SEMFIRE

Segurança, Exploração e Manutenção de Florestas com Integração de Robótica Ecológica

D1.2: Functional and Technical Specification

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1 Introduction

The SEMFIRE project contemplates several challenges within the field of forestry robotics and field robotics. This document follows Deliverable 1.1 [4], which has provided an overview of the forestry clearing end-user requirement analysis, including the typical equipment used and operations conducted, and some operational intervention scenarios within forest maintenance tasks, both with heavy machinery and with manual tools.

This deliverable identifies the challenges for forestry robots imposed by the end-user requirement analysis and intervention scenarios previously delineated, and proposes detailed functional specification of the SEMFIRE ecosystem. Moreover, a technical specification of the robotic platforms to be developed within the context of the project is reported, by identifying the main hardware design decisions taken this far, thus serving as an initial seed for Deliverables 2.1 (*Scouts* technical manual) and 2.2 (*Ranger* technical manual) of SEMFIRE.

In the remainder of this deliverable, we will focus on a detailed use case, which pose significant challenges for collective robotic operation in forestry maintenance environments.

The remainder of this document is organized as follows. Section 2 presents a detailed use case, which poses significant challenges for collective autonomous robot operation for precision forestry maintenance autonomous. Section 3 presents the detailed functional and technical spefication of the SEMFIRE ecosystem, including selected platforms and sensors. Lastly, Section 4 presents the main conclusions of the document and the main lines of future work.

2 Use-Case Analysis

The analysis of the literature on robot for precision forestry [1, 2, 3], and the experience of our end-users from Sfera Ultimate has led to the emerging of a number of relevant questions, that not only shows the potential of the work, but also provides useful guidelines for future work. With particular relevance for the current work, the literature highlights that:

- There is very little work in automated solutions dedicated to the issue of precision forestry;
- There is a lack of solutions for robotic teams;
- There is a number of untackled problems due to hardware specificity.

With these issues in mind, this deliverable highlights and details a very specific use case: the application of robotic teams in precision forestry for fire prevention, exploring the issue of the lack of work in precision forestry and robotic teams. The use case aims also to test various technologies in the field, advancing their technological readiness level (TRL), thus addressing many of the issues raised.

2.1 SEMFIRE Use-Case

Our solution for autonomous precision forestry is comprised of a heterogeneous robotic team composed of two types of robots (detailed in Section 3.2):

- The Ranger, a 4000kg autonomous robot, based on the Bobcat T190, equipped with a mechanical mulcher for forest clearing;
- A swarm of Scouts, small UAVs equipped with additional perceptual abilities to assist the ranger in its efforts.

The Ranger is deemed as a marsupial robot, as it is able to carry the swarm of Scouts via a small trailer, while recharging their batteries.

1. Initial Deployment The mission starts with the placement of the Ranger in the proximity of the operating theatre (OT). The Ranger can then be teleoperated or driven to a specfic starting location, while carrying the Scouts. This enables the easy deployment of the robot team, even over difficult terrain, as the Ranger's mobility capabilities can be harnessed to assist in this phase of the missions. Once the robotic team is placed close enough to the target area, a human operator signals the start of the mission.

With the mission start, the Scouts autonomously spread while maintaining a multimodal connectivity among each other and the Ranger through distributed formation control, thus leading to a certain degree of spatial compactness above the target area, defined by a combination of human input via a dedicated interface, and the Scouts' own positions.

2. Reconnaissance This phase of the mission consists on having *Scouts* collectively exploring the target area with the goal of finding the regions of interest (ROIs) within this area that contain combustible material, e.g. fuel accumulation such as flammable debris, that should be mulched. The result of this phase is a semantic map that results from the collective exploration of the OT, containing information on the location of regions that need intervention and of regions that should be preserved, among other elements. After the semantic map is obtained, the Scouts fly to key points that delimit the target area, while maintaining communication, and remain stationary. The Scouts then perform two main tasks: aid the Ranger in localizing itself, and monitoring the progress of the clearing task, by assessing the fraction of existing debris over their initial state.

3. Clearing At this point, the Ranger starts the mulching procedure, the main goal of the mission that will reduce the accumulation of combustible material. This mission essentially consists of cutting down trees and mowing down ground vegetation (e.g. bushes, shrubs, brush, etc). At this point, the artificial perception layer becomes especially relevant, namely to *i)* localize the team in space through the fusion of GPS, LIDAR and UWB multilateration; *ii)* due to the powerful tool it is wielding – a heavy-duty skid-Steer forestry mulcher that can cut up to 10 cm and mulch up to 8 cm of material, and *iii)* to identify and keep a safe distance from external elements within the OT (e.g., unauthorised humans or animals).

As the trees are cut down, vegetation is mowed and fuel is removed, the structure and appearance of the operational environment changes significantly from the state it has been in during the reconnaissance phase. The mission ends when the volume of combustible material in the target area falls below a pre-defined threshold, ideally zero.

4. Aftermath The end of the mission needs to be confirmed by a human operator, who can at this point indicate new ROIs for exploration and intervention, or teleoperate the Ranger to finish the mission in manual mode. When the end of the mission is confirmed by the operator, the Scout swarm regroups on the trailer in an autonomous manner, and the team can then be moved to another location or stored.

2.2 Human Intervention

A specialized human operator, the *Foreman*, represents the expert knowledge in the field, and acts as a supervisor to the robotic team. At any point in the mission, the *Foreman* can issue commands to override the autonomous decisions of the autonomous Ranger. This includes emergency stops for interruption of operations at any time and due to any reason, as well as control takeover of the Ranger to remotely finish a clearing procedure at a safe distance. The *Foreman* is also responsible for refining the target area, and a human team can intervene before or after the robotic mission to clear areas that are considered too inaccessible for the robots; as some areas may require expertise or precision that makes it impossible for the Ranger to intervene.

(a) Usable image: good perspective, illumination and not blurry.

(b) As the robot moves, perpective changes will affect the results.

(c) Since the robots will move in the field, some images will be blurred.

(d) Illumination differences will naturally be an issue in the field.

Figure 1: Examples of pictures taken outdoors, which could be captured by a camera attached to a robot in the field. Several issues can affect these images, hindering perception.

2.3 Analysis

The use-case described above, represents several challenges from a technical and scientific perspective. Namely, the platforms need to be robust to very adverse outdoor conditions, and encompass safety mechanisms during all phases of operation. As illustrated by the challenges mentioned in Fig 1, adequate techniques for artificial perception are required, and also techniques for localization, navigation, aerial control and communications within the multi-robot system must be developed to support high-level collective decision-making, marsupial multi-robot system operation, Scouts' exploration, deployment, formation control and regrouping, and the clearing operation of the Ranger robot, which brings the added challenge of safely controlling the mechanical mulcher for forestry maintenance. Finally, there will be a significant effort envisaged for system integration, which will allow to interface SEMFIRE with the human operator, e.g. representing the overall environment as perceived by the robots in a GUI, or allowing to have access to live video streams from the Ranger platform at a safe distance. In the next section, we provide detailed specification to address all the challenges identified.

3 Functional and Technical Specification

In this section, we present the specifications for the SEMFIRE project. We start by detailing the needed functions and features that the system is expected to have, and in section 3.2, we describe the platforms and sensors that have been chosen to fulfill the functional specifications that have been delineated.

Table 1: Functional Specification Table (Hardware and Low-Level).

Function/Module	**Requirement**	**Specification**
Outdoor Robotic Technology	Ranger locomotion in all types of terrains, and reliefs. Operation of the platforms for long periods of time. Robustness to adverse outdoor conditions, e.g. in dusty, and watery atmospheres.	Ranger Incline/decline traversal ability over 15°. Ranger autonomy over 12 hours, and Scouts autonomy over 30 minutes of continuous operation. IP54 protection.
Low-Level Drivers	Acquisition of data from the platform sensors, and availability of the data to high-level software modules.	Low-level driver for ROS developed and available for all sensors chosen (*cf.* Section 3.2)
Ranger's Mechanical Mulcher	Manual and automated control of the mechanical structure and mulcher operation, with precise end-effector position tracking.	Low-level ROS driver to control the arm, including encoders to track the end-effector configuration. Fast de/activation of the mulcher, with ability to cut up to 10 cm and mulch up to 8 cm of material.
Marsupial System	Carrying of the team of at least 4 Scouts to the field by the Ranger before the mission, and collecting back the Scouts after the mission. Charging of Scouts by the Ranger, while being carried.	Inclusion and development of a trailer to be attached to the Ranger for carrying and charging the Scouts, allowing their take-off and landing for operations.

3.1 Functional Specification

For each challenge identified previously, we describe the intended function, requirements and specifications, which may also serve as guide for possible targets of performance to the modules designed and developed in the SEMFIRE multi-robot system.

The functional specifications are divided in 4 main features categories, organized from Table 1 to 4:

1. Hardware and Low-Level (Table 1).
2. Supporting Features (Table 2).
3. High-Level Features (Table 3).
4. Safety and Integration (Table 4).

Table 2: Functional Specification Table (Supporting Features).

Function/ Module	**Requirement**	**Specification**
Localization	Precise 6D localization (x, y, z position, and φ, θ, ψ orientation) of the Rangers and Scouts in a common global reference frame during all times.	Multimodal EKF approach for localization with cm-level precision, fusing several key sources of information, such as visual odometry from cameras, laser-based SLAM estimates using 3D LIDARs, IMU integration for orientation tracking, and global positioning both from GPS-RTK and a field deployed UWB triangulation system.
Ranger Navigation	Execution of navigation path plans from the current configuration to a target pose, in different types of terrains and reliefs, with several obstacles in a dynamic and challenging outdoor environment.	ROS navigation software developed and adapted to the specificity of the platform (e.g. avoiding in-turn rotations as recovery behaviours, and providing safe mechanisms for manoeuvrability), without collisions during operation.
Scouts Aerial Control	Control of the aerial platforms with the ability to maintain fixed heights and poses, as targeted by users and the application.	Aerial control and stability software that allows sending precise target aerial configurations for Scouts, while avoiding collisions with the environment and with other Scout teammates.
Artificial Perception	Holistic forestry scene analysis, including recognition and tracking of relevant entities and events.	A perceptual architecture for decision-making will be developed, including (A) an artificial attention system for allocating and directing sensors and computational resources to task-relevant regions of interest within a scene, while selecting the appropriate scale of detail of analysis, driving (B) a semantic segmentation layer for identifying objects of interest and regions of interest within the objects (including relevant trees, vegetation, combustible material, traversable areas, and humans) with a targeted precision of 95%. A semantic map will be maintained to support and keep track of entities and events detected.
Communication	Provide an infrastructure for explicit communication between all agents of the SEMFIRE team.	An access point will be included in the Ranger platform, and all Scouts will connect to it, and maintain their connectivity at all times, constraining their operation by always guaranteeing the persistent connectivity of the communication infrastructure.

Table 3: Functional Specification Table (High-Level Features).

Function/Module	Requirement	Specification
Decision-Making	Based on the events and entities detected by the artificial perception layer, and the overall state of the environment, a decision-making component chooses the current operation mode for each platform.	A decision-making module based on Finite State Machines (FSMs) will be developed for intelligent switching of operations during missions, with a low error (below 2%) in situation assessment.
Scout Exploration	Collective reconnaissance of the target area with Scouts.	Tightly coupled with the artificial perception layer, the RDPSO swarm exploration approach will be used for forestry reconnaissance, feeding the semantic map with the combustible material detected with a reconstruction reliability of 90%.
Scout Initial Deployment	Take off and spreading of Scouts in the environment after the start of the mission	A synchronized take-off routine will be implemented to allow for sequential initial deployment of each Scout in the environment without collisions or any anomalies.
Scout Formation Control	Formation flight of Scouts while maintaining multimodal connectivity among each other and the Ranger.	Formation control strategies will be implemented with geographical restrictions for maintaining communications connectivity with a high reliability (the system should be connected 99% of the time), and for optimization of Scouts' positioning, thus assisting the localization of the Ranger via the UWB triangulation system.
Scout Regrouping	Autonomous landing of Scouts in the Ranger's trailer.	A synchronized routine will be implemented to allow for sequential landing of each Scout in the Ranger's trailer without collisions or anomalies, considering their distance to the trailer and battery status.
Ranger Clearing	Sequential visit to all ROIs and mulching procedure to eliminate fuel accumulation via the Ranger platform.	An algorithm for effectively visiting all identified ROIs will be developed, minimizing the traversal distance of the Ranger. A synchronization module will be responsible for coupling the Ranger navigation with the mulcher's control.

Table 4: Functional Specification Table (Safety and Integration).

Function/Module	**Requirement**	**Specification**
Human Remote Control	Remote teleoperation and mulcher control of the Ranger by the Foreman.	Teleoperation module to control the Ranger and its mulcher, at any time during the mission, overriding the navigation and mulcher control software.
Safety	Routines for safely stopping the system, aborting or pausing the operations. Compliance with ethical, legal and safey regulations.	Remote emergency stop by hardware (human operator), and emergency stop service by software (developers). Manual override of the mulcher operation and Ranger locomotion in all stages of the mission. Ability to ground all Scouts.
Graphical User Interface	Means for providing human input to bias the SEMFIRE multi-robot system operation.	A GUI will display the semantic map to the human operator and allow for the manual identification of ROIs, as well as streaming video from the Ranger, and other features.
System Integration	Seamless communication and interoperability of the different layers of the decoupled SEMFIRE system.	Integration of all sensor drivers and software modules, clear definiton of inputs/outputs as per the defined system architecture, re-use of standard components, and integration tests.

Figure 2: The Ranger platform without the mulcher attachment. The platform is based on the Bobcat T190, and is being equipped with a sensor and computational array, using the black box at the top.

3.2 Technical Specification

In this section, we detail the platforms and sensors chosen to implement the system to fulfill the functional specification that has been delineated in the previous section.

The robotic team for autonomous precision forestry is composed of two kinds of robots:

- The **Ranger**, a single heavy-duty robot in charge of the main task, and equipped with large computational and perceptual power;
- The **Scouts**, a swarm of UAVs in charge of widening the Ranger's range of perception by gathering data from a wide spatial range.

The Ranger is based on the Bobcat T190 track loader, which will be modified to include a number of additional sensors, as described below. The Scouts are lightweight UAVs, equipped with fewer sensors, but able to cover a much wider space.

Ranger

The base of the Ranger is a Bobcat T190 (Fig.2) tracked loader. This platform was selected by a number of reasons, chiefly among them:

- It is able to carry the tools, namely the mechanical mulcher, necessary to complete the task;
- This particular model is completely *fly-by-wire*, meaning that it is possible to tap into its electronic control mechanisms to develop remote and autonomous control routines;
- It is a well-known, well-supported machine with readily-available maintenance experts.

The platform will be extended in numerous ways, namely in sensory abilities (Fig. 3), which will include:

- Two LeiShen C16 Laser Range Finders[1];
- Five Intel RealSense D435 RGB-D Cameras[2] with five AAEON UP Board Atom for sensor acquisition;
- One FLIR AX8 thermal camera[3];
- One Teledyne Dalsa Genie Nano C2420 multispectral camera[4];
- In-house UWB transponder(s);
- GPS and RTK devices[5];
- Inertial Measurement Unit(s)[6]
- Multiple encoders to extract the robot's kinematics, including rotational encoders to measure the movement of the tracks and linear encoders to measure the movement of the arm;
- Mini-ITX computer equipped with a Geforce RTX 2060, an Intel Core i7–8700 CPU and 16GB of DDR4 RAM;
- Tulipp FPGA+ARM Platform including a Xilinx XCZU4EV TE0820 FPGA and a ARM Quad-core Cortex-A53 CPU with a Mali-400 GPU;
- One custom-made CAN bus controller, based on an ATMEGA ARM CPU and two MCP2551 CAN Bus transceivers[7]
- Two TP-LINK TL-SG108 Gigabit Ethernet Switches[8];
- One ASUS 4G-AC68U WiFi Router;
- Ten RGBD LEDs for status notification;
- One Touchscreen GUI;
- One Rear Projection GUI.

The C16 LRFs will will act as the main sources of spatial information for the machine in the long range, providing information on occupation and reflectivity at up to 70 meters away from the sensor at a 360-degree field of view. Being equipped with 16 lasers per device, these sensors will provide a very wide overview of the platform's surroundings, namely the structure of the environment, and potentially the positions of obstacles, traversability and locations of trees.

[1] `http://en.leishen-lidar.com/product/leida/MX/15d44ea1-94f5-4b89-86eb-f5a781b04078.html`

[2] `https://click.intel.com/intelr-realsensetm-depth-camera-d415.html`

[3] `https://www.flir.com/products/ax8-automation/`

[4] `https://www.edmundoptics.eu/p/c2420-23-color-dalsa-genie-nano-poe-camera/4059/`

[5] We have tested the Emlid Reach RS+ (`https://emlid.com/reachrs/`) and Emlid Reach M+ (`https://emlid.com/reach/`) devices, but have not yet decided if these exact models will be used.

[6] We have tested the UM7 (`https://www.pololu.com/product/2740` device, but have not yet decided if this exact model will be used.)

[7] `https://www.microchip.com/wwwproducts/en/MCP2551`

[8] `https://www.tp-link.com/pt/business-networking/unmanaged-switch/tl-sg108/`

Figure 3: Close-up of a preliminary version of the main sensor array installed on the Ranger. Visible sensors, from top to bottom: LeiShen C16, Genie Nano C2420, FLIR AX8, and RealSense D415.

The RealSense cameras, with their much narrower field of view and range, will be installed on the machine to create a high-resolution security envelope around it. These sensors will compensate for the gaps on the LRFs' field of view, to observe the space closer to the machine. This will allow for the observation of the machine's tracks, the tool, and the spaces immediately in front and behind the robot, ensuring the safety of any personnel and animals that may be close to the machine during operation.

Perception will be complemented by a FLIR AX8 thermal camera, which will be mainly used to detect human personnel directly in front of the robot, *i.e.* in potential danger from collisions with the machine or the mulcher attachment.

The Dalsa Genie Nano will allow for multispectral analysis of the scene, assisting in the detection of plant material in various stages of decay; this will be very useful in the detection of combustible material for clearing.

Robot localization will be estimated by combining information from the cameras, the 3D LIDAR, the inertial measurement unit (IMU), the track encoders, and from the GPS and RTK systems, also by using UWB transponders. The latter provide distance readings to all other devices, with ranges in the hundreds of meters, which will allow for triangulation approaches to be used between the Ranger and Scouts. This information will be fused to achieve a robust global and localization of the Ranger and Scouts during the mission.

The Mini-ITX computer (i7-8700 CPU) will be the central processing unit of the Ranger, gathering the needed information from all components and running high-level algorithms and decision-making components. It is equipped with a powerful Geforce RTX 2060 GPU, which provides the needed power to run heavy computational approaches.

The Xilinx XCZU4EV TE0820 FPGA is responsible for running the low-level drivers and low-level operational behaviours of the platform. It will run ROS on top of the Ubuntu operation system and allows for transparent communication with sensors, and the higher-level CPU.

The custom-made CAN bus controller allows to inject velocity commands to the under-

Figure 4: The in-house Drovni platform developed at Ingeniarius. This platform will serve as basis for the development of the Scouts.

lying CAN system of the Bobcat platform and to control the mulcher operation. It consists of a custom board that integrates two MCP2551 CAN bus transceivers, and which will be installed between the machine's manual controls and the actuators, defining two independent CAN buses. This way, it becomes possible to make use of the CAN bus to control the machine.

The TP-LINK TL-SG108 Gigabit Ethernet Switches interconnects the CPU, with the FPGA, the five AAEON UP Boards, the C16 lasers and the WiFi router, allowing for fast data acquisition and communication between all processing units, enabling distribution of computation and remote access and control.

Furthermore, the Ranger platform also provides an array of ten LEDs to notify about the behaviour of the system, one touchscreen GUI to be used inside the Bobcat's compartment, and a read projection mechanism, allowing to project information in the compartment's glass.

Scouts

The Scouts, based on the Drovni platform (Fig. 4), are mainly composed of in-house UAV platforms, equipped with a sensor array that complements the abilities of the Ranger. Specifically, the Scouts will be able to complement the Ranger's localization abilities. The Scout's exact sensor array has not yet been fully defined: given the relatively low payload of the Scouts (particularly when compared to the Ranger), the decision on which exact sensors to use has to be carefully weighed. However, the basic sensor modalities have been selected; the Scouts will be equipped with:

- One Intel RealSense D435 or equivalent;
- A UWB transponder;
- GPS and inertial sensing, e.g. provided by a Pixhawk board[9];
- Potentially a multispectral camera such as the C2420 used on the Ranger.

Most of the sensors in the scouts, namely the UWB transponders, GPS and inertial units, will aid in the localization of the scouts. This will allow, together with the information from the Ranger, to obtain a very precise localization of all agents in the field, which is a crucial

[9] `http://pixhawk.org/`

(a) Joytstick.

(b) Touchscreen with a Graphical User Interface.

Figure 5: Envisaged tools for the Human Operator.

element of precision field robots. The RealSense camera will allow for the implementation of computer vision and ranging techniques that will be able to, for instance, aid in the coverage of the field and the localization of relevant areas for the Ranger to act in. An additional multispectral camera may be included to aid the Ranger in detecting biomass for removal. The Scouts will also include relatively limited processing power, such as an Up-Board[10] or Jetson Nano board[11], which will be able to deal with the localization task and pre-process data for decentralized perception in the Ranger.

Foreman

The foreman will be endowed with a standard Joystick controller to remotely operate the Ranger robot, and its mulcher, as well as a Touchscreen with a Graphical User Interface to monitor the autonomous precision forestry mission, which will be similar to the one present at the Ranger's compartment. These tools will him to intervene at any point of the mission, interrupting or pausing the system, being in complete control of the operations and avoiding any potential safety risk.

4 Conclusion

In this deliverable, we started by describing the main use case scenario of SEMFIRE, as an aid to understand and clarify system requirements and expectations regarding functionality, providing a basis for the definition of the different system features and specifications, which were detailed in section 3.1 and 3.2, as functional and technical specifications respectively.

During development and integration within the project, we expect to refine and adjust these specifications, e.g. incorporating new features that might not have been accounted for, or adjust the expectation regarding a technical feature that may prove unfeasible.

The detailed functional and technical specification provided in this deliverable will guide the definition of the general integration architecture of the project in Deliverable 5.1, which will present the architecture diagram, clarifying all connections between components of the project and definition of the parameters, technologies, type of communication, and even technical language for each input/output interface between the different modules, serving as a reference for all the upcoming development in SEMFIRE. Additionally, the technical manual of both Ranger and Scouts platforms will be described in Deliverable 2.1 and 2.2, and are expected to present upgrades regarding the equipment chosen and reported in Section 3.2.

[10] `https://up-board.org/`

[11] `https://developer.nvidia.com/embedded/buy/jetson-nano-devkit`

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