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# Multi-target Simultaneous Exploration with Continual Connectivity

Thomas Nestmeyer, Paolo Robuffo Giordano, Antonio Franchi

The difference between a group of many single robots and a multi-robot system is the ability to communicate and then cooperate together towards a common objective in a decentralized way. In this sense, parallelizing the execution of several small tasks that, together, form a complex mission is a fundamental component of successful multi-robot applications. Many of these applications as, e.g., exploration, surveillance, large-scale medical supply or search and rescue, typically require the inspection of a certain number of locations in the workspace: these can be assumed known a-priori, or generated on-line. Along this line, in this work, we assume that a black-box target generator provides, possibly online, a list of targets for each robot. The problem is to design a decentralized feedback control law that lets the robot sequentially visit all the targets and stay close to each target for a given duration in order to fulfill its objective.

While exploration with a fixed topology method is given in [1], periodical connectivity is used in [2]. To have more flexibility and the possibility to communicate at all time, we aimed for a method that allows a time-varying topology but guarantees continual connectivity. For this reason we built our solution upon the framework described in [3]. The main challenge in combining a continual connectivity maintenance method with an exploration algorithm is that the robots have to simultaneously visit their targets without getting stuck in ‘local minima’ (such as, blocked by obstacles or by concurrent but incompatible sub-tasks).

In our proposed method each robot of the group is modeled as a second order dynamical system on which three forces are acting simultaneously: the damping force representing both typical friction phenomena and a stabilization term; the connectivity force whose decentralized computation and properties are described in [3]; the control input force, denoted with  $f_i^z \in \mathbb{R}^3$ , used to actually steer each robot in order to realize the multi-target exploration task. In [3] it is proven that, as long as  $f_i^z$  is bounded, the action of the connectivity force will ensure obstacle/collision avoidance plus continual connectivity of the underlying graph.

The design of  $f_i^z$  depends on the behavior each robot is assigned at a certain time. A connector is a robot that has no active target. Therefore it simply applies  $f_i^z = 0$  and helps keeping the connectivity in the group thus enabling other robots to move more freely. An anchor is a robot that is close to its target and stays in the target area for the (finite) time needed to perform the required operation (e.g., pick and place). In this case the force  $f_i^z$  is generated as the gradient

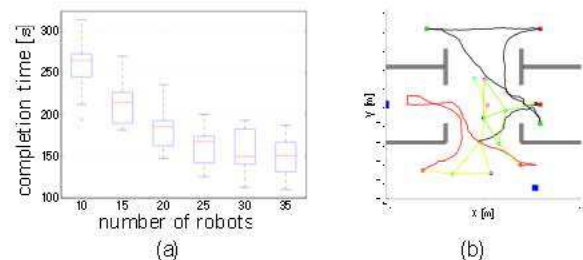


Fig. 1: Sample from the simulation and experimental results.

of an artificial spring-like potential centered at the target. A traveler is a robot that has not yet reached its next target. It computes online an obstacle-free path towards its next target and, at the same time, a force  $f_i^{\text{travel}}$  that would allow the traveler to follow such path in absence of the connectivity force. Among the travelers a prime traveler is elected in a decentralized way as the robot that has the shortest remaining path to its target. The prime traveler applies  $f_i^z = f_i^{\text{travel}}$ . If the prime traveler comes close to its next target, it switches into the anchor behavior and triggers the distributed election of a new prime traveler among the remaining travelers. All the other travelers are called secondary travelers. By means of a distributed protocol, they receive from the prime traveler a real number  $\rho$  (traveling efficiency) that encodes the quality of the tracking of the prime traveler, and they use it in order to apply an input force  $f_i^z = \rho f_i^{\text{travel}}$ . In this way the prime traveler can pull, if needed, the rest of the group and therefore the completeness of the algorithm can be guaranteed.

We performed extensive Monte Carlo simulations with about 1800 total trials in which we evaluated the method in three different scenarios using 10 travelers and from 0 to 25 connectors. Figure 1a shows how the time needed to reach all the targets decreases w.r.t. the number of connectors in one of these scenarios. Many other metrics have been evaluated in our simulations. We also conducted experiments with real quadrotors in order to prove the practicability of the method. Figure 1b shows the trajectories of two real-quadrotor travelers while the remaining quadrotors are keeping the topology connected. Videos concerning the experiment and the simulations can be watched at <http://antoniofranchi.com/videos/expconn.html>.

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T. Nestmeyer and A. Franchi are with the Max Planck Institute for Biological Cybernetics, Spemannstraße 38, 72076 Tübingen, Germany. E-mail: {thomas.nestmeyer, antonio.franchi}@tuebingen.mpg.de.

P. Robuffo Giordano is with the IRI SA/INRIA Rennes, Campus Universitaire de Beaulieu, 35042 Rennes cedex, France. E-mail: prg@irisa.fr.