Human-assisted Parallel Multi-target Visiting in a Connected Topology

Thomas Nestmeyer, Paolo Robuffo Giordano, Antonio Franchi

I. INTRODUCTION

One major benefit of a multi-robot system over a group of many single robots is the ability to cooperate together towards a common objective by sharing information in a decentralized way. In a successful multi-robot system, a complex mission is typically parallelized through several small tasks which, when treated all together, lead to overall task completion. For a human operator in control of the group of robots, it is quite challenging to perform these tasks for each single robot at the same time. Therefore one is generally interested in methods that provide as much autonomy as possible.

Many multi-robot applications require a successive visiting of a certain number of locations in their workspace as, e.g., exploration, surveillance, large-scale medical supply or search and rescue. These targets can be either known beforehand, or generated while execution. In this latter case, assume that a black-box target generator provides online a list of targets for each robot. The problem is then to design a decentralized and fully autonomous feedback controller that lets the robots sequentially visit all the assigned targets and to remain close to them for a given duration for fulfilling local objectives at the target locations. Depending on the complexity of the task at the current target, a human assistance can be of great advantage to get the job at the target properly done. This arises the need for a method that lets a human operator take control of a single robot in the moment where it is near its target and where full automation does not lead to the desired outcome.

Different strategies have been proposed in the literature in order to achieve and maintain a communication network among the cooperating robots. In [1] exploration with a fixed topology method is given, while [2] uses the concept of periodical connectivity. We aimed for a method that could allow a time-varying topology while guaranteeing continual connectivity in order to have more flexibility and the possibility to establish a communication channel among any two robots at all times. 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 visit their targets in parallel without getting stuck in ‘local minima’ (such as becoming blocked by obstacles or by concurrent but incompatible sub-tasks).

II. AUTONOMOUS TARGET VISITING

In our proposed method each robot of the group is modeled as a second order system on which three forces are acting simultaneously: the connectivity force whose decentralized computation and properties are explained in [3]; the damping force that represents typical friction phenomena and acts as a stabilization term; the control input force, denoted by \( f^{\text{c}}_i \), that is actually steering each robot to realize the multi-target visiting task. In [3] it is proven that, as long as \( f^{\text{c}}_i \) is bounded, the action of the connectivity force will ensure obstacle and inter-robot collision avoidance plus continual connectivity of the underlying graph.

To achieve the parallel target visiting without getting stuck, we design \( f^{\text{c}}_i \) depending on an assigned time-varying behavior.

- A connector is a robot with no active target. Therefore it simply applies \( f^{\text{c}}_i = 0 \). Being only tied to the connectivity and damping force, it helps keeping the connectivity in the group and thus enabling other robots with assigned targets to move more freely.
- A traveler is a robot with an assigned target and still needing to travel towards it. Therefore it determines a smooth obstacle-free path towards its next target upon receiving it from the target generator and, during motion, computes a force \( f^{\text{travel}}_i \) that would allow the traveler to follow such path with a given constant speed in absence of the connectivity force.
  - Among the travelers, a prime traveler is elected in a decentralized way as the robot with the shortest remaining path to its target. The prime traveler applies \( f^{\text{c}}_i = f^{\text{travel}}_i \).
  - All the other travelers are denoted secondary travelers. By means of a distributed protocol, they receive a real number \( \Lambda \) (traveling efficiency) from the prime traveler that encodes the quality of the tracking of the prime traveler. Furthermore they determine their direction alignment \( \Theta_i \) between the connectivity and control input force. After a weighted mixing of these two quantities into one value \( \rho_i \in [0, 1] \), they use it in order to apply an input force \( f^{\text{c}}_i = \rho_i f^{\text{travel}}_i \).

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 CNRS at IRISA, Campus de Beaulieu, 35042 Rennes cedex, France. E-mail: prg@irisa.fr.
traveler, it triggers the distributed election of a new prime traveler among the remaining travelers. The task of an anchor is then to stay in a certain target area for some (finite) time needed to perform the required operation (e.g., pick and place). In this case the force $f_z$ is generated as the gradient of an artificial spring-like potential centered at the target. When the anchoring behavior is over, depending on the existence of a successive target and a current prime traveler, the robot afterwards switches into a secondary traveler or prime traveler to reach its next target or into a connector if there is no further target.

III. HUMAN ASSISTANCE IN THE ANCHORING BEHAVIOR

The human assistance can be exploited in the anchoring behavior in order to help a generic robot $i$ to perform a complex task, for which full autonomy is not yet available. This includes, e.g., fine navigation with an onboard camera in a cluttered environment to find a given object. To be able to do so the robot simulates the behavior of a virtual second order system subject to the aforementioned forces. This system acts as a virtual proxy that is considered by the robots in the connectivity framework as the robot $i$. The robot $i$ then temporarily decouples from the limitations imposed by the forces described so far and gives full remote control to the human. Therefore the robot is free to move in the target area, but prevented to leave that area in order to be able to keep the communication with the rest of the group. When the human assisted task is completed, the robot moves back to the current position of the virtual proxy and reattaches to it.

IV. SIMULATIONS AND EXPERIMENTS

We performed extensive Monte Carlo simulations with about 1800 total trials in which we evaluated the method in three different environments using 10 travelers and from 0 to 25 connectors. Figure 1 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 quadrotor aerial vehicles used as mobile robots in order to prove the feasibility of the method and the use of the human assistance. Figure 2 shows the trajectories of the two travelers (red and black) while the remaining quadrotors are keeping the topology connected (shown in lemon at the beginning and lime at the end of the experiment). The blue circles indicate the area in which the human assistance in the anchoring behavior is active.

Videos concerning the simulations and experiment can be watched at [http://antoniofranchi.com/videos/expconn.html](http://antoniofranchi.com/videos/expconn.html). In the last video, where the experiment is shown, the decoupling and human takeover can be seen (shown as a red ball around the decoupled robot in the lower left part).

REFERENCES

