Good Experimental Methodologies for Mobile Robot Olfaction

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***Abstract*—This article identifies problems frequently found in mobile robot olfaction and proposes a set of good experimental methodologies for common tasks addressed in this field. These methodologies are expected to allow a fair replication of experimental work done by different groups and to compare the results obtained with different algorithms addressing a common task.**

I. Introduction

Olfaction is not a common sense in the mobile robotics field, but the large number of important applications that can be solved with this sense fostered the research in this area, particularly during the past 15 years [1]. The usefulness of integrating olfaction in mobile robots is particularly evident when the robots need to carry-out some chemically related task, like environmental monitoring [2]. Additionally, robots with olfaction can also be useful for applications currently carried-out by men with the collaboration of trained animals owning well developed sense of smell (e.g., dogs). Some of those applications consist in finding odour sources e.g., in the detection of explosives and other hazardous or elicit substances, finding buried landmines [3], or finding people in search and rescue operations [4]. Other applications, like uncoordinated cooperative patrolling, may explore the use of chemical trails, or chemical odours to aid area coverage applications [5].

The main basic tasks addressed by mobile robot olfaction have been the search and tracking of odour plumes and the localisation of their source [6]; the mapping of odour fields [2], [7] and the tracking of volatile chemical trails [8], [9].

Some of the major problems faced by the researchers working in this field are the randomness associated with the transport of chemical substances in the environment and the consequent uncertainty found from the detection side. These problems are amplified by the lack of fast, sensitive and very selective gas sensors.

Another source of problems is the variability of environmental conditions from run to run. Mobile robot olfaction experiments are usually very much time consumable. If the experiments are done indoors, the most frequent case reported until now, the airflow conditions can be very well controlled, but the environment tends to become poisoned by the accumulated chemicals released during the experiments. In this case it is usually necessary to wait for a long time between each experiment until the environment becomes clean again. If the experiments are done outdoors, the above problem is not a concern, but the variability of the airflow conditions can be so high that it will be difficult to draw conclusions about the results obtained.

Two consequences of these problems are the following: usually the results of the research works are supported by a limited number of experiments (lack of statistical proof) and when the described experiments are tried by another research group, the results obtained are not necessarily similar to the ones originally described (lack of generality). This situation makes very hard to separate the science from the heuristics and understand the validity of a proposed olfactory navigation algorithm.

Another problem found in this area is the wide range of scientific disciplines involved, from chemistry, fluid mechanics, sensing and sensors, and mobile robot control, to name just the major areas. This interdisciplinarity requires a deep knowledge of a wide variety of materials and methods that are employed in the experiments. Either by the lack of knowledge from the authors or because the authors do not give enough relevance to these materials and methods, they are frequently described in a vague way, making almost impossible to replicate the described experiments.

This paper intends to provide a brief introduction about the research in "mobile robot olfaction" and identify the main methods, materials and equipments that can be used in this research area. The paper will provide suggestions and advices of good experimental methodologies to make repeatable and verifiable experiments.

II. Olfactory navigation

Olfactory mobile robot navigation deals with the control of a mobile robot operation based on sensed olfactory information. The most common tasks in this field are the search and localisation of an odour source releasing chemical substances to the environment - usually volatiles to the atmosphere. These chemicals are transported through the environment, generating an odour plume. In this case, the mobile robot task consists in searching the environment, trying to make contact with the plume. After detecting the plume, the robot should track it until its source. This source can be identified, either by means of another sensing modality (e.g. vision) or reasoning about its localisation by the concentration pattern acquired around a suspicious area. This task can be done by one or by multiple robots [10] searching for one or multiple sources [11]. Most of the research done so far in this area deals with olfaction in the atmosphere, but the same physical principles can be applied to underwater environments [12], [13]. The mapping of odour fields is another related task [14]. In this case the goal is not explicitly finding an odour source, but accurately mapping the average gas concentration in the area. The localisation of the corresponding odour source can be estimated from the areas of highest average concentration.

The use of chemical trails is another branch explored by olfactory mobile robot navigation. Chemical trails are an efficient way to exchange information between cooperating olfactory agents. For example: a robot can mark a path to be followed by other robots with volatile chemical marks or a group of patrolling or exploring robots can use this type of marks to inform the cooperating partners about areas that were already explored or visited. This is also useful in coverage tasks, where a robot can use chemical marks to inform the other robots about the areas that were already covered [15].

The possibilities of this sensing modality are clearly wide, so in order to keep the article focused, only the problem of searching and localising odour sources in atmospheric environments will be treated [16], [17], [18], [19].

A. Searching odour sources

The problem can be defined as follows: *find all odour sources inside a limited environment using a set of mobile robots equipped with olfactory systems*.

The following sections provide some insights and suggestions about the *methods* and *materials* that can be employed to set up experiments in this area; to identify useful metrics to evaluate the searching algorithms presented; and to provide insights about fundamental aspects that should be described in order to make the work repeatable and verifiable by other researchers.

III. Methods and Materials

Experiments in mobile robot olfaction are frequently not done with proper methods and materials. Sometimes this happens because the researchers don't have access to those materials, but another possibility is the lack of knowledge about those materials. This section surveys the main materials and methods used to experiment in this area.

A. Working environment

The working environment, or the area where the search is to be performed, can be an indoors enclosed space or an outdoors space. Chemical volatiles in the atmosphere are mainly transported by the action of airflow produced by advection and convection phenomena. The interaction of the airflow with surfaces and thermal gradients produce turbulence. This effect produces highly irregular concentration patterns while the chemical volatiles move from the source across the environment [20], [21].

Most olfactory experiments are done indoors, in a limited testing volume, and under very *controlled airflow* conditions. The airflow conditions range from no airflow until airflow generated by ventilators [18] or inside air tunnels [21], [22], [23]. Different types of *anemometers* can be used to characterise the airflow inside the testing arena, namely: mechanical vanes [24], thermal anemometers [25], ultrasound anemometers [26], and artificial hairs [27].

B. Gas sources

The gas sources are usually generated from natural or forced evaporation of common volatiles and other non-dangerous substances, namely: water vapour and common hydrocarbons (ethanol, methanol, butane, etc). The forced evaporation of these substances is achieved by means of bubblers, ultrasonic evaporators [28], heating system (e.g. smoke machines, small boilers), or by the action of nozzle injectors. The use of ion sources [29], smoke generators or joss sticks (incense) is also a possibility [30].

Whatever the method employed, in order to allow replication of the experiments it is important to characterise the chemical source, measuring the *release rate* and the *concentration* obtained in a set of verification points inside the testing environment.

C. Olfactory systems

The olfactory system is another critical unit that needs to be characterised. If the work involves the use of multiple types of gases and their classification, then an electronic nose should be used [18], otherwise, a single gas sensor will be enough. Regarding the olfactory system, the main parameters to be characterised are its sensitivity, selectivity[1], and response time.

Since the knowledge of the airflow is very important to improve the performance of any odour source searching algorithm in normal atmospheric conditions, the fuse of the gas concentration with the airflow information is very common in advanced olfactory systems. When an anemometer is used, its sensitivity and error parameters should also be characterised.

The *probability of detection* and the *detection width* are two useful characteristics that were never characterised in the past works of mobile robot olfaction. In order to provide better scientific foundations to these works, in the future these parameters should be identified and reported.

1) Gas sensors: There are a large variety of gas sensors that can be employed to sense gases with robots, but due to its simple operation, reliability and robustness, commercial metal oxide gas sensors are the type of sensors more frequently used for these works [31]. These sensors are cheap, can detect oxidising gases in the parts per million (ppm) range and have a response time from one to several seconds (this is appropriate to the dynamics of most mobile robots). Some researchers try to explore the intermittency of odour plumes with faster sensors [32] or sensing methods [33] or even employing insect antennas [34], [35] or ion detectors [29] as very fast and sensitive olfactory systems.

[1] important for experiments using multiple gases

D. Robot platforms

The robotic platform provides the ability to move across the environment. The type of platform employed is not important, as far as it does not affect the results of the work. Some platform characteristics to take into account are the size of its body (the bigger the platform, more it will interfere with the environmental airflow, being itself a source of turbulence). Big platforms also tend to consume more power. This may interfere with the environment in two ways: First, the generated heat produces thermal gradients that produce convective airflows around the platform. Second, these platforms tend to employ an embedded PC with internal ventilation to cool the electronics. This ventilation also produces airflow currents into and from the platform, influencing the global airflow landscape.

Almost all the works in this area employed small differential drive mobile robots. Some researchers employ medium size platforms. In these cases it would have been important to assess the disturbances caused by the platform, but that was never reported.

E. Validating systems

A common weakness of most research in this area is the lack of validation of the presented results against the ground truth. For example, robot trajectories and concentration acquisitions are frequently referred to spatial localisations provided by the robot odometry. It is known that this type of localisation is very sensitive to cumulative errors. In cases where the results depend from the localisation (e.g. odour mapping) it is important to use an accurate absolute localisation method to correct the odometry (e.g. DGPS for outdoors, and triangulation or trilateration methods for indoors).

Another phenomenon that is seldom evaluated during this type of experiments is the real distribution of odour concentrations. This is difficult to measure, but it can be estimated with a fixed sensor array distributed over the testing area.

F. Simulation of olfactory experiments

A large number of works in this area are only supported by simulations. Simulations can be used to show that a given method works or they can be used to test a method in a variety of situations in order to assess how well it works.

Simulations are very useful, particularly to verify and demonstrate the validity of a given concept or idea, hard to demonstrate experimentally. Simulations are also useful, since they allow running multiple experiments at reduced cost and in a short period of time. This convenience allows optimising algorithms and to identify the influences among different parameters of a system under study. But in order to be useful, *simulations need to use realistic models* of the physical phenomena that they are simulating, otherwise there is the risk of hiding serious faults.

IV. Searching experiments

Odour source searching algorithms should be validated and evaluated with a set of meaningful experiments. It is not rare to show the results of a searching method *only* by a set of trajectories from a starting position until the source. This is not a proper way to evaluate a searching method [36]. Some convenient metrics that can be used to assess quantitatively the performance of a searching method are:

- The success rate
- The statistics of the time to reach the goal
- The rate of finding the sources (for multiple source experiments)

The values obtained with these metrics should be compared with the lowest time achievable (i.e. the time taken if the robot knows in advance the localisation of the source and the best path to arrive there) and with the expected time obtained if the robot is controlled by a random walk.

Of course that the performance obtained with a given searching algorithm depends also from the hardness of the environment. The hardness in this context is related with how clean of obstacles the way from the robot to the source is and how turbulent the environment is.

Some frequent problems that mask the real performance of the searching algorithms are:

- Too simplistic searching environments. The use of very small searching scenarios, most of the times without any obstacle between the robot and the source hide the real qualities of the searching algorithm. Some works report the tracking of odour plumes with the robot at less than 2 meters away, downwind from the odour source!
- The use of sensors with very slow response times compromise the performance of the searching algorithm. The response time of the sensing system should be taken into account when the data is analysed.

V. Discussion and conclusions

This paper addressed the odour source searching problem with mobile robots. The importance of describing in a clear and complete way all the methods and materials employed during the experimental demonstrations was highlighted. A set of performance metrics that can be employed to quantitatively evaluate the proposed algorithms was identified.

In the future, a benchmark for odour source searching and localisation should be proposed. This area is now becoming mature and such benchmark would be a useful tool for all the researchers in this area. This benchmark can be based on an odour search competition. Competitions have the drawback of limiting the experimental scenarios, but they also have the merit of defining a problem in a standard environment that everyone can use to compare its own performance with the performance of the works proposed by other research groups.

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