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Frontex Research Grants 2024

Excellence
in Research

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RESEARCH
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PROGRAMME

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Legal Disclaimer

This report comprises the executive summaries extracted from the final research reports of the projects funded under the Frontex Research Grants Programme, Call for Proposals 2022/CFP/RIU/01.

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Introduction

The Frontex Research Grants Programme acts as a catalyst to foster innovation and improve border management capabilities across the European Union. Established to support cutting-edge research and development, the Programme aims to provide European border authorities with the solutions they need to address the evolving challenges at the borders. By funding promising small-scale projects, it provides an opportunity for researchers, developers and end-users to collaborate in developing tailor-made technologies. This is in line with Frontex's long-term vision to deliver digitally enabled innovation and integrated capabilities, contributing to a more interoperable and future-proof European Integrated Border Management.

In its 2022 funding cycle, the Frontex Research Grants Programme selected four innovative projects: SEMS4USV, SWEETIDS, DMDLBVEC and TUTELARY. These projects addressed critical issues in border management, from advanced surveillance to enhanced border checks. The research carried out under these initiatives represents not only an investment in state-of-the-art technology but also a commitment to fostering the R&I community. These projects embody the Programme's core mission to shape the research ecosystem in a way that addresses current operational challenges and responds to emerging threats in border management.

This booklet shows that the projects' results delivered in 2024 provide valuable insights and practical solutions to real-world border security challenges. SEMS4USV advances the use of sustainable energy in unmanned vehicles for maritime surveillance, SWEETIDS explores innovations in document checks, DMDLBVEC investigates new methods for data integration and analysis within border control environments and TUTELARY focuses on the development of advanced surveillance tools. These projects showcase the diversity of research topics supported by Frontex and the depth of expertise contributing to the Programme's success. This compilation of the executive summaries extracted from the projects' final research reports provides an overview of their objectives, methodologies and key findings.

This booklet serves as a first step in ensuring the transfer of knowledge generated through the Programme to the European Border and Coast Guard community, academia, industry and society at large. The results presented provide immediate benefits and lay the groundwork for future advances in the field. By highlighting the beneficiaries' achievements, it underlines the value and impact of the Programme in addressing contemporary border management challenges. Many additional events and initiatives are planned to continue offering guidance and support to beneficiaries in operationalisation of their results. Further updates and the full versions of the reports can be found on the Frontex website.[1]

1 https://www.frontex.europa.eu/innovation/eu-research/research-grants/

SEMS4USV - Smart energy management system for sustainable extended-range marine unmanned surface vehicles

Beneficiaries

Escola Superior Náutica Infante D. Henrique (Portugal)

Instituto Superior Técnico, University of Lisbon (Portugal)

Executive summary[2]

This project dealt with the need to develop advanced technologies in border surveillance by improving the sustainability of fossil-free unmanned marine surface vehicles (USV). The main objectives were a) to demonstrate the feasibility of a fossil-free catamaran-type USV with electric propulsion, capable of extended autonomy (Figure 1), b) to develop a smart energy management system (SEMS) to govern the propellers based on the mission profile and the predicted and actual weather/sea conditions, and c) to demonstrate the integrated USV and SEMS prototypes in real river and sea environments.

Figure 1. Unmanned surface vehicle developed by the project

The project was divided into six main activities: 1) updated revision of state of the art in energy management systems, 2) definition of typical profiles of border surveillance missions, 3) model development and resilience experimental tests, 4) development of a smart energy management system, 5) experimental tests and system validation, 6) reports and results dissemination.

Instituto Superior Técnico (IST) carried an updated revision of the state of the art concerning SEMS. Special attention was devoted to SEMS implemented in marine applications capable of handling multiple scenarios and variables, from weather and sea conditions to hydraulic, mechanical and electric variables, and to provide an optimised scenario to meet the mission specifications. Algorithms capable of adapting to historical experimental data were reviewed. The integration of multi-objective optimisation algorithms, such as genetic algorithms and

2 Full report available at https://www.frontex.europa.eu/innovation/eu-research/research-grants/sems4usv-smart-energy-management-system-for-sustainable-extended-range-marine-unmanned-surface-vehicles-b8qAek

machine learning, to be used for the optimisation of the SEMS hyper-parameters, was also reviewed.

Furthermore, both Escola Superior Nautica Infante D. Henrique (ENIDH) and IST identified and defined typical mission profiles and variables for border surveillance actions. Two types of mission profiles were identified: long-endurance reconnaissance missions and time-sensitive delivery missions. Each type of mission was evaluated regarding the performance index, such as maximising time or range with minimum energy consumption. The long-endurance missions are a) persistent patrol /environmental monitoring, b) track vehicle/object, c) search and identify and d) stationary zone vigilance. The time-sensitive missions are a) spill response, b) rescue and delivering aid and c) goods delivery. Within each mission an identified objective function was used for optimisation.

External sources of environmental forecast information were also identified to improve the mission planning (wind speed, water flow, sea wave characteristics, etc). To obtain the environmental information, a list of open-source databases available on the web was identified, and the technical API parameters to obtain the information automatically were reported. In addition, the most important sensors for carrying maritime missions were listed to help identifying those suitable for this project.

Using a white-box approach, the USV was divided into white-box subsystems, such as the propeller, electric motor, batteries, photovoltaic panels and hull dynamics (Figure 2). For each subsystem white-box, the correlations between the input and output variables were identified. After identifying the input variables for the USV model, and their behaviour, the correlation between these and the hydrodynamic, mechanical and electric quantities was determined.

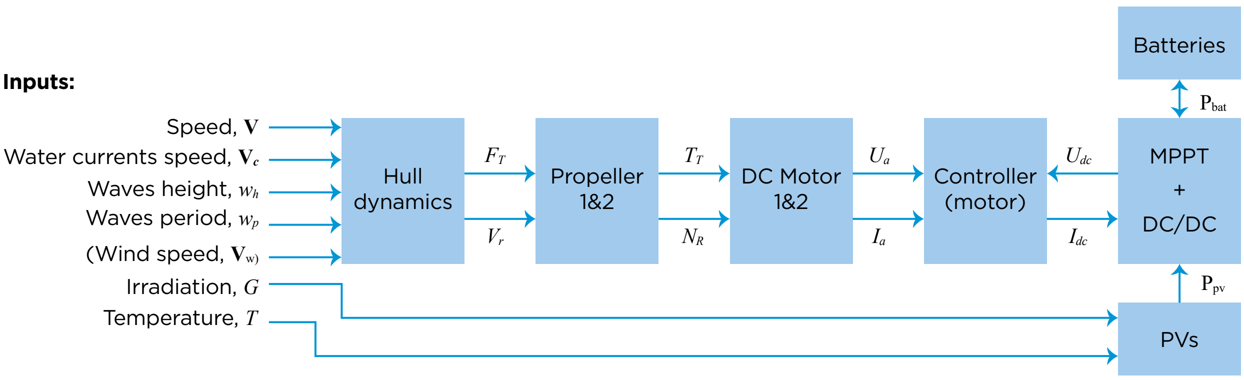
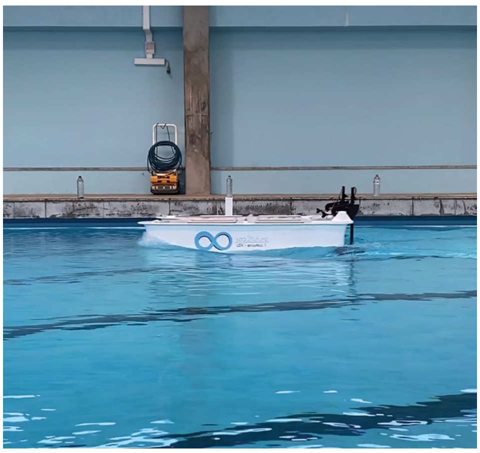


Figure 2. Proposed USV white-box model



(a)

(b)

Figure 3. Photos of the experimental environments: (a) pool and (b) enclosed harbour

The modelling of the USV was also carried out, following the previously defined white-box approach. In addition, to validate the USV model, experimental tests were performed in an indoor swimming pool and in an enclosed harbour on the River Tejo (Figure 3). The pool tests allowed analysis of the USV's behaviour without wind, water currents or waves, while the enclosed harbour tests allowed analysis in a more realistic context. With these, the hull and propeller models were calibrated to be further used in the optimisation scenario.

Figure 4(a) and (b) show the experimental and simulation results for a throttle of 50% and 100%, respectively. It can be seen that the simulation results oscillate around the experimental ones. Finally, Figure 5 shows the time evolution of the energy consumption for the four scenarios. From the energy point of view, the results clearly indicate that the USV simulation model is capable of estimating energy consumption for all different throttle values applied to the motors. Model validation was achieved, and the model can be used to perform optimisation scenarios.

Finally, a simulation model of the entire unmanned marine surface vehicle was developed in Matlab software, which was used by the Smart Energy Management System for energy optimisation.

After the development and validation of the USV model, the Smart Energy Management System was developed; its framework is shown in Figure 6. The procedure starts with the definition of the mission profile with target waypoints, the mission constraints and uploading the predicted environmental conditions. After this, the energy optimisation algorithm starts by performing path and speed optimisation using the algorithms. After the definition of an optimised path, a target speed and path profile are defined and provided to the remote driver. The remote driver will follow the defined path and speed and, using a supervision algorithm, will decide to carry out the whole mission or re-optimise the mission if any significant deviations occur.

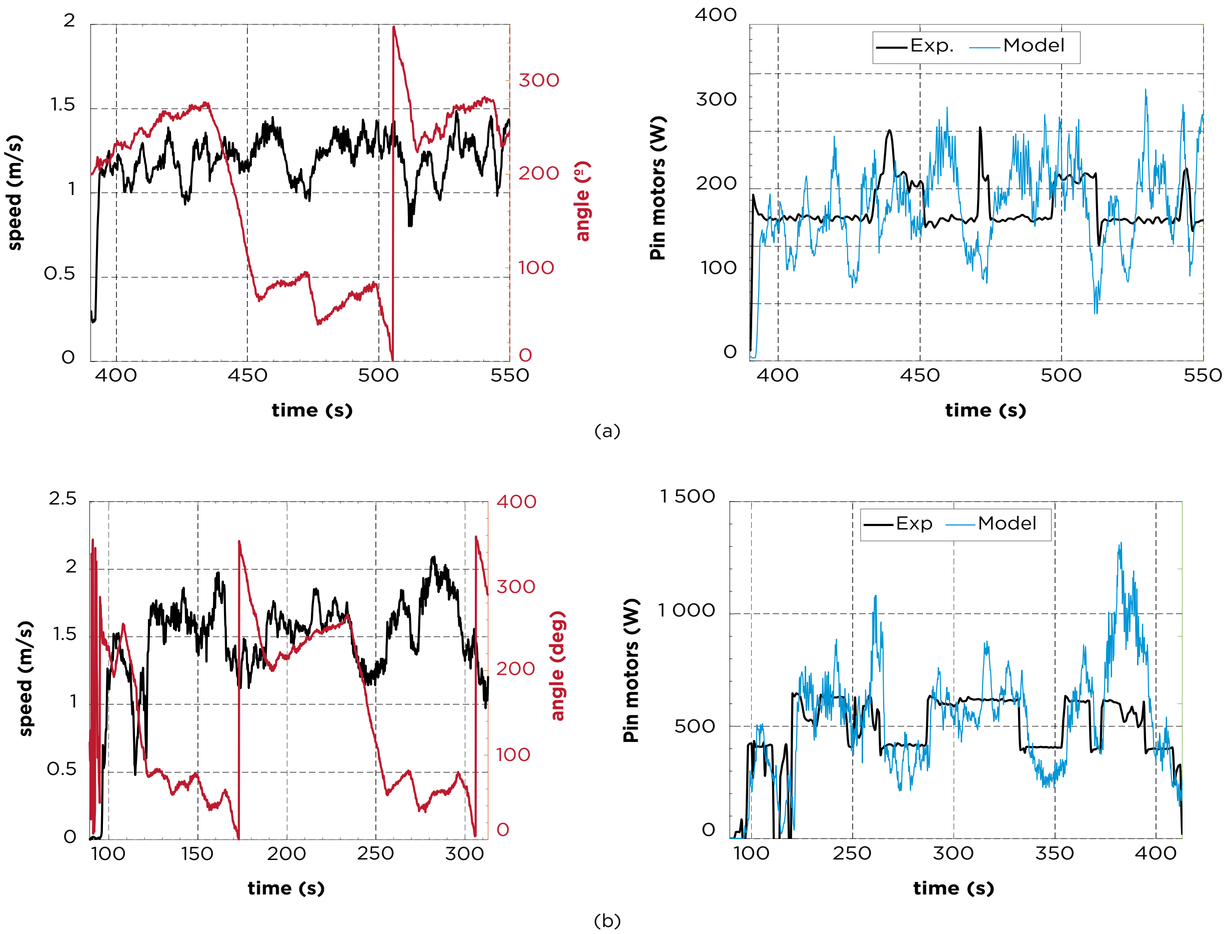


Figure 4. Experimental and simulation results for instantaneous battery power at (a) 50% and (b) 100% of throttle

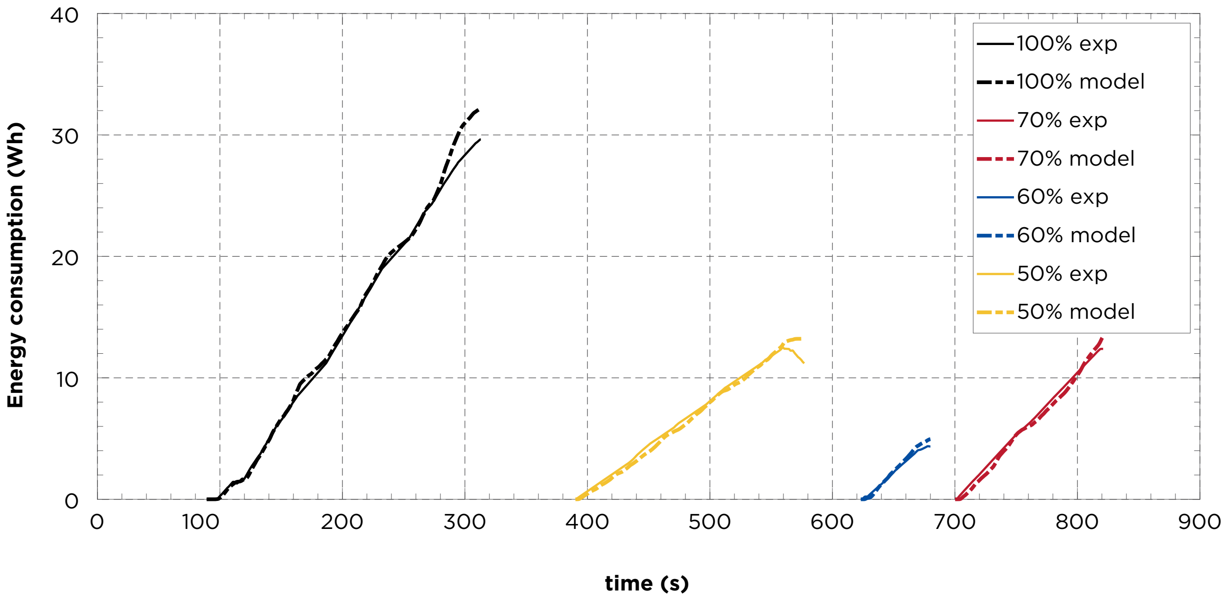


Figure 5. Experimental and simulation results for energy consumption at different throttle levels

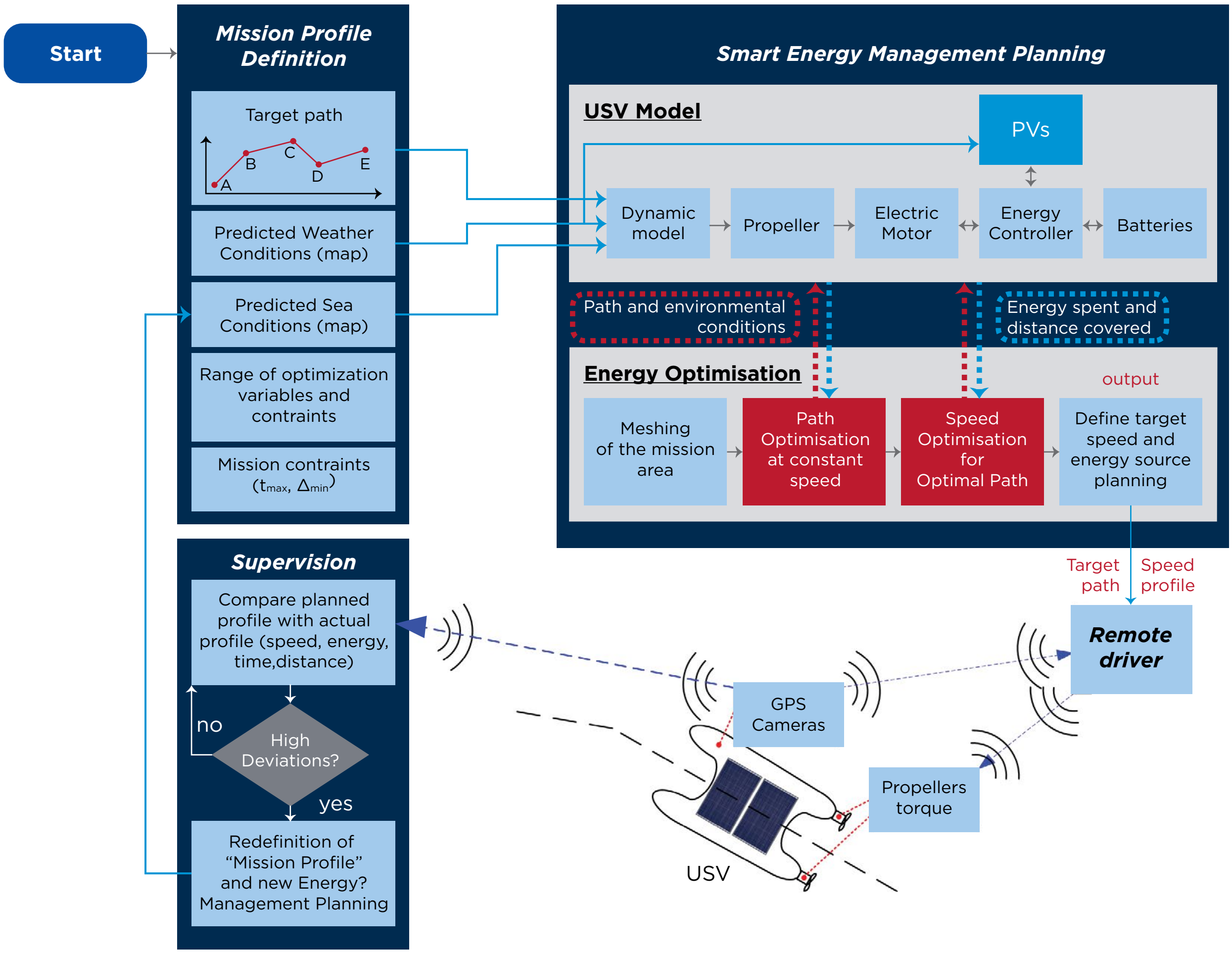
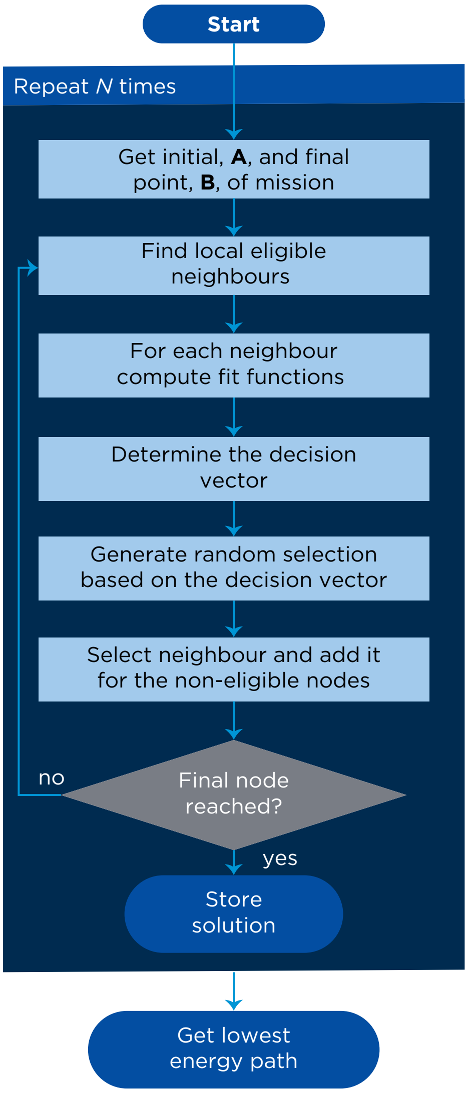


Figure 6. Proposed Smart Energy Management System framework

Energy optimisation is the core of the Smart Energy Management System and is divided into four steps: 1) meshing of the mission area, 2) path optimisation at a constant speed, 3) speed optimisation for the optimal path and 4) definition of target speed and energy source planning. During the path and speed optimisations, the previously developed USV model was used to estimate the energy consumption for the desired path. The speed optimisation was based on a non-linear programming solver provided by Matlab through the function fmincon. The target path was divided into Ns subsections, where the speed was considered constant. Then, considering the target time mission, the speed was optimised to minimise energy consumption for the desired time mission. For path optimisation, two algorithms were proposed: a Bidirectional Graph-based algorithm (BdG) and an A-star based algorithm with probabilistic behaviour (A*Pb). The BdG algorithm considers constant environmental conditions along the mission, and thus is only suitable for short-duration missions. The A-star based algorithm with probabilistic behaviour is able to handle time-variable environmental conditions, being suitable for long-duration missions.

The new A*Pb algorithm, which is a mixture of A* and probabilities, assumes actual sea conditions vary over time (Figure 7). While it is not able to guarantee the overall minimum, following a Monte Carlo logic it is always able to obtain a required energy equal to or lower than that of the BdG algorithm. In cases where sea conditions start favourable, it is able to find paths that avoid areas where sea conditions change from favourable to unfavourable.



(a)

Pseudo-code:

Get initial, A, and final target points, B;
For j=1:N (run algorithm N times)
  Define "path" structure with subindexes "nodes", "time", "energy";
  Define "history_nodes" for nodes already travelled;
  While not reaching final node:
    Identify neighbour nodes, excluding those already in "history_nodes";
    For each neighbour:
      Define $\Delta d = d_i - d_f$. Where di is the distance between initial and target node, B, and df the distance between the neighbour and target node, B;
      Obtain weather conditions considering time instant
      Define the energy, E, required to travel from initial to neighbour node, using the USV_model function;
      Define fit function as f = Δd/E;
      Update mission time;
    end
    Generate the decision vector, fv, as the cumulative sum of all fit functions;
    Generate a random number: sel=rand*max(fv);
    Get the selected node based on the selection number, sel: indx=fv<=sel; inds=inds(sum(indx)+1);
    Update Path.nodes with selected node;
    Update Path.time with the travelled time;
    Update Path.energy with the accumulated energy;
  end
end
Obtain shortest energy path

(b)

Figure 7. (a) Flowchart and (b) pseudo-code of the A*Pb algorithm

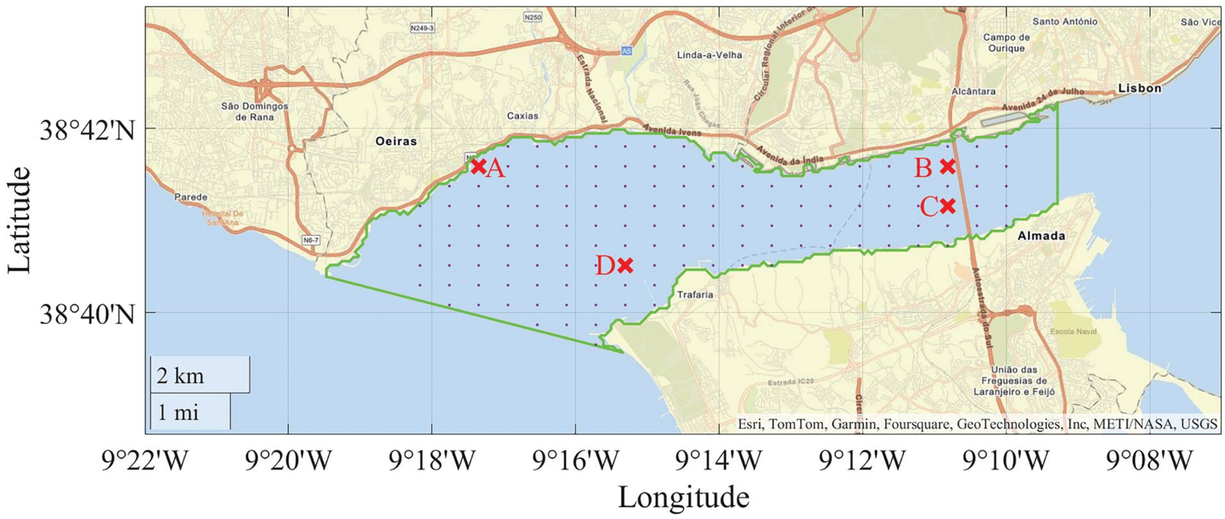


Figure 8. Mission map

Both algorithms were tested on a mission carried out in the mouth of the River Tejo, in Lisbon. The mission started at waypoint A, and the USV was to travel to points B, C and D and return to A.

Figure 9 shows the performance of the different algorithms for the defined mission, considering different times of the day when the mission started. As can be seen, the bidirectional graph-based (BdG) algorithm is not suitable for long missions where the environmental conditions change. The calculated energy can present significant deviations from the predicted ones. This is because the environmental conditions will change throughout the mission, and because of this and the fact that the BdG algorithm builds a graph based on the initial conditions, this algorithm will fail to predict the correct USV consumption for long missions. The new proposed A-star algorithm (A*Pb) with probabilistic behaviour is capable of handling time-varying environmental conditions and defining optimal paths that take advantage of favourable environmental conditions over time. Therefore, we can see that for the starting time missions of 5h and 9h, the A*Pb algorithm is capable of finding a path with lower consumption than the BdG algorithm.

After the development of these algorithms, a software application was created to carry out the mission planning and implement the SEMS. These were tested under real environmental conditions. The proposed algorithms were presented at two conferences: the 22nd IEEE Mediterranean Electrotechnical Conference 2024 (MELECON 2024), and the 1st International Conference on Sustainable Initiatives in Maritime Sector, 2024 (SIM'24).

Starting time mission	Bidirectional Graph-based algorithm (with static environmental conditions)			A-star algorithm with probabilistic behaviour (with time-variable environmental conditions)		
	Calculated Energy	*Predicted Energy	Duration of the mission	Calculated Energy	*Predicted Energy	Duration of the mission
0h	2.37kWh	2.01kWh (-15%)	7,0h	2.01kWh	2.01kWh	7,8h
5h	2.06kWh	5.19kWh (+152%)	6,3h	3.05kWh	3.05kWh	7,5h
9h	1.64kWh	3.49kWh (+113%)	6,4h	3.09kWh	3.09kWh	7,4h
12h	2.37kWh	2.04kWh (-14%)	7,0h	2.04kWh	2.04kWh	7,7h

** "Predicted Energy" is the actual energy the USV would require when considering the predicted environmental conditions.*

Figure 9. Performance comparison between algorithms

The final experimental validation of the developed USV and SEMS was carried out at the interface between the sea and the River Tejo, Lisbon. For this mission, the USV was remotely controlled, via radio. However, the USV already had all required equipment for autonomous operation (sensors and camera). We decided not to carry out an autonomous operation due to the presence of other vessels, which required obstacle identification and other algorithms for object tracking. This will be further developed after this project.

During this mission the USV was equipped with the following sensors:

- Voltage, current and temperature sensors for the photovoltaic panels, batteries and motors
- GPS signal with position, orientation, speed and IMU (inertial moment units)
- Camera.

An application of the proposed Smart Energy Management System (SEMS) was developed for this project. This application is run on a dedicated computer at a ground base station and communicates in real-time with the USV, through radio (this can be improved to Lora, GSM or Starlink) for the USV control system. The objective of this SEMS is to optimise the mission a-priori and supervise the mission to help in decision making. If a new route or mission profile is required due to unpredicted events, the SEMS will recalculate the mission in real time and provide it to the USV.

The SEMS application was used to plan the mission and to supervise it in real time. Before carrying out the mission, the predicted environmental conditions for the next 24h were uploaded. Then, using the SEMS, the mission optimisation was performed for different starting times, and the time was selected that would result in the lowest energy consumption. For 17 July 2024, the resultant optimised mission should be carried between 10:00 and 11:00. After the mission optimisation, the optimised path and speed profiles were obtained and communicated to the remote driver[3] to carry out the mission. Throughout the mission the outputs of the USV sensors were provided in real time to the SEMS application to allow supervision of the mission and to decide if any actions would be required.

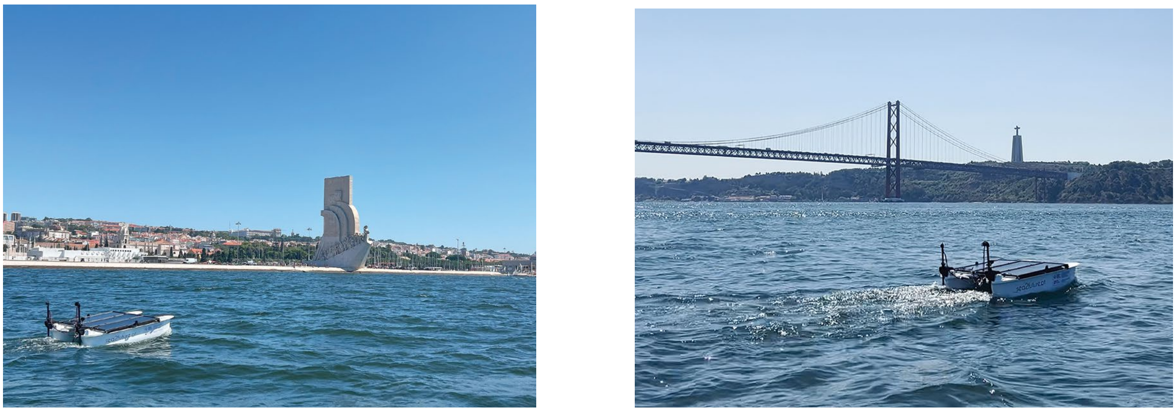
In fact, during the mission a recalculation of the mission profile was required due to increased wave conditions. This was done by the SEMS in real-time and the recalculated results were communicated to the USV driver.

In the first part of the mission, unexpected wave patterns occurred, which led to a deviation from the predicted energy consumption. Therefore, in the middle of the mission it was decided to re-optimise the speed profile so that the mission could be finished with a 20% energy reserve in the batteries. The remaining part of the mission was carried out without any deviations and the remaining battery energy was 24%. With this mission the importance of the photovoltaic system was verified (it contributed to 21% of the energy), as well as the possibility of navigating only with energy from the panels, at low speeds. It was concluded that without the PVs and SEMS, the mission could not be finished. The SEMS extended the range by up to 20%, and the PVs by 25-50%.

(a) (b)

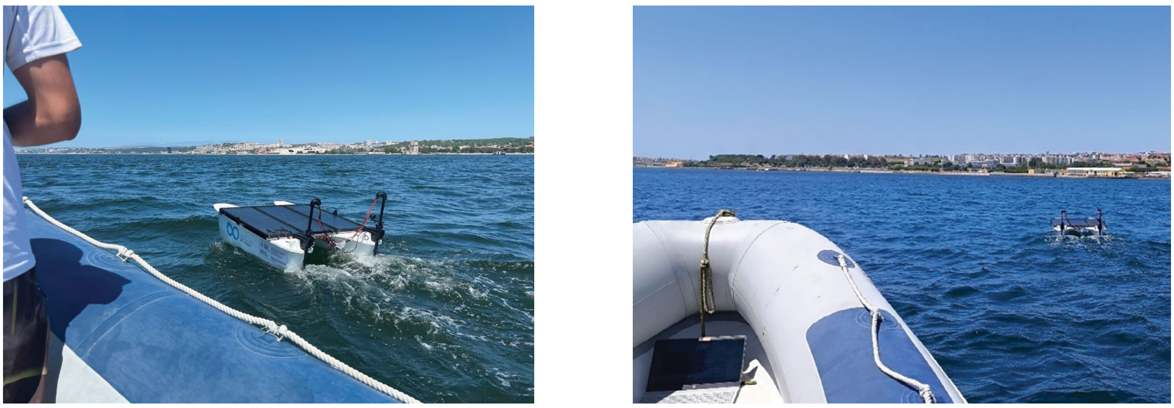
Figure 10. Photos before the mission started. Preparation phase (waypoint A)

[3] A physical person controlling the USV through a radio RC. The USV can also be made fully autonomous. However, during the experimental tests, it was preferred to control the USV remotely by a driver because of the presence of other vessels and obstacles on the sea/river, which would require more advanced techniques for obstacle identification and recognition, in addition to path following. These capabilities will be developed and added to the USV.



(a) (b)

Figure 11. Photo between waypoints (a) B and (b) C



(a) (b)

Figure 12. Photo between waypoints: (a) C and (b) D

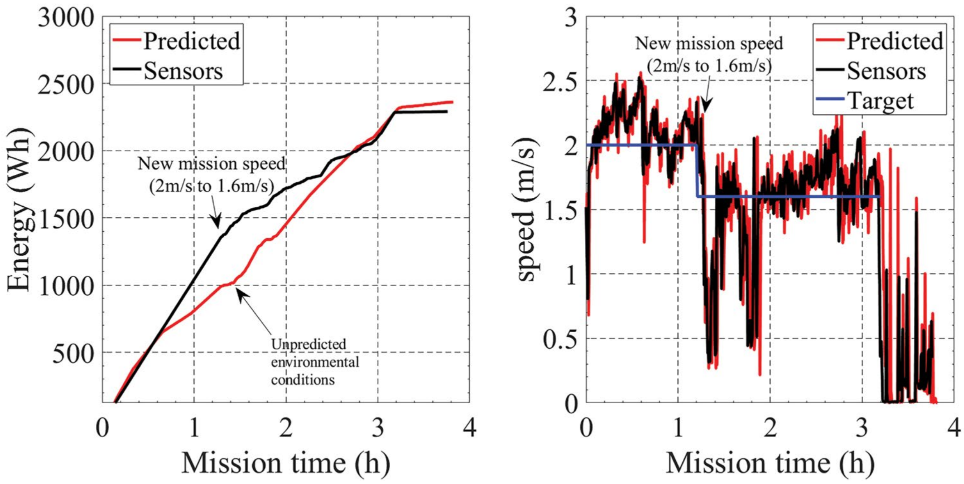


Figure 13. (a) Evolution of predicted and measured cumulative energy consumption and (b) target and measured speed

Without the SEMS, the shortest path would have been taken. Figure 14 shows the comparison between the optimised SEMS path and the shortest path. Even with a small deviation between paths, the energy consumption would have increased 16.4% from 2.31kWh to 2.69kWh. Therefore, considering a safety margin of 20% on the batteries, the mission would have stopped at different points, depending on the inclusion of PVs. These points are marked in Figure 14 ("with PVs, no SEMS" and "without PVs, no SEMS").

With the conclusion of this project, the research team consolidated some new ideas on possible future developments and applications for the developed system:

- Adding autonomous visual recognition: detection of obstacles (other vessels) or identification of targets;
- Adding autonomous manoeuvrability to avoid extreme environmental conditions, such as avoiding capsize;
- Integration of the USV in external surveillance systems, such as communications with other vessels and systems; and
- Inclusion of systems for receiving and managing aerial drones, trying to solve the issue of how to safely land drones.

As far as possible future applications, the research team believes that the system can be used in:

- European Border and Coast Guard community: border management, supporting fighting cross-border crimes, performing surveillance and improving situational awareness through real-time collection of information;
- Drone-USV interactions: to allow drone battery charging and sea/aerial coverage;
- Delivery of emergency goods for humanitarian aid;
- Multiple USV grid surveillance to create a grid search;
- Extending the application of the SEMS to other types of vessels.

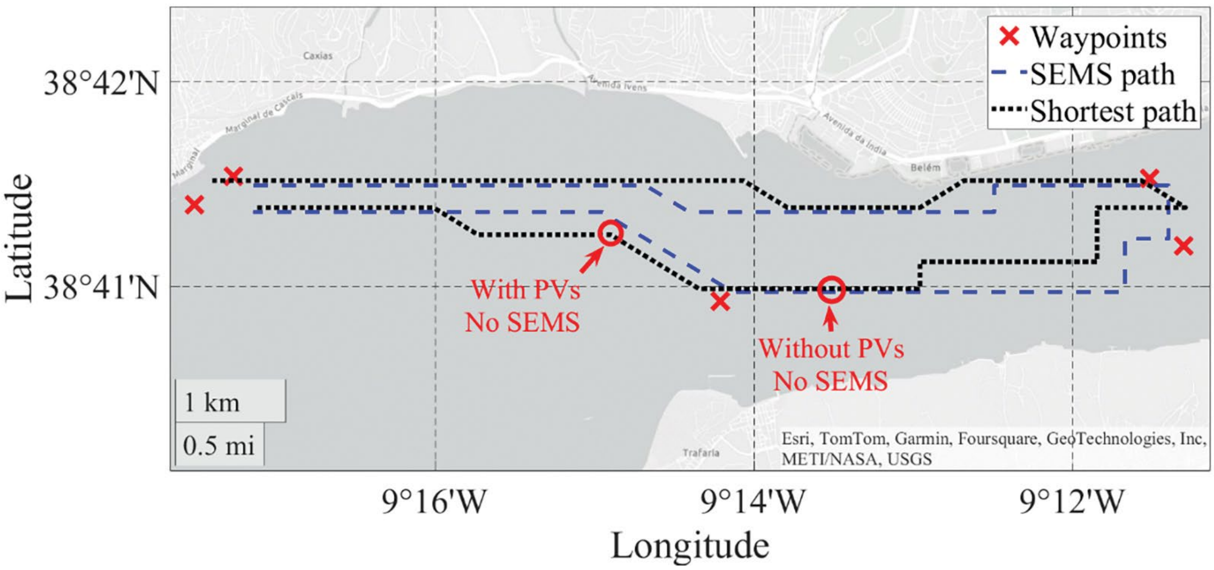


Figure 14. Comparison between the optimised SEMS path and the shortest path

SWEETIDS – Sweet spot ID documentation system

Beneficiary

CAMPUS 02 GRAZ FACHHOCHSCHULE DER WIRTSCHAFT

CAMPUS 02 Fachhochschule der Wirtschaft GmbH (Austria)

Executive summary

Today's travel and identification documents contain many security features, most of which only cover a small part of the document. The objective of the SWEETIDS project was to create a system that can take high quality detailed images of these partial areas ("sweet spots") of documents under different light sources. The images can be used to create document QCCs ("quick check cards") that show the security features for training and comparison purposes, which are the main operational applications in border checks.

It is shown that the large, expensive machines currently in use are not always necessary and often can be replaced by cheaper devices that put the focus on the sweet spots of ID documents, creating images with a smaller file size. They are comparable to those seen in (high quality) mobile document checking devices, and can be transmitted easily, including over slow lines or with mobile devices.

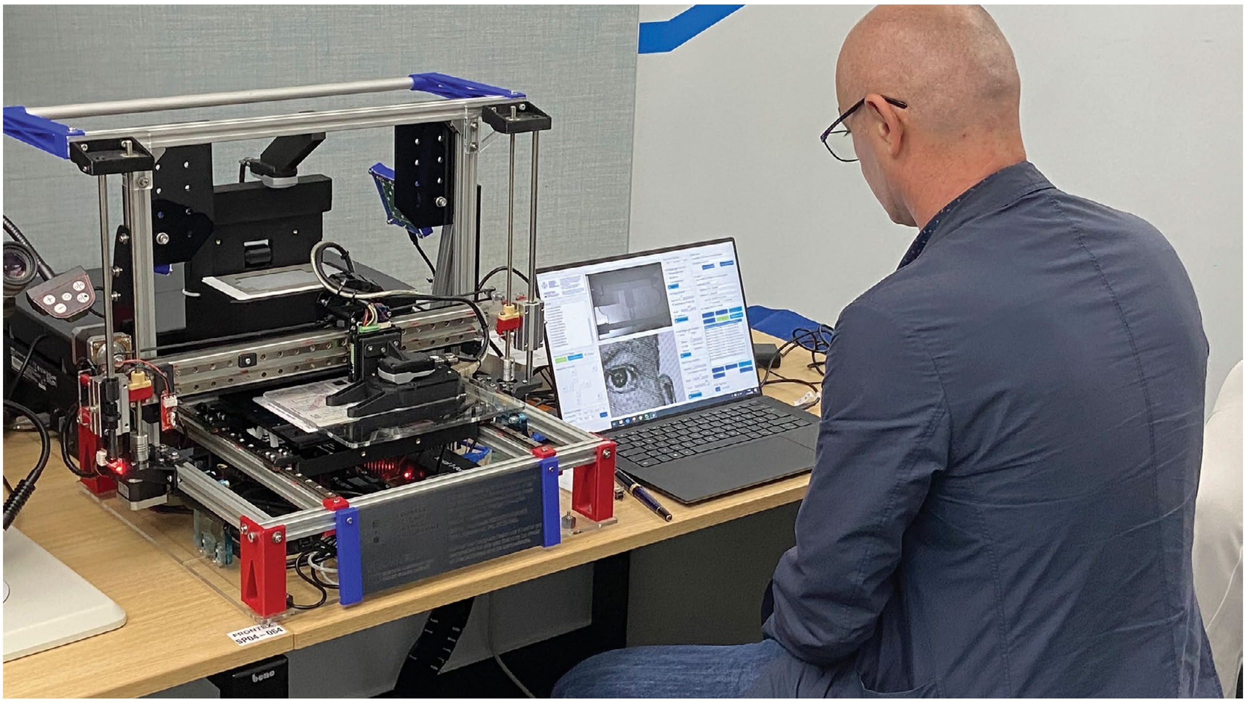


Figure 15. The fully working SWEETIDS prototype

When experts check documents for falsification, they always look for certain aspects, e.g. manipulations at the border of the person's picture, overprints on significant parts of the holder's face, changes in the check digits of the MRZ, printing techniques on certain positions, OVIs (Optically Variable Inks), DOVIDs (Diffractive Optically Variable Image Devices) over pictures, manipulation of the age digits and Anti-Stokes particles. So only the sweet spots, or ~10% of the document's surface, are relevant for authenticity checks, while the remaining 90% bloat the file size without contributing significant value. A low-resolution image of the whole document is enough as an overview; it is not necessary to use a super-high-resolution camera system with a multistage lens system. By focusing on certain positions, good optical and digital magnification and proper lighting deliver enough information for a deep inspection, even with the slight distortions caused by the simpler lens system.

As the main result of the project, a working prototype (Figure 15) shows the feasibility of the idea. It consists of a moving optical light head with camera, optics and light on an X/Y/Z-stage, as well as a full-page setup with transmitted light capabilities. It is operated in two steps, where all full-page images are taken first, then the document is changed to the moving head area, where all the detail images can be captured.

All actuators, sensors and light sources are connected to a controlling computer. A graphical user interface (Figure 16) allows the user to move the camera and light head and to activate the light sources individually. The images are taken by two cameras, one for full-page images and one for the details.

The system was designed with reasonable pricing and portability in mind, which will allow a rollout to many locations, contributing to a safer Europe by reducing document fraud. While the optical and mechanical structures are important for high-quality image reproduction, the software is the key for automation, including operation by rather unskilled personnel. The overall goal was to automate the image taking process as much as possible, allowing easy creation of graphical document summaries, complemented by many other ideas that can be implemented in the future, adding extra value.

During the final practical exercises all aspects were tested and evaluated by Frontex document experts, giving the following results on three performance aspects:

Quality of the images and their usefulness for document inspection and the creation of QCCs and document alerts: A direct comparison of detail images taken from a passport specimen showed that the image quality is on the same

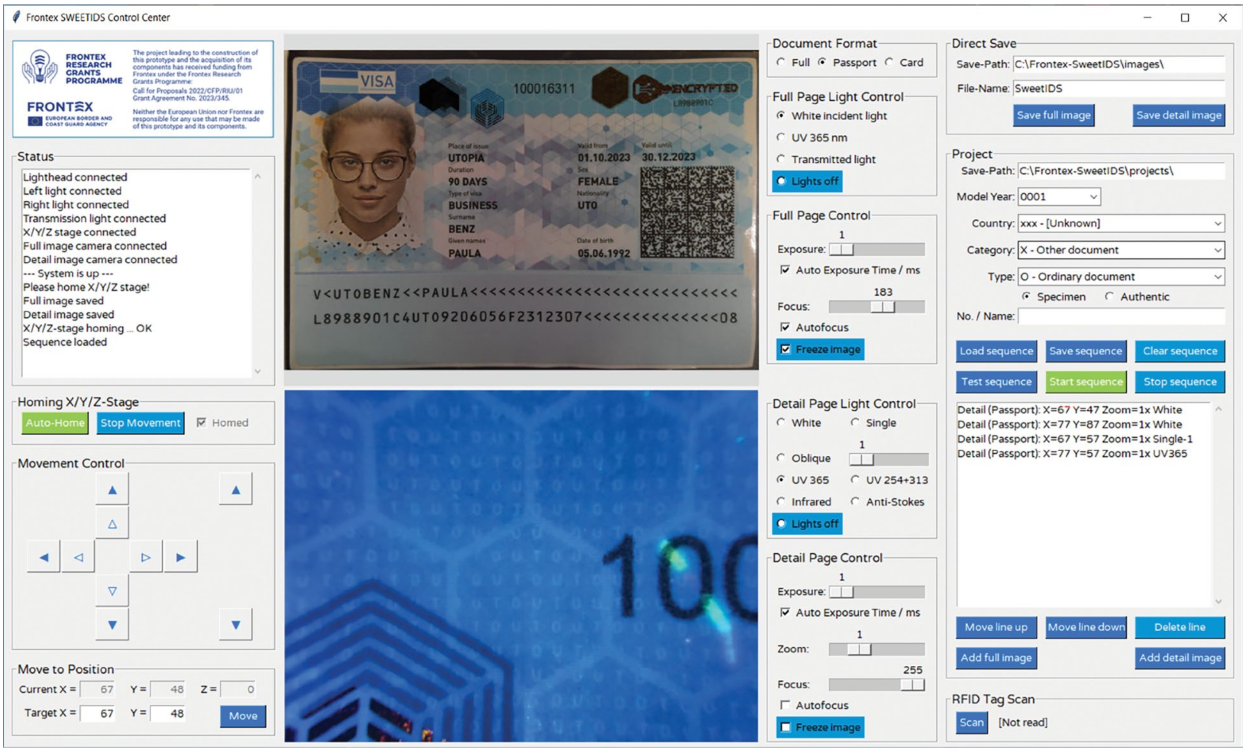


Figure 16. The user interface

level as that delivered by professional and expensive VSCs. It therefore can be considered as fully sufficient.

User experience including necessary prior knowledge and training: After receiving brief instructions, the test users were able to carry out the task of defining a set of images for a QCC taken on a genuine specimen. In a second run the same document type was handled, but this time a falsification. To compare it to the specimen, the same images had to be taken. Therefore, the sequences previously created to examine the genuine specimen could be used. Since this needed only a very few actions, such as inserting the document, loading and starting the sequence, and finally copying the results to external storage, this was an easy task that needed only one minute of instructions. Overall, the user feedback was very positive.

Time necessary to create the images: While the first run took more time to find all the settings necessary to create the individual pictures, the second run with the falsification using a predefined sequence could be done in under 5 minutes. Experts remarked that at the border up to 10 minutes is acceptable to create a document alert, but it often takes up to one hour with conventional equipment. Therefore, the usage of the project result will give an exceptional advantage on speed.

The images (Figures 17 and 18) show a sequence of the files that were created during a test run with a Swedish passport specimen. The first document listed is the sequence file that includes all necessary information to document and replay the entire process for this document.

The resulting images are crisp, with high image detail quality (Figures 19 and 20), suitable to see manipulations and detect falsifications. During the test and at the final demonstration, the potential of automation to improve document checking at the borders became clearly visible. This paves the way for further research, and development of the prototype into a serial product, with the potential to be rolled out to all European border front-line document inspection posts. More and faster document checks and alerts, that can be performed by personnel with only basic training and skills, will significantly contribute to the detection of more falsifications, which in turn will have a great impact on securing the EU borders.

Figure 17. Automatically created files of test run for full page images of the Swedish passport specimen

Figure 18. Automatically created files of test run for detailed images of the Swedish passport specimen

Figure 19. Crisp detail with high image quality (original size: 4 x 3 mm)

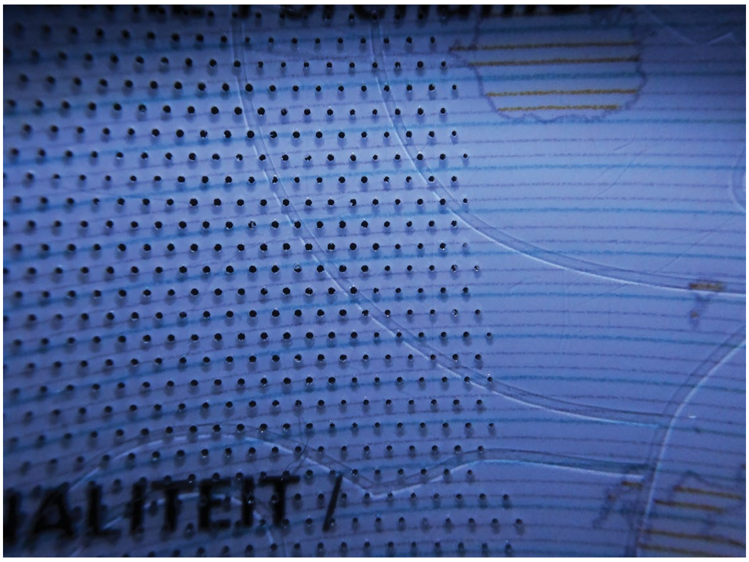


Figure 20. The variation of the diameters of the laser engraving holes can easily be recognised

DMDLBVEC – Developing of the collecting and digitalising methodology of the data from the land border violation places using Unmanned Aircraft Systems which is suitable as evidence in court

Beneficiary

SISEKAITSEAKADEEMIA
Estonian Academy of Security Sciences

Estonian Academy of Security Sciences (Estonia)

Executive summary

The project focused on the development of a new methodology for collecting evidence from land border violation crime scenes, in circumstances where communication with the neighbouring country is limited or absent, while respecting that country's sovereignty.

This research activity used drones in the form of single drone (UAV - unmanned aerial vehicle) and full system with sensors (UAS - unmanned aerial system), as their top-down view allows a greater range of view into a neighbouring country than terrestrial photography. Drones also have other advantages, which will be discussed later.

The research methodology was kept as simple as possible, including experiments that simulate and approximate as closely as possible the events taking place at real locations of border violation incidents. An area of interest (AOI) is an area simulating an incident at the border, in which a scenario is conducted by experts of the Estonian Police and Border Guard Board to create a scene, from which data is then collected. The drone-based method gives data for both sides of the border line (Figure 21 – blue and red areas), thus offering full coverage of the AOI, while evidence collected using classic forensic methods is available only for one's own country (Figure 21 – red areas) but not for the neighbouring country (Figure 21 – blue areas).

The data collection process started with a drone, as it does not create side traces, followed by classical forensics methods. The data was then processed and analysed. In later stages, conventionally collected evidence and drone-based evidence were compared. The applicability of the results for various procedures — from the measurements of a criminology expert to the procedure of a border agent — was examined separately.

Data collection processes were performed for all winter and summer test areas (Figure 23), moving from simple to more complex, starting with the daytime (maximum light) sandbar and ending with the nighttime (low light) bog. This sequence allowed for the rapid identification of unsuitable conditions for drone-based evidence collection in summer, highlighting where it was not worth investing significant resources (e.g. R and RE channels in the dark). The same principle – from simpler to more complex - was also applied to processing the data collected by the drone, making it possible to save the corresponding resource as well (for example: the TIR orthomosaic has no added value).

During planning, it was noted that data collection could follow a simpler process in summer than in winter, when there was limited experience with UAVs and their payload capabilities.

Locations (Figure 22) were chosen to be as realistic as possible. For both seasons, there were a border strip, forest, and swamp or bog. For winter there was a specific need to conduct tests on a frozen lake.[4]

Equipment was chosen according to the following criteria: the ability to capture images in daytime maximum light and nighttime low light, and to analyse the state of green vegetation. Platforms were selected based on their ability to carry the chosen sensors. Since the platforms have different payload capabilities, one drone was not enough.

The two platforms used were a DJI Matrice M350[5] with payload Zenmuse H20N, and a DJI Mavic 3M[6] with integrated sensors. The two platforms use in total three types of sensors (RGB, NIR and Multispectral), as each platform has an RGB sensor in the payload and one platform-specific sensor (NIR sensor for the Matrice M350 and multispectral sensor for the Mavic 3M). Figure 24 shows the parameters of both drones, and the most important deliverables. Both types of drones were used for each test in 14 missions during winter experiments. For the Matrice M350 platform, there is a specific thermal infrared sensor, and for the Mavic 3M, a multispectral sensor.

Experiments and scenarios were created to be both as realistic and as simple as possible: individual(s) crossing the border, leaving different traces and using different aids (e.g. a ladder). Different lighting conditions (maximum light and low light) were included as environmental factors, as well as time between the creation of traces and their monitoring (a few hours vs. immediately after).

The drones have three different types of sensors: RGB, TIR and multispectral, which in turn has various output subtypes (G, R, RE and NIR) as well as combinations of these. For all the sensors there are two output formats (photo and video), and for the H20N payload there are two additional output options according to the optics used, namely “zoom” and “wide angle”.

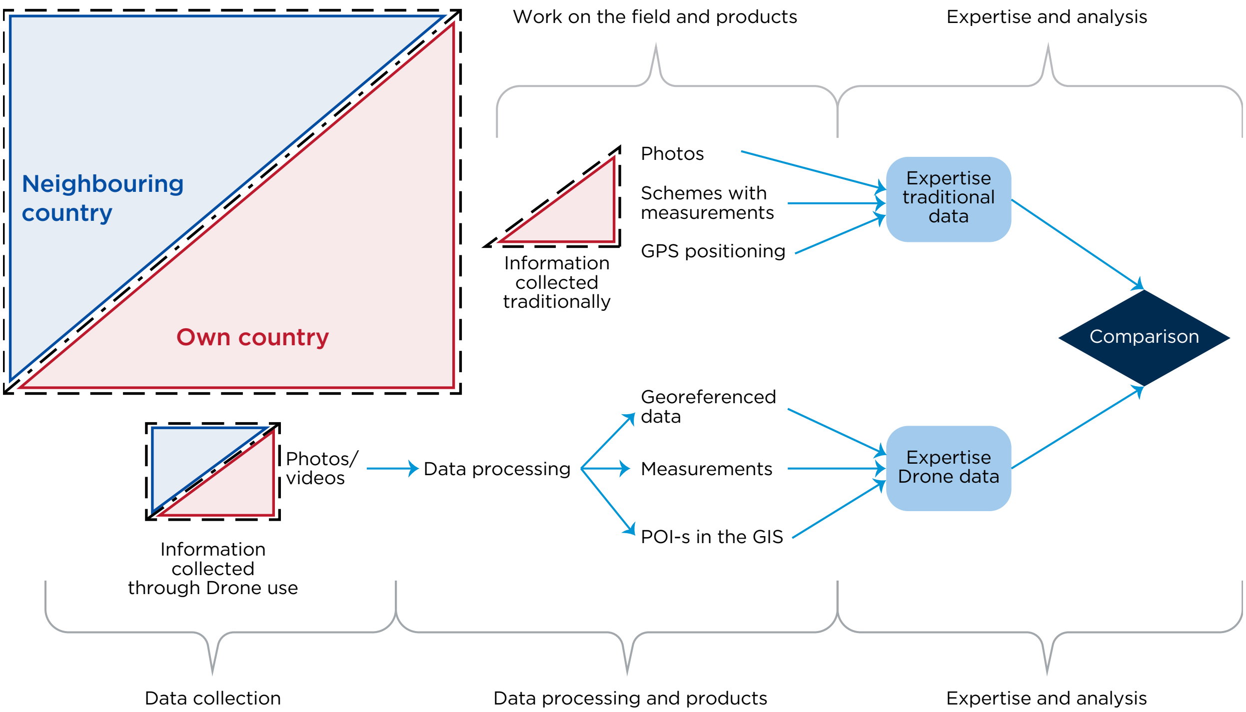


Figure 21. General structure of research (scenario based)

4 Estonian-Russian border on lake Peipsi is over 120 km in length, and lake area on Estonian side is about 1550 km^2; in addition to lake Peipsi there is the 77-km-long Narva River and border areas on the Baltic Sea.

5 “DJI” is the brand, “Matrice” is the series, “M350” is the model of the drone.

6 “DJI” is the brand, “Mavic” is the series, “3” is the model, “M” is the version of the drone.

Border and forest, winter

Lake, winter

Bog and forest, winter

Border, summer

Forest, summer

Bog, summer

Figure 22. Locations

Season	Location	Conditions	Matrice M350		Mavic 3M	
			Images	Videos	Images	Videos
Winter	Sand bar, forest with wood and brush (Peppier)	Maximum light old traces	51	8	102	2
		Maximum light	81	8	90	2
		Low light	81	-	216	-
	Marshes and bog (Varsaallika)	Maximum light	96	-	126	-
		Low Light	63	-	1-14	-
	Frozen Lake	Maximum light	51	-	90	-
		Low light	66	4	144	-
Summer	Sand bar	Maximum light	111	-	234	-
		Low light	90	-	114	-
		Maximum light, sandbar lengthwise	73	16	-	-
	Forest (Männiku)	Maximum light	39	-	102	-
		Low Light	15	-	30	-
	Marshes and bog (Männiku)	Maximum light	21	-	78	-
		Low Light	15	-	24	-

Figure 23. Number of photos and videos

The following section presents the outputs, their derivates and results for RGB, TIR and multispectral sensors, georeferenced orthomosaic and pictures, and georeferenced videos.

RGB is the most common type of output – photo or video in visible spectrum – and therefore does not need additional explanation.

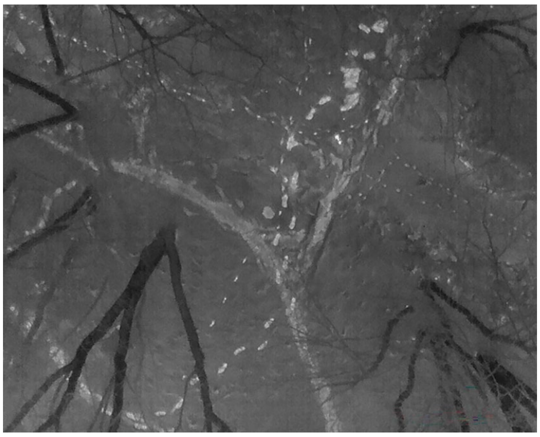
Thermal infrared sensor (TIR) output has certain advantages and disadvantages. The main advantages are the ability to see in the dark and to detect warm objects. The main disadvantage is coarser pixel size, which makes it difficult to use for measurements: in the actual project no measurements were taken from TIR images, due to the lack of detail from the coarse pixels.

In the context of finding traces, wintertime impressions in the snow (Figure 24) become visible even through later snow cover. This is because the object that causes the impression compacts the snow, and geothermal energy passes more easily through that compacted snow than through the fluffier and more insulating later snow.

In summer, there is no such geothermal energy conductivity, as all surfaces are warm, and the main use of TIR is for real-time situational awareness – to see if there are persons and vehicles in the dark – as past traces are not seen (Figure 25).

Within the scope of this project, it can be concluded that the winter TIR photo allows users to find traces that are difficult to find with the RGB sensor under normal conditions, as can be seen from the reference RGB. Both, in winter and summer, the TIR sensor is suitable for increasing situational awareness.

Multispectral sensors have different outputs (Figure 26): in this particular case separate channels (G, R, RE and NIR) (files for channels are named: *.tif) and combinations



TIR

RGB

Figure 24. TIR output, winter with reference RGB

Figure 25. TIR, summer, situational awareness (14.05.23, 00:42)

of channels, in later text described as “indexes” (files for indexes are named: *_F.jpg).

The results show that in winter, certain indexes can bring out slopes in the snow that are hard to detect on a photo. In summer (the main reason for testing multispectral outputs), the results are less conclusive, but promising, when combining different channels (Figure 27).

Georeferenced orthomosaic is a detailed, georeferenced image of a place, created by piecing together high-resolution photos taken from drones or other aerial platforms. This process, called orthomosaic mapping, uses special software and photogrammetry (Figure 28) to make sure all the images fit together perfectly, even if the ground is not flat.

The main advantage of orthomosaics is the usability with GIS software, in situations where the scene of incident cannot be covered with a single photo (broad and deep scenes).

The main drawback in the actual context is that there is no possibility to fly over the other country’s territory, and therefore the mosaic over the border becomes more distorted and has gaps further away from the border (Figure 29).

Georeferenced pictures are calculations based on a single image file (Figure 30) and have the advantage over orthomosaics that there is no need for an excessive number of photos. The main drawback is that a single file can have certain mistakes (e.g. wrong coordinates, distortion, calculation errors) that can render the results unusable.

Georeferenced videos are synchronized from two files (Figure 31), the video itself and the flight log, to create full motion KLV. The advantage is that with the right software (e.g. ArcGIS), it is possible to measure various dimensions and have a continuous georeferenced view of long scenes (measured in kilometres). The drawbacks are inaccuracies and the fact that it is video and not photo.

Additional calibration or additional testing (Figure 32) would have the purpose of understanding whether the differences between calculated dimensions from drone photos and the dimensions acquired by classical criminology methods are random or systematic, and if systematic, what the relevant factors are.

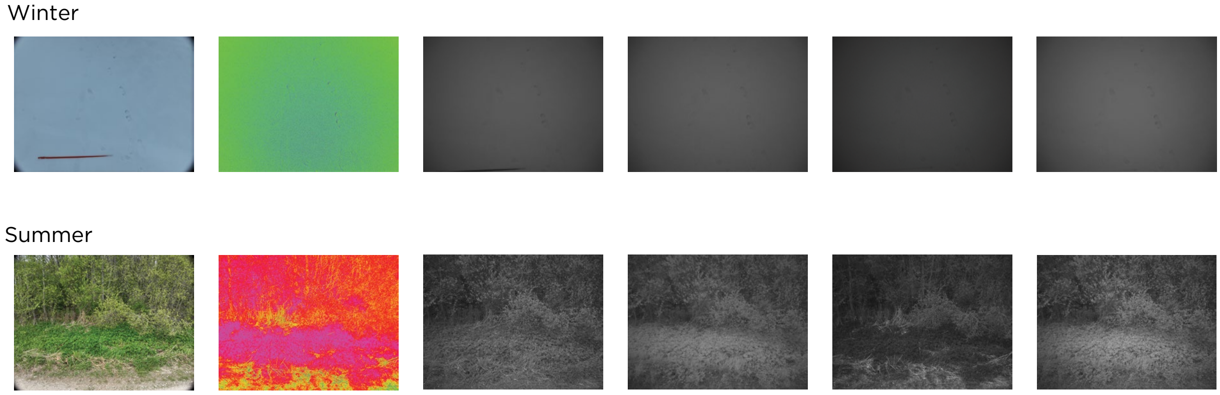


Figure 26. Mavic 3M output channels

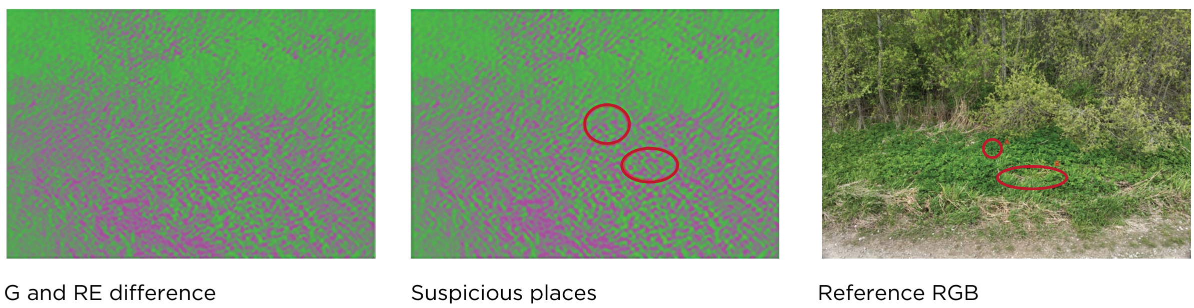


Figure 27. Possible traces with combination of qualitative visual analysis

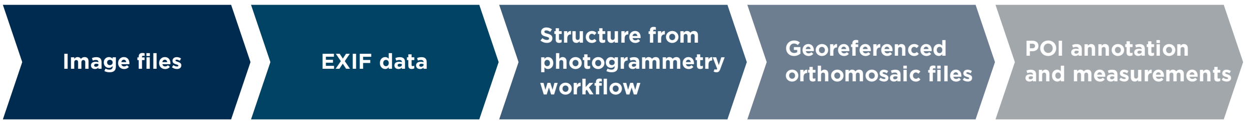


Figure 28. The process of creating georeferenced orthomosaics (simplified diagram)

Orthomosaic

RGB

Figure 29. Orthomosaic with distortions, with reference RGB

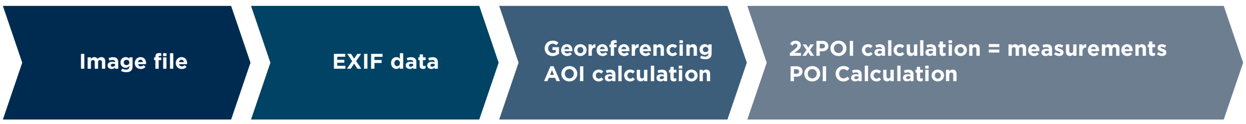


Figure 30. The process of creating georeferenced image files (simplified diagram)

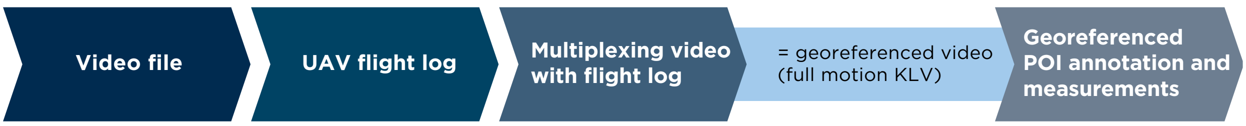


Figure 31. The process of creating georeferenced videos (simplified diagram)

Tests included different altitudes (5 to 15 meters) and camera angles (-90° directly down to -30° from horizontal). Three parameters of 10cm x 10cm square were measured, namely height (h), width (w) and diagonal (d). Testing revealed consistent results across all tested altitudes (see *Figure 32* for the tests conducted at 10m, with resulting coefficient and its polynomial fitting). Specifically, objects with smaller negative camera angles appear wider from left to right and lower from near to far in the calculations.

Since the calibration test was conducted last, it must be noted that there are few photos in the previous material where the rule can be perfectly applied: distortion occurs at the edges of the photo, which requires separate testing. So ideally, the camera should be at an angle of -75° and the object should preferably be parallel or right angle perpendicular to the vertical axis of the centre of the camera view.

The main conclusion is: UAS-based data gathering or remote sensing can, in certain situations, replace or supplement traditional criminological methods in cases of border violations. The main advantage and a new development is that UAS-based work does not destroy evidence or create supplementary traces on the scene; it does not interfere with use of dogs.

In Estonia there are three types of proceedings in case of border violation, where photo evidence gathered from the scene can be used:

- Offence proceedings, as criminal or misdemeanour proceedings, depending on circumstances. The need is for evidence that can be used in court. The key aspects include measurability and thus suitability for expert assessment, as well as situational awareness considerations.
- Border representatives' proceedings. The most important aspect is to give a good overview, situational awareness, traces that describe the event and proof that a border violation has taken place, all to communicate with the Russian Federation as described by its agreement with Estonia.[7]
- Asylum proceedings, where it is crucial to provide an overview, situational awareness, traces that describe the event and proof that a border violation has taken place. All that is used as proof of the asylum seeker's statements.

As a consequence, the main question for future use is whether UAV-based remote sensing is effective for any of these aspects, ranging from situational awareness to measurements.

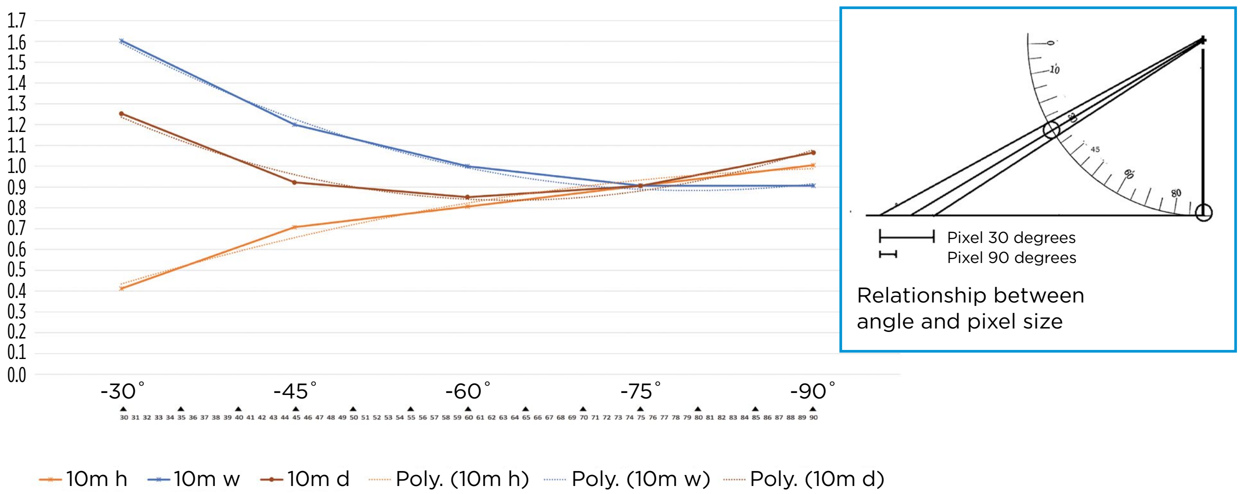


Figure 32. Coefficient between measurement and reality

[7] Kokkulepe Eesti Vabariigi valitsuse ja Vene Föderatsiooni valitsuse vahel piiriesindajate tegevusest. RT II 1997, https://www.riigiteataja.ee/akt/78585

The tests demonstrate that UAS works well for providing a general overview and showing traces when the soil (e.g. sand) or ground cover (e.g. snow) is suitable. Thus it can be stated that the use of UAS gives an applicable result in terms of situational awareness for all three types of proceedings.

Expert judgments in a criminal proceeding require high accuracy in the early collection of evidence, which requires adherence to certain rules when taking photographs, as shown by the calibration measurement. As a general rule, the object is in the centre of the image, the measured side is parallel or right angle perpendicular to the direction of the lens; the relationship of the specific tilt angle of the camera and the parameters measured from the photo to the actual dimensions must be known.

The winter test also showed that TIR can reveal hidden footprints in the snow: the better conductivity of compacted snow has better release of geothermal heat than surrounding fluffy snow.

With summer tests and the multispectral camera, the results were inconclusive: NDRE, NDVI and similar indexes did not show any usable result. There were some vaguely usable results in higher grass, where the difference between G and RE did show differences not visible for human eye on the field. As recommended in the literature,[8] in multispectral remote sensing it is important to apply machine learning. Corresponding research work is one of the directions to be developed further. Other directions, as experience shows, are further improvement of measurement accuracy, and automation.

Based on the outcomes of this research, it is possible to make several recommendations and suggestions to UAS users for border events:

Ability

1. Sensors - The RGB camera must be of sufficient quality; it is important to know the needs of affiliated organisations (e.g. forensic experts). The presence of TIR is good for night vision, winter tracks and searches for warm bodies.
2. UAV type and UAS configuration: a compromise must be found between portability and capability.
3. Calibration (test field): if it is important to use the data for measurements, the behaviour of a specific camera in specific circumstances must be known. It is important to reduce the number of confounding variables.

Planning

4. Season (winter vs summer): In winter, several sensors (TIR) work better, but it is necessary to take into account, for example, the difficulties of orientation on lake ice. In summer, it is more difficult to find traces, because quite often no impression is left on the ground and TIR does not work on hot surfaces. Therefore, the situation must be approached differently depending on the season.
5. Locations - Fully constructed borders, forests, wetlands and bodies of water all require different approaches; the same goes for darkness and light. Therefore, in parallel with the previous calibration, the aspect of local specificity must be tested with each specific sensor and platform.

Operations

6. Data gathering methods must correspond to the case and to the needs of affiliated organisations and operational needs. In this test series, it was confirmed that the georeferencing of individual photos and the use of POIs are functional. Video observation of long areas also works, as well as creating orthomosaics.
7. The sequence of operations is crucial, as some traces are time-sensitive. When dogs are used, drone photos can provide a general overview of the original situation.[9]

Security aspects

8. Flight security can be a limitation for the use of UAS, as GNSS may be jammed/spoofed, and the data is usable only for situational awareness.
9. In case of GNSS problems, it is good to use bigger UAS, where UAV and payload can be operated by different persons: one does the flying and other takes

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8 Xiuping Jia. Field Guide to Hyperspectral/Multispectral Image Processing. SPIE Press 2022. Bellingham, Washington USA

9 Depending on situation drone can be used differently, two examples: A) UAS based overview > UAS based data gathering from details > Use of dogs; B) UAS based overview > use of other methods; the example A is for a situation, where there are measurable traces collectable with UAS, B is summertime situation where there are no measurable traces with UAS, but situational awareness is needed as usual.

the photos, reducing the workload-related risk of accidents.

10. Data security with an unfriendly neighbour means that all equipment must have clean/new data carriers, so that in case of losing the equipment you only lose the actual case data.

In general four main directions of research and development are envisaged:

1. Multispectral and AI;
2. Automation, both in UAV/UAS usage and in data processing;
3. Creating a calibration/test field;
4. Usage of tethered drone with GNSS free navigation.

TUTELARY - Coastal surveillance system exploiting photonics-based radar security

Beneficiary

consorzio nazionale interuniversitario per le telecomunicazioni

Consorzio Nazionale Interuniversitario per le Telecomunicazioni (Italy)

Executive summary[10]

The project TUTELARY aimed at developing a coastal surveillance system based on a coherent multi-input-multi-output (MIMO) multistatic photonic radar in a port environment.

The scope of the project was distributed (i.e. multistatic) radar systems, which in principle can guarantee higher performance than monostatic systems thanks to their distributed nature. This kind of system is more effective in detecting stealthy targets, and small targets in general, because several radar antennas can look at a target from different angles.

The proposed approach to multistatic radars was based on photonics techniques that are used to generate, transmit and receive coherent multiband signals through optical fibre links to multiple widely distributed radar peripherals. The use of photonic techniques for the generation of the radar signal in principle allows flexibility in terms of radar frequencies and generating the same source coherent signals at different bands at the same time, thus enabling coherent multiband radar detection. Coherent radar processing, in turn, allows high spatial system resolution and potentially imaging, that cannot be achieved with non-coherent multistatic radars. Photonics, through optical fibres, is also the only way that permits the distribution with low loss of power of the radar signals to widely distributed peripherals. This approach is also very robust against electromagnetic interference thanks to the properties of optical fibre.

The main scientific objectives of the TUTELARY project were:

- To develop a fully operational field trial system in a port scenario. The system had to be expanded from two to three coherent radar peripherals (RPs) working on two frequency bands and tested for different real targets for performance evaluation.
- To develop algorithms and signal processing techniques for multistatic and multiband coherent Multiple-Input Multiple-Output (MIMO) photonics-based radar to enable the system to accurately detect and track multiple targets of reduced dimension.
- To improve reliability and robustness of the system in detecting, tracking, imaging and size estimation of multiple targets by integrating the proposed signal processing techniques and algorithms into the system.

[10] Full report available at https://www.frontex.europa.eu/innovation/eu-research/research-grants/tutelary-coastal-surveillance-system-exploiting-photonics-based-radar-security-rtVqHt.

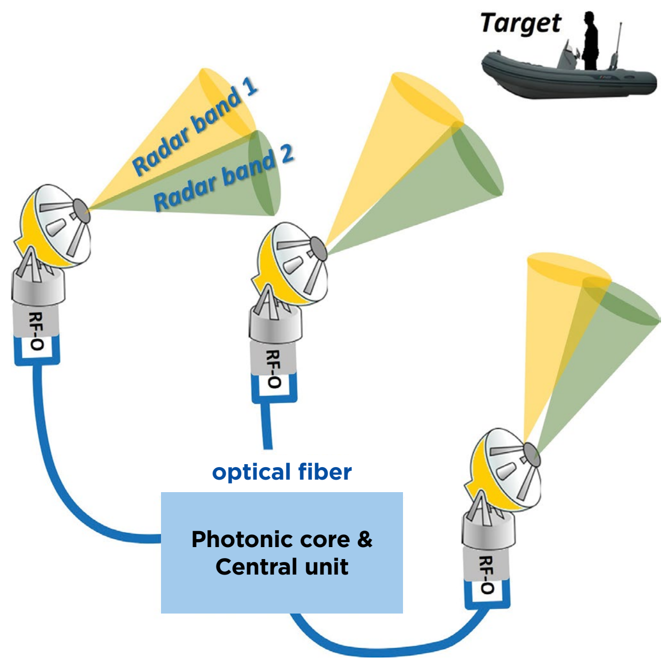

Figure 33. Concept of a distributed multiband coherent photonic-based multistatic MIMO radar

The system proposed within the project fits into the scenario of port security, maritime security and border security in general. The number of threats and fields related to these security domains is quite broad, and include environmental, search and rescue, territorial disputes, cyber, environmental disaster and climate change, irregular migration, maritime smuggling and trafficking, terrorism and piracy, narcoterrorism and drug trafficking. All of them need a combination of technologies to be effectively counteracted, together with the cooperation of several entities and international bodies. Use cases regarding costal surveillance often include attacks conducted by small vessels and vectors that need a radar system with high resolution to be detected. In the coastal scenario, the proposed system could be integrated into other surveillance systems and assets to detect threats, to form an integrated advanced protection system.

The state-of-the-art analysis conducted in the project showed that there are issues in the detection of targets in the maritime scenarios with conventional monostatic radars, mainly related to the targets' change in orientation and small size. These issues can be mitigated by the use of network of radars, i.e. by multistatic systems that combine the information from radar heads located at different positions. Among multistatic systems, MIMO maximises the cooperation among the radars of the network, by enabling the centralised processing of signals from the different radar heads, thus improving the overall system resolution. Most commercial radars work on a single band, typically X-band or S-band. The use of multi-band radars that employ two or more bands at the same time bring several main advantages: improved resolution, enhanced detection, reduced interference.

Thus, the TUTELARY approach, based on a multiband MIMO radar network, can bring advantages over conventional monostatic single-band radar systems. Following the proposed approach, the true coherent fusion of the signals collected by the radar heads is enabled by the use of photonics that allows the generation and distribution of the same radar signal to all the peripherals through optical fibre, which also is very robust against electromagnetic interference and has low losses. Only a few MIMO radar demonstrations in a real scenario have been reported in the literature: NeXtRAD (UHF, X-band), MIRA-CLE (X, Ka band), an S-band MIMO radar, MELISSA (X-band). Most of the systems have co-located antennas, i.e. they cannot effectively counteract a target with a fast-changing radar cross-section (RCS), due to limited spatial diversity. Only the NeXtRAD system has widely separated antennas.

Project TUTELARY stemmed from the EU ROBORDER project, involving CNIT, which implemented a first demonstrator of a photonics-based MIMO radar, with only two radar peripherals at 2.9 and 9.7 GHz operating frequencies.

The features of the proposed photonics-based MIMO radar network with widely distributed antennas can provide enhanced monitoring capabilities in terms of target detection and localisation, thanks to the ability to fuse coherently the received signals.

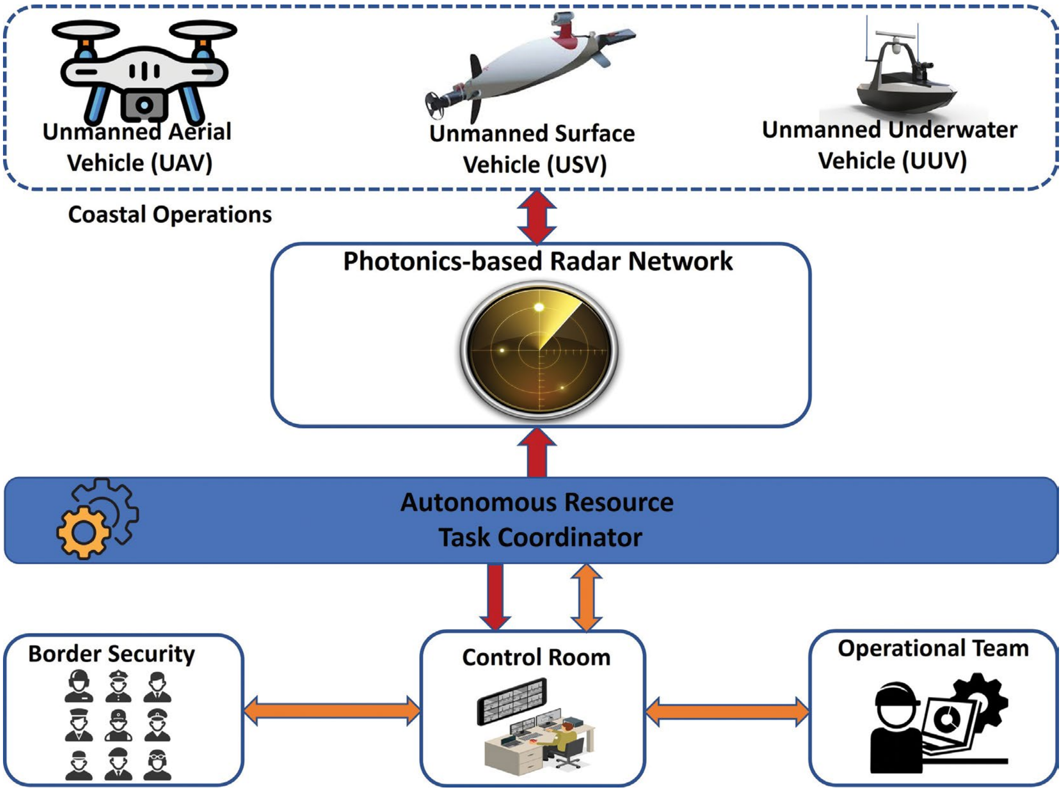

Figure 34. Application scenario in a coastal surveillance system of the photonic-based radar developed within the TUTELARY project

The project started with the identification and examination of various use cases pertaining to border-related threats in the coastal scenario. Then the implementation stage was initiated. Since the radar system demonstrator at the port of Livorno had only two RPs working, a study was conducted to identify a suitable location for the third peripheral. Once this location was identified, the system was finalised, including a Photonic Network Core and three radar peripherals, connected by optical fibre for synchronised and coherent operation. The system was deployed using existing fibre links in the port area.

The system generates and distributes coherent multiband signals through the fibre to each radar peripheral. The field-deployed peripherals only include the optoelectronic and electro-optic converters, RF front ends and antennas. Optical fibre is used for low loss, low distortion and electromagnetic interference-free RF signal distribution. Testing and operational checks were conducted on each subsystem, as well as on the centralised photonic radar system as a whole. Algorithms and signal processing techniques to enhance the system's ability to detect and track objects with high resolution were investigated and implemented for the scenario of coastal surveillance in the use cases. Different Key Performance Indicators (KPIs), including range and cross-range resolution, were considered to evaluate the algorithms' performance. Field trial tests on the fully operational photonics-based radar network for coastal surveillance were conducted on real non-cooperative targets moving in the port area.

The photonics-based approach was adopted in this project to build a coherent and largely distributed multiband radar system. The radar architecture uses distributed photonics-based up- and down-conversions, with a central unit (CU) which builds the radar network core, shared among all the peripheral radar nodes, or radar peripherals (RPs), and a further dedicated stage in each RP. As this architecture is fully centralised, the photonic core inside a single CU can generate signals that are transmitted via optical fibres to widely distributed RPs, resulting in a coherent radar system with largely distributed nodes. Photonics provides unprecedented frequency flexibility and phase noise stability, while optical fibers are highly effective to implement wideband transmission links that distribute the radar signals. Each RP can transmit and receive RF signals at different carrier frequencies, namely f_{RF1}, f_{RF2}, ... f_{RFN}.

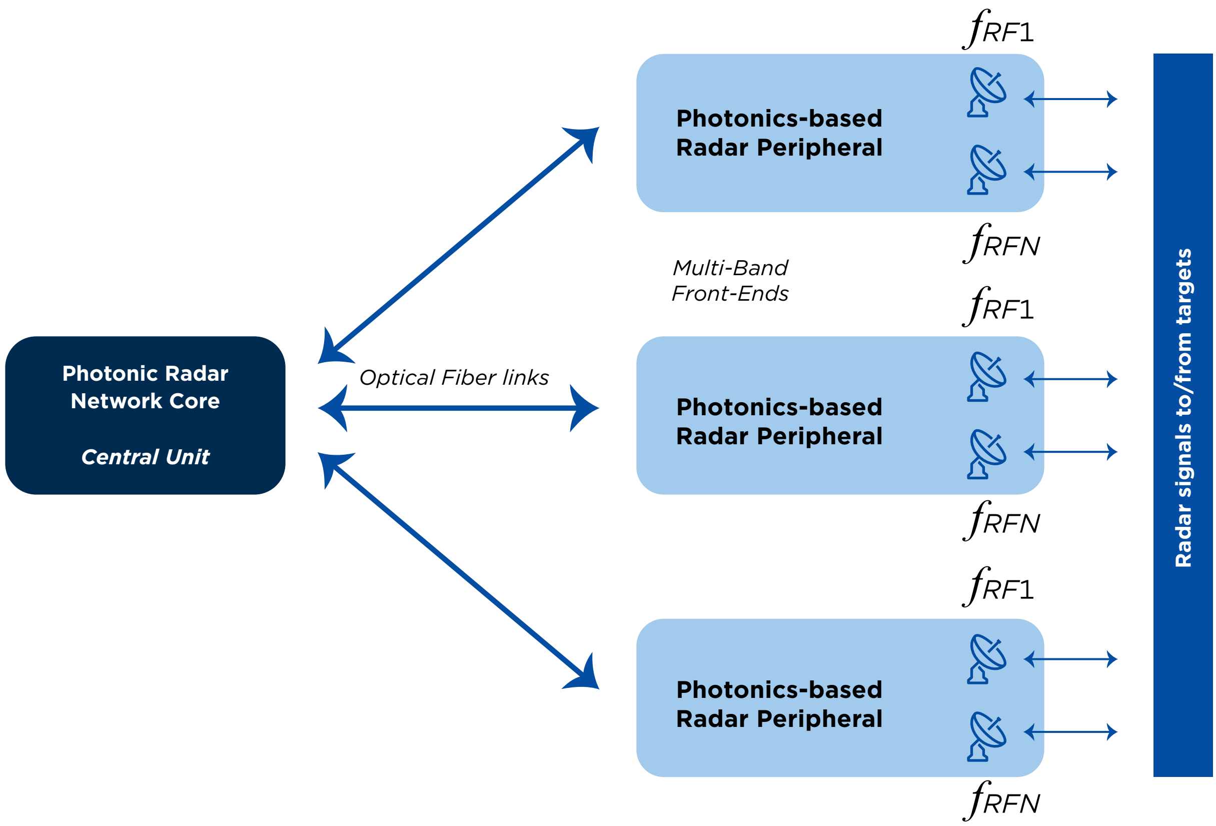

Figure 35. Photonics-based distributed radar network architecture

Algorithms and signal processing implementation

The full exploitation of the distributed coherent radar architecture capabilities requires the implementation of coherent MIMO processing tools and algorithms. The numerical tool that was developed can implement both coherent and non-coherent MIMO processing, allowing users to adapt the system to different needs in terms of signal bandwidth, modulation format, carrier frequency, antenna gain and number of radar signal bands.

A numerical analysis carried out with the implemented numerical tool shows that coherent MIMO processing has higher performance in terms of probability of detection than non-coherent processing, increasing the time interval within which the target is detected for a fixed antenna distribution. The results were obtained for the port demonstrator scenario. The two main processing algorithms for target tracking, i.e. Kalman filtering and particle filtering, were compared for a coherent MIMO case, showing that particle filtering performs better in terms of target speed estimation than Kalman filtering.

The 2-D ambiguity function was provided as an output of the simulations after coherent and non-coherent data fusion for the estimation of the KPIs of range and cross-range resolution. The results highlight the benefit of coherent processing, which allows reduction of the size of the lobes of the ambiguity functions compared to non-coherent processing. The cross-range resolution with coherent processing is 5 m, much higher than with non-coherent processing (about 25 m). With coherent processing, the range resolution is about 2.5 m, close to the range for non-coherent processing for the port antenna distribution.

The KPIs found by simulations indicate that the distributed radar based on 3 peripherals can resolve a vessel with precision of less than 5 m and RCS as small as 1 m^2, thus being able to resolve a small vessel.

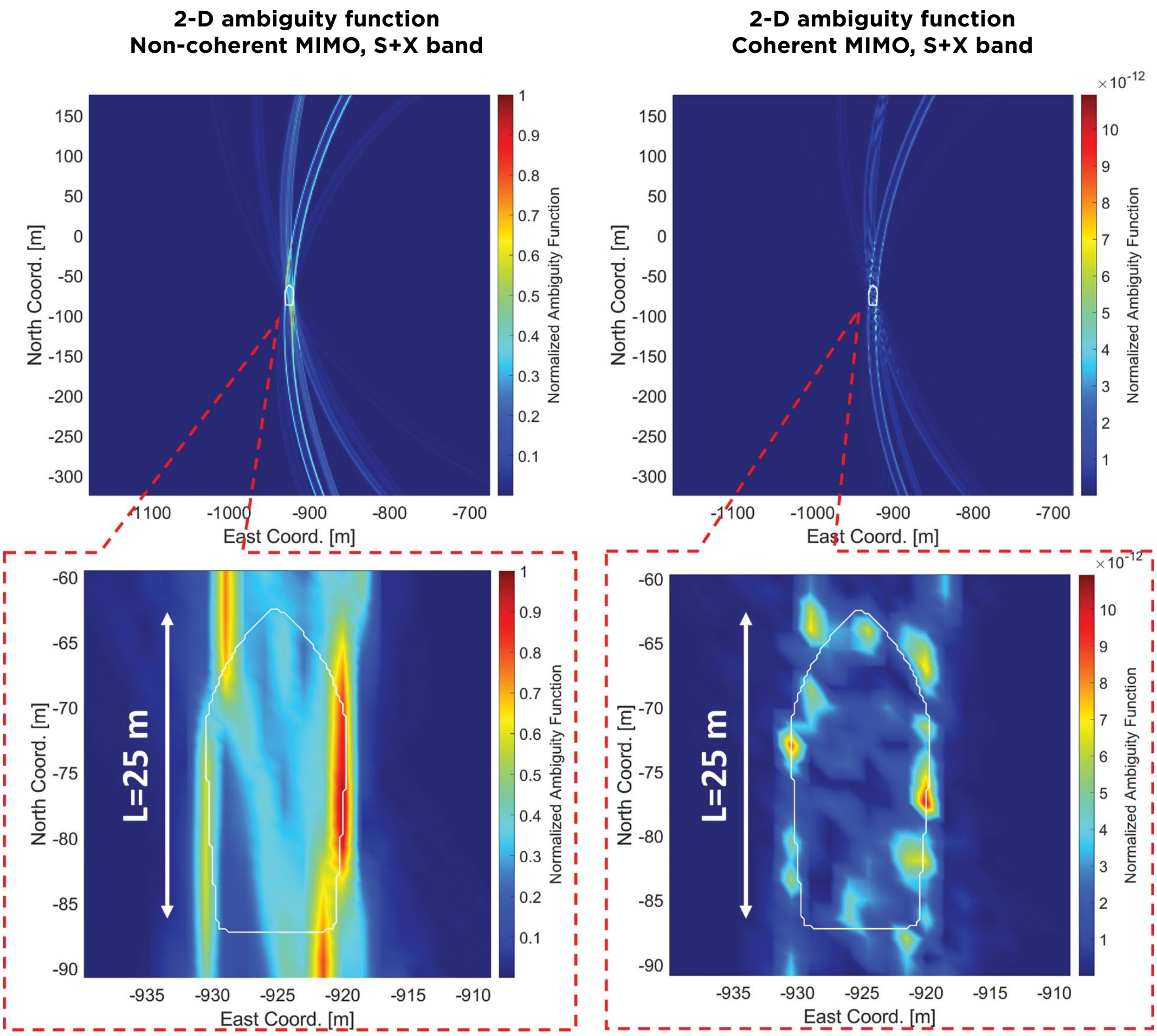

Figure 36. Simulated 2-D ambiguity function for non-coherent (left) and coherent (right) processing after fusion of data in S and X band for a vessel of 25 m length and RCS of $10m^2$. White line outlines the target vessel.

Preliminary system tests

System tests were conducted in a laboratory environment before installation in the port environment. This approach was necessary to check the system performance. Tests on the central unit included testing the equalisation of the signals (modulated and unmodulated) to be transmitted to the radar peripherals. The signals equalisation is good, with crosstalk among consecutive modulated signals spectra lower than -8 dB. Tests on the radar peripherals successfully characterised the devices and signals that play a role in the system performance. This characterisation was focused on the modulators, the radar frontends gain and the gating (control) signal delay. The tests for the evaluation of overall system performance were focused on the characterisation of the cascade of the central unit and the additional radar peripheral to be installed at the new location. The tests showed that the system performance was in line with expectations. The minimum detectable signal is −110 dBm for X-band and -102 dBm for S-band, referred to a detection threshold of 6 dB.

The software, based on a graphical user interface (GUI) and implemented in LabVIEW programming language, confirmed the capacity to properly control the system elements and devices.

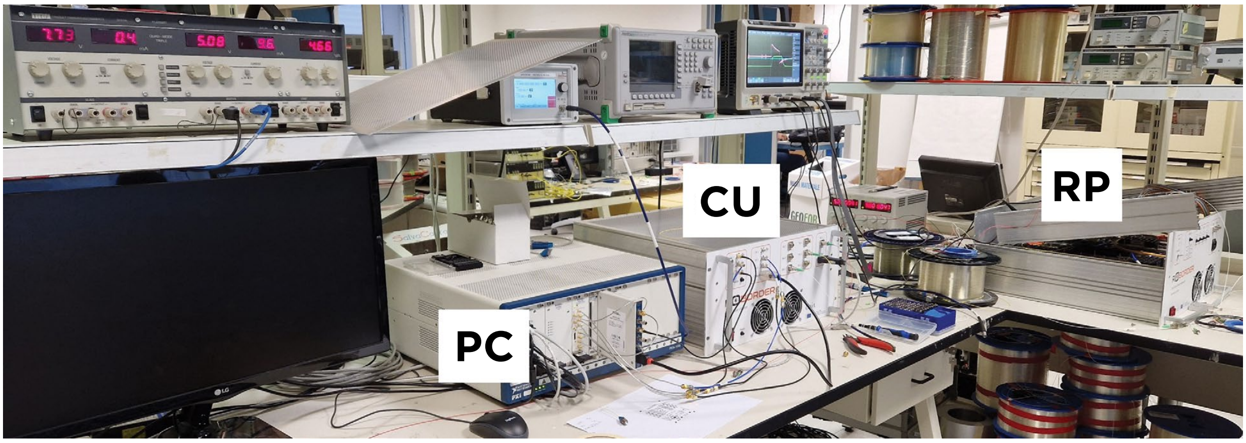

Figure 37. Experimental setup for lab system test. CU: central unit; RP: radar peripheral; PC: personal computer

System implementation and field trial

The process of radar installation started with the search for a suitable location for the third radar peripheral. The location was chosen based on its position with respect to the other two peripherals to maximise the angular diversity, and on the availability of an optical fibre connection to the system central unit within the port communication infrastructure. The building of the Capitaneria di Porto (the Italian Coast Guard) was chosen, and the radar was installed after obtaining the necessary permissions.

The radar illuminates a portion of the water corresponding to the entrance of the port in such a way that it is possible to monitor a large number of ships, even if the monitored area is not very large. The size and location of the monitored area is limited by the position of the RPs, which is bounded by the presence of the optical fibre already installed at the port. Obviously, a larger antenna separation (when possible) could allow monitoring of a broader area and make it possible to acquire data for a larger set of vessel positions.

Data from the automatic identification system (AIS) was monitored for ships passing through the area illuminated by the radar antennas. Typically, the speed of the ships transiting the monitored area is lower than 6 kn, i.e. 11 km/h. When a ship was travelling in the monitored area, acquisitions were activated by the software running at the central unit. Several acquisitions were taken for different ship positions in order to have more chances to receive backscattered echoes at the different radar peripherals.

After signal acquisition, the data were processed to generate range-Doppler maps and 2-D ambiguity functions as radar outputs.

The experimental results from the field trials show that the system is able to acquire data from all the three installed radar peripherals for both S and X band. The measurements show that the system is working and able to provide 2-D ambiguity functions maps after coherent fusion of the data from the different radar peripherals for the evaluations of the range and cross-range resolution KPIs, as well as range-Doppler maps for the estimation of target distance and speed. The system performs better in X band than in S band, for reasons that have to be further investigated.

Effective exploitation of the coherent processing to the demonstrator needs to address some points to demonstrate performance in line with or close to the simulations. In fact, the application of coherent MIMO processing requires the perfect rephasing of the received echoes. For this operation, the position of the antennas must be known with a precision in the order of magnitude of the signal wavelength (2.5 cm to 15 cm). This accuracy is currently not available, because it requires very precise measurements that cannot be achieved by just GPS data. It was also found that the power of the optical signal from the central unit carrying the radar signal to be transmitted is lower at two of the radar peripherals due to the way they are connected to the central unit, i.e. by sharing the same optical fibre. This situation was unavoidable due to the available fibre network at the port. This lower optical power causes a reduced signal-to-noise ratio of the signal transmitted by the antennas, with the consequence of lower power available for the received echoes. Future system improvements will probably require replacing the optical amplifiers within the central unit with more powerful ones to improve the transmitted signal power and counteract the additional losses caused by the sharing of the optical path among two radar peripherals.

For effective use of the proposed radar system, further in-depth analysis of the technological aspects is crucial

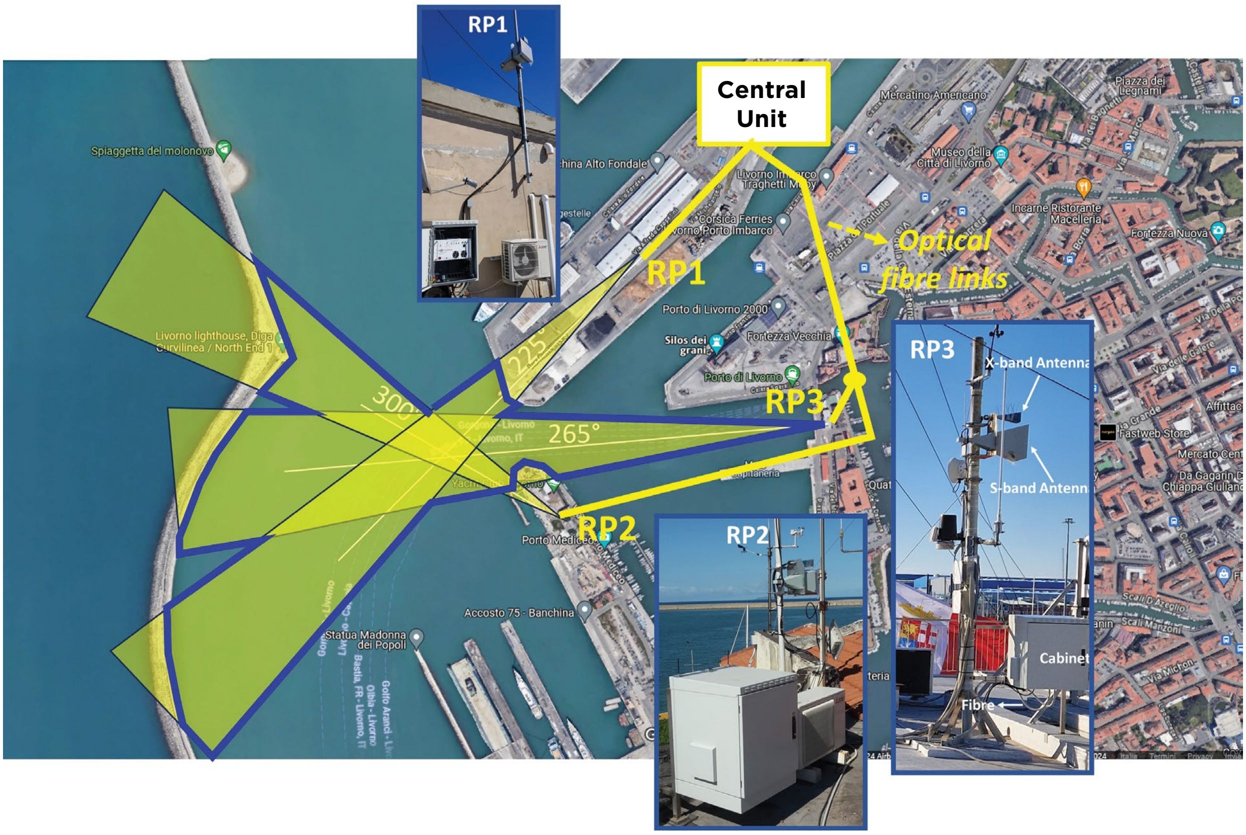

Figure 38. TUTELARY system demonstrator deployment at the port of Livorno RPs: radar peripherals

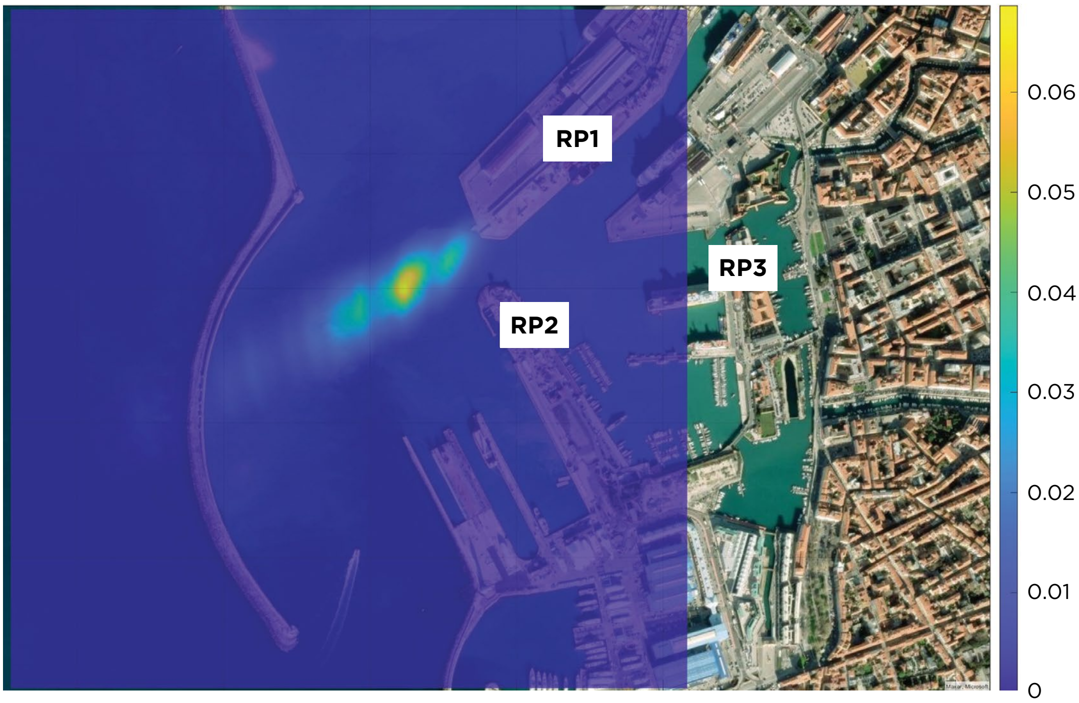

Figure 39. 2-D ambiguity function (range/cross-range map) obtained in X band after field trial data fusion

in order to improve the system from the point of view of portability and compactness. Improvements in terms of real-time processing capability and radar beam forming are also desirable. Moreover, it is necessary to identify more system applications to expand possible commercial use. It would also be very important to further investigate the potential stakeholders and technological partners that could collaborate with CNIT for a more accurate definition of the system requirements and to solve the technical issues found through the research conducted under the TUTELARY project, to increase further the system's Technology Readiness Level, ideally up to the industrialisation and commercialisation phases.

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