First characterization results obtained in a wind tunnel designed for indoor gas source detection

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***Abstract*—This paper presents the preliminary characterization results of a custom wind tunnel for designed for performing experiments on locating a volatile gas source with a mobile robot. Such experiments require a previous characterization of the wind tunnel as well as the definition of the configurable agents which are present during the experiments. This paper presents the experimental data gathered from the real environments. This paper shows the behavior of the evolution and diffusion of the gas depending on the gas injection rate, the mobile robot position, and the wind force. The mobile robot is equipped with a LIDAR for self localization, with a photo ionization detector (PID) for gas measurement, and with an anemometer for wind measurement. This paper shows the results obtained in static and dynamic experiments.**

***Keywords*—wind tunnel; gas detection; mobile robot**

I. INTRODUCTION

Since last decades, gas-sensing devices have been widely used in security applications in many different contexts and the use of embedded sensors in mobile robots is becoming an attractive research field. The main aim of such applications is to estimate the localization of gas leakages in a delimited area. The advances in mobile robot relative localization and mapping [1] have involved improvements in the development of gas distribution algorithms as they can provide live information about the localization of the gas-sampling data which eases and improves the accuracy of the estimation methodologies to find the gas source. For example, the proposal of [2] was one of the first approaches to implement robot Simultaneous Location and Mapping (SLAM) for gas leak source localization. The proposals of [3, 4] shown the results of similar experiments with a mobile robot with a LIDAR, an anemometer, and a Photo Ionization Detector (Fig. 1). There are other alternatives which are not focused on the use of SLAM and just focusing the effort on detecting the gas plume and trying to follow it with one [5] or several robots [6]. In this context, wind tunnels are usually used for gas source-finding experimentation under turbulent conditions [7] and to study the gas diffusion behavior which allowed the development of improved algorithms in order to distinguish different chemical agents in the same experimentation area by using non-selective sensors [8].

Fig. 1. Mobile robot with embedeed sensors.

This paper is focused on performing the characterization of a custom wind tunnel in order to study the gas diffusion behavior and define future experiments in gas source-finding applications. This work presents results from several tests and experiments with different gas and wind parameters. The results have been obtained in static experiments (fixed-position sensors) and in dynamic experiments (robot onboard sensors). Such results will be useful for future supporting decision-making directives of a mobile robot which is trying to find the gas leak.

II. MATERIALS AND METHODS

This section describes the mobile robot, the wind tunnel and the other equipment used in the experiments.

A. Mobile Robot

The mobile robot (Fig. 1) was designed as a polyvalent platform based on a HP laptop with a Core2 Duo processor at 1.66Ghz and 2GB of RAM. The laptop handles all the communications with the sensors by USB and RS232 interfaces as well as a motor control board which handles 2 DC motors. The robot motion speed set for the dynamic experiments in this paper is 0.2m/s. The software running the mobile robot is fully implemented in MATLAB.

1) LIDAR

The robot navigation, localization and obstacle avoiding methods is based on the information obtained from a Hokuyo UTM-30LX laser range sensor (LIDAR) which is placed at the front part of the robot. The sensor has a maximum range of 30 meters with an angular range from -135º to +135º. A single sensor scan is scattered into 1,081 points with a resolution of 1mm which are submitted to the mobile robot through a USB interface. The mobile robot has a SLAM procedure based on occupancy grid matching in order to self-localize the mobile robot in the experimentation area.

2) Photoionization Detector (PID)

The gas concentration levels are measured with a ppbRAE 3000 photoionization detector by RAE Systems. Although this device is a non-selective sensor, it can be configured to improve the detection of a wide scope of different gasses. The sensor sends the gas concentration with a resolution of parts per billion through a common RS232 interface.

3) Windsonic Anemometer

An anemometer is placed at the top of the mobile robot in order to register the wind behavior. The sensor used is the Windsonic anemometer by Gill Instruments Ltd. which is able to measure the wind speed in m/s as well as its direction in degrees at 4Hz of sampling frequency.

B. Acetone Evaporator

In this paper, the gas leak is emulated with a syringe filled with acetone mounted into a KDS model 200 syringe pump by KD Scientific Inc. Such mechanism allows dispensing acetone at a configurable flow which drops over an aluminum hot plate and evaporates.

C. Wind Tunnel

The experiments were carried out in a custom built wind tunnel (Fig. 2) with the following dimensions: 3.5m (width) x 4.8m (large) x 1.8m (height). The structure construction is based on Styrodur® insulation boards and aluminum profiles. The wind profile is emulated with 4 extractor fans HXM-400 by Soler&Palau: one pushing from one side and the other three extracting from the other side. The wind tunnel is placed inside a laboratory with large windows which allows fast air removal between experiments.

Fig. 2. Wind tunnel image.

III. EXPERIMENTATION

The experiments proposed in this paper have been designed to reveal and characterize the gas and wind behavior at different spatial points located into the wind tunnel (depicted as red circles in Fig. 3). In a first experiment the mobile robot will statically measure the accumulation of the gas as well as the wind lectures. The experiment timeline is based on the measurement of the gas concentration during two stages: in the first stage the acetone drop is started and maintained during 20 minutes, in the second stage the acetone drop is stopped and the gas evolution recorded during 20 additional minutes. The experiment is repeated at representative spatial points and for different gas injection intensities. Another round of experiments will be performed varying the velocity of the wind inside the tunnel. After each experiment, the gas is drained-out until the PID reads baseline gas concentration levels (~0ppb). Then, a new experiment or measurement can be initiated.

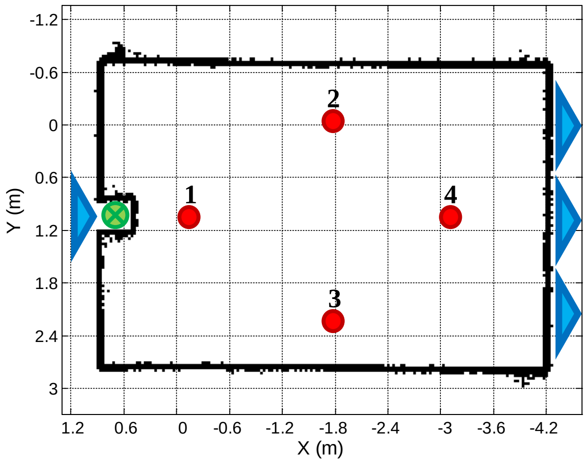

Fig. 3. Wind tunnel map with fans (blue triangles), gas source (green circle) and static measurement points (red circles).

The second set of experiments stage proposes to employ the mobile robot to perform a dynamic exploration along the wind tunnel area. The mobile robot will be performing different measurements from the PID and the anemometer during its dynamic exploration. In this case, the SLAM procedure will provide the exact relative coordinates in where the samples are taken with a maximum error of 3cm thanks to the laser range sensor of the robot. The frequency of these dynamic measurements has been fixed in 1Hz. In this second set of experiments the mobile robot will perform a zig-zag path which goes from one side of the wind tunnel to the opposite side and stops, and a semi-random exploration based on a forward displacement until reaching an obstacle followed by a semi-random turn (the range of the turn is defined in each case by the obstacle). The semi-random exploration guarantees the exploration of the complete area in the case of long exploratory experiments (in this paper, 1 hour) [9].

IV. Results

This section describes the measurement results gathered from the experiments proposed in this paper.

A. *Experiments with variable gas supply*

The first case to study consists on measuring the gas profile concentrations in the four static locations labeled in figure 3. The measurement experiment is repeated for the following gas flow intensities: {150, 300, 450, 600} µl/min. The fans have been powered at full speed (100% power). Figures 4, 5, 6, and 7 show the evolution of the gas concentration at the four locations used and figure 8 the profile of the wind intensity and direction at the flour locations defined previously.

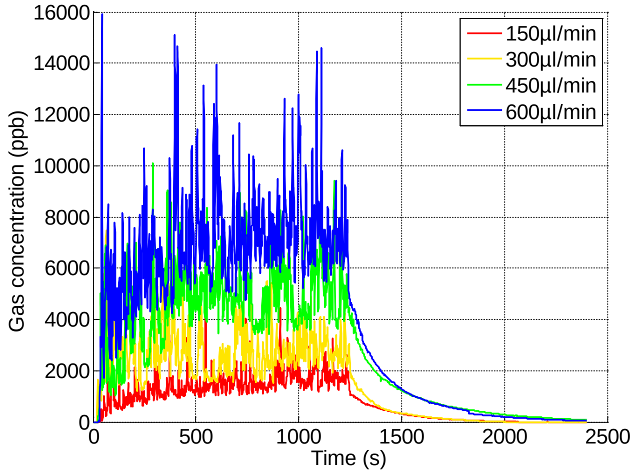

Fig. 4. Static measurement: gas evolution measured at point 1.

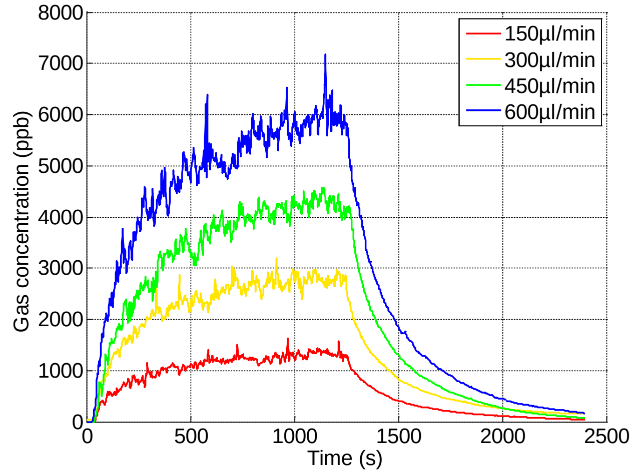

Fig. 5. Static measurement: gas evolution measured at point 2.

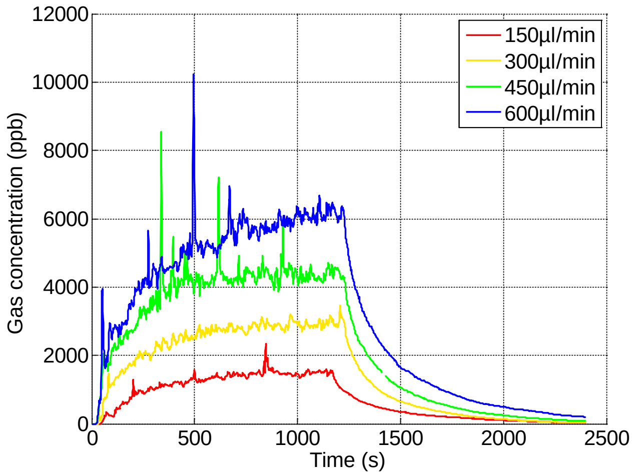

Fig. 6. Static measurement: gas evolution measured at point 3.

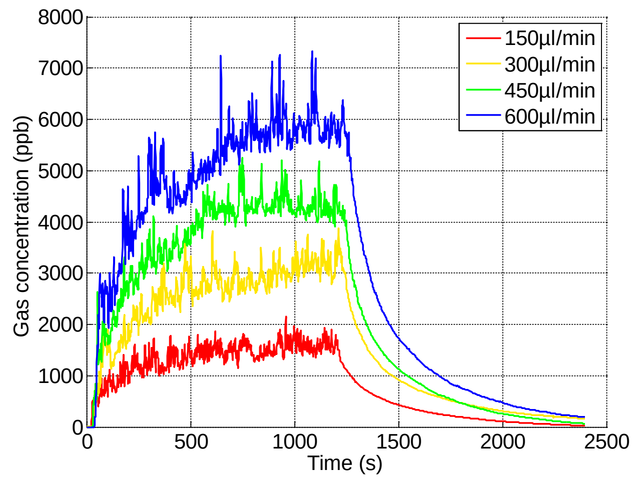

Fig. 7. Static measurement: gas evolution measured at point 4.

At first sight, the results show similar evolution patterns at the different points locations. In all results, the gas concentration reaches a stable value with is proportional to the gas drop. In all cases the gas concentration reaches a stable value approximately after 800 seconds. In all cases with a 150 µl/min injection, the gas concentration rises suddenly from 1,200ppb to 1,600ppb; in the case with 300µl/min, the rise is from 2,600ppb to 3,000ppb; in the case with 450µl/min, the change is from 4,000ppb to 5,000ppb; finally, in the case with 600µl/min, the gas concentration rises from 5,500ppb to 7,000ppb.

At second 1200, the syringe pump stops the acetone drop and this action is depicted in figures as a sudden alteration of the gas evolution tendency. Such decaying tendencies have a typical exponential decay which departs from the stabilized gas concentration level and decreases tending to zero. The more gas is freed in the wind tunnel, the more pronounced is this decay.

The airflow generated by the fans has different tendencies depending on the relative position considered in the wind tunnel. Figure 8 shows the wind vectors for the four locations analyzed. Point 1 registered the strongest wind intensity and uniform direction tendency because of its proximity with the propelling fan. Point 4 has similar registers as point 1 but with half of its wind force. Alternatively, the samples from points 2 and 3 show low speed vectors without a predominant direction as a clear indication that they are out from the central generated airflow.

Gas concentration samples shown in figure 4 and 7 have direct contact with the airflow and show more turbulent behavior (peaks) than samples in figure 5 and 6. Point 2 and 3 provides more stable sensor lectures and reveals that there is an unbalanced diffusion between the two sides. The gas concentration levels are slightly less in point 2 as it seems that the air tends to escape from the wind tunnel mainly by such side. In order to validate this last conclusion an experiment based on smoke tracing was performed. The picture on figure 9 shows the trace of the freed smoke. The smoke tends to pass through the left fan close to point 2, so, there is less gas accumulation in that side.

B. *Experiments with variable air flow intensity*

The wind factor has been also studied as an interfering agent during the measurements. Their effect of the apparent saturation concentration of the gas inside of the gas has been measured for different wind intensities. Figure 10 show the results of the same experiment as the previous section but this time the gas injection was fixed at 300µl/min and the fans were set at different power levels. Figure 10 shows a clear dependence between the wind intensity and the evolution of the concentration of the gas when the fan power operates at 100% and 50%. However, at levels less than 50%, the gas concentration level increases until the acetone injection stops. So, a power fan range between 0% and 50% showed a strong effect in the distribution and attenuation of the gas evolution in the tunnel.

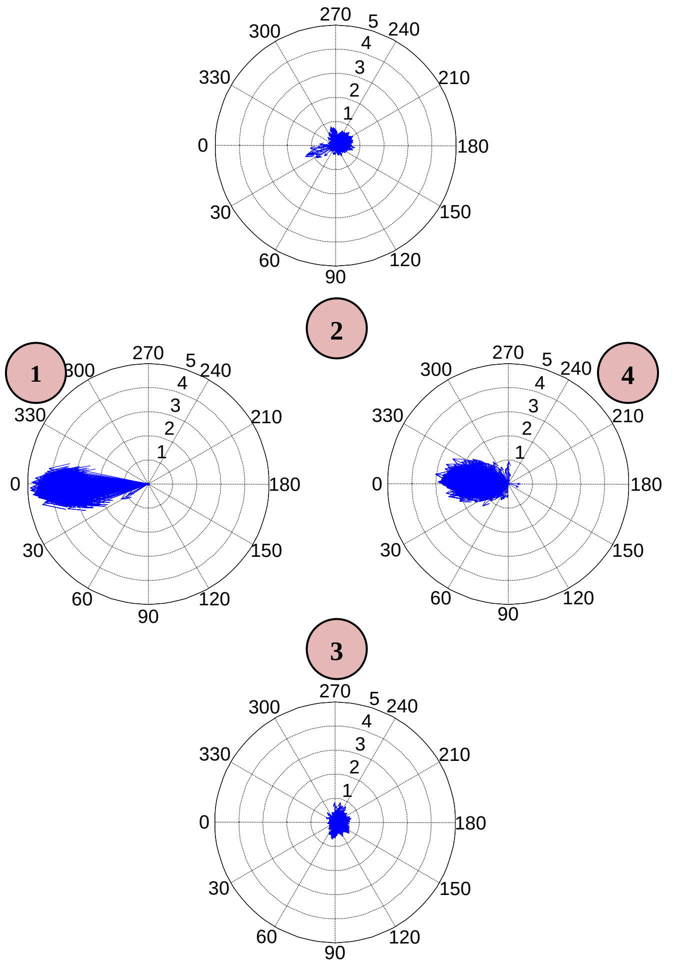

Fig. 8. Wind intensity and direction (m/s) at the four static measurement points defined in the case of fans at full speed. The direction depicts the procedence of the wind.

Fig. 9. Image of the smoke test to make the air dispersion tendency visible.

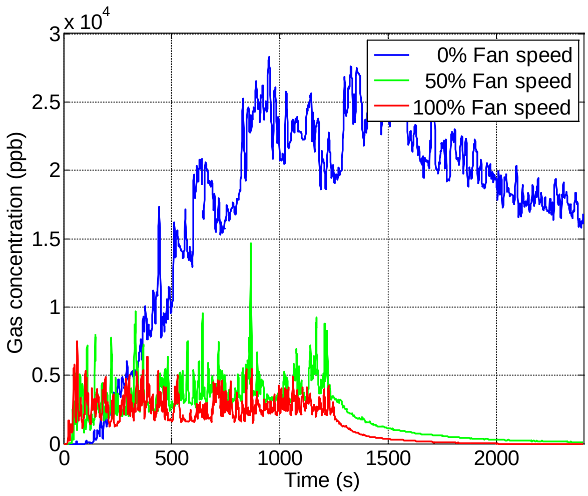

Fig. 10. Gas evolution at spatial point 1 obtained for different fan speed levels.

C. *Mobile robot zig-zag exploration*

The results from dynamic experiments will provide information about the spatial and temporal evolution of the gas concentration measured in the wind tunnel. This first exploration consists on performing a zig-zag or boustrophedon [10] path along the wind tunnel (Fig. 11). The implementation of this exploration procedure will started in one side of the room and will be repeated until reaching the other side of the tunnel. In this experiment, the acetone flow was set to 300µl/min and the fans power was at 50%.

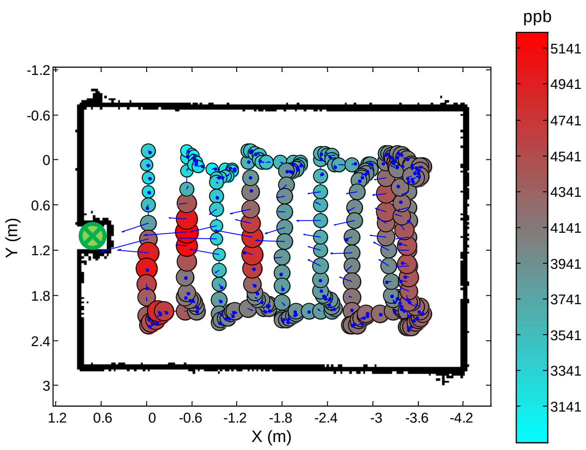

Fig. 11. Final sampling with a semi-random robot exploration.

Figure 11 shows the results obtained. The robot path is depicted as a blue underlying line with a circle at the sampling measurement points where the color and diameter of the circle is correlated with the absolute gas intensity measured. Figure 11 also includes the information of the wind intensity and direction registered in the sampling points as a blue arrow; their module is proportional to the wind speed and their direction points to the origin of the airflow. The highest gas concentration measurements (red circles) were taken near the gas source and when the robot just passes within the gas plume that becomes more diffuse at the other side of the wind tunnel.

D. *Mobile robot semi-random exploration*

In this dynamic experiment the mobile robot performed a semi-random exploration during 1 hour. The information acquired as result of this experiment is shown in Figures 12 and 13. On the one hand, the data obtained during the first 9 minutes of the experiment was continuously increasing. On the other hand, the measurements from minute 9 to minute 51 showed a dynamic turbulent plume. In this experiment, the acetone flow was set to 300µl/min and the fan power was at 50%.

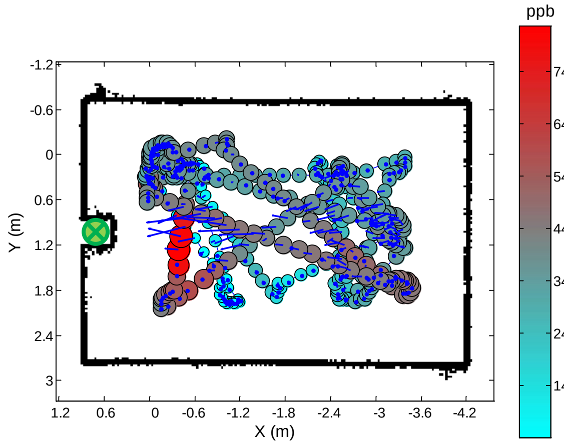

Fig. 12. Initial sampling with a semi-random robot exploration.

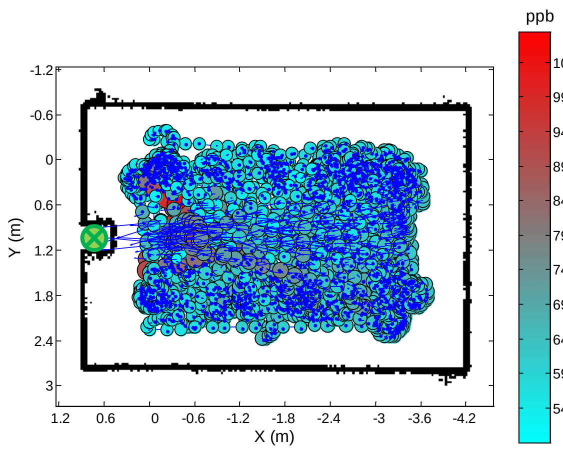

Fig. 13. Final sampling with a semi-random robot exploration.

Figure 12 shows the results from the first part of the exploration. Even thought the gas was not stable, the highest concentrations were detected near the gas source. In this case, the gas plume also showed an average constant evolution of the concentration and some peaks of concentration Figure 13 shows the result from the second part of the experiment. In this case the concentration appears very uniform along the tunnel with some high concentration peaks close to the gas source and the gas plume.

V. CONCLUSIONS

This paper presents the first characterization results obtained in a custom wind tunnel designed for indoor gas source detection. This wind tunnel has been prepared to develop further studies for plume and gas source location applications with mobile robots. The main objective of this paper is to investigate the evolution of the gas concentrations in the tunnel and to evaluate the influence of the wind source in this evolution.

The results obtained have confirmed that the gas injection rate is directly correlated with the average concentration of gas in the tunnel in the case of turbulent conditions. However, depending on the wind airflow, the gas concentration levels experience different average intensities and noticeable intensity peaks. The intensity and direction of the wind has been also investigated and a smoke tracing has verified the asymmetry of the wind plume inside the tunnel.

The static characterization results have been complemented with two dynamic measurements in order to obtain representative information of the gas evolution during a mobile robot exploration. These results have been confirmed that the gas source and gas path can be measured with a PID sensor. Future work will be focused on implementing different path planning algorithms for gas source finding in the indoor area defined by the wind tunnel and in to estimate the probabilistic distribution of the plume of the gas.

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