Abstract — This paper proposes the use of a platoon of mobile robots to carry a number of repeater antennas in order to guarantee a constant communication between a rescue operator (human or robot) and a fixed base station. These mobile antennas suitably move to dynamically ensure a multi-hop communication link, handling the occurrence of obstacles, signal fading area and failures such as, e.g., the fault of one or more mobile robots. The control objective is achieved in the framework of a kind of behavioral control, namely the Null-Space-based Behavioral control (NSB). The effectiveness of the proposed strategy is verified in preliminary experiments obtained using a platoon of Khepera II mobile robots.

I. INTRODUCTION

The capability to guarantee a constant communication among operators involved in rescue operation represents a significant issue in rescue robotic. Both wired and wireless communication techniques have different drawbacks. Cables used for wired communication largely reduce the mobility of the robot especially in scenarios where more robots need to cooperate. On the other side, in wireless framework one has to trade-off the requirement to have “large” communication device and the need to miniaturize the robot. Indeed, where there is the desiderata to have “small” robots able to easily move through ruins and inside holes, the presence of large obstacles to radio propagation imposes the use of low-frequency communication channel and hence large antennas.

A promising solution is the use of multi-hop strategy where a set of mobile antennas dynamically self-configure their position to continuously guarantee the communication among the rescue operator and a fixed base station, as schematically depicted in Figure 1. This kind of configuration is generally denoted as Mobile Ad-hoc NETwork (MANET) and has the peculiarity that each node operates as both an host and a router. Therefore, any node can communicate directly with nodes that are within its transmission range and, in order to reach a node that is out of its range, data packets are relayed over a sequence of intermediate nodes using a store-and-forward multi-hop transmission principle. Note that this strategy allows also to reduce power consumption, hence improves the endurance of the batteries.

Fig. 1. Sketch of the coverage problem to be solved; the autonomous agent needs to be connected with the base station by the use of a platoon of mobile antennas.

The use of MANET in field robotics has been only recently investigated. The first studies on this topic were related to the use mobile robots to provide adaptive sensor network in a dynamic environment. In [18] Delaunay tessellation and Voronoi diagram are used to define an algorithm able to maximize the coverage area of the network. In reference [9], to guarantee the communication for a mobile robot involved into a dynamic coverage problem, a static network of markers is autonomously dispersed by the robot during its motion (these markers are also used to improve localization capability). In reference [16] cooperative communication, i.e., the capability of a group of mobile robots to establish and maintain a wireless
ad-hoc network, is achieved through a distributed approach where each robot defines its local optimal trajectory by minimizing a functional that accounts for network connectivity, obstacle avoidance and other aspects of interest. A behavior-based architecture is proposed in [20] to encourage a team of robots to maintain a local communication network while exploring an area; during the exploration, any two robots that form a bridge connection, i.e., a link whose removal disconnects the network, are forced to perform connectivity-behavior task when their distances are greater than a given threshold. An algorithm that, starting from an arbitrary initial connected condition, modifies the robots’ location to achieve a fault-tolerant bi-connected configuration is proposed in [8]. Recovery behaviors to autonomously re-establish communication after a failure between some or all of the nodes in the network are discussed in [19]. A rendezvous algorithm for coordinated motion of mobile robots with limited mobility and communication constraints is proposed in [12]; in this approach, network connectivity is guaranteed imposing to each robot, at each sample time, to move toward the circum-center defined by itself and its neighbours and restricting the travel distance.

In this paper, following the preliminary results in [3], [4], we consider the problem of dynamically adapting the configuration of a platoon of mobile robots equipped with a wireless device (that we will call antennas) so as to realize an ad-hoc network to support communication of an autonomous agent, i.e., an autonomous driven vehicle or an human, with a fixed base station. Antennas coordination for agent coverage is achieved in the framework of kinematic control of platoon of mobile robots [5], by resorting to properly defined task functions. This approach has shown to be efficient and reliable in simultaneous handling of several control objectives, namely, agent-antennas-station connectivity, obstacle avoidance and fault tolerance of the mobile antennas. Preliminary experimental results, using a platoon of Khepera II mobile robots, show the effectiveness of the proposed approach.

II. NULL-SPACE-BASED BEHAVIORAL CONTROL

Behavior based approaches, widely studied for mobile robotic applications [7], are useful to guide a multi-robot system in an unknown or dynamically changing environment. These approaches give the system the autonomy to navigate in complex environments avoiding off-line path planning, using sensors to obtain instantaneous information of the environment and increasing flexibility of the system. Among the behavioral approaches, seminal works are reported in the papers [10] and [6], while, lately, behavioral approaches have been applied to the formation control of multi-robot systems as in, e.g., [15], [13]. Among the multiple approaches proposed in literature, a behavior based approach to control one single mobile robot has been presented in [2], namely the Null-Space-based Behavioral (NSB) control. The NSB differs from the other existing methods in the behavioral coordination method, i.e., in the way the outputs of the single elementary behaviors are assembled to compose the final behavior.

Generally, a mission may requires the accomplishment of several tasks at the same time. A common approach is to decompose the overall mission of the system in elementary tasks, i.e., the behaviors, solve them as they were working alone and, finally, combine the outputs of the single tasks to obtain the motion command to each robot. As discussed in [2] the NSB uses a geometric, hierarchy-based composition of the tasks’ outputs to obtain the motion reference commands for the robot that allows the system to exhibit robustness with respect to eventually conflicting tasks. The basic concepts for a generic robot of the team are recalled in the following.

Let define the position of the \( k \)-th robot as
\[
P_k = [x_k \ y_k \ z_k]^T
\]
and the generic task variable to be controlled for the \( k \)-th robot as
\[
\sigma = f(p_k).
\]
The corresponding differential relationship is:
\[
\dot{\sigma} = \frac{\partial f(p_k)}{\partial p_k} v_k = J(p_k) v_k,
\]
where \( J \in \mathbb{R}^{m \times 3} \) is the robot configuration-dependent task Jacobian matrix and \( v_k \in \mathbb{R}^3 \) is the robot velocity.

An effective way to generate motion references \( p_{d,k}(t) \) for the \( k \)-th robot starting from desired values \( \sigma_d(t) \) of the task function is to act at the differential level by inverting the (locally linear) mapping (2), in fact, this problem has been widely studied in robotics (see, e.g., [17] for a tutorial). A typical requirement is to pursue minimum-norm velocity, leading to the least-squares solution:
\[
v_{d,k} = J_k^\dagger \sigma_d = J_k^\dagger (J_k J_k^\dagger)^{-1} \sigma_d.
\]
At this point, the vehicle motion controller needs a reference position trajectory besides the velocity reference; this can be obtained by time integration of \( v_{d,k} \). However, discrete-time integration of the vehicle’s reference velocity would result in a numerical drift of the reconstructed vehicle’s position; the drift can be counteracted by a so-called Closed Loop Inverse Kinematics (CLIK) version of the algorithm, namely,
\[
v_{d,k} = J_k^\dagger (\sigma_d + \Lambda \tilde{\sigma}),
\]
where \( \Lambda \) is a suitable constant positive-definite matrix of gains and \( \tilde{\sigma} \) is the task error defined as \( \tilde{\sigma} = \sigma_d - \sigma \).

The Null-Space-based Behavioral control intrinsically requires a differentiable analytic expression of the tasks defined, so that it is possible to compute the required Jacobians.

To go in detail, let us consider the mission for the \( k \)-th robot composed by multiple elementary tasks. Using the subscript \( i \) referring to the \( i \)-th task quantities for the \( k \)-th robot, on the analogy of eq. (4), the \( i \)-th task velocity is computed as
\[
v_i = J_i^\dagger (\sigma_{i,d} + \Lambda_i \tilde{\sigma}_i).
\]
If the subscript \( i \) also denotes the degree of priority of the task with, e.g., Task 1 being the highest-priority one, according
to [11] the CLIK solution (4) for the three-task case is modified into

$$v_{d,k} = v_1 + \left( I - J_k^1 J_1 \right) \left[ v_2 + \left( I - J_k^2 J_2 \right) v_3 \right]$$  (6)

where $I$ is the identity matrix of proper dimensions. Remarkably, eq. (6) has a nice geometrical interpretation. Each task velocity is computed as if it were acting alone; then, before adding its contribution to the vehicle velocity, a lower-priority task is projected onto the null space of the immediately higher-priority task so as to remove those velocity components that would conflict with it. Thus, the Null-Space-based Behavioral control always fulfills the highest-priority task at nonsingular configurations.

Notice that, in a decentralized framework, each robot has its independent supervisor that, at each sample time, dynamically identifies the proper tasks to be applied for the specific robot and suitably arrange their priority (see Figure 2).

III. THE MANET CASE

The strategy described in the previous Section can be used to suitably coordinate the motion of a set of mobile antennas to implement a MANET that dynamically adapts its coverage area (see Figure 1).

Specifically, in the following we consider a platoon of $n$ mobile antennas that must ensure the communication between a mobile agent (e.g., a human operator or a rescue-robot) executing its mission and a fixed base station (e.g., an Internet access point). Obviously, the antennas needs to avoid any unknown obstacle eventually present in the environment.

Each antenna is supposed to cover in open space a circular area $I_k$ centered in $p_k$ and of radius

$$r_{\max,k} = r_{\max,k}(k,pw_k)$$  (7)

where $pw_k$ is the current level of power used for transmission. It can be noticed that $r_{\max,k}$ depends on the characteristic of the $k$-th antenna. Moreover, it depends also on the level of power used for transmission $pw_k$. During the execution of a mission the level of power used for the transmission may be varied in order to preserve the battery level or, on the other side, can be decreased when the battery level is low. Finally, in presence of obstacles it is advisable to decrease $r_{\max,k}$ to take into account the possible reduced propagation.

In order to guarantee adequate operative margins, we will constraint each antenna to dialogue in a smaller region, identified via the radius

$$d_{\max,k} = (1 - \Delta) r_{\max,k}$$  (8)

where $\Delta$ is a design parameter. Moreover, in order to avoid collisions, all other bodies in the environment (i.e., base station, other antennas, agent and obstacles) must be farther than $d_{\min,k}$ from each antenna (see Figure 3). Notice that this definition is similar to that of comfort zone in [20], therefore, this term will be used in the following to denote the area shown in Figure 3.

Then, at time $t$ the $k$-th antenna is able to directly communicate with all antennas which are inside the region $I_k(t)$. The set of all direct communication paths constitute a graph that can be synthetically represented via the associated incidence matrix $G$ whose entries satisfy

$$g_{ij} = \begin{cases} 1 & \text{if } p_j \in I_i \\ 0 & \text{otherwise} \end{cases}$$

Notice that, since $p_k \notin I_k$, it results $g_{kk} = 0$ by definition.

It is immediate to recognize that bi-directional communication between any two vehicles is guaranteed if and only if the associated graph is fully connected, then our goal is to ensure this property while the agent performs its own mission moving along unknown trajectories. This can be achieved imposing that the antennas dynamically organize as a virtual chain where...
the distance among any two elements of the chain is less than $d_{\text{max}}$, the first element of the chain is close to the base station and at least one antenna has inside its coverage area the mobile agent. Notice that the order of the antennas inside the virtual chain is not static, but it changes over time.

To implement this goal in the NSB decentralized framework, we need to properly defined the task functions and properly arrange them in a priority order. It is worth noticing that the priority is dynamic, in the sense that the supervisors (Figure 2) are in charge of dynamically modifying for each antenna the relative priorities among the tasks. Specifically the tasks that each vehicle may be required to satisfy are:

- **Obstacle avoidance.** It allows to avoid any impact of the antenna with fixed or mobile obstacles. This task has always the highest priority;
- **Keep the next antenna in the comfort zone.** This task keeps the antenna in the comfort zone of the next one in the virtual chain;
- **Keep the previous antenna in the comfort zone.** It keeps the antenna in the comfort zone of the previous one in the virtual chain;
- **Reach a target.** The agent is supposed to be driven by a simple reach-a-target task. Moreover, in case of failure of one antenna, and thus interruption of the chain, this task allows to recover the communication between the agent and the fixed base.

A. Supervisors

Let us assume a planar case, each vehicle, thus, is characterized by 2 Degrees-Of-Freedom (DOFs); as described in [2], the selection of the specific tasks to be activated is of crucial importance to avoid a request for a number of DOFs larger than the robot possibilities. The use of the NSB approach allows to avoid the occurrence of control noise that can arise with a competitive behavioral approach; it is, however, always a good programming rule to avoid asking a unfeasible mobility.

The agent is driven resorting to the sole task to reach a target, i.e., a 2-dimensional task that fulfills its DOFs. In case of presence of an obstacle its avoidance is handled as deeply discussed in, e.g., [1].

The antennas are driven by resorting to the two mono-dimensional tasks of keeping the successive and precedent antenna connected. In this, case too, the presence of an obstacle may require to add the corresponding task.

Finally, a global supervisors is also in charge of handling failure of one antenna, in this case we have two, disconnected, chains that need to be connected again. This emergency situation is solved by changing role at some robots, in detail, the antennas before and after the failed one becomes agents and receive as task the reach-a-target one with desired target the last known position of the failed robot while the agent becomes an antenna and follow the free-floating chain it belongs too. Notice that, in case of a planar case, the failed antenna is probably stacked in its position and need to be avoided as obstacle while in case of a 3-dimensional problem the antennas failed down and its not present anymore in the area.

B. Tasks’ description

The expressions of the first 3 tasks are analytically similar, i.e., the control objective is a proper distance and they are, thus, mono-dimensional tasks. Concerning, e.g., the obstacle avoidance task, its expression is given by

$$\sigma_o = \|p_k - p_o\|,$$  \(9\)

where $p_o$ is the vector representing the closest point of the obstacle to the antenna. The Jacobian, and the corresponding null projector, can be easily derived from the analytical expression \(9\). It is worth noticing that the latter has a nice geometrical interpretation, it simply project the generic vector into the normal component of the vector $p_k - p_o$.

The tasks aimed at keeping the chain connected have an analytical expression close to \(9\) the only difference being the presence of the comfort zone and, obviously, the different desired values. Details can be found in [4]. Moreover, as explained in [2], it does have sense to keep separate tasks with different meaning but same analytical expression to gain the parameters tuning advantages of the NSB method.

The task to reach a target intrinsically requires to control all the DOFs of the agent. Its expression is simply given by the robot’s position; referring, e.g., to the agent, we do have:

$$\sigma_r = p_n.$$  \(\)  

This task can be used only alone or as secondary task of the mono-dimensional obstacle-avoidance one.

IV. Experimental setup

The feasibility of the proposed strategy was firstly analyzed via simulations considering a synthetic indoor-like environment and then experimentally tested using as antennas up to 4 Khepera II mobile robots available at the LAI (Laboratorio di Automazione Industriale) of the Università degli Studi di Cassino. The Khepera II, manufactured by K-team, are differential-drive mobile robots with a unicycle-like kinematics and with an approximative dimension of 8 cm of diameter. Each Khepera has a Bluetooth turret that permits communication with an external Bluetooth devices. In the proposed set-up, each robot communicates with a remote Linux-based PC, where a Bluetooth Dongle, building Virtual Serial Ports, allows the communication with up to 7 robots (see fig. 4). The remote Linux-based PC is aimed at implementing the NSB approach referring to a centralized structure.

The vehicles positions are measured resorting to a vision-based system, made up of two high resolution color cameras and two frame-grabber Matrox Meteor II, running on another Windows-based PC. In particular, the upper turrets of each robot have a set of colored LEDs that are used to detect positions, orientations and identification numbers of each robot. The position measurements are performed at a sampling time of 100 ms while the estimation error has an upper bound of $\approx 0.5$ cm and $\approx 1$ deg. Moreover, the vision system
permits to identify other elements, in our test a wheeled disk, that are used as mobile targets. The measurement is sent over the LAN to the Linux-based PC using the UDP/IP protocol.

Fig. 4. Experimental set-up available at the LAI (Laboratorio di Automazione Industriale) of the Università di Cassino.

Following the approach described in the previous Section, the NSB elaborates the desired linear velocity for each robot of the team. Because the Khepera are unicycle-like robots (and not omnidirectional), an heading controller has been derived from the controller reported in [14] to obtain wheels’ desired velocities. Thus, the remote Linux-based PC sends to each vehicle (through the Bluetooth module) the wheels’ desired velocities with a sampling time of 120 ms. The wheels’ controller (on board of each robot) is a PID developed by the manufacturer. A saturation of $40 \text{ cm/s}$ and $180 \text{ deg/s}$ has been introduced for the linear and angular velocities, respectively. Moreover, the encoders resolution is such that a quantization of $\approx 0.8 \text{ cm/s}$ and $\approx 9 \text{ deg/s}$ are experienced.

V. SIMULATIVE AND EXPERIMENTAL CASES STUDIES

As mentioned before, the strategy has been firstly largely analysed via a MATLAB based simulator. In this case the agent has to move inside several indoor-like scenarios to explore the different rooms. Antennas, as shown in Figure 5 and in the videos available at [http://webuser.unicas.it/lai/robotica/video/], have to suitably arrange to guarantee that the mobile agent be always connected with the base station. Moreover, to verify the effectiveness of the supervisor, some randomly chosen antennas fault, becoming further obstacles. In this event, as shown in Figure 5, the other antennas automatically re-configure to manage the “emergency” and to restore the connection between the agent and the base station.

Using the set-up described in the previous section we experimentally test the strategy using 4 Khepera II mobile robots that have to dynamically change their configuration to guarantee the connection between the base station and a mobile agent (one of the robots) following a dynamic target (in our case a wheeled disk pushed by hand).

As shown in Figure 6 (and in the video at [http://webuser.unicas.it/lai/robotica/video/]) the NSB based control strategy is able to handle both the static situation (i.e., the wheeled disk is at rest) and when it freely moves. Figure 7 reports some snapshots that illustrate how the mobile antennas modify their positions according to the agent task, while figure 6 reports several steps of the performed mission showing the comfort zones and the coverage ranges of each antenna.

Moreover, to verify the robustness of the algorithm, at a randomly selected time instant we induce the fault of one antenna (we cover the vehicle as illustrated in Figure 6, in this way the vision system is unable to identify it as a robot and considers it as an obstacle). As evident, the supervisor is able to manage this situation inducing a suitable re-allocation of the antennas. However, as the antenna recover its functionality (i.e., in our
test bed when the vision system is able to identify the robot, the antenna is re-introduced into the virtual chain (see also the video at http://webuser.unicas.it/lai/robotica/video/).

Fig. 8. Snapshots that illustrate the functionality of the supervisor while managing the fault of one antenna.

VI. CONCLUSION

This paper proposes the use of a platoon of mobile antennas to overcome some of the classical drawbacks of wired and wireless communication techniques in rescue scenario. Specifically, we suggest to adopt a multi-hop communication strategy to guarantee communication between rescue operators and a fixed base station. To this end, the mobile antennas have to dynamically reconfigure their position. This is achieved using the Null-Space-based Behavioral approach framework via the definition of suitable task functions. The strategy has been extensively analyzed in simulation and the paper illustrates some preliminary encouraging experimental results. Work in progress are devoted to experimentally test the strategy in an indoor environment and in a typical rescue scenario.

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