marks the beginning of the second methodological stage 'Design & Sensor Technical Specifications'. This stage includes all the necessary sub steps to transform the end user needs to technical specifications. The initial sub step at this second stage is the analysis of end-user requirements and the technological gap analysis to ensure that the current state-of-art sensors can offer a reliable solution to the challenges that border guard authorities face. The second sub step includes analysis of the operational parameters and possible constraints, the analysis of requirements and scenarios as well as the definition of functionalities that lead to high level consensus of functional and non-functional requirements and finally the elaboration of the operational scenarios using technical terms from the technological perspective, which was entitled "technical scenario". Following the aforementioned steps, we concluded with the final list of the specifications for sensors, as also shown in the below Figure 2. The whole process can be found on Section III.C.

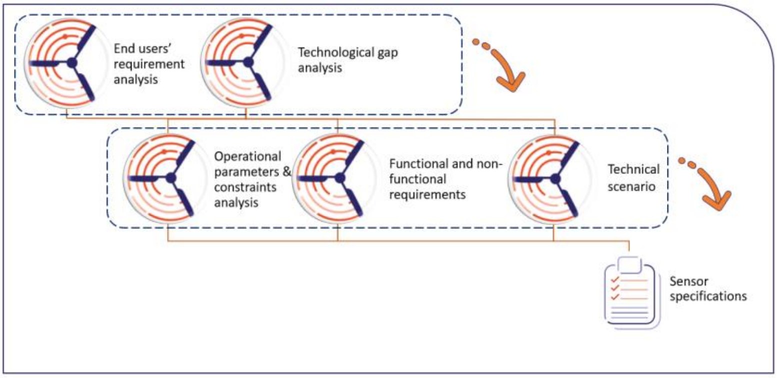


**Figure 2: Design & Sensor Technical Specifications stage - detailed sub steps**

The elicitation of system's architecture and platform's specifications exceeds the scope of this paper which focuses only on the sensors' technical specifications. The rest of the general stages of the Waterfall method meaning the "Implementation", "Verification" and "Maintenance" will not be addressed in this paper.

## *A. Collection of information and draft list of requirements & scenarios*

A carefully designed questionnaire was distributed to six specific border guards' authorities in Greece, Bulgaria, Ukraine, Belarus, Republic of Moldova and Romania. The questionnaire consisted of open-ended questions, was limited only to BorderUAS end users and was designed to: (a) present the respondents with the overall scope of BorderUAS platform, (b) present the respondents with the probe questions and (c) help discern user requirements and scenarios. The questionnaire consisted of eight sections and 51 questions in total, covering the whole spectrum of its operation from legal questions and environmental characteristics to storage and networking capabilities, and aiming to collect and analyse the needs in the deployment and the operational use of a lighter-than-air UAV for border surveillance.

In parallel to the questionnaire analysis, the collection of basic background information was conducted and supported by reviewing the literature and analysing the relevant documentation. The analysis was made following 3 basic steps:

- parameters definition, which includes (i) the literature public sources that were taken into consideration (academic publications, EU research reports, grey literature, etc.), (ii) the language (English), (iii) the time of publication (later than 2015), (iv) the key terms that were used as search strings ('border', border guard authority', 'border surveillance', 'UAV', 'border surveillance', 'airborne surveillance', 'illegal border crossing', etc.)

- collection and evaluation, aiming to review the relevant literature to verify their relevance to the topic and the extent of the useful content
- analysis and report of findings, to complement the questionnaire analysis and the initial set of requirements and scenarios.

Gathering all the aforementioned information and after analysing it, we concluded with the draft list of user requirements and scenarios, as indicated in the below sections.

### *B. Refinement, validation and final list of requirements & scenarios*

To achieve an end-user-based system design that addresses effectively operational needs, as well as to validate the final outcome in real-life operational environments, two workshops were organised, engaging border authorities in order to determine, refine and finalise the list of end user requirements and trials' scenarios. The workshops conducted online, having the format of discussion, leaving the floor to the end-users to freely express their needs. One of the main goals was to introduce the relevant to the project technological capabilities and restrictions, and then validate and refine the already identified requirements and scenarios. The first workshop was dedicated to creating the consensus among the end users regarding the main terms, the BorderUAS objectives and operational capabilities, as well as to conclude with the final list of requirements and prioritising them using the MoSCoW technique [38]. The second workshop aimed to elaborate and modify the scenarios which represent real life incidents and would be used to validate the BorderUAS solution in the actual pilot sites. The overall goal was to achieve a certain level of agreement on the specific scenarios representing both the operational side, as well as the technological side meaning the BorderUAS key attributes and capabilities.
Following the aforementioned workshops, the requirements and scenarios were reported in a comprehensive and concrete way. Requirements were divided in specific categories according to the field or functionality that they refer to. The scenarios were documented per pilot location maintaining a specific format.

### *C. From end user needs to technical requirements*

In the current section a scenario from the technical point of view is presented, aiming at a better understanding of what the end users ask for and whether these needs are feasible.
The concept description of the use case scenario must define the following issues, which drive the technical functionality.

- Region of operation and the terrain

- Operational Scenario in technical terms, defining situations of interest and actions for dealing with emergency conditions
- Operational modes and constraints

In the current methodology, as also depicted in Figure 2, the focus was on four main pillars: (a) a technological gap analysis study, reviewing a range of relevant projects/initiatives and technologies in the domain of border surveillance; (b) the definition and analysis of end user requirements and scenarios with major focus on cross-border surveillance end users and stakeholders; (c) an end user requirements elicitation phase containing a threat analysis of the business processes entailed in the end user scenarios, and (d) surveying and discussing with key stakeholders, aiming to validate the obtained outcomes and identify technical barriers and facilitators for HIT [39] adoption linked with cybersecurity and interoperability. In that respect the outcomes derived from this process were: comprehensive end user requirements definition; consensus for functional and non-functional requirements; barriers and facilitators for technology acceptance; recommendations for the technical design.
According to the performed analysis, full adherence is currently not universally met. Further to the above, lack of integration in a holistic approach was clearly identified. Thus, it was of utmost importance to highlight challenges and open issues for their application in the foreseen pilot sites and create links among the available information sources and assets, as part of a meta-analysis. From the technical perspective, BorderUAS end user pool was utilised to perform workshops to validate the above mentioned outcomes (Section III.B), but also including lack of awareness, lack of usability constraints, while important facilitators concern the adoption of standards and the efforts to establish a common legislation framework across EU. In order to present the findings from this engineering methodology, the region of operation as well as an overall operational scenario of indented use was presented. Concluding, the targeted functional and non-functional requirements that will be used to specify the sensor specifications were also described.

### 1) Region of operation and terrain

There are two issues associated with the terrain in relation to the technical functionality. First, the nature of the environment needs to be defined, i.e., if the area is densely forested, or if there are rivers, seaside, as well as the main roads of traffic or the "suspicious" tracks. Another important parameter is the annual weather forecast, i.e., yearly statistics about foggy, cloudy, and sunny or rainy days. This information is useful for fine-tuning the algorithms and the equipment settings, although more short-term weather forecasts should ideally be taken under consideration, as it might affect terrain conditions which, in turn, might suggest change on the methodologies for the processing of information. More specifically, these pieces of information will support in tuning the algorithms to the normal motion of the region under surveillance, i.e., normal tree movements, leaves' motion patterns, water regions and motion in wetlands, marshes, swamps, rivers and lakes. Second, it is needed to map the image viewed by the camera to georeferenced details. Thus, any point identified in the camera view must be mapped to the ground terrain with georeferenced coordinates e.g., from known maps or GPS location. In order to achieve this mapping, it is required to obtain the details about the flight coordinates and the camera parameters like direction, zoom and field of view (which are recorded at all times). An easy way to perform approximate mapping is using specific landmarks that can be identified both on the terrain and in the camera image. Algorithms for both of these issues will be developed for each of the use case scenarios.

### 2) Indented use and operational barriers

In the current section, an actual operational scenario independent of the environment of the use case has been studied. The BorderUAS airship flies about 500 meters above the ground scanning the area at low speed. The cameras are in '*Surveillance mode*', where images (optical, thermal or hyperspectral) at low resolution are compared with the terrain model in order to identify irregular patterns over time. In case that one camera detects any irregularity at an image point (x, y), it focuses in a region of interest around this point and switches to the '*Tracking mode'*, where the movement is tracked. Based on the expected regular movements in the area, the event is marked as "normal" and the camera returns to the surveillance operation. In case that the motion is interrupted, or it follows irregular or "suspicious" patterns, then a trigger for the other cameras is initiated, so that all cameras focus on a similar Region of Interest (ROI) around the point (x, y), after mapping it to their own coordinates. The tracking patterns between the cameras are compared and if they preserve some similar or consistent characteristics, then the tracking from one camera follows the other so as to complement each other at points where one view is interrupted. In parallel, the optical camera further proceeds with some identification of the size and the shape of the object under tracking. At this point we need to define the nature of the target being identified and more spherically whether it is a human or an animal (moving in isolation or in groups), or an object e.g., a vehicle.

The moving target (i.e., animal, object) is first **detected** by fast procedures focusing on fast detection and on minimizing false negatives rather than minimizing false positives, so as to increase the accuracy of detection and minimize the possibility of targets not detected at all. The role of machine learning and of the fusion of information acquired by cameras is critical. The detection process must also take into consideration the case of a stationary target for which motion has been detected recently (initially moved and then stopped or the other way around).

The nature of the moving target (whether it is an animal, a human or a vehicle) can be determined during a second processing stage, i.e., the identification stage (following detection). The identification of the target requires intense and more elaborate processing focusing on the region of interest. Whether both processing stages are implemented on the UAV on the land station is an issue to be decided (in order to ensure fast detection in real-time, the detection stage is implemented on the UAV).

If the subject is identified as an animal, then the tracking becomes less intensive. Otherwise, an alert alarm is triggered to the operator and the ground station of border police. Furthermore, a synthetic aperture radar (SAR) and acoustic sensors can be fed with the current position and direction of object tracking, so that they can also provide even more focused characteristics about the object or subject of interest. Information from all the sensors, e.g., shape, speed of motion, tracking pattern, sound spectrum, SAR reflection pattern, are all combined within a machine learning tool (already trained) in order to provide a concise decision about the nature of this event.

In the case of multiple objects in the same region, the net motion pattern and shape are considered, alarming for a group of subjects moving along the same path. Motion in different regions of the camera can be handled as before as independent events in different ROIs in the cameras. In this case, the acoustic sensor should periodically switch from one event to the other, as to complement the already gathered information regarding each case.

## IV. Implementation and outcomes

Based on the methodological stages defined in Section III, the implementation and some high-level outcomes and findings are presented in the current Section. The first stage that refers to the process, the collection and the validation of end user needs in border areas is analysed in Section IV.A. These findings are used to define sensors' technical specifications as reported in Section IV.B; indicative examples of the outcomes are described in the current section.

### *A. Extraction of end users' requirements and scenarios*

By implementing the first stage of the methodological approach (Sections III.A, III.B), the end-user needs (requirements) and the incidents of interest (scenarios) were successfully reported.

Regarding the requirements, they were divided in 6 categories (Table 1) with the relevant coding and numbering, which were also prioritised by the border guard authorities using MoSCoW method.

**Table 1: End user requirements categories**

| Category | Coding | Description |
|---|---|---|

| | | |
|---|---|---|
| System | SYS | includes the requirements relevant to the BorderUAS system as a whole. It also includes Legacy system connectivity, security considerations, networking and awareness relevant requirements |
| UAV platform | UAV | includes the requirements relevant to the capabilities of the UAV platform |
| Sensors | SEN | includes the requirements relevant to the capabilities of the sensors |
| Analytics (Detection, Tracking, Recognition, Identification, Events) | AI | includes the requirements relevant to the intelligence of the system (data fusion, analysis/processing of raw data) |
| Command and Control | C2 | includes the requirements relevant to C2 platform |
| Legal | LEG | includes end-user requirements relevant to legal aspects |

The total number of requirements (see Figure 4) was 123, 21 of those being System requirements, 16 of them were related to UAV, 21 were relevant to Sensors, 25 referred to the Analytics, 38 concerned the Command and Control and 2 were categorised as legal requirements. The graphs below represent the percentage of Must (M), Should (S), Could (C) and Wont (W) requirements for each of the aforementioned categories.

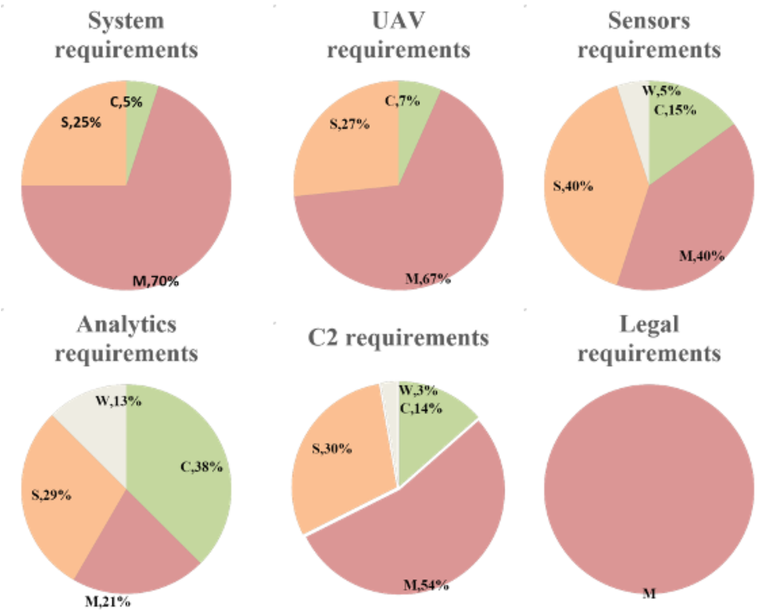


**Figure 3: The total number of requirements in pie-style representation**

The final list of the identified requirements was reported to traceability matrices per category; indicative examples can be found below (Table 2):

**Table 2: Indicative end user requirements**

| Category | Description (BorderUAS system must/should/could/won't) | MoSCoW rating |
|---|---|---|
| SYS | be able to operate in remote/inaccessible for border guard units areas | M |
| SYS | be able to provide the user with no more than 20% false alerts | M |
| SYS | be able to provide secure communication links among all its subsystems | M |
| UAV | be able to take-off in altitude range from at least 0m to 1500m AMSL | M |
| SEN | be able to have PTZ capabilities | S |
| SEN | be able to provide acoustic imaging | S |

| | | |
|---|---|---|
| AI | be able to detect multiple objects and events, simultaneously | M |
| AI | be able to provide the user with near real time mapping of the area | C |
| C2 | be able to allow for controlling the platform using the minimum human resources | M |
| C2 | be able to provide the user with different interfaces (on demand) displaying captured data by different sensors | M |
| LEG | comply with applicable and relevant ethical and legal rules both in a European and national manner | M |

To document and properly report the identified scenarios of interest a certain template was filled in by the relevant border guard authorities as depicted below. Some indicative scenarios that were identified by the end users are presented in the below Tables.

**Table 3: Indicative scenario (a)**

| Scenario Relevance | Scenario (a): Description |
|---|---|
| Emergency – missing people  | • Heavily rainfall has caused floods to the near-to-the-borders towns. Civil Protection, Fire Service, other relevant authorities and volunteers are requested to support the affected areas.<br>• BorderUAS is requested to go above the area of interest to identify safe areas as well as to detect and track persons in danger.<br>• BorderUAS provide the relevant authorities with the information requested (exact location of safe areas -aerial view-, detection of trapped persons)<br>• In addition, BorderUAS is requested to seek for missing people, thus it detects persons who have fallen unconscious on reefs.<br>• SaR activities from Fire Service, Coast guard and relevant authorities are successfully implemented by transferring the persons in danger to the nearest safest zones. |

**Table 4: Indicative scenario (b)**

| Scenario Relevance | Scenario (b): Description |
|---|---|
| Signs of border violation  | • BorderUAS platform is already deployed, implementing its typical monitoring missions across EU borders.<br>• A group of nine (9) persons, having their faces covered, walk scattered towards the land border area.<br>• Five (5) of them head directly to the fence trying to damage it, using some hidden from-the-previous-day tools.<br>• In the meanwhile, the rest four (4) cause damages to the nearby border management buildings, where inventory items are stored.<br>• BorderUAS detects and tracks these activities, informing in parallel the local coordination centre.<br>• Local patrol units are sent to the area to take over. |

In total, 18 high level scenarios were reported by the end users, 5 of them being for the first pilot area, 5 for the second and 8 for the third trial.

### *B. Sensor specifications*

With the above-mentioned technical scenarios and the overall previous outcomes (Section IV.A), we can consider that for a set of sensors for event detection and localization from a distance (SAR, acoustic cameras, high-resolution cameras, hyperspectral cameras, short/long-wave infrared cameras (SWIR/LWIR) and LIDAR), the minimum requirements can be as follows (including sensor definition and target property requirements):

- **SAR**
    - The main characteristics of SAR should be operation in the P-band (i.e., ultrahigh frequency: 0.3-1GHz) or L-band (1-2GHz) to penetrate the forest canopy, but at the same time with a relatively wide bandwidth to increase the spatial resolution (e.g., the Northrop Grumman Multi-Band SAR offers bandwidths up to 500MHz in the L-band or up to 700MHz in the P-band).
- **SWIR – LWIR**
    - Fusion of SWIR and LWIR cameras is required to allow switching from night vision to thermal and back while focusing on the same target.

    - SWIR should allow for vision through glassy surfaces that block thermal emission signals (e.g., very important in a case of surveillance of vehicles with windows when people should be detected behind the glass).
    - Auto-focus mechanism is also required to ensure performance where the human involvement in the device operation is highly limited SWIR+LWIR high frame rate (50-100 Hz) will allow better pixel alignment between different imaging systems.
    - Host of two high-resolution SWIR-LWIR cameras, with a camera direction control.

- **Acoustic sensors**

  A sensor is required to be developed providing an audio stream and real-time acoustic map of the area that is being surveyed. The parts of the acoustic camera are:
    - Detection block - consisting of a number of microphones (32/64/128/256). The number of microphones will be chosen according to the required characteristics of the system (frequency range, spatial resolution, selectivity, dynamic range).
    - Microphones should be developed (or selected on the market, as an alternative) according to the required characteristics (sensitivity, self-noise, frequency range etc.).
    - Interface block – an interface between the detection block and a platform for acquisition, data processing and/or storage. The interface module will be designed according to the microphone and signal characteristics, as well as input characteristics of the platform for acquisition, data processing and/or storage. It will contain a low-noise microphone preamplifier and ADC block, placed next to the microphone to avoid signal interference and noise generation.
    - Platform for acquisition, data processing and/or storage should be designed according to the BorderUAS system requirements and will be based on a System-on-Chip technology.

- **High resolution optical sensors**
    - The desired ground resolution should be a few centimetres, but at the same time we aim for a large ground swath. Fortunately, imaging sensors have become quite large in pixel resolutions, which allows for a simple camera system fulfilling our requirements. For example, 50-150 mega-pixel cameras are now available on the market, with 8,000-14,000 pixels in a row. If we want 2cm/pix on the ground then such cameras would cover approximately 160-280 meters of ground (actually, more than that due to the projection effects on the Field of View (FoV) edges).

- **Hyperspectral optical sensors**
  - The dimensions of disturbed vegetation vary from centimetre scaling. This means that the spatial pixel size projected to the ground needs to be at least in the range of 10cm/pix and preferably smaller than this. The spectral coverage has to cover wavelengths before and after the "red edge" at about 720 nm. The following requirements are also necessary to cover the resulted end user requirements:
  - Time constraint, where we need a fast deployment and avoid complicated time-consuming solutions,
  - Without a plug-and-play solution for hyperspectral data processing that would help us bridge the time required for the initial learning of how to operate the hyperspectral data stream, and
  - With a goal to demonstrate this border security concept under limited operational conditions.
  - Therefore, the optimal approach is to use a snapshot mosaic camera as the main technological approach, even though the long-term strategy can be to invest more time and resources to utilize a line scan camera.
- **Optical systems (lenses)**

  A special attention must be given to the choice of lenses and their FoV. The end user mission specifications will dictate these properties. Specific requirements on the used lenses need to cover the following aspects:
  - When using fixed lenses (i.e., fixed FoV) and when zoom lens?
  - Type of objects to detect and recognize?
  - Size of scanned (imaging footprint)
  - Spatial size for the ground
  - Sensor altitudes (i.e., typical above the ground flight altitudes)
  - Type of non-ideal visibility conditions be provided as a service
- **LIDAR**
  - This sensor has to penetrate through the forest canopy and bounce from the ground and low vegetation. This is achieved by "full waveform" LIDARs, which measure not only the first/strongest signal that bounces back, but everything that comes back from multiple targets as the laser beam partially passes through the canopy and vegetation. This is illustrated on Figure 5 in which we observe that the full waveform is a LIDAR return signal created by the laser beam being reflected multiple times from various targets along the path all the way to the ground. Distance is deduced from the time of flight. It shows an outgoing pulse transformed into a complicated return signal (i.e., waveform) that contains information about various targets along the ray path, and not only

the largest amplitude signal. This full waveform can be then analysed to detect the ground and low vegetation.

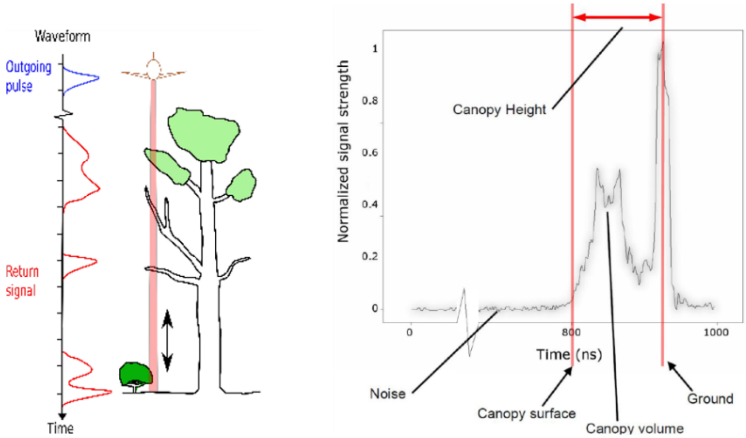


**Figure 4: Basic concept underlying the LIDAR technology. Sources: [40] [41]**

There is a list of several key features that a LIDAR can fulfil our end user requirements:

- Full waveform detection
- Ability to reach 10x10 $cm^2$ point density resolution on the ground on natural targets (soil, rock, vegetation) from at least 300 meters above the ground (preferably 500m)
- Small weight (max about 10kg)

## V. Conclusions and Future Work

The effective surveillance of external EU borders should always include state of the art technologies, aiming to reduce the risk that border guards and relevant patrols units face, being in parallel more effective and cost efficient. This can be achieved through airborne surveillance, by combining multiple sensors on a specifically designed UAV platform. To develop a solution that could be proved useful for the end users, a dedicated methodology was followed which was introduced to the current paper. The methodological approach allowed the consortium to safely move from end user needs to technical specifications, engaging as much as possible the end users to this process. Their engagement could be considered fundamental to develop a solution "from the end users to the end users" addressing all challenges that Border Guards face at European External Borders. The extensive list of requirements -123 in total- indicates the plethora of specific needs for the different subsystems and functionalities that they wish to have. The most of them being labelled as "Must" requirements, stimulate the necessities that should be taken under consideration during the development phase of the project, in order to meet them in the best possible way. In total, 18 different high-level scenarios were described by the end users, which were focused on the borders of consortium end users, representing real incidents. These requirements and scenarios were analysed, resulting to the technical specifications of the sensors that the UAV will carry as payload. Thus, the consortium could focus on specific technical characteristics that were indirectly requested by the end users; specifications of each sensor were analysed and reported in Section IV.B.

The forthcoming steps include the actual development and acquisition of the sensors that will fulfil the needs. However, to successfully respond to borderline challenges, the relevant detection and data fusion algorithms will be developed, so as to improve the situational awareness of the border guard authorities through the fused information provided and support the decision-making process. The development should focus on the complete list of needs that were identified under the scope of BorderUAS project.

The current study was conducted for the purpose of border external security and specifically considering the border surveillance. However, the specific study and methodological approach could be expanded and utilised as the basis for similar airborne platform in different domain, such as for maritime surveillance, monitoring vessels or maritime infrastructure, oil spill surveillance or environmental monitoring, mapping of inaccessible areas or even oceans, etc.

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