Design Principles for Cooperative Robots with Uncertainty-Aware and Resource-Wise Adaptive Behavior

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Abstract. In this paper we describe several principles for designing and implementing bio-inspired robotic collaborative search strategies. The design approach is particularly oriented for algorithms that can tackle search problems that deal with uncertainty, such as locating odor sources that have spatial and temporal variance. These kind of problems can be solved more efficiently by a reasonable amount of collaborative robots, and thus we propose a low-cost platform based on the open-source philosophy. The platform allows to evaluate different collective strategies that emerge from the interaction among robots that are aware of the uncertainty and make a wise use of all available sensors and resources. This includes an adaptive use of sensor signals and actuators, and a good communication strategy. We introduce GNBot, a flexible open-source robotic platform, and a virtual communication network topology approach to validate uncertainty-aware and resource wise bio-inspired search strategies.

Keywords: Cooperative robots, search algorithms, smart sensing, adaptive behavior, low-cost robotic platform, 3D printing, open-source, machine olfaction.

1 Introduction

Environmental exploration and monitoring, surveillance, target search and rescue, etc. are tasks that can be undertaken by cooperative robots (for a recent review on this topic see [1]). When the environment is fully characterized and the monitoring/search targets are stationary, straightforward rule-based heuristics including brute force approaches lead to efficient cooperative search. Bio-inspired approaches can come into play when search strategies have to deal with a large degree of unavoidable uncertainty.

The problem of odor source detection, localization and characterization using cooperative swarm robots has been studied for more than a decade considering mainly stationary odor sources [2,3,4,5,6]. Finding multiple odor sources that vary on time using cooperative search strategies has attracted less attention [7].

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This problem requires the use of search algorithm solutions that ensure that all sources are located in minimum time, avoiding obstacles, overlapping, and redundant interactions among robots which have limited resources to perform the search. Bio-inspired strategies that consider knowledge about the different range limitations of the employed sensory modalities, adaptive modality information integration, and feedback from the resource status can contribute to the design of algorithms that deal with these severe restrictions.

This is particularly relevant in the cases where there is uncertainty in the definition of the search region, in the effective range of the sensors, the efficient use of available energy resources (see Fig. 1), and on the latency and specific distribution of the odor sources [8,9,10]. Examples of such strategies are Lévy walks that combine clusters of short length steps with longer movements between them. In several animal species this strategy leads to optimal search [11]. Of course, Lévy walk strategies are changed or at least modulated when relevant information from different modalities becomes available during the search, including behavioral information from the same or other species. In this paper we propose a set of hardware and software design principles for open-source and low-cost collaborative robots to implement and validate a wide range of such bio-inspired adaptive strategies useful for uncertainty-aware robotic search.

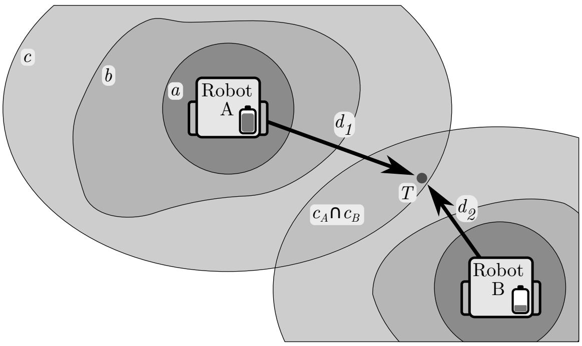

Fig. 1. *Handling uncertainty based on knowledge from the different sensor ranges and energy resources.* The figure illustrates different sensor ranges for two robots. The a-range represents the proximity sensor; b-range is the effective odor detection range for the electronic nose; and c-range represents each robot's estimation of its effective search area. In this example, the swarm must ensure that target T is sensed for the presence of odor sources. In the figure, robot B is closer to the target ($d_2 < d_1$), but its battery is lower than robot A's. The uncertainty of robot B to get close enough so that point T is covered by the sensory range, combined with the cooperative strategy among both robots, could tip the balance towards the motion of robot A. In general, movement decisions could be modulated by the different range limitations of the employed sensory modalities, and by the limited resources of the robots at a given time.

2 Flexible Robotic Platform

For the robot design we used as a base existing open-source projects in which most mechanical parts are intended to be manufactured with a low-cost 3D printer. These are called *printbots* [12], and one example is the MiniSkybot[1]. Printbots provide an accelerated design path not only for creating basic educational robots [13] but also for making robots that can be used for research, such as the platform presented in this paper. With this technique it is possible to easily reuse, develop and incorporate the most useful parts of previous designs in order to fulfill the requirements of a robot needed for a given task.

Regarding swarm robotics, printbots have been preferred over other solutions for both the reduced manufacture cost and, most importantly, for the high adaptability of the designs to the search problems. For instance, the usage of 3D printed structures opens the possibility of easily testing the performance of various spatial distributions of the odor sensors in the robot, by manufacturing custom parts that can accommodate the different configurations.

2.1 Specifications of the GNBot

The proposed robot design (see Fig. 2) is a derivative of the ArduSkybot[2], an educational printbot based on the Arduino UNO[3] electronic board, and it also incorporates work from the Vector-9000[4] competition robot. From these projects, we integrated both hardware (mechanical parts and electronic boards) and software (robot firmware and a basic communication strategy). On the hardware side, the ArduSkybot design was modified to incorporate the Arduino MEGA[5] board to allow the addition of more sensors. The Printshield board -designed for the ArduSkybot- was the base to design the GNBoard, which provides a compact solution to contain most sensors and allows easier interconnection. The GNBot also incorporated a light sensor array developed originally for the Vector-9000, and this project also provided the software base with a framework to interface with the computer in a fault-tolerant manner.

The selection of sensory input was oriented towards the odor source localization task, and thus an electronic nose was made part of the robot. The odor sensor works with a heater element whose temperature can be controlled electronically by a power transistor placed for this purpose on the GNBoard. Sensor temperature control allows the usage of different modulation strategies to enhance sensor performance and to allow adaptation to the intensity of odor sources [14]. The mounted sensor is the *TGS-2600* gas detector from Figaro[6], but any sensor with a similar polarization scheme could be used.

[1] `http://www.iearobotics.com/wiki/index.php?title=Miniskybot_2`
[2] `https://github.com/carlosgs/ArduSkybot`
[3] `http://arduino.cc/en/Main/ArduinoBoardUno`
[4] `https://github.com/carlosgs/carlosgs-designs/tree/master/Vector-9000-a-fast-line-follower-robot`
[5] `http://arduino.cc/en/Main/ArduinoBoardMega`
[6] `http://figarosensor.com/`

Next, the other key element that had to be taken into account was the monitorization of battery voltage in order to give robots knowledge of the status of their energy resources. The implementation of this sensing capability was done by placing a resistive divider that adapts battery voltage to the $[0, 5]V$ range that can be measured with the Arduino board. Robots also incorporate an IR analog rangefinder (ref: *GP2Y0A21*) to avoid collision with obstacles and other robots within the search environment, as well as a light sensor array intended to be used to identify light landmarks. Finally, an electronic compass (ref: *HMC5883L*) provides the orientation knowledge. This way, each robot and the swarm can have a basic multi-modal perception of their status and location in the search area.

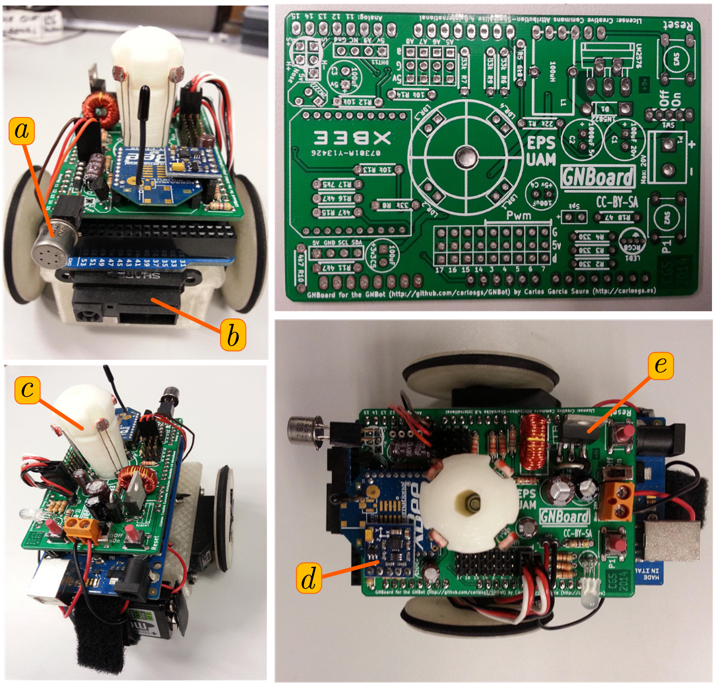

Fig. 2. *The GNBot and GNBoard.* List of sensors present in the robot: *a)* TGS-2600 odor sensor, *b)* IR rangefinder, *c)* LDR light sensor array, and *d)* electronic compass module. Battery voltage is also monitored by the power supply *(e)*. The base actuators are two-servo motors and the wireless interface is based on a ZigBee module (*XB24-BWIT-004*).

The motion of the robot is achieved using two continuous rotation servo-motors (*SM-S4303R*) as the main actuators. Servo-motors provide a compact and low-cost solution to achieve the digital speed control needed, and they are frequently used in bio-inspired robot designs [15,16]. The main downside of this kind of actuator is the high current demand -particularly during transient motions- which requires the use of an adequate power supply. For our design we decided to use a switching power supply rather than a linear regulator, provided the much higher efficiency. Switching power regulators also have a broad input voltage range, allowing to make better use of the full capacity of the batteries since they can be connected in series without negative effect in the performance. The power supply of the GNBoard uses an *LM2576-5* switching regulator that is capable of delivering up to 3A, which is more than sufficient to cover the energy demand of the entire robot.

The development of this platform is kept open-source and accessible via GitHub[7] to allow re-use and community evolution of the project.

2.2 Adaptability of Sensors and Actuators

Collaborative search algorithms may require adaptive control of the sensory input in order to maximize sensitivity, and the proper management of actuator elements to reduce energy demand during the exploration. A first approach can include monitoring events on the battery performance (see Fig. 3) to implement basic decision making on the search strategy.

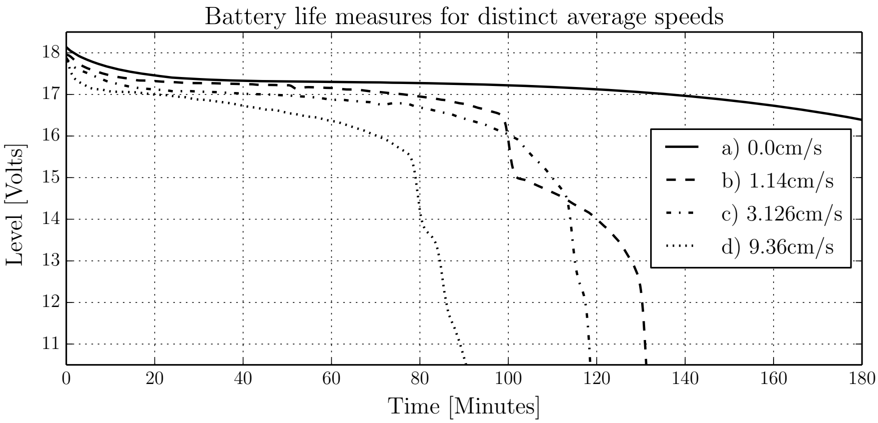

Fig. 3. *Battery life measures for distinct average speeds.* One GNBot powered by two fully-charged 9V 300mAh rechargeable batteries in series configuration was the setup used for this study. A simple obstacle-avoidance routine was used to ensure the continuous motion of the robot. *Operating time: a) 255min b) 131min c) 119min d) 91min. Distance range estimation: a) 0m b) 90.29m c) 222.26m d) 505.44m.*

The measurements in Fig. 3 show that servo-motors do not have a linear *power/performance* relationship, as they maintain a very high power consumption even at very low speeds. Using this information the search strategy can be adapted to maximize search range. This can be done, for instance, by disabling

[7] `https://github.com/carlosgs/GNBot`

the motion of the robot when waiting for the olfactory sensor measurement to be completed. The knowledge of various differentiated stages on the battery life is useful information that can be incorporated to trigger a decision-making event during search, to optimize the use of energy resources. For example, abrupt changes on battery level can trigger a speed change, shutting down high consumption sensors such as the electronic nose, or altering the decision of which robot approaches a given target (cf. Fig. 1). In the case of search strategies based on Lévy walks, the motion decision extracted from the Lévy distribution can also be modulated in real time with the battery life estimation.

Apart from bio-inspired energy management, sensing often requires to implement gain-control in different sensory modalities to better adapt to variability in each environmental context. Modulation of the temperature of single odor sensors can serve as a virtualization of sensor arrays and it also allows for spatio-temporal encoding which can be needed for more advanced detection and classification tasks. The GNBoard is conveniently provided with the circuitry necessary to achieve this sort of adaptive modulation in odor sensing.

2.3 Communication among Robots

In the case of collaborative swarm robots, one of the key design decisions that needs to be made is the selection of a proper communication method. Not only there is a trade-off between the *working range, maximum information throughput and cost*, but there are some other facts that must also be taken into account:

- *Working environment:* Radio-Frequency (RF) communications generally provide a robust system for most applications, but sometimes other solutions can provide a better balance between performance and cost. For instance, for underwater applications RF signal attenuation may become an issue, and the use of sound waves, light pulses, or even tethering with a cable become reasonable options.
- *Power requirements, adaptivity and remote-end sensing:* Since mobile robots have very limited energy resources, an efficient system should be generally preferred in order to maximize the operation time. In the same line, some interfaces provide a way to switch among different power schemes in real time, as well as having the capability to measure the signal intensity received from the other end. These should be preferred since the adaptivity in communications is key towards an optimal usage of energy resources.
- *Networking capability:* Not all communication systems offer the possibility to address data to different end nodes, and this is a must to allow scaling up the size of the swarm. This issue is further discussed in the next section.

ZigBee[8] (*IEEE 802.15.4*) has been chosen as an integrated solution, since it is a highly configurable platform that is compatible with most of the points detailed above. It provides an excellent networking layer, and since it is designed for low power applications, ZigBee has the possibility of adapting RF energy usage

[8] `http://www.digi.com/technology/rf-articles/wireless-zigbee`

in real time. The main downsides of this solution are the maximum throughput rates and the timing constrains, that must be taken into account when considering the use of more complex sensory input such as real time video streams.

Communication with the robots through these modules is asynchronous via User Datagram Protocol (UDP), and thus real time event handling is critical. The links must be fault tolerant, which can be achieved by using redundancy to ensure that messages are received and processed correctly by each node, and soft-state should be preferred to avoid deadlocks and allow fast recovery. Reliability in communications is a key element to implement the virtualized network topology explained in next section.

2.4 Virtualization of the Network Topology

Uncertainty-aware and resource-wise collaborative search algorithms may rely on very different network topologies to maximize the chances of successful search and minimize time or energy consumption while, at the same time, dealing with context-specific communication range restrictions. In particular, the spatial scale of the search problem and the actual detection range of the odor sources are important factors to design the network topology, that could be changed for instance according to the energy level information. As shown in Fig. 4, a base tree topology makes it possible to emulate and test many different architectures.

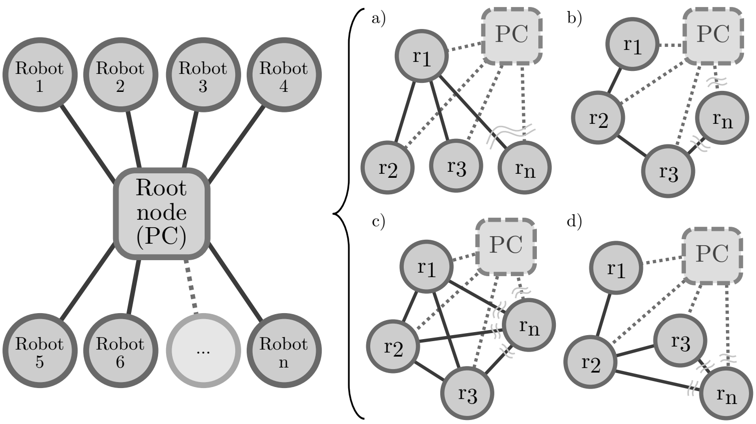

Fig. 4. *Network topology.* The star architecture shown on the left serves as the base to emulate a wide range of topologies. While underlying communications are centralized, the implemented algorithms can have very different requirements. As all information flows through the central computer, virtualized connectivities between robots can be defined in order to achieve various architectures such as *a) tree/star*, *b) line*, *c) fully interconnected*, or *d) mesh*, among others. The emulation of many other characteristics of physical links (*variable delays, jitter, data corruption, packet loss...*) can be used to test the resilience of the implemented search algorithms in a controlled manner.

The approach used is to abstract all the calculations to a root computer, effectively using each robot as a peripheral. A centralized infrastructure is used to command each autonomous robot independently, but a convenient layer of abstraction allows testing algorithms that are decentralized (see panels *a*-*d* in Fig. 4). Main advantages of this approach are:

- First, it is able to reduce costs since robots are kept simple, with reduced computational ability. For a fixed funding, cutting down the cost of each robot makes it possible to create more of them and thus have a bigger swarm.
- Second, as all data flows through the root node, it can be logged and analyzed in order to evaluate the performance of each algorithm and allows easier debugging. Having all information in one place is particularly convenient when testing distributed algorithms.
- Third, it provides a layer of abstraction. The code that specifies the behavior of each robot runs on the central computer, and thus a high-level programming language (such as Python[9]) can be used. This way it is possible to focus on developing the algorithms rather than dealing with the limitations of memory and power of the micro-controller on board each robot.
- Finally, it is important to emphasize that the centralized architecture supports a large dynamic range of complexity of the algorithms, that can be kept simple (i.e. chaotic search [17]) or complex (i.e. particle filtering [4]).

The emulated topologies could be dynamically reconfigured in real time to adapt to the search requirements (i.e. groups of robots may establish separate sub-networks when getting far from others to do local search, and later share the search results with the rest of the group). The chosen ZigBee communication protocol natively supports the deployment of such architectures in the real world, which makes it very convenient towards the actual implementation of the virtually-optimized topologies.

3 Discussion

In the case of odor searching tasks, collaborative robot strategies have to face uncertainty arising from the definition of the search area, the latency of the targets, the actual range and efficiency of the different sensory modalities, the available resources and expected duration, etc. Bio-inspired strategies that use adaptive context-dependent sensory integration and decision making can help to implement collaborative search under severe uncertainty conditions.

Many behavioral and neuroethological studies emphasize the capacity of different animals to switch between different navigation and search strategies (e.g. see for review [18,19]). Animals have an extremely flexible and efficient sensory-motor integration that results in successful search strategies that guarantee survival in situations where uncertainty is large such as the localization of odor sources in order to find nutriment. The incorporation of relevant information

[9] `http://www.python.org/`

regarding various sensor modalities into Lévy walk strategies, as in some animal species [11], provides inspiration for the design of novel search strategies for collaborative robots that work environments with such kind of uncertainty restrictions.

The wide variety of possibilities for designing and implementing bio-inspired searches which rely on different sensory information integration and motor decision making, calls for novel flexible robotic platforms that can meet the requirements arising from handling uncertainty and resource availability within these paradigms. The approach discussed in this paper addressed this issue from the perspective of a solution that allows maximum flexibility, scalability and reuse. We have proposed several hardware and software design principles and an open-source robotic platform, the GNBot, which allow the usage of low-cost robots for the design and validation of collaborative and adaptive search algorithms.

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