On Multi-Robot Active Collaborative Inference in Unknown Environments via Belief Space Planning

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Autonomous operation under uncertainty is essential in numerous problem domains, including autonomous navigation, object manipulation, multi-robot localization and tracking, and robotic surgery. As the robot state is never accurately known due to motion uncertainty and imperfect state estimation obtained from partial and noisy sensor measurements, planning future actions should be performed in the belief space - a probability distribution function (pdf) over robot states and additional states of interest.

While typically, belief space planning approaches consider the environment is known, in certain scenarios of interest (e.g. navigation in unknown environments) this is not a feasible assumption. In these cases, the environment is either a priori unknown, uncertain or changes dynamically, and therefore should be appropriately modeled as part of the inference and decision making processes. Such a concept was recently developed in [3], where random variables representing the observed environment have been incorporated into the belief and locally optimal motion plans were calculated using a direct trajectory optimization approach. Simulation- and sampling-based approaches that consider a priori unknown environments have also been recently developed in the context of active SLAM (see, e.g. [2]). A limitation of these approaches is that the belief only considers the environment observed *by* planning time and does not reason, in the context of uncertainty reduction, about new environments to be observed in the future as the robot continues exploration.

We aim to alleviate this limitation, considering the problem of cooperative multi-robot autonomous navigation in unknown environments. While it is well known that collaboration between robots can significantly improve estimation accuracy, existing approaches typically focus on the inference part, considering robot actions to be determined externally. On the other hand, active multi-robot SLAM approaches (e.g. [1]) typically focus on coordination aspects and on the trade-off between exploring new regions and reducing uncertainty by re-observing previously mapped areas (performing loop closures). In contrast, we consider the question - how should the robots act to collaboratively improve state estimation while autonomously navigating to individual goals and operating in unknown environments?

Addressing this question requires incorporating multi-robot collaboration aspects into belief space planning. To that end, we present an approach to evaluate the probability distributions of multiple robot states while modeling future observations of mutual areas that *are unknown at planning time* (Figure 1). The key idea is that although the environment may be unknown a priori, or has not been mapped yet, it is still possible to reason in terms of robot actions that will result in the same unknown environments to be observed by multiple robots, possibly at different future time instances. Such observations can be used to formulate non-linear constraints between appropriate robot future states. Importantly, these constraints allow collaborative state estimation without the need for the robots to actually meet each other, in contrast to the commonly used direct relative pose observations that require rendezvous between robots (e.g. [4]). We show how such constraints can be incorporated within a multi-robot belief, given candidate paths that can be generated by any motion planning method. One can then identify the best path with respect to a user-defined objective function (e.g. reaching a goal with minimum uncertainty), and also refine best alternatives using direct trajectory optimization techniques.

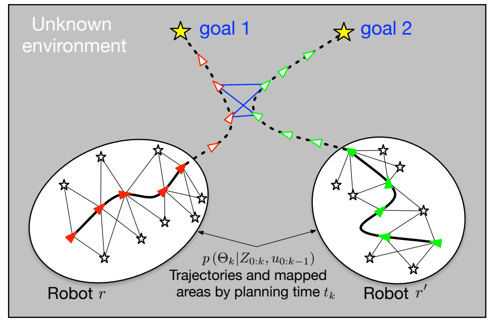

Fig. 1. Illustration of the proposed concept. Multi-robot indirect constraints representing mutual future observations of unknown environments are shown in blue.

We present preliminary results of our approach in a multi-robot autonomous navigation scenario and show that modeling future multi-robot interaction within the belief allows to determine robot trajectories that yield significantly improved estimation accuracy.

References

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