Bio-inspired Distributed Sensors to Autonomous Search of Gas Leak Source

Ronnier Frates Rohrich[1], Luis Piardi[1,2], José Luis Lima[2,3] and André Schneider de Oliveira[1]

***Abstract*— This work presents multiple small robots in an unhealthy industrial environment responsible for detecting harmful gases to humans, avoiding possible harmful effects on the body. Mixed reality is widely used, considering that the environment and gases are virtual and real small robots. Essential components for the experiments are virtual, such as *gases* and *BioCyber-Sensors*. The results establish the great potential for applications in several areas, such as industrial, biomedical, and services. The entire system was developed based on ROS (Robot Operating System), thus the ease in diversifying different applications and approaches with multiple agents. The main objective of small robots is to guaranty a healthy work environment.**

***Index Terms*— BioCyber-Sensors, Small-scale mobile robot, Mixed Reality, Gas Detection**

I. INTRODUCTION

Many segments of science can benefit from the development of small-scale robots, both with quantitative and qualitative gains. For example, some applications present satisfactory results, such as [1], optimization technique using a swarm of robots could improve the transport, loading, and unloading bays in a warehouse. Time and productivity have been increased in that work. Inside of bio-medicine, nanorobots stand out within the application in the treatment of diseases that affect humans, as presented in [2]. However, it is not merely building a scenario with small robots and a realistic environment to perform tests and experiments. A methodology using Mixed Reality associating these two issues allows applications close to the real world, but with more safety, flexibility, and faster than other approaches [3].

Some of the benefits that the robotics has been bringing are the possibility to perform efficiently dangerous tasks because they can eliminate the need for people to work in hazardous environments. Small-scale robots can access enclosed and confined spaces that could be important in highly hazardous environments [4], such as [5], that presents a robot to search gas leakage source without exposing humans to inappropriate or dangerous places. However, implementing a similar situation in a controlled environment is expensive and demands much time to develop a complete solution.

Two significant technological challenges are highlighted in this work. At first, it was developed a small-scale soft swarm-robot to work collaboratively to perform one or more tasks autonomously, in [6], it was explained how to define swarm behaviour and the properties of swarm systems. Already in [7] was presented a first low cost small, scalable robot system, details of topology, assembly, communication, controller, and the cost was explored, but the applications were incipient. The second is to create an accurately, flexible, and quickly similar environment founded in the real world. One idea was explored in [8], where a simulation framework was developed to enable the validation of mobile robots and gas sensing algorithms under realistic environments. It is possible to simulate gas dispersion in 3D scenarios with different gases and air flows. However, the solution to detected leakage gases is limited by one robot, and then just one measurement point is not enough to analyze the gas dispersion.

Mixed reality must be a valuable tool for research in small-scale robots in the next years. This fact is confirmed by the increase in the number of works in this area, as presented in [9] [10] [11]. Therefore, Mixed Reality was chosen to be part of the solution presented in this work. The methodology and tools developed in this work are responsible for opening different ways in the application of small-scale robots. Bio-inspired by bacteria, the small robots were created to have technical features that can be enumerated as locomotion, communication, and simple development, when they are compared with other small robots. The principle of these tiny robots are uniquely small, low cost, and flexible for different applications. All parts are found for purchase in conventional stores, and there is no need for any specialized hardware or components. The software that can be used for programming is free. That is an important point, whereas the robotic must be tangible reachable by Universities and students from emerging countries as well as developed countries. Also, in this work, it is presented a system for augmented reality, that was used in several related works, such as kilobots [12]. Thus the information from the virtual environment provides a way to receive data of swarm state.

Unfortunately, a lot of accidents and tragedies at different levels have happened in many industries of the most varied branches. A leakage gas is a notable example, because gases are generally highly flammable, with a high risk of explosion. Gas monitoring is essential for both disaster prevention measures and gas detection.

The expected and analyses of results must be prepared considerations about the range of speed of robots, the influence of surface in locomotion, the possibility of multiple BioCyber-Sensors when using a swarm of robots, and the most important, monitoring with many robots many places

[1]Universidade Tecnologica Federal do Parana (UTFPR) Av. Sete de Setembro, CEP 80230-901, Curitiba-PR, Brazil {rohrich, andresoliveira} @utfpr.edu.br

[2]Research Centre in Digitalization and Intelligent Robotics (CeDRI), Instituto Politécnico de Bragança, Campus de Santa Apolnia, 5300-253 Bragança, Portugal {piardi, jllima}@ipb.pt

[3]INESC TEC - INESC Technology and Science, Porto, Portugal

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at the same time. This approach allows for more excellent work safety in industrial plants.

Real small robots working in a virtual environment that have every condition founded in the real-world is a significant advantage to test different solutions that should be present in this work.

An outline of this paper is as follows. Section 2 describes the methodology of the system and small-scale robots. The virtual environment and the properties of gases are shown in section 3. Mixed reality and the experiments are described in section 4. Experimental results are presented in section 5, and finally, section 6 concludes the paper and presents the future works.

II. Distributed Search of Gas Leak Source

This work has an emphasis on solving problems of the society using small and scalable solutions. The next sections describe the leading technologies used to create a small system composed of small-scale robots and a virtual environment. The concepts and inspirations on which small-scale robots were based are addressed, as well as their technical and dimensional features. It is also described the virtual environment used to integrate the small-scale robots with virtual gas and *BioCyber-Sensors*.

A. Monera *robot*

The changes and possibilities that the electronics and computation bring to the robotics are extraordinary in the last years. Thus, generating approaches and applications that were just science fiction stories. The mobile robots have benefited in this regard because the cost of electronic devices is falling. In this work is presented a small-scale robot, it is called ***"Monera"***. Figure 1 shows *Monera* used in this work to detect leakage gases.

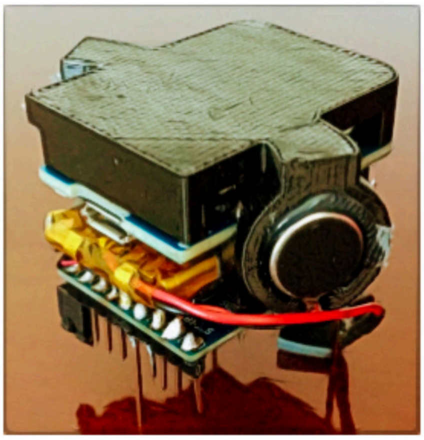

Fig. 1: Monera robot

The *Monera* used a development board called *"Wemos"* based on ESP8266EX processor and the microcontroller is Tensilica 32-bit RISC CPU Xtensa LX106. This device has integrated a Wi-Fi chip and other features, such as 4MB of flash memory, 80MHz os system clock, around 50k of usable RAM. Other common features that are founded in the major of microcontrollers can also be found in this device, such as analogue and digital I/O pins, *UART*, *SPI*, and *I2C*. Each small robot has an AR-TAG to identify their respective ID. The TAG is the most appropriate way to implement the main features of the *Monera*. This element is also responsible for providing data that is used to move, interact with the environment, and monitoring that in the application that must be described in the next sections. Two DC motors vibration are used to move the robot. Different levels of PWM (Pulse Width Modulation) are applied to the motors to do the desired movement. Robots were built for this experiment, and it is possible to see in Figure 2.

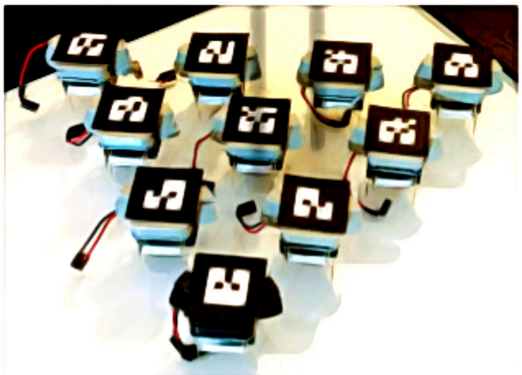

Fig. 2: Swarm robots used in the experiments

The locomotion of the ***"Monera"*** was inspired by ***"kilobot"*** [7]. Still, the physical arrangement, designed features, choice and integration of components, software development, hardware tests, everything was by the author of the article.

B. Small-scale environment

The arena is a simple structure composed of a metal support structure, a camera support arm, a glass surface, and a camera. It was designed to facilitate the transfer, so the dimensions are small. The structure that supports the glass has 0.4 x 0.5 m, and it is made of aluminium. The surface must be as polished as possible, because the friction between the surface and the support structures of the small robots is harmful to their locomotion. Despite the wide variety of surfaces found in industrial environments, such as smooth, rough, temperatures, the main physical characteristic that differentiates the movement of mobile robots is the speed of the movement. Thus, it is possible to replicate different speeds in virtual environments, with the purpose of simulating different types of surfaces for the movement of robots. The camera supports arm is made of steel with an adjustable length of approximately 1.20 m that allows an angle adjustment that varies between 0° and 90° totalling a range between 0 and 1 meter of the height of the camera. In Figure 3 is presented the whole real environment, where the small mobile robots are located.

C. Mixed-Reality features

One appropriate scenario is fundamentally important to execute the tests of this work. Therefore, it was used the

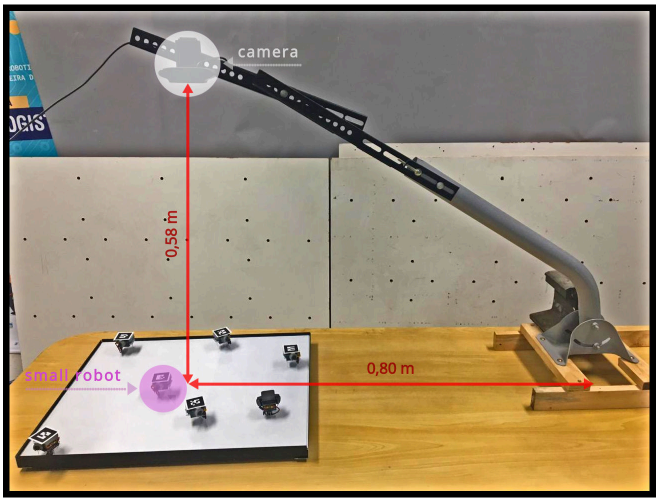

Fig. 3: The real environment is presented. Every real components can be observed (glass surface, small robots, AR-Tags)

Virtual Environment presented in [8], entitled ***GADEN***. It is a simulation framework development to use with ROS to enable work with a wide variety of features of different gases in modular environments. An important point of this work is that from results, it was concluded that the simulation framework provides a good approximation to the real world because a wind tunnel was built to compare the characteristics in both scenarios (real and virtual), this structure is present in [8]. In the same direction as the main objectives of this work that seeks to reduce the time between simulation and implementation, as presented [3], physical and virtual elements can co-exist with this approach. The branch of mobile robots, MRO (Mobile Robot Olfaction), is used to integrate small-scale mobile robots, virtual sensors, and virtual gases in experiments. Besides, GADEN has a great advantage, and it involves gases disperse, but sensing mechanisms. This simulator presents a three-stages structure, as shown below:

1) *Definition of the Environment* - Every component of the simulation is defined at this stage. Since obstacles in general, such as doors and windows, until influence on wind flows;
2) *CFD (Computation Fluid Dynamics) Wind Simulation* - it is used for the wind flow simulation. Open-source CFD projects (OpenFOAM) are a key to this stage because every important parameter is defined here, such as *Reynalds Number*, wind conditions, and material properties. A CAD model importer is responsible for generating the Mesh required by OpenFOAM.
3) *Gas Dispersion Simulator* - The filament-based atmospheric dispersion model was implemented [13]. This model is based on physical phenomenons that occur during the gas dispersion, independent if this dispersion is a short or long time.

In Figure 4 a filament of gas is represented, besides virtual gas sensor (yellow ball), source of the gas (parallelogram green), top image from the camera with the real small scale robots, therefore is presented the general scenario of the experiments.

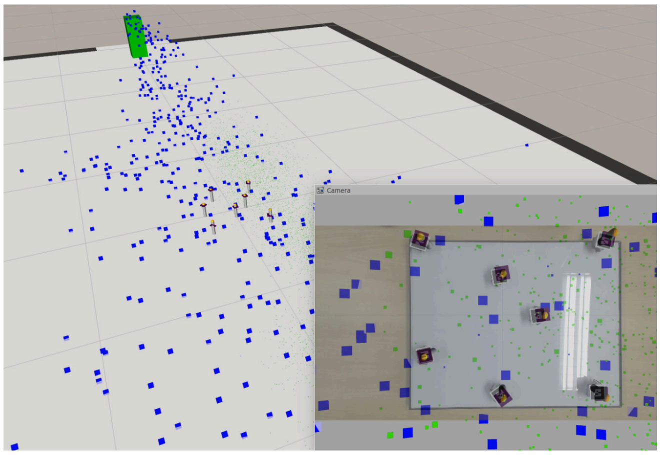

Fig. 4: The general scenario of experiments

Finally, there are *BioCyber-Sensors* that detect and measures the concentration and speed of different gases. In this experimentation, two technologies have been implemented. First, is the MOX (Metal oxide), a standard technology for MRO. It is used to detected gases in the air. This sensor was modelled following the manufacture data-sheet, and it is used to identify different types of gases, such as ethanol, methane, hydrogen, and acetone. The second virtual sensor is the PID (Photoionization detector). It provides a gas concentration in ppm units. These virtual sensors are a part of the mixed reality architecture developed in this work, where they are integrated with small scale robots, thus enabling mobile sensors to detect and measure the concentration of gases at different points. This architecture led to bio-inspired behaviour that is explained in the next section. The sensors are represented in Figure 5 by the yellow balls and the purple AR-TAGs indicate the position of small robots. Still, in Figure 5, the image (a) represents the ARENA used with the real small scale robots. The small robot inside the red circle is an example of how the structure between real and virtual systems work together. It is possible to see many real small robots composed of their virtual elements, such as AR-TAGs, sensors for detection and measurement of the characteristics of a gas.

III. Bacteria-Inspired Smart Behaviour

The behaviours that bacteria have carried out over billions of years have guaranteed survival on the earth. The formation of colonies containing several bacteria is the main characteristic to be highlighted during the evolution of this species. A fundamental and straightforward cognitive mechanism that was present in section 3 of bacteria is the *"Chemotaxis"*, it is responsible to "feel" the environment and inspired the behaviour of the robots in this work. Because the same activity that a bacteria colony has when it is immersed in an overgrown food environment is applied for robots, and when a harmful substance is detected, the colony must avoid this specific area. In table I, it is possible to verify a

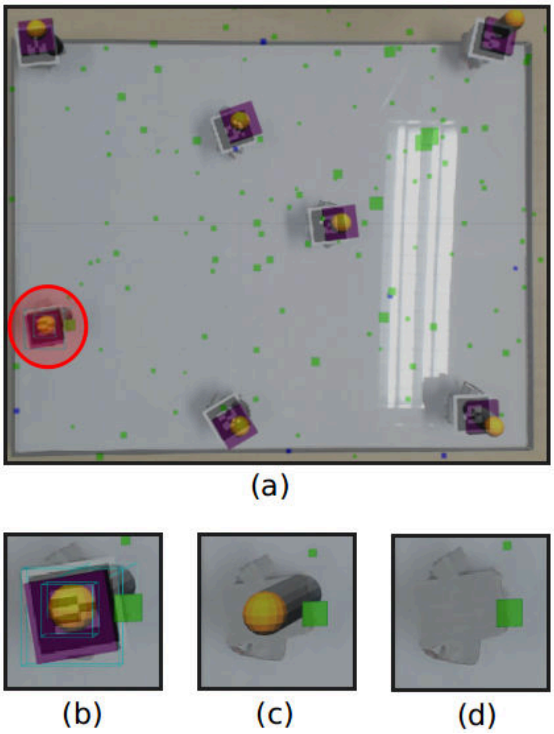

Fig. 5: The composition of small scale robot and the virtual components, "step by step". In Figure 5, (a) is a image from the camera that cover whole arena, image (b) is the closest image from one small robot with every virtual element and in image (c) the same robot without the AR-TAG. Finally, in Figure 5, image (d) the same frame of the small robot, but without every virtual element.

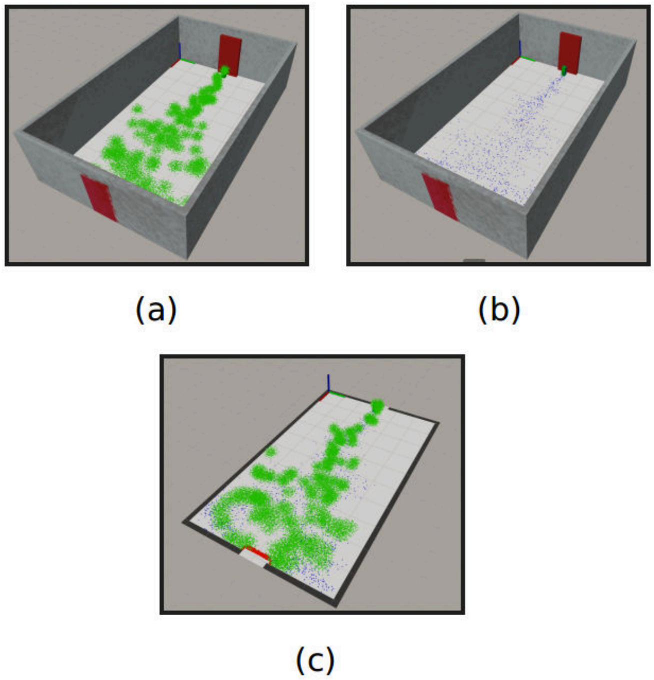

Fig. 6: The virtual environment introducing the composition between filament and gas dispersion

similarity between some features that the robots and bacteria have in common. The planning of this work is to explore these behaviours to solve problems founded in industry, as presented in [14].

TABLE I: Analogy between the behaviours of bacteria and robots that was used to inspired the action of robots

Behaviour	**Bacteria**	**Robots**
Stay alive	*Find food*	*Find power source*
Feel environment	*Chemical receptors*	*Sensor monitoring*
Decision making	*Quorum sensing*	*Fuzzy logic*
Cluster	*Colony*	*Swarm*
Regions to avoid	*With antibiotic*	*With obstacles*
Communication	*Chemical messages*	*ROS messages*

A. Gas detection approach

The use of mobile robotics directed at monitoring and detection of gases represents an essential milestone within mobile robotics, as it avoids the exposure of operators to a toxic atmosphere that can cause damage due to prolonged exposure to toxic gases [15], [5], [16].

Often, due to the inherent property of the gases, stationary sensors are not sufficient to perform efficient monitoring and detection in indoor environments. Some approaches propose the use of a mobile robot to perform this type of surveillance, but the requirement for sophisticated sensors, often resulting in the adoption of generic sensors, for example, those of the MQ series, more specifically MQ-2 (Liquefied Petroleum Gas (LPG), propane, i-butane, methane, alcohol Hydrogen, and Smoke), MQ-4 (methane and natural gas), MQ-5 (LPG, natural gas and methane), MQ7 (Carbon Monoxide and Hydrogen), and others of the MQ family. The prototyping and development of new approaches are limited because, as presented, these sensors have outputs for different types of gases (not able to differentiate) found in several environments, including industrial and requires a previous heating time for its correct operation and measurement.

However, the use of a robot swarm collaborating to obtain information about gas dispersion in an indoor environment, at first intrigues several researchers in the area. Despite the possibility of integration with mixed reality, by the robot being the real entity, and the gas being virtual, thus virtually sensed, results in a new field with potential exploration. Together with ROS using its available tools along with the proposed approach, it aims to mitigate the development of swarms systems with bio-inspired principles, such as the survival of bacteria dependent on the search for gas sources to monitor harmful environments.

Using the GADEN package [8] available in ROS, acetone in its gaseous state was simulated. This element is widely used in the chemical industries, such as paper, plastic, pharmaceuticals, cleaning, and ink, due to its characteristic of solvent. Since it is a colourless gas with a boiling temperature of 56 ^{o}C, in addition to being toxic in high concentrations in the human body and highly flammable, it represents a high risk for manufacturers that deal with this type of chemical

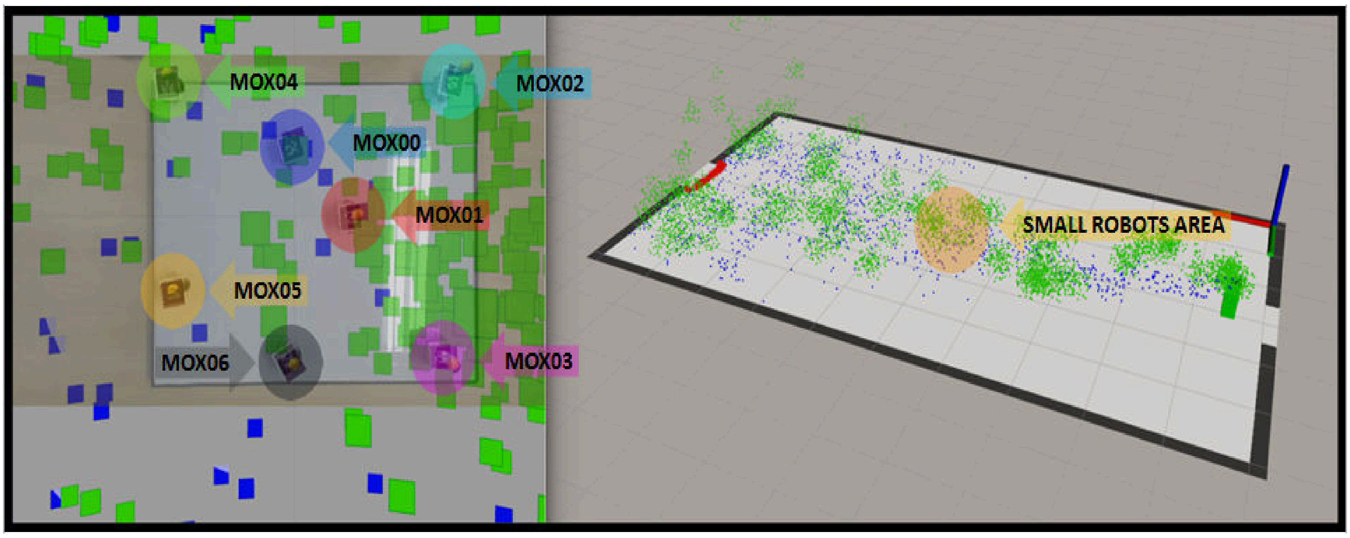

Fig. 7: Experiment of distributed search of gas leak source.

element. The adoption of mobile robots aims to monitor and detect irregularities with much more flexibility and speed within an indoor environment.

IV. Mixed Reality and Experiments

The experiment consists of using small robots to detect gases. Their behaviour was bio-inspired by bacteria that need food to guarantee the survival of a colony of bacteria. For this, virtual and real elements were related to features found in the bacterial biome. *Virtual Environment* is an empty room that is 10 x 6 m and has two doors that define the direction of the airflow of the wind, *Gas* is the energy source (food), and *small scale robots* are the bacteria. Therefore, the search for gas by small robots is equivalent to the search for food by bacteria. In Figure 6 is presented an environment with gas (source energy for bacteria colony).

In Figure 7, every system is integrated into the same environment. The active filament (blue dots) represents the behaviour of the gas according to the simulated airflow to the environment, gas dispersion (green dots), small robots that can be seen in the image that comes from the camera. The movement of the robots is an association between the set of real electronic components used for the construction of the robot. The AR-TAG fixed on the upper of the robot. The camera is responsible for reading the AR-TAG and collected the information for the fuzzy control system.

V. Results and Discussion

The objective of the work was to use a mixed reality involving small-scale robots in the virtual environment. Therefore, a mix of real and virtual components from an unhealthy environment to humans was performed. Thus it was built a complete system for the detection of gases with active sensors. A fuzzy control system was implemented to move the small robots, and it was proved to be suitable for manipulating robots that run through the vibration motor, the details of this control can be explored in [17], it was a previous work of this paper. Bio-inspiration in the behaviour of bacteria for small robots is a promising way to approach the problem, because it is possible to implement cognitive mechanisms observed in a colony of bacteria to increase the efficiency of the application, such as *chemotaxis*. It is the way that the bacteria feel the environment, as presented in [17], where bacteria are attracted by "food."

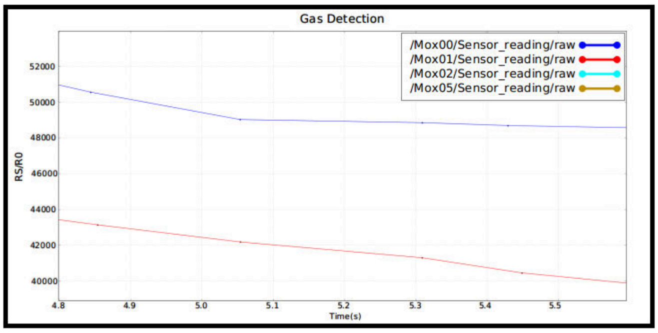

Fig. 8: Result of the initial measurement of gas detection using virtual *BioCyber-Sensors* installed on small-scale robots

The final result of the mixed reality, in this work, can be seen in Figure 8, where the *MOX* was detected at different times the scalar variation of the gas detection values.

Ten seconds after the beginning of the experiment, an increase in the gas concentration was observed, as shown in the Figures 9 and 10.

It was also possible to verify at this moment that one of the virtual sensors installed in a small robot was not detecting any gas, as shown in Figure 11.

Results confirm that the developed system in this work is available to monitoring harmful gases instantly in different points of the environment, becoming a powerful support tool in several areas.

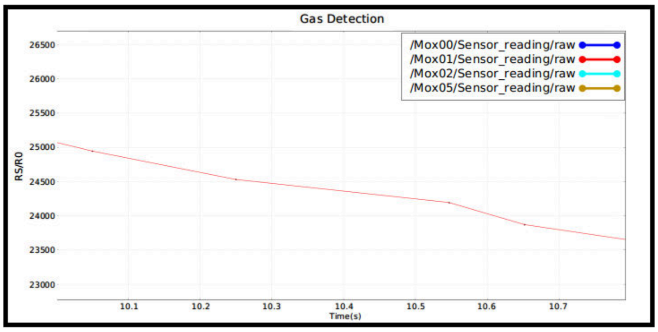

Fig. 9: Detection of the **MOX01**

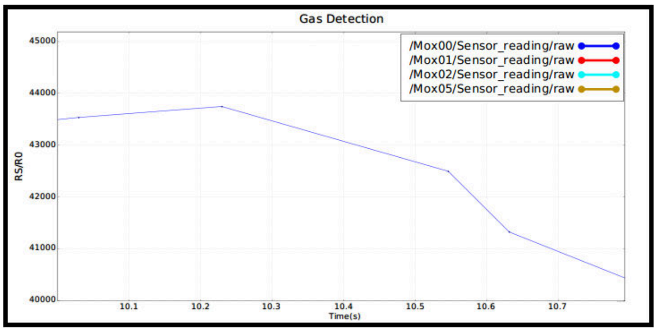

Fig. 10: Detection of the **MOX00**

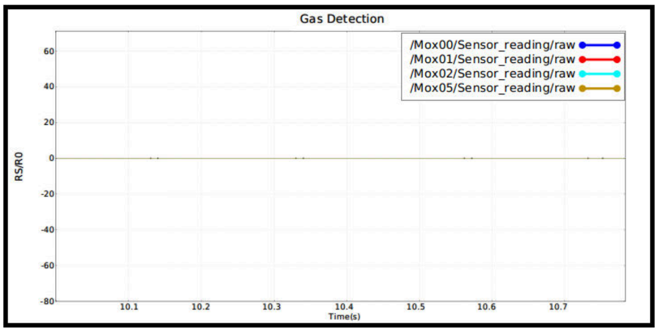

Fig. 11: No detection of the **MOX05**

VI. CONCLUSIONS

The use of small-scale robots proved to be active and with the potential for the growth of applications in different areas of engineering. In this paper, it is possible to verify the benefits of using mixed reality technology, for example, the development of an environment harmful to human beings, which has gas dispersion. Real robots, associated with virtual sensors (*BioCyber-Sensors*), have become efficient elements for detecting and measuring gas. In future works, it must be possible to generate a map, including a point cloud, and monitoring the gases with more accuracy. This paper leaves open the possibility of refining the mixed reality system presented here for more sophisticated 2D until a 3D map.

Prediction of the gas movement and instant monitoring of sudden changes occurred through the detection of new gas sources or even due to unexpected air flows. Thus, it should be possible to achieve intelligent mobile sensing using robots on small scales, and it is also possible to improve the results with new cognitive mechanisms, such as *Quorum Sensing*. This capability can enable faster messaging between members of the bacterial colony, in other words, between small-scale robots. Other objectives are to use configurable virtual environments and to structure a methodology for applications also in the biomedical area, building environments that simulate parts of the structure of beings of organic matter and how small robots would act, both for the diagnosis of diseases and for the treatment itself.

REFERENCES

[1] A. Farinelli, N. Boscolo, E. Zanotto, and E. Pagello, "Advanced approaches for multi-robot coordination in logistic scenarios," *Robotics and Autonomous Systems*, vol. 90, pp. 34 – 44, 2017.

[2] R. Tripathi, A. Kumar, and A. Kumar, "Chapter thirteen - architecture and application of nanorobots in medicine," in *Control Systems Design of Bio-Robotics and Bio-mechatronics with Advanced Applications*, A. T. Azar, Ed. Academic Press, 2020, pp. 445 – 464.

[3] W. Hönig, C. Milanes, L. Scaria, T. Phan, M. Bolas, and N. Ayanian, "Mixed reality for robotics," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 28 Sept.-2 Oct. 2015, pp. 5382–5387.

[4] W. Hu, G. Z. Lum, M. Mastrangeli, and M. Sitti, "Small-scale soft-bodied robot with multimodal locomotion," *Nature*, vol. 554, no. 7690, pp. 81–85, 2018.

[5] J. Braun, L. Piardi, T. Brito, J. Lima, A. Pereira, P. Costa, and A. Nakano, "Indoor environment monitoring in search of gas leakage by mobile robot," in *Robot 2019: Fourth Iberian Robotics Conference*. Springer International Publishing, 2020, pp. 339–350.

[6] H. Hamann, *Swarm Robotics: A Formal Approach*. Springer International Publishing, 2018.

[7] M. Rubenstein, C. Ahler, and R. Nagpal, "Kilobot: A low cost scalable robot system for collective behaviors," in *2012 IEEE International Conference on Robotics and Automation*, May 2012, pp. 3293–3298.

[8] J. Monroy, V. Hernandez-Bennetts, H. Fan, A. Lilienthal, and J. Gonzalez-Jimenez, "Gaden: A 3d gas dispersion simulator for mobile robot olfaction in realistic environments," *Sensors*, vol. 17, no. 7, 2017.

[9] M. Filipenko, A. Angerer, A. Hoffmann, and W. Reif, "Opportunities and limitations of mixed reality holograms in industrial robotics," 2020.

[10] J. Guhl, S. Tung, and J. Kruger, "Concept and architecture for programming industrial robots using augmented reality with mobile devices like microsoft hololens," in *2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Sep. 2017, pp. 1–4.

[11] J. A. Frank, S. P. Krishnamoorthy, and V. Kapila, "Toward mobile mixed-reality interaction with multi-robot systems," *IEEE Robotics and Automation Letters*, vol. 2, no. 4, pp. 1901–1908, Oct 2017.

[12] A. Reina, A. J. Cope, E. Nikolaidis, J. A. R. Marshall, and C. Sabo, "Ark: Augmented reality for kilobots," *IEEE Robotics and Automation Letters*, vol. 2, no. 3, pp. 1755–1761, July 2017.

[13] J. A. Farrell, J. Murlis, X. Long, W. Li, and R. T. Cardé, "Filament-based atmospheric dispersion model to achieve short time-scale structure of odor plumes," *Environmental Fluid Mechanics*, vol. 2, no. 1, pp. 143–169, Jun 2002.

[14] L. S. Junior and N. Nedjah, "Efficient strategy for collective navigation control in swarm robotics," *Procedia Computer Science*, vol. 80, pp. 814 – 823, 2016.

[15] J. E. Sánchez-Sosa, J. Castillo-Mixcóatl, G. Beltrán-Pérez, and S. Muñoz-Aguirre, "An application of the gaussian plume model to localization of an indoor gas source with a mobile robot," *Sensors*, vol. 18, no. 12, p. 4375, 2018.

[16] L. Piardi, "Application of a mobile robot to spatial mapping of radioactive substances in indoor environment," Master's thesis, Instituto Politécnico de Bragança, 2018.

[17] R. F. Rohrich, M. A. S. Teixeira, L. Piardi, and A. S. de Oliveira, "A bio-inspired approach for robot swarm in smart factories," in *Iberian Robotics conference*. Springer, 2019, pp. 303–314.