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SEMFIRE: Towards a new generation of forestry maintenance multi-robot systems

Micael S. Couceiro[1,2], David Portugal[1,2], João F. Ferreira[2,3] and Rui P. Rocha[2]

Abstract— Europe has been affected by an alarming number of wildfires every year, ravaging nearly half a million hectares of forestry areas and resulting in an unacceptable amount of human losses. The year 2017 was one of the worst ever recorded, with devastating wildfires raging across the globe. Bearing these shocking facts in mind, this position paper aims to lay the foundations of crucial new upcoming research in the field of forestry robotics by presenting an overview of the SEMFIRE project. SEMFIRE proposes the development of a robotic system designed to reduce the accumulation of combustible material in forests, thus assisting in landscaping maintenance tasks for wildfire prevention. This paper describes the multi-robot system envisaged by SEMFIRE, combined with pervasive local positioning, multi-robot navigation and coordination in forests, and an innovative artificial perception architecture.

I. Introduction

According to statistics presented by the European Commission, Europe is affected by around 65.000 fires/year [1]. More than 85% of the burned area is in Mediterranean countries – Portugal leads these unfortunate statistics, with an average of 18 thousand fires/year over the past 25 years, followed by Spain, Italy and Greece, with an average of 15, 9 and 1.5 thousand annual fires/year, respectively. In 2017, Portugal was one of the most devastated regions worldwide, with 500.000 hectares (nearly 1.5 million acres) of burned area and over 100 fatal casualties [2]. The summer of 2018 brought similar immeasurable losses to Greece, with wildfires causing nearly 100 victims until late July.

Unsurprisingly, wildfires have a significant impact on the economy that goes much beyond the simple loss of wood as a primary resource. In fact, they lead to the lack of forest regeneration capacity and therefore to an incommensurate negative effect on the environment. This, in turn, results in a vicious circle – rural abandonment reduces effective monitoring and prevention of wildfires, which in turn leads to more migration away from rural areas, substantial decreases in tourism and increased unemployment, therefore reiterating the progressive lack of interest in forest management [3]. As would also be expected, wildfires deeply affect subsidiary industries, such as apiculture and forest farming, as well.

One of the most effective measures for forest fire prevention is to foster landscaping maintenance procedures, namely to "clean" forests, actively reducing fuel accumulation by regular pruning, mowing, raking, and disposal [4]. Ribeiro et al. identified forest debris, such as brushes, as combustible material and a major cause of wildfires, and many organizations, and civil protection authorities, have launched awareness campaigns to force institutions, such as parish councils and forest associations, to clean forestry areas they are responsible for [3].

Nevertheless, these and other adopted measures have not yet solved this crisis, as is the case in Portugal. Even though Portugal is aggressively moving to complete a 130.000 hectare primary fuel break system, fuel break construction and commercial harvesting alone does not lead to sufficient fuel removal. In fact, despite the resources invested in fire prevention worldwide, the number of fires has continued to increase considerably year after year [2]. The need to keep forestry areas clean by actively reducing fuel accumulation leads to a huge investment, with a strong focus on necessary human resources [3].

Unfortunately, finding people willing to work in forest cleaning is difficult due to the harsh and dangerous conditions at stake. Ancillary technology, such as motorized tools handled by humans (brush cutters, chainsaws, branch cutting scissors, among others), has proved to be helpful. More recently, mulching machines have been used and considered as one of the most efficient ways to clean forestry areas. These machines allow to grind small, medium and even large trees to wood chips that are then left scattered upon the forest floor as a mulch. Compared to more loosely arranged fuels, the available oxygen supply in this dense fuel bed is reduced, resulting in potentially slower rates of fire spread than would have occurred if the area were left untreated. However, adding to typically high cost and time constraints, safety is always a matter of concern. Handling such tools requires skill and, in most situations, the lack of worker awareness leads to a high risk of accidents and injuries, including cuts and wounds, back injuries, crushing, deafness, and falls [5]. For this reason, it is imperative to devise technological solutions to allow workers to engage safely, while simultaneously speeding up operations. Engineering and computer sciences have been starting to be employed to deal with this issue,

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[1]M. S. Couceiro and David Portugal are with Ingeniarius, Ltd., 3025-307 Coimbra, Portugal, {micael,davidbsp}@ingeniarius.pt

[2]M. S. Couceiro, D. Portugal, J. F. Ferreira and R. P. Rocha are with Institute of Systems and Robotics, University of Coimbra, 3030-290 Coimbra, Portugal, {micaelcouceiro, davidbsp, jfilipe, rprocha}@isr.uc.pt

[3]J. F. Ferreira is with the School of Science and Technology, Nottingham Trent University (NTU), United Kingdom, joao.ferreira@ntu.ac.uk

converging to one particular domain: robotics.

This paper presents the research planned for SEMFIRE[1], a 3-year project starting in October 2018 proposing the development of a multi-robot system (MRS), so as to reduce fuel accumulation (e.g. forest debris), thus assisting in landscaping maintenance procedures (e.g. mulching). This is an application domain with an unquestionable beneficial impact on our society and the proposed project will contribute to fire prevention by reducing wildfire hazard potential.

II. Related Work

The literature in robotics addressing vegetation focusses almost exclusively on thick vegetation identification, so as to drive around and overcome it, in a similar way to outdoor obstacles [6]. The majority of existing technical solutions addressing vegetation clearing rely on two key principles: man-operated commercial machines, such as the small-sized Brush Blazer[2], and remotely controlled machines, which are typically manned systems converted for teleoperation, such as modified robotic Bobcat systems [7]. Following these principles, several different and interesting designs have been presented for harvesters [8], fire-fighting vehicles [9], and even beach cleaning solutions [10].

Forest cleaning robots share many of the technical challenges faced by fire-fighting robots; therefore, given the substantial amount of research dedicated to the latter, it is well worth analysing conclusions drawn in this context. Indeed, despite many advances in key areas, the development of fully autonomous robotic solutions for these problems is still in a very early stage. This stems from the huge challenges imposed by rough terrain traversability [11] (e.g. steep slopes), autonomous outdoor navigation and locomotion systems [13], limited perception capabilities [14], and reasoning and planning under a high-level of uncertainty [15]. For instance, a remotely-controlled robust outdoor robot for fire protection with a caterpillar engine has been used for fire assessment and monitoring of fire situations, without any way to suppresses fires [16]. Ohkawa et al. described a modular robotic brush-cutter with a centre articulated body, a manipulator, two laser imaging detection and ranging (LIDAR) devices, global positioning system (GPS), and an innovative sensor steering mechanism for the articulated vehicle [17]. Yet, the wheeled locomotion system and cutting mechanism would face high difficulties in rougher terrains or with denser vegetation, as with most forests. Furthermore, GPS does not provide the intended accuracy in the presence of thick vegetation, which makes it infeasible for localization and mapping in this context [18].

[1]SEMFIRE stands for Segurança, Exploração e Manutenção de Florestas com Integração de Robótica Ecológica – Safety, Exploration and Maintenance of Forests with the Integration of Ecological Robotics, in English.

[2]https://www.pecobrushcutters.com/why-brush-blazer/

Besides fire-fighting, advances in agricultural robotics provide good prospects for the development of autonomous brush clearing robots, because the technology involved relies heavily in harvest automation [19]. In fact, the EU has funded several projects in this area, such as VineRobot [20], proposing the development of an autonomous robot for precision viticulture. Presently, there are several autonomous lawn mowing commercial solutions with proven performance, like the solar-powered Vitirover and Sthil's iMow MI 422 [21]. Most of these products are able to maintain lawns in any weather, with slopes up to 35%. Nevertheless, these do not present any traversability capabilities for forestry areas.

Olsen et al. used computer vision and image processing techniques to identify and spray herbicide in specific weeds [22]. Their fully autonomous wheeled robot with eight cameras is still a work-in-progress, but the early prototype has reached impressive performance with a 90% accuracy rate in identifying lantana weed, thus receiving wide media coverage. Even though this work highlights the possibility to enhance perception in outdoor all-terrain vehicles, one cannot rely entirely on computer vision and image processing with cameras. Hellström et al. presented a study which points precisely to the limited degree of automation and autonomy for forest vehicles [23]. The authors present a robotic prototype that achieves precise localization with available multimodal sensory solutions, such as GPS, odometry and inertial measurements, and autonomous driving over predefined paths, using laser scanners and radars for obstacle detection.

While these solutions are undoubtedly interesting, they all use a single and independent robot. Yet, in forestry operations, coordination, communication and cooperation between multiple robots can provide a considerable amount of flexibility, both in terms of perception and locomotion. The advantages of using multiple robots instead of a single robot solution for forest coverage, and several other applications, have been vastly documented. Besides distributed control, increased autonomy, communicative agents and greater fault-tolerance, MRS can benefit from the assistance of nearby teammates during emergencies, failures or malfunctions [24]. Robotic teams allow having many robots in numerous places, carrying out diverse tasks at the same time, i.e. space distribution. In fact, most missions are solved much quicker if robots operate in parallel [27], [28]. This is commonly seen in robotics research for search and rescue. For instance, the EU FP7 project ICARUS [25] has contributed to the deployment of MRS in the real-world, seamlessly integrating command, control, communications, computers and intelligence equipment for crisis managers in search and rescue scenarios. Additionally, in the CHOPIN project [26], in which part of the SEMFIRE's team participated, several architectures and models for cooperation in teams of humans and in teams of mobile robots were studied. Among the many challenges tackled in CHOPIN, special attention was given to the efficient sharing of information and to the collaborative context awareness within urban search and rescue missions.

In summary, and despite the significant advancements in robotics over the years, forestry operations, especially in uneven and irregular terrains, are extremely challenging due to the harsh characteristics of the environment [29]. In fact, the state of the art in robotics has not yet provided a way to assist human teams under such harsh conditions. Most approaches either need human input (i.e., remote teleoperation [30]) or focus on single robot solutions [31]. The few existing MRS mainly target forest fire monitoring [32] or are limited to controlled laboratory settings [33]. The SEMFIRE project intends to bridge this gap by proposing the development of an autonomous MRS for forestry maintenance, with minimal human intervention.

III. The SEMFIRE Project

The main goal of SEMFIRE[3] is to develop a multi-robot solution designed to reduce fuel accumulation by autonomously fostering landscaping maintenance tasks. The lack of alternative, feasible and all-encompassing solutions for this problem, as seen in section II, is a telltale of the technological and scientific endeavours at stake. SEMFIRE follows the lines of research promoted by the Institute of Systems and Robotics from University of Coimbra (ISR-UC)[4], the technologies developed by Ingeniarius[5], and the forestry maintenance services provided by SFera Ultimate[6]. Additionally, SEMFIRE keeps an open communication channel with end users, such as the Municipal Council of Penacova (Câmara Municipal de Penacova)[7], Góis Parish Council (Junta de Freguesia de Góis)[8], and Góis Forestry Association (Associação Florestal do Concelho de Góis)[9], as well as with many European initiatives, such as the European Forest Fire Information System (EFFIS)[10].

Aiming to push forward the development of field robotics in the context of this application, we propose in this project to attain the following specific scientific objectives:

- to design and develop a heterogeneous team of robotic platforms for forest clearing, reconnaissance and surveillance;
- to integrate the latest advancements in traversability analysis, path-planning and navigation of field robots in outdoor terrains;
- to develop a marsupial deployment strategy in forestry areas;
- to implement swarm exploration and coverage algorithms for collective reconnaissance and surveillance of forestry areas;
- to implement innovative computer vision methods for the detection, identification and characterization of the environment needed for landscape maintenance procedures.

An overview of the SEMFIRE architecture is presented in Fig. 1. The following subsections further outline the project, starting by introducing the envisioned deployment of SEMFIRE in a forestry maintenance operation.

A. Use case

SEMFIRE combines a wide range of technologies, with robotics at its core. The key elements of the SEMFIRE solution are the two different types of mobile robotic platforms: Ranger and Scout. The Ranger is a large-sized powerful multi-purpose tracked robotic mulcher, based on the renowned Bobcat platform. It is equipped with a forestry mulcher attachment to cut down thin trees and shred ground vegetation to grind them into mulch. It can operate in fully autonomous and semi-autonomous mode (with human control). Scouts are small assistive flying robots with swarm self-organizing capabilities to explore and supervise wide forestry areas. Fig. 2 illustrates the deployment of the SEMFIRE solution in the field.

The SEMFIRE use case scenario considers one Ranger, at least four Scouts initially parked on top of the Ranger, and one remote operator (be it on-site or over the internet). The operator moves the Ranger platform to the target site via remote control, and then sends the command for the landscaping maintenance mission to initiate. At this point, the swarm of Scouts, thus far carried by the Ranger, is autonomously deployed. The first task, called reconnaissance, is to collectively explore the surrounding environments with the intent to find new regions of interest (ROI) with forest debris and define the area of operation (AO) of the Ranger. The AO is defined by the swarm of Scouts, but can be refined by the operator in order to add or remove up to a fraction of the target area. After mapping the surrounding environment and identifying the regions of interest (ROI), the swarm switches to a patrolling behaviour – the surveillance task. While enacting this behaviour, the swarm of Scouts checks the state of the ROI, assessing the fraction of existing debris over their initial state.

During surveillance, the Ranger starts its own subsidiary mission: to reduce fuel accumulation. This mission essentially consists of cutting down trees and mowing down ground vegetation (e.g. bushes, shrubs, brush, etc.). During this mission, the artificial perception layer (section III-C) is particularly crucial for the Ranger, mainly 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. Moreover, the Ranger's perception capabilities are augmented by the

[3]http://semfire.ingeniarius.pt/
[4]https://isr.uc.pt/
[5]http://ingeniarius.pt/
[6]http://www.sferaultimate.com/
[7]http://www.cm-penacova.pt/
[8]http://freguesiadegois.pt/
[9]http://www.afcgois.pt
[10]http://forest.jrc.ec.europa.eu/effis/

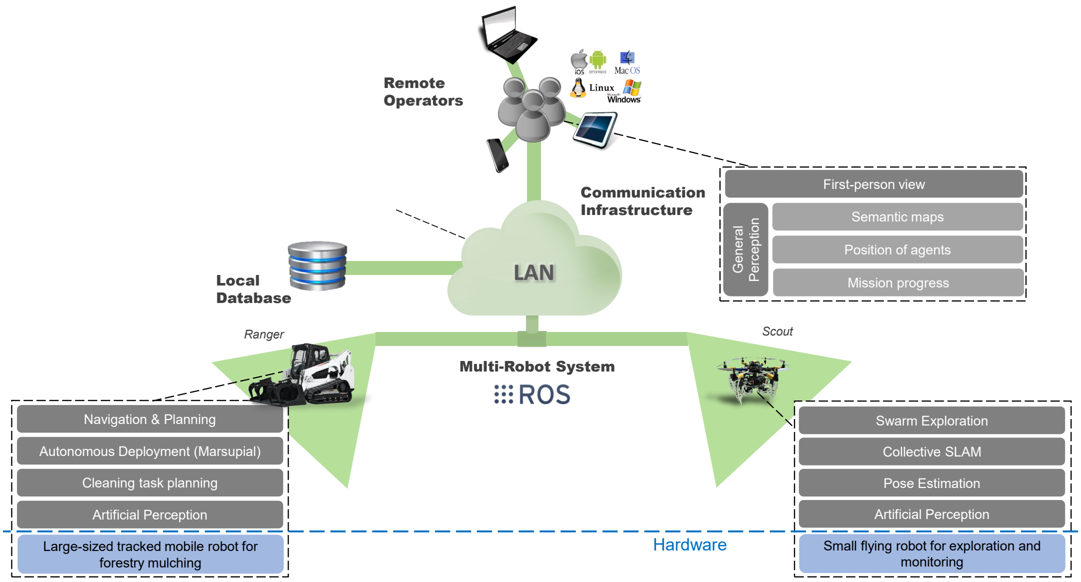

Fig. 1. Overview of the architecture of the SEMFIRE forestry maintenance multi-robot system.

Fig. 2. Illustrative deployment of the SEMFIRE solution. 1) the powerful multi-purpose Ranger can autonomously mulch down the thickest brushes as well as cutting down small trees to reduce the risk of wildfires; 2) the area is explored (finding new regions of interest with forest debris) and patrolled (checking the state of these regions of interest) by Scouts, having the additional task of estimating the pose of each other and the Ranger and supervising the area for external elements (e.g. living beings).

Scouts' perception systems during surveillance. Additionally, having a semantic map of the AO, and a highly accurate and precise pose estimation based on a Scouts' multilateration procedure, the Ranger can safely perform its tasks by keeping a dynamic workspace depending on the task it is carrying out (i.e. locomoting, mowing down brushes, or cutting trees).

Once the mission ends, in other words, the identified fuel accumulation in the AO falls below a given threshold, the system enters an idle state until the human operator confirms success. If the system was unable to fully remove all forest debris from the AO (e.g. by being unable to identify a given region), the operator can remotely define a new ROI within the AO or directly teleoperate the Ranger until the goal is fulfilled. Once the mission is complete, the swarm of Scouts regroups autonomously in coordinated fashion, returning to the Ranger, which can then be, once again, teleoperated to either move to another AO or return to base.

B. Heterogeneous Team of Forestry Robots

The design of the robotic platforms Ranger and Scout will take into account aspects of autonomy, safety, robustness, locomotion, sensing and actuation needed in forestry areas to perform related activities and overcome the absence of autonomous solutions in the state of the art.

Both solutions are being designed as modular robots with high flexibility to incorporate extensions and existing sensors or actuators, namely brush cutters, navigation sensors, etc. Robots will be integrated in the Robot Operating System (ROS) middleware [34], benefiting from the development led by the community and the consortium, such as algorithms, routines, and low-level drivers.

Briefly, the Ranger is being developed to support the following main features:

- Robust structure based on a Bobcat compact track loader powered by two powerful diesel engines to operate in tight places and overcome steep slopes;
- Hydraulic heavy-duty forestry mulcher attachment capable of mowing down brushes up to 8 cm in diameter and cutting down small trees with up to 10 cm diameter;
- Sensing system comprising stereo cameras, 3D LIDAR, multispectral camera and infrared camera;

- Charging station capable of ensuring at least 4 hours autonomy to four Scouts, using the very safe lithium yttrium iron phosphate, LiFePO4 (no spontaneous combustion and does not react with moisture or with oxygen);
- Maximum payload, excluding attachment, sensor kit and charging station, of 750 Kg, capable of transporting at least four Scouts for initial deployment (marsupial robotics) and one person for mobility assistance.

Likewise, the Scout platforms are being conceived to include the main features listed next:

- Robust carbon and aluminium frame with six-blade multi-rotor module;
- Communication set combining WiFi and ultra-wideband (UWB) for communication and pose estimation, respectively, as well as internet access using 3G/4G technology and global navigation satellite system (GNSS), whenever available;
- Sensing system comprising stereo and infrared cameras;
- Flying locomotion system to accomplish most of the reconnaissance and surveillance mission while avoiding obstacles and entrapment situations;
- Easily swappable battery with autonomy of up to 30 minutes, extendible by docking to the Ranger.

As expected, both robots will be equipped with a multimodal sensory system, which corresponds to the largest slice of the budget in equipment, in order to endow them with perception capabilities of the surrounding environment through artificial perception methods.

C. Artificial Perception for Landcover Classification and Robot Navigation

Artificial perception systems for the SEMFIRE robots simultaneously face the following major challenges, arguably in increasing order of difficulty:

- It should allow the robots to navigate in harsh outdoor terrains through the site while effectively and safely avoiding obstacles.
- It should provide the robots the ability of being safe to both humans and local fauna.
- It must allow the robots to find, select and act appropriately in respect to the diverse vegetation encountered in the target site, according to the designated task and the tree species comprising forest production for that site, namely in distinguishing between what should be protected and what should be removed.

These systems, in particular the one corresponding to the Ranger platform, will comprise a perceptual architecture for decision-making, 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.

A hierarchical classification scheme will be developed, using customized spectral features from remote sensing data and other characteristics, to generate the classified images (see, for example, [35]). The objective will be to enhance the discrimination of each element at subsequent levels of the hierarchical classification scheme through different spectral and 3D imagery information collected though in-situ sensors, both from Ranger and Scouts. Given the dynamic nature of the AO, landcover classes are iteratively reclassified along the hierarchy – the bottom layer corresponds to the classes that need to be absolutely removed (e.g. highly combustible accumulated biomass), going up to less susceptible fuel components, and finally the top layer corresponds to the classes that need to be highly preserved (e.g., human lives). The classes of fuels will encompass pine needles, brushes, logging debris, hardwood leaves, and other ecologically important elements in the area [36]. The integration of detailed and georeferenced field data will promote a spatially-explicit and highly descriptive definition of the forest types linked to a given mission.

As for navigation, the implementation of low-level sensor fusion techniques will allow to integrate the multimodal input received from different sensors, providing the navigation system with precise estimates of self-localization, and allowing for advanced path-planning, traversability analysis, mapping of the environment, accurate manipulation of vegetation cutting systems and, as expected in a MRS, an efficient coordination between robotic agents.

D. Collective Behaviour for Reconnaissance and Surveillance

As described in Section 1A, the collective behaviour of Scouts is divided in two phases: i) reconnaissance; and ii) surveillance.

In the reconnaissance phase, a fleet of cooperative Scouts will examine the AO thoroughly, providing a semantic map to the human operator and the Ranger. Therefore, the robotic team of Scouts needs to be able to perform a cooperative exploration of the environment, signalizing the position, type and density (i.e. status) of forest debris, and defining them as ROI (e.g. mapping of debris concentration in the AO). Similar operations have been recently addressed using optimization and foraging [37]. In fact, the problem of searching for ROI is analogous to foraging in animals, thus the swarm of Scouts can benefit from a swarm-based algorithm, such as the Robot Darwinian Particle Swarm Optimization (RDPSO) previously proposed by the research team [27].

In the surveillance phase, the team of Scouts should cover the whole scenario, identifying the status of any existing ROI, e.g., to monitor the evolution of the landscaping maintenance task in reducing fuel accumulation and transmit this information to the Ranger and the human workers. The problem proposed in this phase finds similarities with the multi-robot coverage problem, where Scouts should visit and clear the whole environment. More particularly, it resembles an inspection or patrolling mission, where the map is already available to the robots and important ROI are defined. Therefore, the team of Scouts is expected to reorganize and visit all of these locations in an effective way and report new situations back to the remaining agents, such as undetected ROI or unfinished/incomplete cleaning task. Again, multi-robot coordination architectures already proposed by the consortium and evaluated under different applications can be employed, such as the Concurrent Bayesian Learning Strategy (CBLS) for multi-robot patrolling [28].

IV. Conclusions

The 3-year SEMFIRE project, coordinated by a technology-oriented company, Ingeniarius, in close collaboration with a research provider, ISR-UC, and a forestry maintenance service provider, SFera Ultimate, will go beyond fundamental and laboratory science, contributing with significant advancements to the design of autonomous robotic solutions for forestry operations. Such contributions include multi-robot cooperation, robot navigation, locomotion and traversability in rough outdoor terrains, deployment architectures and marsupial robotics, communication strategies in the field, agents' localization, multi-robot coordination for exploration, coverage and inspection, computer vision and pattern recognition.

Notwithstanding these ambitious objectives, SEMFIRE is just the genesis of a series of other interconnected projects the consortium has been constructing. Multiple initiatives are taking place, not only to tackle the challenges at stake, but to also embrace other topics neglected by SEMFIRE but with high relevance for the successful deployment and commercialization of these solutions in the field. Among these topics one can highlight the need to further integrate human-in-the-loop techniques, since forestry missions might significantly benefit from human expertise and experience through communications and interaction with the robotic system. Therefore, human-robot interaction, wearable technology and augmented reality are some of the topics these initiatives will address in a near future.

References

[1] J. San-Miguel-Ayanz, E. Schulte, G. Schmuck, A. Camia, P. Strobl, G. Liberta, C. Giovando, R. Boca, F. Sedano, P. Kempeneers, and D. McInerney, Comprehensive monitoring of wildfires in Europe: the European Forest Fire Information System (EFFIS), European Commission, Joint Research Centre Italy, 2012.

[2] F. Moreira, and G. Pe'er Agricultural policy can reduce wildfires. Science, 359(6379), 2018, pp. 1001.

[3] C. Ribeiro, S. Valente, C. Coelho, and E. Figueiredo, A look at forest fires in Portugal: technical, institutional, and social perceptions. Scandinavian Journal of Forest Research, 30(4), 2015, 317-325.

[4] F. C. Dennis, Fire-resistant landscaping. Colorado State University Cooperative Extensio, 1999.

[5] C. Slappendel, I. Laird, I. Kawachi, S. Marshall, and C. Cryer, Factors affecting work-related injury among forestry workers: A review. Journal of safety research, 24(1), 1993, 19-32.

[6] K. M. Wurm, R. Kümmerle, and K. Stachniss, Improving robot navigation in structured outdoor environments by identifying vegetation from laser data. In Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems, 2009, pp. 1217-1222.

[7] B. Skibba, Range Rovers: Robots Roam Camp Guernsey to Prove UXO Range Clearance, Unmanned Systems, October, 2011.

[8] M. W. Hannan, and T. F. Burks, Current developments in automated citrus harvesting. In 2004 ASAE Annual Meeting (p. 1). American Society of Agricultural and Biological Engineers, 2004.

[9] E. Ham, Remotely operable fire-fighting vehicle, US7264062 B1 Patent, US 11/152,735, September, 2007.

[10] T. Ichimura, and S. I. Nakajima, Development of an autonomous beach cleaning robot "Hirottaro". In 2016 IEEE International Conference on Mechatronics and Automation (ICMA), 2016, pp. 868-872.

[11] B. Suger, B. Steder, and W. Burgard, Traversability analysis for mobile robots in outdoor environments: A semi-supervised learning approach based on 3D-lidar data. In Proc. of the IEEE International Conference on Robotics and Automation (ICRA 2015), Seattle, Washington, May 26-30, 2015.

[12] M. Pecka, K. Zimmermann, M. Reinstein, and T. Svobod, Controlling Robot Morphology From Incomplete Measurements. IEEE Transactions on Industrial Electronics, 64(2), 2017, pp. 1773–1782.

[13] R. Siegwart, P. Lamon, T. Estier, M. Lauria, and R. Piguet, Innovative design for wheeled locomotion in rough terrain, Robotics and Autonomous Systems 40, 2002, pp. 151–162.

[14] M.K. Habib, and Y. Baudoin Robot-Assisted Risky Intervention, Search, Rescue and Environmental Surveillance, International Journal of Advanced Robotic Systems, 7 (1), 2010.

[15] S. Panzieri, F. Pascucci, and G. Ulivi, An outdoor navigation system using GPS and inertial platform, IEEE/ASME transactions on Mechatronics 7(2), 2012, pp.134-142.

[16] R. Zinko, V. Jameljanovs, and J. Sulojeva, Usage of Robots for Increasing the Effectiveness of the Fire Protection, Scientific Journal of Riga Technical University, Safety of Technogenic Environment, Vol 1, 2011.

[17] S. Ohkawa, Y. Takita, and H. Date, Development of the autonomous brush-cutting robot using center articulated steering vehicle, Transactions of the Japan Society of Mechanical Engineers 80 (812), 2014.

[18] R. G. D'Eon, R. Serrouya, G. Smith, and C. O. Kochanny, GPS radiotelemetry error and bias in mountainous terrain. Wildlife Society Bulletin, 2002, pp.430-439.

[19] T. Hellström, P. Lärkeryd, T. Nordfjell, and O. Ringdahl, Autonomous forest machines: Past present and future, Department of Computing Science, Umea University, 2008.

[20] M. P. Diago, and J. Tardaguila, VineRobot: On-the-go Vineyard monitoring with non-invasive sensors, 19th Meeting of the Group of international Experts of vitivinicultural Systems for CoOperation (GiESCO), June, 2015.

[21] R. W. Hicks, and E. L. Hall, Survey of robot lawn mowers. In Intelligent Systems and Smart Manufacturing, International Society for Optics and Photonics, 2000, pp. 262-269.

[22] A. Olsen, S. Han, B. Calvert, P. Ridd, and O, Kenny, In Situ Leaf Classification Using Histograms of Oriented Gradients. In Proc. of the 2015 International Conference on Digital Image Computing: Techniques and Applications (DICTA), 2015.

[23] T. Hellström, P. Lärkeryd, T. Nordfjell, and O. Ringdahl, Autonomous Forest Vehicles: Historic, envisioned, and state-of-the-art. International Journal of Forest Engineering Vol. 20, No. 1, 2009, pp. 31-38.

[24] M. S. Couceiro, and D. Portugal, Swarming in Forestry Environments: Collective Exploration and Network Deployment. In Swarm Intelligence - From Concepts to Applications, IET, pp. 323-344, 2018.

[25] G. de Cubber, D. Doroftei, D. Serrano, and K. Chintamani, The EU-ICARUS project: Developing assistive robotic tools for search and rescue operations. In Proc. of the 2013 International Symp. on Safety, Security and Rescue Robotics (SSRR 2013), Linköping, Sweden, Oct 21-26, 2013.
[26] R. P. Rocha, D. Portugal, M. S. Couceiro, F. Araújo, P. Menezes, and J. Lobo, The CHOPIN project: Cooperation between Human and rObotic teams in catastroPhic INcidents. In Proceedings of the 2013 International Symposium on Safety, Security and Rescue Robotics (SSRR 2013), Linköping, Sweden, Oct 21-26, 2013.
[27] M. S. Couceiro, C. M. Figueiredo, R. P. Rocha, and N. M. Ferreira, Darwinian Swarm Exploration under Communication Constraints: Initial Deployment and Fault-Tolerance Assessment, Robotics and Autonomous Systems, 62(4), Elsevier, April, 2014, pp. 528-544.
[28] D. Portugal, and R. P. Rocha, Multi-Robot Patrol with Bayesian Learning. Autonomous Robots Journal, 40 (5), Springer, June, 2016, pp. 929-953.
[29] M. Bergerman, J. Billingsley, J. Reid, E. van Henten, Robotics in Agriculture and Forestry. In Springer Handbook of Robotics. Springer International Publishing, 2016, pp. 1463-1492.
[30] K. Vestlund, and T. Hellström, Requirements and system design for a robot performing selective cleaning in young forest stands. Journal of terramechanics, 43(4), 2006, pp. 505-525.
[31] T. Hellström, T. Johansson, and O. Ringdahl, Development of an autonomous forest machine for path tracking. In Field and Service Robotics, Springer Berlin Heidelberg, 2006, pp. 603-614.
[32] D. W. Casbeer, R. W. Beard, T. W. McLain, S. M. Li, and R. K. Mehra, Forest fire monitoring with multiple small UAVs. In Proceedings of the 2005, American Control Conference, 2005, pp. 3530-3535.
[33] A. Marjovi, J. G. Nunes, L. Marques, and A. de Almeida, Multi-robot exploration and fire searching. In 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2009, pp. 1929-1934.
[34] M. Quigley, K. Conley, B. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, and A. Y. Ng, ROS: an open-source Robot Operating System. In ICRA workshop on open source software (Vol. 3, No. 3.2, p. 5), 2009.
[35] P. Ghamisi, M. S. Couceiro, F. M. Martins, and J. A. Benediktsson: Multilevel image segmentation based on fractional-order Darwinian particle swarm optimization. IEEE Transactions on Geoscience and Remote sensing, 52(5), 2382-2394, 2014.
[36] C. P. Weatherspoon, and C. N. Skinner, Landscape-level strategies for forest fuel management. In Sierra Nevada ecosystem project: final report to congress (Vol. 2, pp. 1471-1492). University of California, Davis, Centers for Water and Wildland Resources, 1996.
[37] J. Suarez, and R. Murphy, A survey of animal foraging for directed, persistent search by rescue robotics. In 2011 IEEE International Symposium on Safety, Security, and Rescue Robotics, 2011, pp. 314-320.