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Autonomous Navigation of Multiple Robots with Sensing and Communication Constraints Based on Mixed Reality

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Abstract
This paper presents a robotic navigation system that uses mixed reality concepts to develop sensing and communication virtual devices, based on the visual localization of the robot in the environment. The main objective of the navigation system is to provide conditions for the use of very simple robots with severe limitations on the mentioned peripheral devices for simulation, analysis and test of multi-robot applications. In an experiment with real robots, each one receives its virtual navigation skills in an independent way from the tool that emulates the function of such peripherals. Thus, the behavior of a group of robots, independently commanded, is implemented in the virtual environment and accomplished in the real world. An experiment composed by real multiple Sphero robots executing an exploratory task within an unknown dynamic environment is carried out to validate the proposed navigation system. The use of mixed reality concepts allows an easy implementation of cooperation mechanisms based on indirect communication skill and fuzzy controllers for the robots' movement. The results confirm the feasibility of the proposed autonomous navigation system.

Keywords Multi-robot systems · Mixed reality · Indirect communication · Autonomous navigation

1 Introduction

Multi-robot systems (MRSs) are an active research field of robotic applications, where multiple robots are used for cooperative tasks, and they are able to achieve a common objective by means of local objectives within a shared environment (Sabattini et al. 2017).

A successful design of a MRS requires debugging, testing and validating steps. In general, these design steps encompass exhaustive simulated and real experiments. Simulations provide a flexible implementation with more controlled environment conditions in which several situations (e.g., experiments with increased levels of complexity) can be easily essayed and also consuming less experiment time. Otherwise, experiments involving real robots inserted into real or laboratory-scaled environments present a more realistic situation, including noises, device failures and other unexpected events. However, real experiments frequently present limitation to gather all information from multiple robots and environment in real time. Thus, the use of specialized, but expensive, hardware is essential to assure the accomplishment and validation of new developments in this area (Millard et al. 2018; Reina et al. 2015).

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Nevertheless, when a robotic application requires multiple robots endowed with customized and/or sophisticated hardware, the developing and production of such devices may be expensive and demand a considerable amount of work, and thus, the realization of several experimental tests is unfeasible (Reina et al. 2015). In this context, it is desirable that the designer has an alternative way to test the basic operation of such devices and confirm their validity within the intended experiment, before prototyping or acquiring them.

In face of such drawbacks, mixed reality systems are valid approaches to complement an experiment that involves real robots, providing a virtual layer in which all peripheral devices for sensing, communication and other purposes are virtually implemented (Hönig et al. 2015). In Millard et al. (2018), for example, a mixed reality tool is proposed to analyze different information obtained from a team of real robots. The authors highlighted the difficulties to interpret a set of swarm data, in real time, when there is no virtual tool to support it. A virtual environment is developed for a swarm composed of Kilobot robots in Antoun et al. (2016) and Reina et al. (2017). Several characteristics of virtual sensing and communication are discussed in these papers. Virtual sensing characteristics are also focused on Reina et al. (2015), supporting tests involving real robots and virtual devices before prototyping. The experimental platform proposed in Arvin et al. (2015) provides implementation of artificial pheromones also in a virtual layer, displayed on a LCD screen.

Specifically, an architecture based on mixed reality for robot soccer applications is presented in da Silva Guerra et al. (2006), da Silva Guerra et al. (2007b) and extended for research and education purposes in da Silva Guerra et al. (2007a). In this architecture, a large number of robots are commanded by a centralized controller with individual scripts for each robot. However, there is no description on how this architecture could be used for an application in which the environment is semi or completely unknown, as it is addressed in the present work. In Gerndt et al. (2008); Simões et al. (2011), the mixed reality approach is also addressed for robot soccer applications and their variations, with more details about the control strategies for robots' locomotion (trajectory and collision avoidance models). Once again, the issues concerning a limited knowledge about the environment are not approached. Moreover, no discussion about the implementation of virtual communication (direct and indirect form) mechanisms is carried out in these papers.

As the above cited works, this paper is also concerned with alternative methods to implement virtual features, by means of mixed reality concepts, in experiments involving real robots with limited hardware. Different from these works, our proposed mixed reality system can be used for navigation at completely or semi-unknown environment. Furthermore, the setup presented by some cited papers considers a LCD display (Arvin et al. 2015; da Silva Guerra et al. 2006, 2007b; Santos et al. 2017) that limits the environment's area, while our setup lays on the USB camera limitation.

Thus, the main contribution of this paper is the development of a complete navigation system based on mixed reality (Millard et al. 2018; Reina et al. 2015; Hönig et al. 2015), specially for MRS applications. Besides the sensing and locomotion skills, this system focuses on direct/indirect communication skills between the robots, as an enhancement of Arvin et al. (2015), in which virtual elements can be inserted in the real environment, and they can be used to model the interactions between the robots and/or with the environment. Therefore, a team of robots within this environment do not need to have any real peripheral devices (sensors, communication devices, among others) and motion controllers, since these abilities are virtually implemented by the mixed reality system. All navigation events are performed in a virtual layer, and they are passed to the MRS management and control layer, in order to translate the resulting actions to the real world. The proposed navigation system employs simple and easy-to-use components, such as USB camera, computer with Robot Operating System (ROS[1]) framework (Quigley et al. 2009) and ARTag identifiers (Fiala 2005), and also all robots are independently controlled by Bluetooth.

Through the proposed approach, the main function of peripheral devices for sensing and communication purposes can be virtually tested in real robots within a real environment. As a result, the performance of a MRS (individual and collective autonomous behaviors of the robots) can be easily and low-costly analyzed and validated before prototyping.

In order to demonstrate its functionalities, the navigation system based on mixed reality is used to analyze the cooperative behavior of the MRS application presented in our former paper (Almeida et al. 2019). In this case, a MRS must explore an unknown environment searching for as many way-points as possible. Only simulated results have been presented in Almeida et al. (2019) to validate the proposed exploration strategy. The requirements for a real implementation of this approach encompass sensing and communication abilities (direct and indirect form), which can be virtually reproduced by a mixed reality system, as proposed in this paper.

This work is organized as follows: The experimental setup used to develop the navigation system is described in Sect. 2; the proposed navigation system based on mixed reality is described in Sect. 3; an overview of the MRS used to illustrate the navigation system performance is presented in Sect. 4, and Sect. 5 brings the main experimental results, while the conclusions and future works are addressed in Sect. 6.

[1] http://wiki.ros.org.

2 Experimental Environment and Mobile Robots Description

The experimental setup used to develop the mixed reality system has the following components: (i) a rectangular plane environment, virtually marked at floor, whose dimensions support the inclusion of multiple small size robots and other objects (goals and obstacles, for example); (ii) an USB camera, positioned above the environment; and (iii) a computer with ROS packages. An overview of this setup is shown in Fig. 1.

All objects within this environment (robots, obstacles, goals, etc.) are identified by detectable visual markers (ARTag), so that the marker's position is the current position of the element during the experiments. The USB camera captures an image of this environment setup to be processed by the computer with ROS packages. From this point, a mixed reality layer is designed to confer virtual characteristics to the real objects in the environment. In special, the robots receive virtual devices that enhance their sensing, autonomous locomotion and communication skills. Data exchange between real and virtual world is mediated by the framework ROS with specific packages. The real and virtual mixed data are used to run individual scripts to each robot, in order to achieve a decentralized behavior and allow a complete analysis of the essayed MRS. An overview of this operational flow is presented in Fig. 2, in which the MRS to be essayed can be coded in any language or tool (C++, V-REP, Gazebo, MATLAB, LabVIEW, etc.), as long as the coded MRS is able to communicate with ROS.

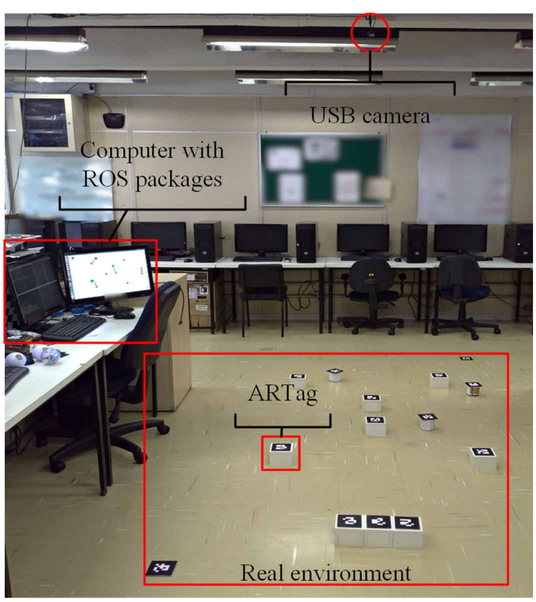

Fig. 1 The experimental setup

2.1 Sphero Robot Description

In this paper, a team composed of Sphero robots[2] (Fig. 3) is used to support the development of our autonomous navigation system based on mixed reality. However, any type of robot can be used in the experiments, provided it has an associated ARTag (Fiala 2005) and Bluetooth communication.

The Sphero robot is a very simple mobile robot with differential drive and enclosed in an impact resistant plastic shell with spherical shape. Its interface is originally designed to provide communication between the robot and an Android device implementing only the manual control of the Sphero. Although this interface supports data sending and receiving, it does not have a way to reprogram its hardware. Moreover, this robot has no peripheral devices to detect obstacles with a safe distance. Instead, a Sphero has only one collision sensor, which requires contact to register such an occurrence.

A ROS package named *sphero_swarm*[3] is available to enable the communication between Sphero robots and a computer, being able to send velocity and orientation commands to the robots through specific ROS topics. This package makes possible the use of Sphero robots in our MRS developments.

Indeed, Sphero robots were chosen to this paper implementation due to their low cost and limited sensing and communication abilities. The mixed reality system is used to virtually confer to the Sphero robots all skills required by the navigation system to be experimented.

2.2 Objects Identification

As discussed above, all robots and other objects within the environment are represented through ARTags that are visual markers as shown in Fig. 4.

The ARTags consist on bicolor patterns that encode an unique identifier, and they are detected by a ROS package named *ar_track_alvar*[4] from a digital image provided by the USB camera. When markers are detected, this package publishes every marker's identification with their position in a specific ROS topic. Each tag used in this platform has 94 mm × 94 mm (Fig. 4b).

The package *ar_track_alvar* assumes the center of the detected image as the reference point coordinate (0,0)) to publish the ARTag position to the ROS topic. In the proposed mixed reality system, this reference point is converted into the ARTags located at the environment corners, and all other elements within this environment have their position based on this reference.

[2] https://sphero.com/collections/for-school

[3] https://github.com/darin-costello/sphero

[4] http://wiki.ros.org/ar_track_alvar.

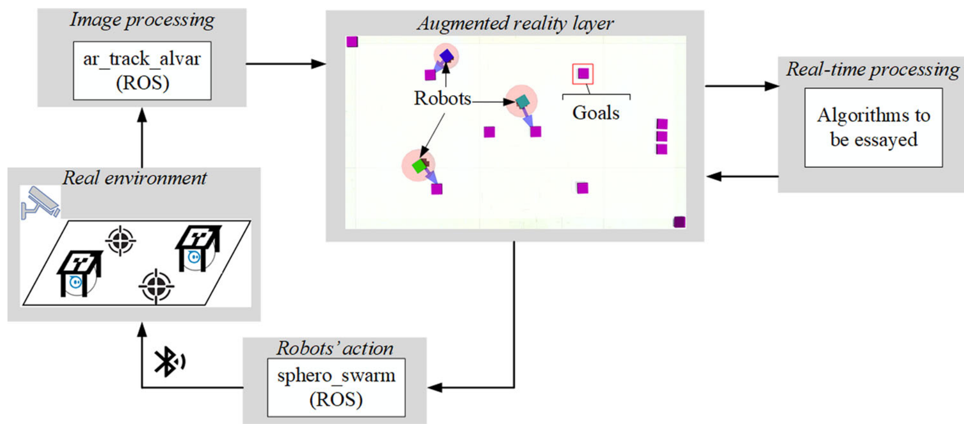

Fig. 2 Operational flow of the navigation system

Fig. 3 Sphero robot

Due to the spherical shape of the Sphero robot, an appropriate sized structure was build in a 3D printer and coupled to this robot, as shown in Fig. 4a, so that its ARTag is always available to the camera as the robot moves.

3 Autonomous Navigation System Based on Mixed Reality

Each real robot in the environment is virtually endowed with a proposed navigation system that is composed of a sensing module (to detect and identify other objects), a communication module (to locally interact with other robots, by means of direct and indirect communication mechanisms) and a motion control module that computes the robot's velocities at each time iteration. These modules imply navigation skills, and they are conferred to the robots according to their ARTags' identification and position. In summary, each robot has its own navigation system that runs in parallel at ROS shell from the central computer.

Indeed, all the MRS data processing occurs in the central computer (see Fig. 1) that executes all the steps of Fig. 2: processing of the image captured by the USB camera, assigning of the virtual characteristics to each robot, computing of control strategy and then sending commands to move all robots. However, all modules are implemented in individual scripts in C++, running in the navigation system through ROS nodes and according to the *ActionLib* framework (Santos et al. 2017), where the client–server paradigm is intermediate by ROS and allows the robots to process a task in preemptive way with standardized messages. Therefore, the individual scripts aim to emulate that each robot executes its own script to perform each skill of the navigation system, achieving a decentralized behavior.

Finally, the mixed reality layer gathers all available information and builds a virtual environment that mixes real (robots, targets, obstacles) and virtual (detection areas, pheromones trails) elements. This layer corresponds to a visual interface in which the user can observe the entire MRS behavior and/or each robot individually.

The sensing and communication modules, the fuzzy controllers composing the motion control module and the mixed reality layer are detailed below.

3.1 Sensing Module

The main objective of the sensing module is to provide the robot an ability to detect objects around it and to calculate the risk of collision with those, as occurring in the majority of real proximity sensors.

To emulate the operation of such sensors, a fixed detection range is adopted to each robot, forming a circular region around it, whose center is the current robot's position (ARTag position) and with a radius of D_{Range}. When any detectable object is within the detection range, the robot is able to know if it is to its left, front or right side, and also calculate the Euclidean distance between its current and object's position. When one or more objects are detected in this way, a collision imminence intensity ([0, 1]) is computed to each one, according to the Euclidean distance previously calculated and normalized by D_{Range} value. In this sense, an intensity 0 (zero) means that the detected object is out of the robot's detection range and it does not offer a risk of collision, while an intensity close to 1 means that the detected object is very

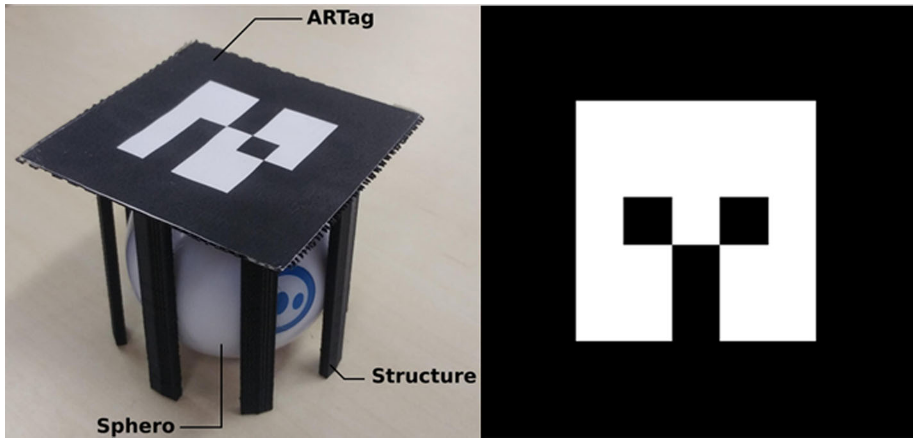

Fig. 4 **a** Structure developed to support the ARTag. **b** ARTag example

close to the current robot's position and it offers a dangerous risk of collision. A robot can identify if the detected object is a goal, a static obstacle and/or other robot (dynamic obstacle).

3.2 Communication Module

The communication module runs after detection and identification procedure (sensing module) and allows the information exchange between the robots in two ways: directly among two or more robots, within the detection range, and/or indirectly through environment markers.

When other robots are detected within the detection range, all involved agents are able to share simple information among them, such as the objects detected by each one and their navigation status (their workload, if they are going toward a goal, exploring the environment, and other tasks). A transitive characteristic is added for this information sharing, as illustrated in Fig. 5, where there are 3 robots (R1, R2 and R3) and 4 goals (G1, G2, G3 and G4). In this example, G1 is indeed detected by R1 and it is shared to R2 by direct communication and to R3 through transitive information sharing (R2 shares G1 detection with R3); G3 is detected by R2 and R3, and this goal is shared with R1 from R2; G4 is detected by R3, and it is shared to R2 and R1 through direct communication and transitive way, respectively; and G2 is not detected by any of them.

This communication is implemented through ROS topics. Each robot publishes in specific ROS topics a list composed of the position of all objects detected by it and other information, according to the requirements of the intended application. These data can be accessed only by the robots involved in the direct communication interaction (within the robot's detection range), allowing the information sharing among them, including the transitive aspect. This implementation is exemplified in Fig. 6, where R1 and R2 publish their detection list (blue dashed line) and subscribe the list published by the other robot (red dashed line). R3 only publishes its list, and it is not subscribed by any other robot. In this situation, robots R1 and R2 share information between them and R3 does not communicate with any other robot.

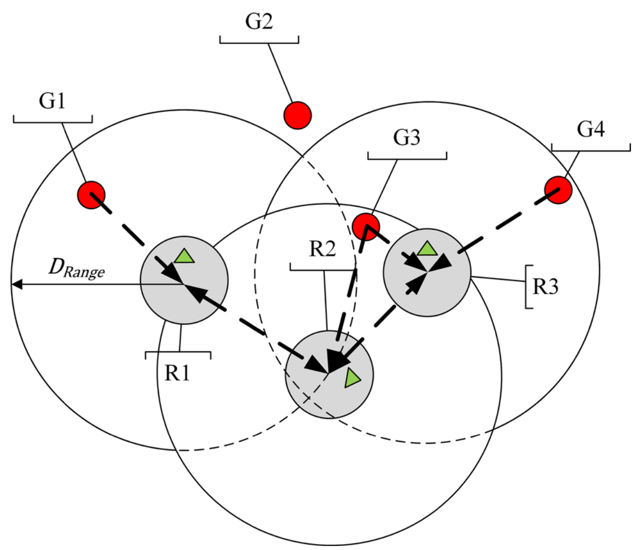

Fig. 5 Detection and communication skills

The robots can also share information through indirect communication mechanism. In this paper, such mechanism is inspired on ants' stigmergic behavior, mediated by changes (markers) in the environment. The robot travels throughout the environment, leaving pheromone that acts as a marker to the other robots. These markers (artificial signals) create a path or trail in the environment. Thus, a communication is locally established by the agents visiting those environment changed areas (Dorigo et al. 2006).

The herein considered pheromone model is according to the Ant Systems (AS) (Dorigo et al. 1996), and it is described by Eq. (1), where $\sigma\ (k)$ is the pheromone existing over an area, at k moment; ρ is the evaporation rate; and $\Delta\sigma\ (k)$ is the quantity of pheromone released at moment k. Thus, a pheromone trail released by a generic robot [Eq. (1)] corre-

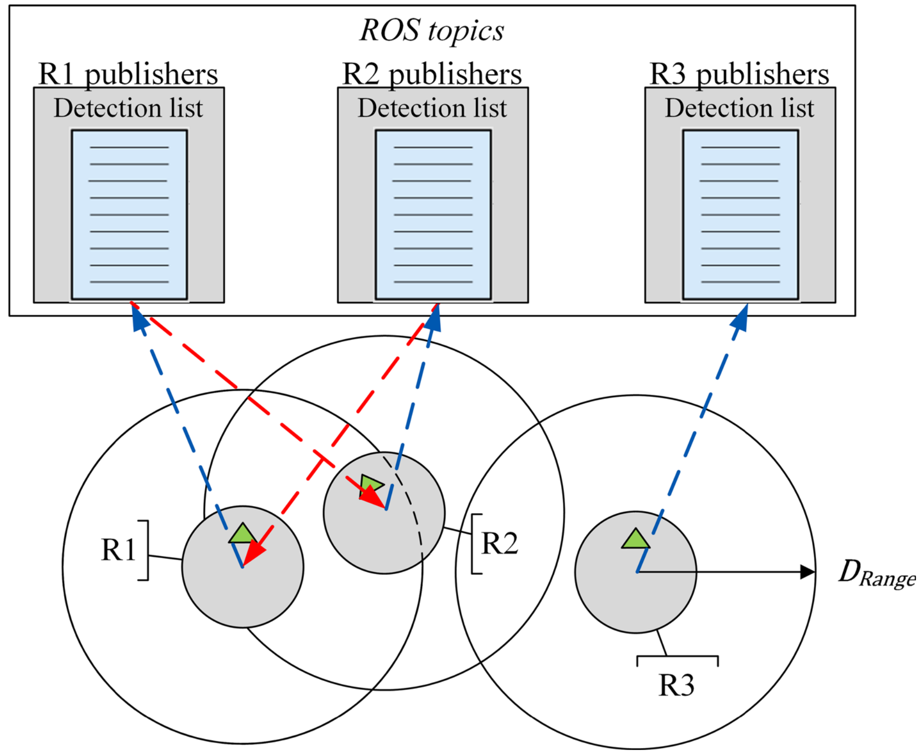

Fig. 6 Robots sharing information through ROS topics: R1 and R2 publish their detection list (blue dashed line) and subscribe the list published by the other robot (red dashed line), while no other robot is close enough to R3 to subscribe its detection list (Color figure online)

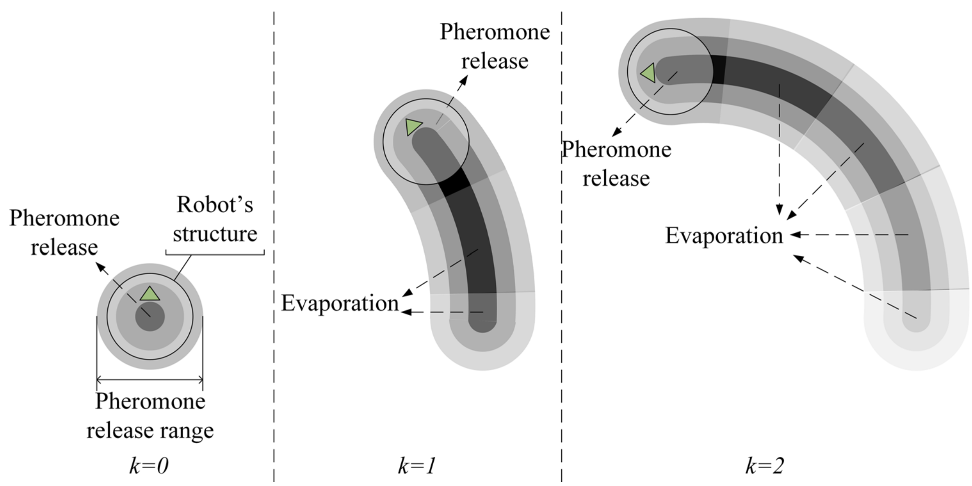

Fig. 7 Illustration of a pheromone trail

sponds to a marked trajectory as shown in Fig. 7.

$$\sigma\,(k) = (1-\rho)\cdot\sigma\,(k-1) + \Delta\sigma\,(k) \quad (1)$$

In our mixed reality platform, the virtual pheromone signals can represent a chemical plume, or a chemical product released in the environment floor, or another way to temporarily change the state of a region of the environment. The artificial pheromone representation is based on a grid map build with the ROS packages *OccupancyGrid* and *costmap_2d*[5]. This grid also uses the previously mentioned corners ARTags as reference. Its resolution is about 0.02 m/cells. Each grid's cell is able to store and make available a range of values, meaning different intensities to a virtual marker, in order to represent the evanescent effect of artificial pheromones (Dorigo et al. 2006).

Therefore, all robots are able to deposit their mark in the grid cells as they move in the real environment. To do this, the ARTags' position (robots' position) in the real environment is converted to the grid map and all distance measurements are computed in terms of number of cells. The value stored in each cell of this grid is published in appropriate ROS topics, and each robot is able to access these data, provided that the

[5] http://wiki.ros.org/costmap_2d.

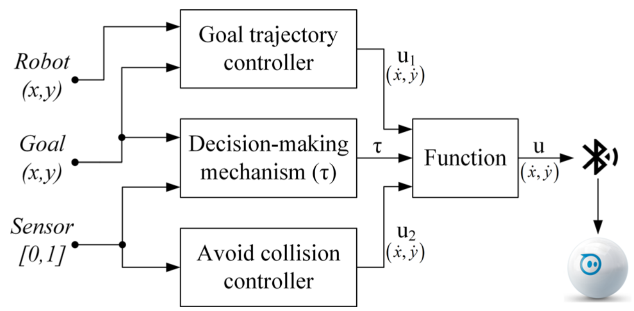

Fig. 8 Fuzzy control system

cell is within its detection range, as occurring in the previously described detection skill.

3.3 Fuzzy Motion Control

An independent fuzzy system is designed for each robot to provide its motion. This fuzzy system receives information about the current robot's position, a position to reach (goal) and nearby obstacles to compute the robot's wheel velocities toward the goal with obstacles deviation. The complete motion system is composed of two fuzzy controllers and a fuzzy decision maker, as presented in Fig. 8.

The "goal trajectory controller" is a PD-fuzzy controller (Passino and Yurkovich 1998), and it uses the difference (error) among the robot and goal's coordinates (x, y) to generate the control action $\mathbf{u_1}$ (velocities $\dot{x}$ and $\dot{y}$) to provide a motion toward the goal position. The input for "avoid collision controller" is composed by the data obtained from the nearest obstacle detected by the robot, that is, the intensity [0, 1] for a collision imminence and if it is on the left, front or right side of the robot. The output consists on the control action $\mathbf{u_2}$, aiming a deviation behavior from the obstacle (the robot maneuvers to an opposite side of the obstacle).

The information about the goal's position and the intensity of the nearest detected obstacle is also used to compute a decision-making variable (τ), which weighs the response of the other two modules and determines the effectively control action ($\mathbf{u}$) to be applied on the robot, according to Eq. (2), where: $\mathbf{u} = \left[u_x \; u_y \right]^{\mathrm{T}}$; u_x and u_y are control actions aiming the movements in the coordinates x and y, respectively. $\mathbf{u_1}$ and $\mathbf{u_2}$ have analogous notation.

$$\mathbf{u} = (\mathbf{u_1} \cdot \tau) + [\mathbf{u_2} \cdot (1 - \tau)] \qquad (2)$$

This decision-making mechanism is developed to achieve the following response: (i) τ has a high value when the obstacle is more distant than the goal; (ii) τ has a low value when the goal is more distant than the obstacle; and (iii) τ has a medium value when both distances are similar. A more detailed description of this fuzzy system, including memberships sets and rule bases, can be found in Almeida et al. (2019).

The resulting control action is published in a ROS topic of the *sphero_swarm* package, and it is sent to each Sphero robot through Bluetooth communication, as presented in Fig. 8.

3.4 Mixed Reality Layer

Finally, the virtual representation of the real environment is presented through the visualization ROS package *RViz*[6] in a mixed reality layer, allowing the user to distinguish all ARTag markers inserted into the environment, mainly to visually differentiate a robot from other objects and to observe the features related to the robots' navigation system, such as the detection range of each robot, planned and developed trajectories, a pheromone deposition, and others.

For illustration purpose, the experimental setup previously presented in Fig. 1 has its virtual representation (90° counterclockwise turned) shown in Fig. 9, where all robots (blue, light green and dark green squares) compute their trajectories (blue arrows) toward a detected goal (pink squares), and deposit a virtual marker (small size black squares) in the environment.

4 Essayed Multi-robot System

We emphasize the goal of the developed mixed reality system. It is a test bed for simulation, analysis and test of multi-robot applications, allowing the use of small and cheap robots without sophisticated peripherical devices. In this system, an experiment combines real robots and virtual components. The complete knowledge about the environment during an experiment allows the user or the MRS designer to analyze if his MRS behaves as designed. As example, the MRS path planner developed by Almeida et al. (2019) is considered to illustrate an implementation of a real MRS running under the proposed navigation system. All robots requirements and planning strategies are taken from Almeida et al. (2019), where multiple robots with sensing, locomotion and communication (direct and indirect) skills must explore an unknown dynamic environment looking for way-points with unknown position, while deviating from static and dynamic obstacles. The analysis of such MRS will be described in two parts: In this section, an overview of the MRS goals and tasks is described and the main details on how this MRS is implemented with this tool are also presented; and an analysis of the MRS behavior and the validation of the proposed navigation system are presented in Sect. 5.

[6] http://wiki.ros.org/rviz.

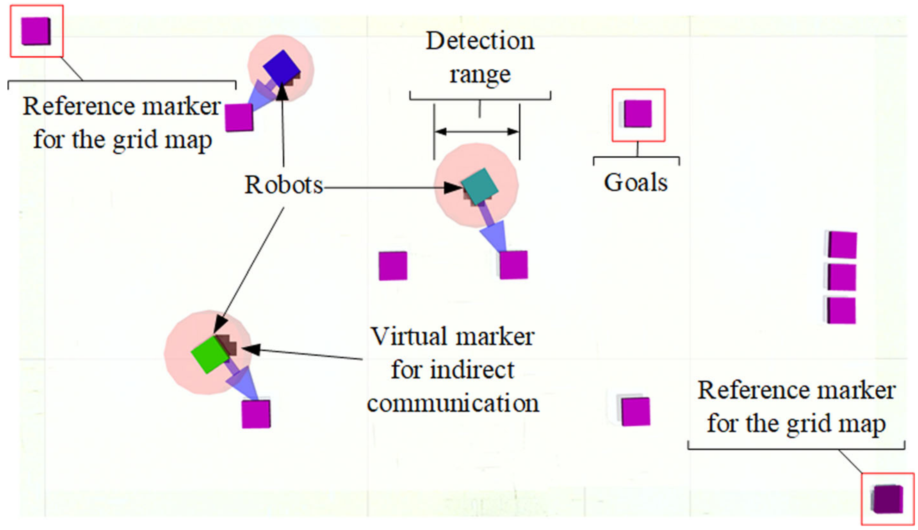

Fig. 9 Experimental setup through the mixed reality layer

4.1 Description of the MRS Tasks and Goals

The main objective of the MRS described in Almeida et al. (2019) is to cooperatively explore an area in an optimized way, in order to find and visit as many way-points as possible during navigation. Way-points are points of interest and may represent victims of a tragedy, land mines, work stations, points of obligatory passage, among others objectives. In this area, there are static and dynamic obstacles from which each robot must deviate to avoid collision and preserve its physical integrity. Everything inside this environment (way-points and obstacles) is unknown to the robots, except their initial and final positions.

All robots perform direct and indirect communication to achieve the mentioned objective in a cooperative way. During direct communication between two or more robots, they apply a policy aiming to equalize the workload assigned to each involved robot, that is, the number of way-points already reached by each one. For the indirect communication, each robot is able to detect and release artificial pheromones during its movements. These signals are used to mark explored areas by the robots, in order to avoid redundant exploration task, as a repulsive behavior.

The presented strategy encompasses a decision mechanism composed of 4 different deliberative decisions, named D1, D2, D3 and D4, as shown in Fig. 10. D1, D2 and D3 compute a trajectory (only one of them is activated), while D4 calculates a path correction due to the pheromone presence, if it is necessary. Only one decision is taken at a time according to the making-decision procedure detailed in Almeida et al. (2019).

The final result of a decision (D1, D2 or D3 and D4) is a goal ((x, y) coordinates of way-point, area to be explored, or end position) and a path with one or two segments (caused by pheromone presence) to reach this goal. From this, each robot computes the appropriate control actions to follow this path and/or avoid collision with obstacles, through its own locomotion control system.

4.2 Detection and Communication Issues

Regarding the detection skill, all robots (ROS nodes) subscribe the position of all ARTags detected by the camera (way-points and robots). However, only those within their detection region are considered effectively detected. It is assumed that the undetected objects (outside the detection region) are completely unknown to the robot. This procedure highlights the detection range importance to define the knowledge about the environment, so that the emerging behavior of each robot is resulting only from its local knowledge.

Direct and indirect communication skills are assigned to the robots. The direct form occurs exactly as illustrated in Fig. 6. The indirect form, through pheromone releasing, is implemented using the grid map illustrated in Fig. 9, and it occurs according to a circular release range around the robot (Range_P), measured in a number of cells. Similar to Fig. 7, the pheromone intensity is strong (1) in the center of the trail and decays to zero (0) along the radius extension. Analogous to Eq. (1), the intensity of the pheromone released in the environment point (x, y), at instant k, is implemented through Eq. (3), where Dist_P is the distance between the cell to be updated and the robot's center.

$$\sigma_{x,y}(k) = \begin{cases} (1-\rho)\cdot\sigma_{x,y}(k-1) + \left[1 - \left(\frac{\text{Dist}_P}{\text{Range}_P}\right)\right] & \text{if } \text{Dist}_P \le \text{Range}_P \\ (1-\rho)\cdot\sigma_{x,y}(k-1), & \text{otherwise} \end{cases} \tag{3}$$

The local information obtained from detection and communication skills is used to implement the decision procedure

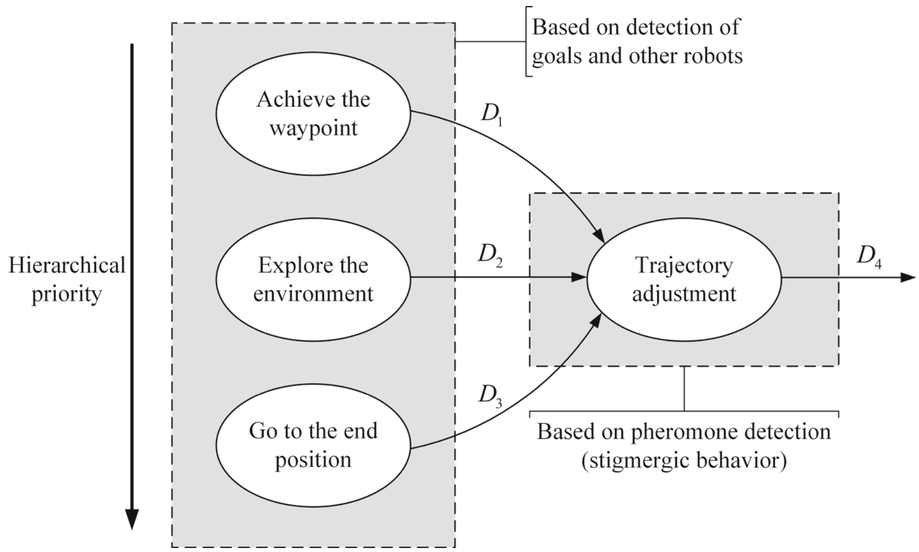

Fig. 10 Decision-making mechanism

presented in Fig. 10, through the scripts designed in the *ActionLib* framework. In this case, each robot computes a trajectory to achieve a way-point (decision D1), or an unexplored area (decision D2) or its end position (decision D3), while deviates from pheromone signals (decision D4), if it is necessary. After this deliberative decision, the robot uses the fuzzy control system presented in Fig. 8 to calculate its movements toward its goal.

5 Experimental Results

In this section, the proposed navigation system based on mixed reality is validated. It is firstly evaluated if this experimental tool is able to provide the required skills (sensing, communication and autonomous mobility) to a MRS, through the mixed reality system as established in Sect. 2.2. For this, the real experiment considers only 1 robot and several way-points scattered in the environment. The objective is to evaluate the performance of the robot's navigation system when it decides to move toward a determined goal, while detects way-points and avoids collision with obstacles. The robot deposes pheromone during its traveling, but the absence of other robots prevents the evaluation of this communication module. The second experiment considers a group of robots and several way-points to be visited. In this case, communication skills are evaluated, mainly the emerging stigmergic behavior due to the use of repulsive artificial pheromones (indirect communication). In this second experiment, the MRS path planner of Sect. 4 is implemented and the respective video is available on Youtube[7].

[7] https://youtu.be/BgoTA0FDzgQ

5.1 Experiment 1: Analysis of the Robot's Navigation System

The robot's navigation system is evaluated using only a single Sphero robot. In this case, the initial configuration of this experiment is presented in Fig. 11a, where there are: 1 robot (green square), 4 way-points with unknown position and a determined robot's end position (pink squares). The mixed reality system helps to highlight the robot's detection range (circle around the ARTag), while the blue arrow indicates the current goal position.

In this experiment, the robot must achieve as many way-points as possible, avoid collision with obstacles and finish navigation at the end position. The way-points become static obstacles as they are reached by the robot. The frames presented in Fig. 11a–f show the navigation evolution until the robot reaches its end position.

The robot (R) at initial position (Fig. 11a) does not detect any way-points (W1, W2, W3 and W4), and therefore, it computes a direct trajectory to its end position. As R follows its first path, W2 is detected and a maneuver toward it is carried out, as shown in Fig 11b. After R reaches its first way-point (Fig 11c), W2 is considered as a static obstacle and the robot makes a detour maneuver over its right side to avoid collision and consequently W3 is detected. After reaching W3 (Fig. 11d), R computes its next trajectory to its end position, because no other way-point is detected. Along robot's path, W4 is detected and R recalculates a new path to reach this way-point, as shown in Fig. 11e. It is possible to see through the pheromone trail that R also deviates from W2, previously reached. Finally, Fig. 11f shows that R avoids collision with W4 after catching it and finishes its navigation at the determined end position. W1 was not detected during this navigation. Although R releases pheromones in the envi-

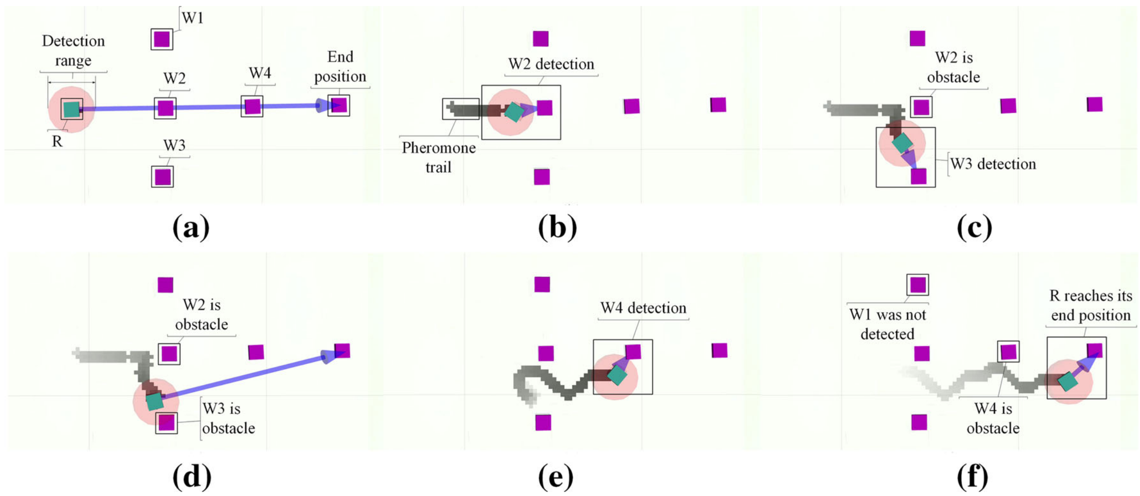

Fig. 11 Navigation results of experiment 1 (Color figure online)

ronment, these signals do not influence the robot's navigation in this experiment.

The results from the experiment 1 show that the proposed navigation system effectively provides a mixed reality (real and virtual features) in which a robot with severe sensing limitations, like Sphero robot, can be used in an experiment requiring missing but necessary resources. It is possible to see the robot following a trajectory to a goal, detecting and making decisions to avoid obstacles, maneuvering in face of an imminent collision, and other behaviors.

5.2 Experiment 2: Analysis of the Stigmergic Behavior in the Multi-robot System

In this experiment, several Sphero robots compose an MRS and the stigmergic behavior for cooperative exploration is evaluated. The decision-making mechanism (decisions D1, D2, D3 and D4) illustrated in Fig. 10 is implemented for this task, as well as the required direct and indirect communication strategies. This experiment has its initial configuration presented in Fig. 12a, where 3 robots (R1, R2 and R3) must navigate within an environment containing 6 way-points with unknown location (W1, W2, W3, W4, W5 and W6) and reach their end position to conclude the MRS' objective. This experiment addresses a task of area exploration, and its evolution is presented throughout the set of frames shown in Fig. 12a–i. It is important to notice that when a way-point is visited by a robot, its status is changed to "reached way point" which leads the other robots to consider it only as a static obstacle. Such flag left by the visiting robot is also an example of indirect communication. The environment is modified by the agent, and this information is indirectly shared with the others agents. In the real experiment, the way points are small wooden cubes with an ARTag in the top (see Fig. 1). After visiting a way point, the robot changes the class of object associated with the cube's ARTag from way-point to obstacle.

Initially, a high concentration of pheromones near the initial position of each robot causes a dispersion behavior, as observed in the computed individual trajectories (blue arrows) in Fig. 12a. In this case, all robots directly share information about their decisions, and the following behavior occurs: R1 and R3 make decision on explore the environment (D2 activation) and carry out maneuvers in opposite sides of the other detected robot; and R2 maintains its computed trajectory to its end position because it has detected robots in both sides. In addition, trajectory corrections due to pheromone detection (D4 activation) are carried out by R1 and R3.

Right after dispersion, the robots can compute new trajectories to their end position (D3 is fired), as presented in Fig. 12b. So far, no way-point has been detected. The first detection occurs in Fig. 12c, when R2 detects W1, and therefore, the decision D1 is fired. R1 and R3 maintain their previous computed trajectory.

Pheromone signals influence R2 and R3's behavior in Fig. 12d. Specially for R2, two important events occur simultaneously: R2 must avoid collision with W1, while detects pheromone signals released by R3. Since no other way-point is detected by R2, D3 is fired to compute the new trajectory to the end position, while D4 decision is also fired to adjust this path and avoid areas that had been explored before by R3. Due to a high risk of collision with W1, the R2's fuzzy controller prioritizes an obstacle deviation maneuver, modifying its trajectory. On the other hand, R3 detects the pheromone signals released by R2 and adjusts its trajectory to take distance from the marked area. R1 maintains its previous decision (only D3 activation).

While R2 performs the mentioned deviation maneuver, R1 does not detect W2 and follows to its end position until

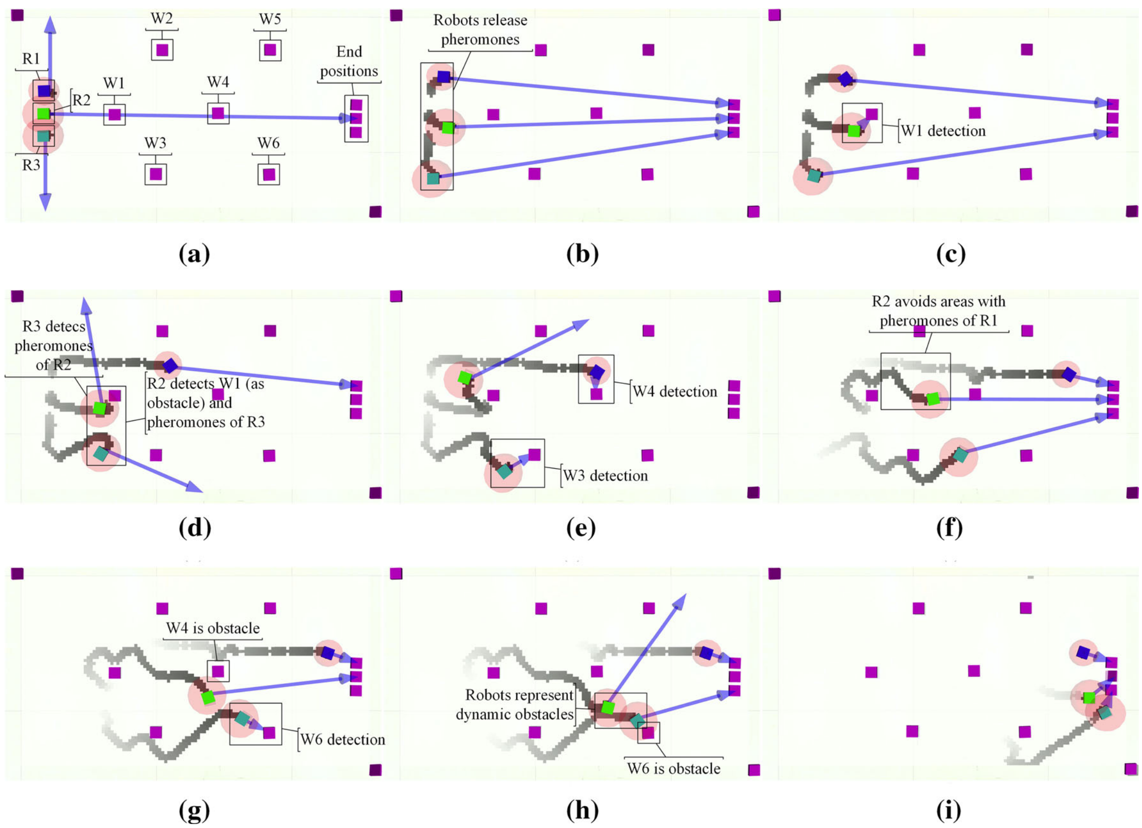

Fig. 12 Navigation results of experiment 2

W4 detection. In parallel, R3 detects W3, as presented in Fig. 12e. After robots reach W3 and W4, Fig. 12f shows that R1 and R3 resume their trajectories to end position (D3 activation), while R2's pheromone trail confirms its deviation from pheromones released by R1 (D4 decision adjusts the trajectory). After this, the R2's path to end position is resumed (D3 is fired).

In Fig. 12g, R1 reaches its end position and does not detect W5. Simultaneously, R2 performs maneuver to avoid collision with W4, previously reached by R1, and R3 detects W6. After R3 reaches W6, it must deal with the approximation of R2, which is considered a dynamic obstacle, and also with the presence of W6 that is an static obstacle, as shown in Fig. 12h. As a consequence, R3 decides to pass through the bottom of the environment to achieve its end position (Fig. 12i). Finally, all robots reach their end position in Fig. 12i, and only 2 waypoints (W2 and W5) remain unreached.

In face of these results, we verify that the proposed platform also provides a reliable tool to implement a stigmergic behavior in the MRS navigation. Moreover, direct and transitive communication ways are also successfully implemented. We still verify that a MRS requiring sophisticated skills can easily be tested without the use of dedicated hardware. And we can conclude that such navigation system is a flexible tool supporting MRS design.

6 Conclusion

This paper proposed an autonomous navigation system to MRS, based on visual localization (ARTags) and mixed reality system, using framework ROS. This tool makes feasible experiments involving multiple robots with sensing and communication constraints, contributing to reduce time and costs and facilitating the debug, test and validation of hardware and/or software (specially related to sensing and communication devices) to be used in MRS design.

This platform uses an USB camera and ARTag markers, associated with each object inserted in the experimental scenario (robots and other elements), to provide environment mapping, including robots' localization. From this mapping data, a mixed reality environment is build in which sensing, locomotion and communications robots' skills are implemented in a virtual way, and independently associated with each real robot in real time. Thus, an experiment using this platform takes advantage of mixed reality concepts for robotics, where simulated characteristics complement an experiment involving real robots.

An experiment using a MRS composed of Sphero robots was presented in this paper, in order to validate the platform's features. The bio-inspired path planner developed by Almeida et al. (2019) was used to manage the essayed

MRS. Although Sphero robots have no peripheral devices to sensing and communication, the autonomous navigation system worked as expected. All requirements concerning object detection and identification, direct and indirect communication, specially pheromones releasing and detection, necessary to run the navigation system, were implemented in the mixed reality layer.

From the presented results, we can observe that the Sphero robots were able to accomplish exploratory tasks in a distributive and collaborative way such as a sophisticated robot. In particular, the emergence of a stigmergic behavior is achieved by the MRS due to the ability to handle with virtual pheromones. This results show the potential and flexibility of the proposed tool.

As in any real experiments, several unexpected conditions, such as environment luminosity, abrupt maneuvers and nonlinearities in the Sphero robot's movement, among others, can affect the ARTag detection and, consequently, also affect the robots' performance, making it difficult for MRS analysis. In this sense, future works will address improvements in the mixed reality system, so that alternative robots localization approaches, errors correction procedures, a decentralized processing, and others can be considered.

Finally, we are now working in the adaptation of the mixed reality system presented in this paper for the development of smart warehouse and also for cooperative cargo transportation, performed by an aerial drones' fleet.

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