Towards a Symbiotic Human and Multi-Robot Planetary Exploration System: Resilient Topologies for Space Exploration

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***Abstract*—This work aims at developing the software infrastructure needed for one or more humans and a multi-robot system (or "swarm") to collaborate in the exploration and mapping of planetary environments such as caves or lava tubes. The intended application of the proposed technology is the in-situ support for a human exploring a lava tube on the moon. Aided by a swarm of small-sized robots which are controlled by an audio-visual interface, the human would issue commands (e.g. "proceed with mapping activities for 300m"), and the robots would self-organize to achieve the tasks. As the robots explore, they will place themselves in key locations to guarantee network connectivity for the whole swarm, including the human(s), at all times by acting as relays. The overall goal is to increase the performance as well as the safety of human space exploration. In this paper, we present approaches, challenges, and results of our recent implementations and tests in a prototyping multi-robot setup.**

I. Introduction

With the Moon and Mars being primary targets for future planetary exploration missions of many space agencies [25, 26], collaborative exploration becomes increasingly important. In this direction, the advancement of joint human and robotic systems is of uttermost importance. While missions on the Moon and Mars can leave humans and equipment almost unprotected from radiation, the time spent outside of protective habitats should be minimized [20]. Natural caves and cavities, which could provide the necessary shelter from radiation, are of prime interest for pre-settlement missions. JAXA's SELENE Lunar Radar Sounder (Kaguya) confirmed the existence of intact cavities below the Moon's surface. These cavities are ancient lava tubes and one has been found to be approximately 60 km in length [12]. For humans to use these lava tubes as shelter, further robotic and robot assisted exploration missions have to evaluate the suitability and associated risks.

A multi-robot system, in contrast to a single all-purpose robot, is potentially more efficient and resilient for exploration and mapping tasks in such vast and unknown environments. Higher levels of redundancy and the ability to explore more risky areas can be achieved by teams of robots. Adding humans to the multi-robot system is planned for future missions, but bears challenges when interfacing with the whole team of robots. Developing a "symbiotic human and multi-robot planetary exploration system" addresses multiple open research questions at the same time: (i) coordination of a "swarm" of multiple (semi-)autonomous robots, (ii) connectivity maintenance in caves, cavities and lava-tubes, as well as (iii) human swarm interaction. Our current research focuses on the software infrastructure for a self-organizing swarm of robots (i) and network connectivity maintenance (ii), while human swarm interaction (iii) will be addressed in a later stage of the project.

The European Space Agency (ESA) is currently building a new artificial analogue facility designed to prepare for future lunar exploration missions. This facility is called LUNA and is located at the European Astronaut Centre (EAC) in Germany [4]. The system and methodology presented here are part of a Networking Partnering Initiative between EAC and Polytechnique Montréal. While the results in this article concern a simpler laboratory testbed, we anticipate the deployment of this work within LUNA's analogue missions by 2019.

II. Problem Statement

Connectivity maintenance and topology control for mapping and exploration tasks are difficult problems to solve in a decentralized, swarm-based, and scalable manner because topology is inherently a global property of the swarm. As the swarm size increases, the amount of information instantly available to any single robot decreases, thus increasing the amount of communication necessary to achieve adequate estimation of a robot's position within the topology of the robot swarm. We study new decentralized topology maintenance approaches, that allow for adequate scalability and robustness to communication noise. This is necessary to create a symbiotic human and multi-robot exploration system to explore lava tubes and caves on the Moon. Consisting of a large number of robots, the system has to operate reliably in such possibly hazardous and communication impairing spaces, to ensure the achievement of predefined exploration goals.

III. Related Work

A. Self-Organizing Swarm Robotics Platforms

Topology control can be used to achieve desired network configurations that, e.g., maximize information flow or terrain coverage, as well as to prevent or fix disconnections that would hinder information flow across the swarm. Existing approaches hinge around well-known results in spectral graph theory [23]. Two results, in particular, form the backbone of current methods. The first result says that a particular form of node centrality measure, known as *eigenvector centrality*, provides insights on the information flow across the network. By calculating the centrality of every node, the swarm can detect whether disconnection is about to occur and perform corrective maneuvers to prevent it from happening [28]. The second result is that gossip-based average consensus can be modeled as a power iteration operation over the network [1]. The works of Bertrand and Moonen [2], Di Lorenzo and Barbarossa [6], and Sahai *et al.* [21] focus on decentralized methods to calculate the eigenvector centrality of a node. These methods can be plugged into virtual physics algorithms [22] to control the topology of a swarm [27]. While these methods offer acceptable results with small swarms, they scale poorly for increasing swarm sizes ([2, 6]) and their convergence is easily disrupted by communication noise ([2, 21]). An alternative approach to topology control takes inspiration from the chaotic dynamics of non-linear oscillators [3]. We conducted first simulations and experiments in [15] to simulate hardware problems, software issues, and communication failures within a multi-robot system. A controller for connectivity maintenance resilient to a certain extent of failures has been implemented and the optimization of its parameters and performance is discussed. More recently, Minelli et al. [14] added an online optimization framework to the proposed control law.

B. User Interface and Human-Robot Collaboration

The control of a networked pool of autonomous robots by an individual or by a team is a daunting challenge because of the complexity of the coordination task and the amount of the information exchanged. Studies have shown that a number of factors substantially affect the human-robot team performance, such as the flexibility in the level of delegation [16, 24], team structure [7], and a number of human factors [5, 13].

IV. Methodology

A. Proposed Approach

To create a resilient human and multi-robot exploration system, we propose a three fold approach: (a) simulation of algorithmic behavior in physics simulators, (b) small scale laboratory tests with simple robotic hardware, and (c) analogue field experiments with heterogeneous swarms of robots. For all phases it is necessary to create portable and reusable software, that can be deployed in physics simulators and on a variety of robotic hardware alike. For that, we used the robotic swarm scripting language *Buzz* [17], which is designed to program heterogeneous multi-robot systems. As simulation environment, we used the multi-physics simulator *ARGoS* [18]. As a result, we obtained a robot controller that is easily transferable from simulation to real multi-robot systems. In Subsection IV-B, we condense the methodology proposed by Ghedini et al. [8, 9, 10] and refer to our approaches proposed in [15] and [14] for more details.

B. System Model, Control Law and Online Optimization

The multi-robot system can be modeled as an undirected and initially connected graph $\mathcal{G}$. From algebraic graph theory, we know that the Laplacian matrix of an undirected graph $\mathcal{G}$ has interesting properties regarding its connectivity [11]. The eigenvalues of the Laplacian matrix are $\lambda_i, i = 1, \dots, N$, thus:

- The eigenvalues are real, and can be ordered such that $0 = \lambda_1 \leq \lambda_2 \leq \dots \leq \lambda_N$
- λ_2 is called **algebraic connectivity** of the graph
- $\lambda_2 > 0$ if, and only if, the graph is connected

Each robots' state is described as its position $p_i \in \mathbb{R}^m$ and the state vector of the multi-robot system is $p = \left[p_1^T \dots p_N^T\right]^T \in \mathbb{R}^{Nm}$. As each robot is modeled as a single integrator system, their individual velocity can be modified directly:

$$\dot{p}_i = u_i \tag{1}$$

where $u_i \in \mathbb{R}^m$ is a control input.

With reference to the kinematic model in Equation (1), Ghedini et al. [10] devised a robust connectivity maintenance control strategy in the form that every robot entity is controlled by a superposition of three control input terms, denoted as:

$$u_i = \sigma u_i^c + \psi u_i^r + \zeta u_i^d \tag{2}$$

The control inputs are defined as follows:

- $u_i^c \in \mathbb{R}^m$ is the connectivity preservation control input which preserves a connected graph, if all robots are initially connected.
- $u_i^r \in \mathbb{R}^m$ is the topology resilience improvement control input, which aims at improving the robustness of the topology against single points of failures.
- $u_i^d \in \mathbb{R}^m$ represents the desired control action, which represents the coordinated objective that the multi-robot system is supposed to achieve.
- $\sigma, \psi, \zeta \geq 0$ represent linear combination gains, which are used to weigh the effect of the separate control laws.

The definition of each individual control action and linear combination of gains influences the global behavior of the multi-robot system. Thus the (online) optimization of the linear combination gains σ, ψ, ζ (see Equation (2)) affects the objective of the system directly. The "*best*" solution is defined as achieving area coverage while keeping a sufficiently high level of connectivity [14]. For this purpose, the objective function was defined as:

$$f_{obj}(t) = \lambda_2(t)\mathcal{A}(t) \tag{3}$$

where $\lambda_2(t)$ is the algebraic connectivity of the network graph and $\mathcal{A}(t)$ the value of the covered area, both at time t.

C. Simulations and Hardware Validation

To understand how different control parameters affect a robotic swarm as a whole, we conducted experiments using the above described optimization of control gains for multi-robot systems as reported in [15] and [14]. The tests were performed within the multi-physics simulator ARGoS and in a laboratory setup with a set of eight simple, terrestrial robots (a small swarm of K-Team Khepera IV).

V. Preliminary Results

The robot controller and the optimization framework have been successfully ported to a resource-constrained robotic platform. With robots equipped with an 800MHz ARM Cortex-A8 Processor and 512 MB RAM each, we were able to replicate the results of previous simulations. The obtained evolution of the objective function f_{obj}, is presented in Figure 1. The initially decreasing coverage C_a and increasing algebraic connectivity $lambda_2$ and objective function f_{obj} correlate with what has been observed in simulations.

This shows, that transferring state of the art algorithms for resilient robotic communication onto resource-constrained real world multi-robot systems is possible. Nonetheless, we are aware of shortcomings of the experimental setup: The experiment was conducted under laboratory conditions and limited to a swarm size of $N = 8$ robots. The study of scalability with respect to larger groups of robots remains open. Further, we observed that the robots operated asynchronously, due to different computing times for the online gain optimization; some finished the experiment earlier than others and stopped communicating with the rest of the team, because a fixed number of control iterations has been used to determine the end of an experiment. This differs from the simulations, because there the optimization has been performed outside simulation time. In addition, we performed all experiments with the limitation of choosing coverage to influence the control actions of the swarm.

To address these shortcomings, we plan further experiments with a larger number of robots and less computing restrained robots. To account for the asynchronous behavior, we suggest to implement multi-threading and a virtual stigmergy [19] based consensus. Another interesting aspect would be to examine the systems performance, when the objective function is changed and exploration and mapping tasks are to be performed along specific directional vectors.

VI. Conclusion and Future Work

In this extended abstract, we present our current approaches and ongoing research towards the realization of a symbiotic human and multi-robot planetary exploration system.

Our starting point is the work of Ghedini et al. [10] that has proven to increase the robustness of initially connected multi-robot systems. The method enables resilient and robust connectivity, even in the case of central nodes failures.

We show that the methodology can be implemented and run on real, resource-constrained robots and we obtain promising results that correlate with simulation results.

In the context of planetary and space exploration, connectivity can be crucial for mission success. When challenging, hard to reach, or occluded environments (like caves) are to be explored, a reliable communication link is beneficial.

Especially with our future work in mind, that is, having one or more human(s) collaborate and influence the swarm, a safe and operationally confident system has to be created.

Next steps include the in Section V mentioned shortcomings, and validating the methodology on different robotic

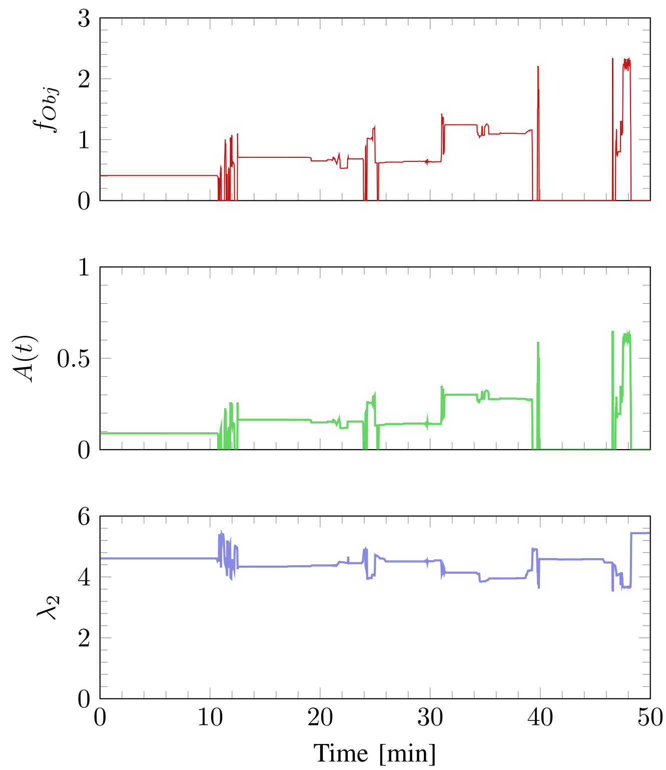

Fig. 1. Evolution of the objective function $f_{obj}(t)$ achieved in real robot experiments using the random search optimization algorithm preset with 400 generated points G_p and an iteration period of $O_p = 50$ [14]. Coverage $A(t)$ and algebraic connectivity $\lambda_2(t)$ are displayed separately.

platforms. Also, a low cognitive human swarm interface will be investigated. The deployment of a more realistic prototype setup in LUNA's analogue environment is expected to take place in 2019.

Acknowledgments

The authors would like to thank Dr. Aidan Cowley and acknowledge the support of the European Space Agency's Networking/Partnering Initiative (ESA NPI), as well as Québec's Ministère des Relations internationales et de la Francophonie.

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