Avalanche Rescue with Autonomous Drones

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***Abstract*—In avalanche rescues, quick operations make a real difference between survival or death. Organized search and rescue operations require large intervention time since professionals are not directly present in the distressed area. For this reason, companion rescue is still the most effective option for localizing and extracting people involved in avalanche incidents. In this context autonomous drones equipped with avalanche transceivers can assist ground operations by reducing localization time, therefore increasing the survival rate. In this paper, technologies and strategies for avalanche rescue with autonomous drones are introduced and their performances are assessed with respect to operational scenarios. In particular, avalanche transceivers operability on board of small autonomous vehicles is evaluated and optimal beacon search trajectories are investigated.**

***Index Terms*—Avalanche rescue, Drones, Autonomous flight, UAVs**

I. Introduction

Winter sport activities show a continuously increasing trend, especially the ones practised in uncontrolled mountain environment (e.g. outside of prepared paths and slopes), such as ski touring and winter mountaineering. This trend is clearly stated by many scientific publications as well as alpine clubs surveys [1] [2].

In this context avalanches become the greatest hazard for the security of both athletes and amateurs; in fact, almost the 90% of avalanche accidents are referred to the following categories: ski-tourers (49%), off-slope skiers (17%), and alpinists (19%), as reported in a survey related to Italian search and rescue [3]. Avalanche victims survival rate decreases not linearly with burial time: the 90% of buried people can survive if extracted within 8 minutes from the avalanche event, lowering to 60% for a rescuing time of 15 minutes [4]. In fact, fatalities occurring in the first few minutes are related to trauma reasons, whereas 15 minutes are commonly considered the maximum survival time before asphyxia. Survivability for longer burial times (i.e. in the range of one hour) may occur in case of presence of air cavities in the snow, and in this case fatalities are due to exposure processes. Looking at these statistics it is clear that successful rescues shall be accomplished in a short time range, that is usually quantified in 15 minutes [5]. The most effective way to achieve this result is the companion rescue, since organized search and rescue teams usually require longer intervention time, not even counting that often mountain wilderness is not covered by phone signal and emergency calls may be delayed.

To date the equipment employed for companion rescue can be categorized in two classes: search devices (electronic avalanche transceivers, commonly known as "beepers" or "ARTVAs") and excavation tools (shovels and probes). Statistics suggest that the search phase (using beepers) should be completed in 5 minutes or less, in order to give rescuers enough time to dig and extract victims. Accordingly, the maximum excavation time should not excess 10 minutes. Although avalanche transceivers are effective devices, the search phase is strongly influenced by ground conditions (loose or unsupportive snow, presence of ice blocks) that could slow rescuers movement.

In this context, it is clear that reducing the search and localization time would allow higher survivability rates or, at least, allocate more time for the excavation phase. Airborne search systems could be highly effective thanks to their higher mobility due to the absence of ground obstacles; in particular drones show potential application to avalanche search operations featuring lightness, agility, and easiness of control. These features are fundamental for this application since they allow for simple transportation and can perform fully autonomous search operations if equipped with proper devices. Currently, drone utilization in avalanche search and localization is mostly limited to academic investigation. The vehicles are usually equipped with an avalanche transceiver antenna, catching the signal from buried victims, and providing guidance information to the on board control system. Among the research projects, the EU-supported SHERPA project aims to the development of collaborative autonomous UAVs and robots [6]; preliminary assessments indicated that this approach can be further developed once some critical issues (i.e. drone dimension, interferences between antenna and drone

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power system) are resolved [7]. The ALCEDO project from ETH Zurich aimed to the design and development of an ultralight UAV capable to reduce search time to less than one minute; unfortunately just limited experimental data is available on literature, not confirming the concept suitability [8]. The Delta Drone company patented a similar concept [9]; however, experimental data proving the effectiveness of the proposed system is currently not available in the literature. Last, researchers from the Politecnico di Torino proposed a system based on an off-the-shelf drone and a deployable custom antenna with a total weight of less than 5 kg. A preliminary experimental assessment indicated that the drone is autonomously capable to locate the signal coming from an avalanche transceiver as long as the fly trajectory is previously determined [10].

In summary, literature review indicates that avalanche search and localization by means of UAVs has been demonstrated to be possible even though just few and preliminary experimental data are available. Concerns are often related to: (i) drones sizes, too bulky to be carried in the small backpacks used in mountain activities; (ii) interference process between drones and antennas, that may reduce transceivers operative range; (iii) the capability to perform fully autonomous fly path determination and beacon localization.

To overcome such limitations the project AVERLA (Autosoccorso Valanghivo E Ricerca Localizzazione Artva - avalanche self-rescue and transceiver search and localization) has been proposed by the University of Padova. AVERLA aims to the miniaturization and integration of the search transceiver on board of a portable drone. Eventually the final goal is to provide mountain users with a miniaturized and fully autonomous UAV for companion rescue in case of avalanche incidents.

In the next section the AVERLA project is introduced and its development plan is presented. Section III introduces the characterization of the avalanche transceiver precision and accuracy both on ground and on board of drones. Last, preliminary investigation on path planning is presented.

II. AVERLA PROJECT

The AVERLA project is part of the "Innovative Student Projects" program of the University of Padova, in the framework of student activities focusing on drones technologies development [11] [12] [13] [14]. The project target is to develop a portable system for avalanche search and localization based on a miniaturized transceiver mounted on a small-scale drone. The system is conceived for fully autonomous operations and aims to localize a buried victim in less than five minutes from avalanche events. The project has been structured in three phases consistent with the major concerns found in the literature review:

- Interference sources identification and definition of transceivers performance characteristics
- Path planning and optimization
- Drone integration and miniaturization

In the following sections the first two phases are singularly presented and preliminary numerical and experimental data is introduced. The third phase is planned for the remainder of this solar year.

III. AVALANCHE TRANSCEIVERS PERFORMANCE ASSESSMENT

Avalanche transceivers are common devices employed in mountain activities. They are radio transceivers which have the purpose of finding buried people after avalanche accidents. In transmission mode, they emit a low pulsed radio signal at 457 Hz; this frequency is currently the international standard for avalanche transceivers. Once commutated into the receiving mode, they can be used as radio direction find devices, to search signals coming from other transceivers.

The electromagnetic field is produced in transmission mode by a single antenna, and therefore has a classic shape with elliptical field lines. When in receiving mode, the most recent models employ three antennas and are therefore able to reconstruct both the direction and the distance of the source antenna.

The range of transmission (i.e. electro-magnetic field magnitude) has been remarkably improved during the last few years passing from 30m (2000) to the actual 70m declared by manufacturers for the most recent devices. All the studies related the AVERLA project will be conducted with avalanche tranceivers having a transmission range of maximum 40m in order to consider averaged performance between old and new generation devices.

A. Transceivers characterization

The characterization of the avalanche transceiver has been conducted by means of ground tests utilizing 2 devices, as reported in Fig. 1. The first (with transmitting purpose) has

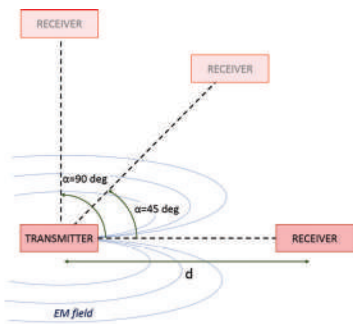


Fig. 1. Avalanche transceiver performance test layout. Receiver and transmitter are always aligned and repeated measures are taken varying the receiver position (distance d, from 5 to 40 m, and angle α, at 0, 45 and 90 deg).

been placed in a fixed position in order to keep constant the electro magnetic field orientation. The second (used as receiver) has been placed at different distances and angular positions (measured from the transmitting antenna axis). The combination between these positioning parameters allowed to take into consideration either the influence of the signal distribution or of its intensity. A comparison between distances indicated by the receiving device and the one directly measured on the test field allowed to evaluate the following two parameters: accuracy and precision. The former gives information about the capability of the receiver to indicate the correct distance from the transmitter while the latter is useful to evaluate the repeatability of the detected distance. The results of the characterization phase are listed in table I and they are graphically shown in Fig. 2 Results showed that the accuracy of the avalanche transceiver is markedly higher when the receiver is placed at 90 deg (i.e. not parallel to the transmitter antenna axis) compared to the null angular position. As expected, the precision decreases as long as the distance is increased as a direct consequence of the signal power lowering.

TABLE I
AVALANCHE TRANSCEIVER MEASUREMENTS SUMMARY

	$\alpha = 0$ deg	$\alpha = 45$ deg	$\alpha = 90$ deg
$d = 5$ m	4.87 ± 0.05 m	5.73 ± 0.25 m	5.87 ± 0.27 m
$d = 10$ m	8.00 ± 0.14 m	9.03 ± 0.25 m	9.57 ± 0.19 m
$d = 20$ m	18.7 ± 0.5 m	21.0 ± 2.2 m	20.0 ± 0.8 m
$d = 30$ m	28.7 ± 0.5 m	28.0 ± 0.8 m	28.7 ± 0.5 m
$d = 40$ m	37.7 ± 0.5 m	44.5 ± 3.5 m	39.7 ± 3.9 m

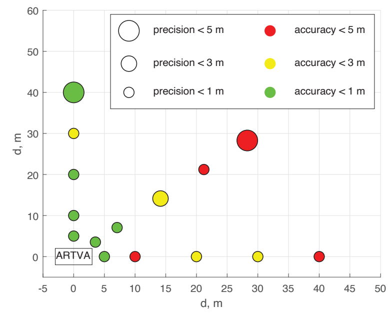


Fig. 2. Avalanche transceiver performance in open field. Circles size indicate transceivers precision for repeated measurements, circles colour their accuracy with respect to the reference position

Further investigation is currently underway to evaluate disturbances produced by drones on avalanche transceivers range and accuracy.

IV. Path Planning

One of the most crucial phases in UAV avalanche rescue is assigning the drone a search path while no signal is detected from the avalanche transceiver. This path shall be optimized in order to minimize the operation rescue time. The first step is to define a target localization algorithm. To this aim the signal of the target is modeled using a Gaussian function:

$$f(x,y) = \frac{1}{2\pi\sigma^2} exp\left(-\frac{(x-x_t)^2+(y-y_t)^2}{2\sigma^2}\right) \tag{1}$$

where (x_t, y_t) represent the coordinates of the target, while σ^2 is the variance; the function is tuned with numerical data from section II.

The objective of the UAV is to find the maximum value of this target function, i.e. the target position. This can be done using a gradient based approach, obtained merging a Newton and a gradient descent method. The Newton method uses the information given by the inverse of the Hessian of the input function, making it more efficient than the gradient method; in case of singularities (non-invertible Hessian) the gradient method is employed. It is important to notice that the gradient of the input function is very small when the distance between the UAV and the target is huge. This make this method useful only when the drone is sufficiently near to the target.
To overcome this issue it is necessary to implement a way to cover the searching area, in order to bring the UAV near to the target. The first idea is to use the approach used nowadays by the rescuers: the target area is covered in a precise and regular way. In a simplified scenario, only one person is buried (missing target) and only one rescuer is available on the field. The rescuer has to move along the normal direction of the avalanche; when he reaches the end, he makes a turn of 90 degrees and move along the direction parallel to the avalanche. The space covered in this part is equal to twice the reach of the avalanche transceiver. At this point he has to move along the normal direction of the avalanche, but in the opposite direction with respect to the initial situation. This procedure is repeated until the target is found, creating a zigzag pattern as reported in Fig. 3.

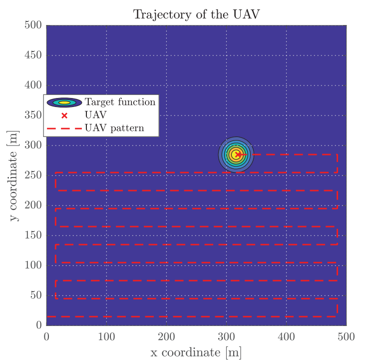


Fig. 3. Path followed by the UAV

In the proposed method, when the UAV is sufficiently near the target, the gradient of the target function overcomes a threshold and the searching algorithm switches to the target localization process described before.
The aforementioned method can be considered the baseline in this work and can be used to define a reference localization time, i.e. the time required to localize the target in the search area. A more refined strategy, based on dynamic coverage, is here proposed and its performance is compared to the baseline one. In this case, a coverage function defines the fraction of the search area that has already been covered by the UAV, i.e if the drone has passed over the point the coverage function as $\tilde{q} = (x, y)$; the goal of the UAV is to fly over the uncovered areas till the target is found. Defining the drone position as $q(t)$ and its sensing capacity as $A(||\bar{q}||)$, the coverage function

can be defined as follows:

$$\mathscr{T}(\tilde{q},t) = \int_0^t A\left(||q(\tau) - \tilde{q}||^2\right) d\tau \tag{2}$$

The objective is to reach $\mathscr{T}(\tilde{q},t) = C^*$, $\forall \tilde{q}$ in the target area. A control law can be designed in order to reach every point of the target area, in the following form:.

$$\begin{aligned} \overline{u}(t) = \overline{k} \int_{\mathscr{D}} h'(C^* - \mathscr{T}_{\mathscr{S}}(\tilde{q},t)) \frac{\partial A(s)}{\partial s} |_{s=||q(t)-\tilde{q}||^2} \\ \cdot (q_i(t) - \tilde{q})\phi(\tilde{q})d\tilde{q} \end{aligned} \tag{3}$$

Where $h'(x)$ is the first derivative of a penalty function that satisfies $h(x) = h'(x) = h''(x) = 0, \forall x \leq 0$, $\overline{k}$ is a fixed feedback gain and $\phi(q)$ is a probability distribution that describes the actual probability of an event to happen in q, in this case a person being buried. Similarly to the previous approach, when the UAV is sufficiently near the target, the algorithm switches to the target localization program. A simulation of this control law can be seen in figures (4) and (5).

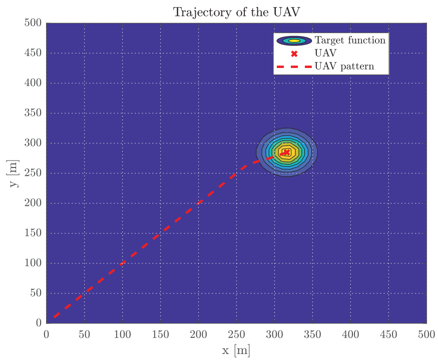


Fig. 4. Path followed by the UAV

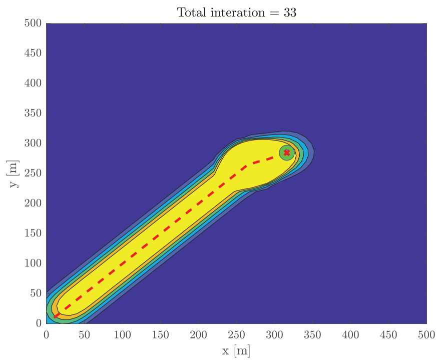


Fig. 5. Effective coverage of the target Area

A set of simulations has been performed to evaluate the performance of this approach with respect to the baseline one. In the first case, the following parameters have been set:

- a single drone is employed to search a single target;
- the sensing radius $r_i = 40m$ is the same of the baseline approach;
- the desired coverage parameter is set to $C^* = 2$;
- the threshold that determines if the agent has sensed a target is set equal to $threshold = 0.5$
- the area of search is fixed to $5 \times 10^5 m^2$. This choice has been made since this is the dimension of the biggest avalanche happened in Europe in the last years.

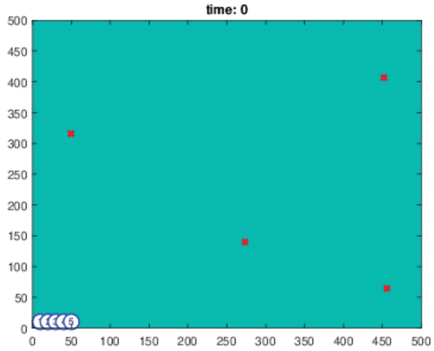
The first case has been iterated 250 times distributing randomly the position of the buried target. Table (II) summarize numerical results in terms of localization times (worst and average cases) and compare them with the baseline configuration.

TABLE II
COMPARISON BETWEEN THE TWO SEARCHING APPROACH.

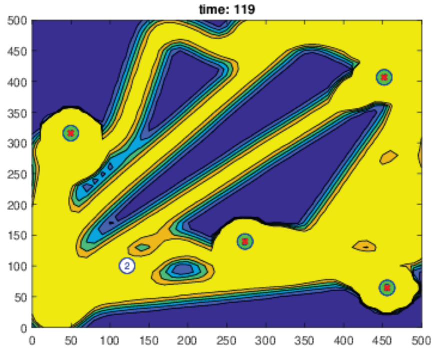
Avalanche level	Max elapsed time	Mean elapsed time
Initial approach	694.28 [s]	340.5 [s]
Dynamic coverage	945 [s]	311.3 [s]

Table (II) suggests that the dynamic approach performs worse than the initial one when the worst case scenario is considered; on the other hand, evaluating overall averaged results, the dynamic method in fact reduce localization time of about 8.5% with respect to baseline strategy. A further refined method is proposed, evaluating the advantage of adding more drones in the target localization. In this case, the network of UAVs is initially assumed to be fully connected (bidirectional communication). This means that every drone knows exactly the position of its companions and the total coverage function is given by the sum of the coverage functions of every UAV, and it is known to every node of the network. In this way it is easier to cover the target area, since every agent is autonomous but has more complete information with respect to the previous case. This assumption allows the reduction of localization time, making it possible to extend the search area or to investigate multiple- target scenarios (i.e. more than one buried target). In this case, it has been proposed to disconnect a drone once it localizes the target, making it hovering over the burial point. Figures 6 (top to bottom) display the simulated scenario with multiple drones and targets.

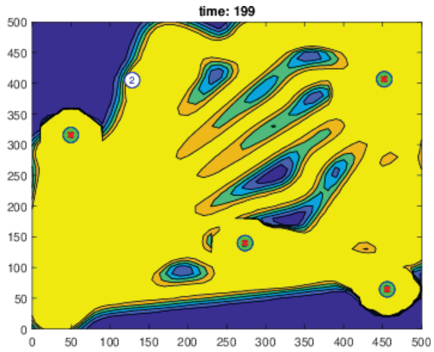
It can be clearly seen that at $t = 199s$ the network has found all the targets in the area and the rest of the time is used by the remaining agent to cover the remaining area, since the number of the targets is initially unknown to the network. The addition of more UAVs results in a slightly better scenario, but the assumption of a fully connected network is too strong and it is known that in reality this scenario can be possible only for small networks, where the drones are very close to each other. To overcome this limit, one last refinement has been applied to the algorithm. In this case, it is assumed that the network is partially connected, meaning that an agent can communicate only with the ones that are sufficiently near to its position.It shall be underlined that to avoid collision it is necessary to set a minimum distance between the UAVs. The control law is therefore updated in order to maintain a ceratin formation throughout the search and to let agents communicate with each other.



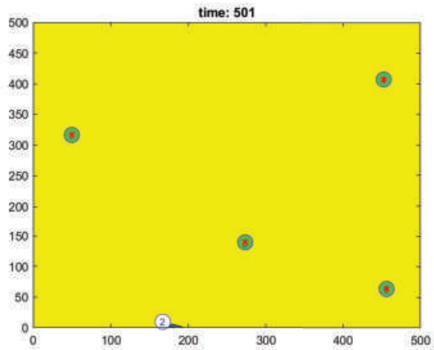
(a) $t = 0s$



(b) $t = 119s$



(c) $t = 199s$



(d) $t = 501s$

Fig. 6. Simulation with a fully connected network of $N = 5$ agents and with $M = 4$ targets.

To avoid impasses (e.g. UAVs trying to navigate in convergent or opposite directions but kept together by the formation control algorithm), a drone leader is introduced in the network; such leader is not affected by formation flight control, allowing the other UAVs to follow it and cover the unexplored area.. The leader is set to change and every time it finds a target, since in such a case it is disconnected from the network. Figure (7) reports a simulation of this localization method.

It is important to notice that, with this approach, in order to find M targets it is necessary to have a network with at least the same number of agents. Figure (8) shows the time elapsed when there are no targets in the area. As expected, increasing the number of UAVs decreases the time necessary to cover the target area. It is worth to notice that 3 UAVs allow to cover the search area respectively in less than 7 minutes (partially connected network) and about 4 minutes (fully connected network), with great advantage for rescue operations. These simulations have shown that the algorithms presented are effective because they can accomplish these tasks in an average time that allows to have an high probability of survival of the buried (i.e. 5 minutes or less even for large avalanches). A multi-UAVs network performs better, since it allows to rescue more people and it improves the coverage of the area. A fully connected network of agents is able to cover a wide area in a very short time. If the full connectivity is not possible for economic or information traffic reasons, a partially connected network is still able to manage the mission with good performances.The most innovative feature of these algorithms is that they are executed with a distributed logic, allowing a more flexible behaviour and an higher adaptability to the operational environment.

V. Conclusions

This work introduces the AVERLA concept for avalanche victims localization and presents the advancements of the research project. To date, ground experiments have been performed to evaluate commercial avalanche transceivers performances; the collected data has been employed in simulations to estimate localization times in function of the search method. Different strategies has been proposed, considering scenarios with single and multiple drones and targets. It has been showed that the proposed search strategy is in average more efficient with respect to the initial zig-zag method: the future implementation on the AVERLA drones will benefit the survivability rate in case of companion rescue.

VI. Acknowledgment

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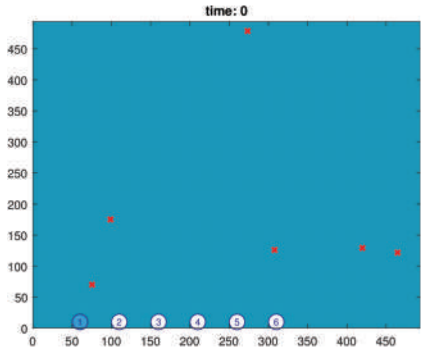
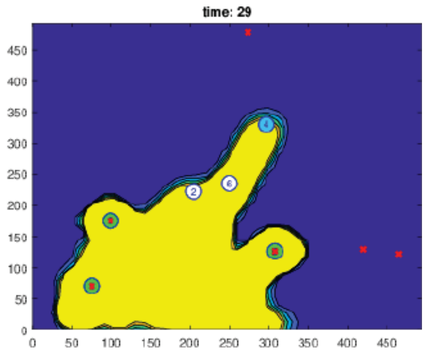
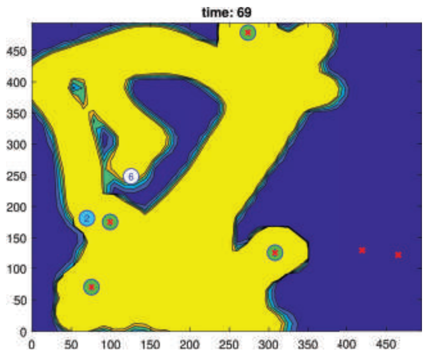


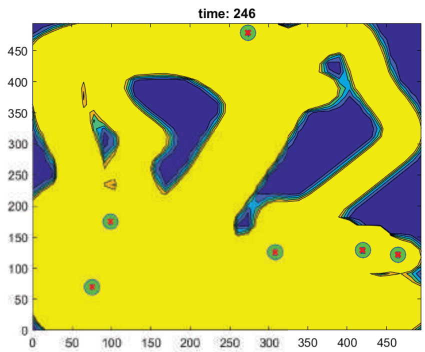
(a) $t = 0s$



(b) $t = 29s$



(c) $t = 69s$



(d) $t = 246s$

Fig. 7. Simulation with a partially connected network of $N = 6$ agents (with formation control) and with $M = 6$ targets. The blue agent is the leader of the formation.

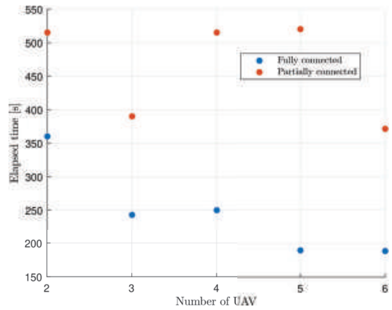


Fig. 8. Comparison of search time between the fully connected and partially connected network.

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