# Towards a Unifying Information Theoretic Framework for Multi-Robot Exploration and Surveillance

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## Extended Abstract

In this talk we discuss our recent work on a mathematical framework for pursuing exploration and surveillance tasks using multiple collaborating robots. We ground this framework in the first principles of information theory, and in doing so establish a unifying model that considers the inter-dependencies of system resources pertaining to robot mobility, sensing, and communication. The framework identifies metrics that characterize system performance and provides qualitative understanding of quantitative results. We show that exploration and surveillance[1] can be considered close relatives who can both be described with the same framework, and as a result approaches developed for one task can adaptively (or even better simultaneously) achieve goals for the other.

Information theoretic approaches in general have a rich history in robotics and sensor networks. Cameron and Durrant-Whyte first proposed a strategy in [2] to optimally place sensors for recognition and localization tasks without explicitly considering the mobility of the sensors. This work resulted in a long lineage of controlling mobile robots equipped with sensors to acquire information from an environment of interest, most notably the research of Bourgault et al. in adaptive exploration [1]. Other significant contributions have come with advances in mutual information methods [6, 5, 11, 8], distributed Bayesian filtering [9, 4, 3, 7], and distributed hypothesis testing [10]. The objective for our efforts is to expose the underlying foundation that has supported this lineage and show how revisiting the first principles of information theory can lead to novel approaches in multi-robot exploration and surveillance.

Besides potentially carrying out an assigned task faster and more efficiently, multiple collaborating robots may become the only viable option to achieve a desired temporal or spatial sample frequency when acquiring observations within an environment of interest. Our proposed framework incorporates aspects of the environment representation to ensure adequate resource allocation when constructing a multi-robot system. Furthermore, the underlying model highlights the known shortcomings with purely centralized control approaches, such as susceptibility to cascading technical fail-

[1]We define exploration (surveillance) as the task of inferring the dynamic (static, respectively) components of an environment of interest.

ures and fundamental limits in terms of scalability. Hence, we strive to build inherent behavior that enables each robot to act independently and intelligently using only information obtained locally, with the ability to better achieve system-wide objectives as more global knowledge is made available over the network.

We first focus our work in the area of distributed exploration and surveillance, with robots forming control actions to steer the system in the direction of increasing utility while using primarily local information. We then discuss a novel approach in which the robots iteratively estimate the state of an environment using a sequential Bayesian filter, while continuously moving to improve the quality of the inference by following the gradient of mutual information. Revisiting the mathematical framework that incorporates robot mobility, sensing, and communication, we show how combining consensus and sampling allows for the decentralization and scaling of information theoretic tasks that are traditionally centralized and computationally intractable.

We demonstrate how higher, more centralized levels of cognition, which may be of artificial or human origin, can provide global guidance to improve overall system performance. These additional control inputs provide the user with the capability to specify emerging monitoring requirements in real-time. While the aforementioned underlying stable behavior significantly reduces the communication requirements, some form of system-wide communication is beneficial to share higher levels of cognition. We therefore address the communication constraints relvant to distributed systems, which may stem from limited transmission power or spectral bandwidth. In addition to our novel coordination algorithm, we propose a distributively organized communication scheme that achieves a high degree of connectivity while imposing a limited amount of constraints on the mobility of the system.

To motivate the presented framework and demonstrate real-world applicability, we present two hardware experiments using quad-rotor flying robots.

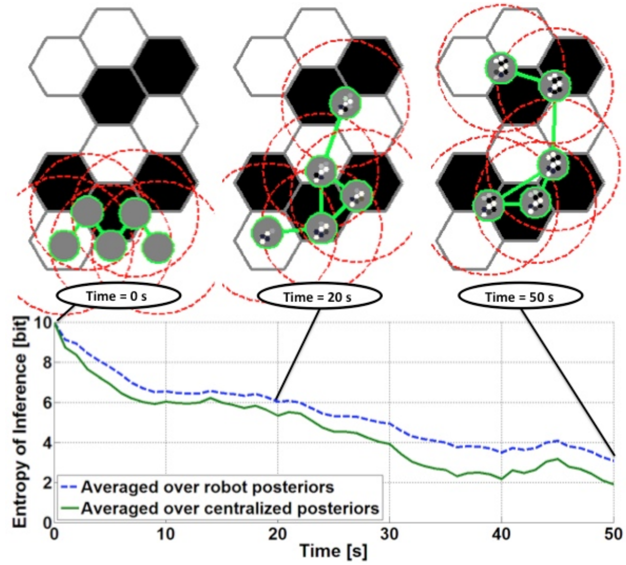


Fig. 1. The top figures show the beginning, middle, and end configuration of 5 quad-rotor flying robots exploring a 10 cell discretized environment, where the state of each cell is either 0 (black) or 1 (white). The robots are represented by the gray circles, within which their prior distributions can be visualized. The green lines represent network connectivity, and the dashed red circles represent sensor ranges. The plot shows the decrease in entropy of the inferences averaged over 10 consecutive runs. These results were first presented in [8]

The first experiment was conducted indoors within a laboratory equipped with a motion capture system. Our task was to deploy 5 quad-rotor flying robots to explore a 10 cell discretized environment of an unknown state. As illustrated in Figure 1, the robots spread out over the environment while simultaneously taking sensor measurements and inferring the state of the environment, thus demonstrating that the underlying framework is capable of achieving stable behavior and gradually decreasing environment uncertainty. In a second set of experiments our task was to achieve similar stable behavior under less ideal conditions, namely in an extended outdoor area with GPS as only source of position information. Moreover, the sensory coverage of the 5 quad-rotor flying robots was inadequate to fully cover the entire environment, and thus the robots never converged to a static configuration (see Figure 2). Finally, we conclude our presentation by discussing properties such as scalability and

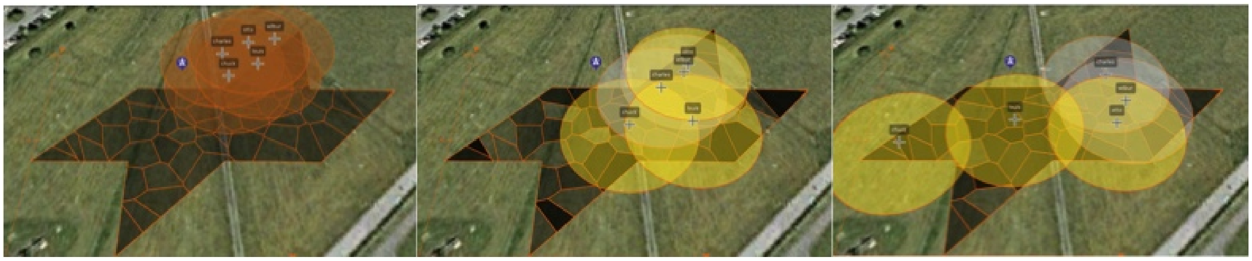

Fig. 2. These figures show the deployment of 5 quad-rotor flying robots tasked to explore an outdoor environment of over $50+$ cells. Unlike the indoor environment, there are not enough system resources (i.e. sensing capability) to fully cover the environment, and thus the robots never converge to a static configuration. This behavior is enabled by the gradient-based controller, which continuously attracts the robots towards areas of the environment with high uncertainty. In addition, a distributively organized communication scheme assigns certain robots to act as static network routers (illustrated by the light blue sensor footprint).

robustness in the results of large scale simulations that involve significantly larger environments and a larger number of robots.

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