Multi-Robot Coordination with Periodic Connectivity

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Abstract Idea

• Multi-robot coordination subject to constraints on the configuration.
• Introduction of the idea “periodic connectivity”.
• Constrained communication.
• Proposed algorithm is based on well-studied NP-hard ‘MIPP’ problem.
• Theoretical guarantees provided.
• Experiments performed both in simulation and on real robots.
Periodic Connectivity

• Robots do not need to be connected continuously.
• Connectivity must be re-established in certain time intervals.
• Not all configurations has this property.
• Advantages:
  1. communicate information gathered (considered in this paper)
  2. coordinate the next phase of the plan.
  3. check whether all robots are working or not.
Problem Description

• K robots in the system.
• **Known map** – discretized into G(N,E): nodes are convex regions, edges are connections between them.
• G’(N’,E’): time-unfolded version of G.
• Each robot \( k \) plans a path \( P_k = \{r_k(0), \ldots, r_k(T)\} \).
• Cost of a path is \( C(P_k) \); \( \text{max } C(P_k) = T \).
• Path union for all robots: \( P = P_1 \cup P_2 \cup \cdots \cup P_k \).
• Maximize a known objective function \( F(P) \).
• In MIPP, objective function is:

\[
\max_{\bigcup_{k=1}^{K} P_k} F(\bigcup_{k=1}^{K} P_k); \quad \text{s.t.} \quad C(P_k) \leq T, \forall k \in \{1, \ldots, K\}
\]

• Connectivity graph \( G_C(N, E_C) \) is given.
• For the MIPP-PC problem, the robots begin in a connected configuration \( P(0) \) and must regain a connected configuration at times \( P(T_1), P(2T_1), \ldots, P(jT_1) \).
Algorithm Design

- **Theorem**: Given the connected configurations $P(0)$, $P(T_1)$, $P(2T_1)$, ..., $P(jT_1)$, MIPP-PC reduces to $j$ instances of unconstrained MIPP.

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**Algorithm 1** Implicit coordination for MIPP-PC

1: Input: robots $K$, graph $G$, connectivity graph $G_C$, objective $F$, interval $T_I$, initial configuration $P(0)$
2: % Initialize all paths to remain stationary
3: $P_k(1, \ldots, T_I) \leftarrow P_k(0)$, for all $k$
4: % $V \subseteq N'$ is the set of visited time-stamped nodes
5: $V \leftarrow \bigcup_{k=1}^{K} P_k$
6: while not converged do
7:   for all robots $k \in \{1, \ldots, K\}$ do
8:     % Reset path for robot $k$
9:     $V \leftarrow V / P_k$
10:    Enumerate some feasible paths $A_k(1, \ldots, T_I)$
11:    Discard paths disconnected at $T_I$
12:    $A^*_k(1, \ldots, T_I) \leftarrow \text{argmax}_{A_k} F(V \cup A_k)$
13:    % Update path for robot $k$
14:    $P_k \leftarrow A^*_k$, $V \leftarrow V \cup A^*_k$
15:   end for
16: end while
17: Return $P(0), P(1), \ldots, P(T_I)$
How it works

2-robot, 1-goal scenario.
Running Time

- Each iteration of the outer loop in Algorithm 1 requires $K$ optimizations of a single path MIPP-PC instance.
- If we enumerate all paths to depth $T_I$, the computation is $O(Kb^{T_I})$, where $b$ is the branching factor of the search graph.
Experimental Results

- Model: robots must find a moving target with a known (or approximately known) motion model.
- The searchers receive reward by moving onto the same node at the same time as the target.
- Probabilistic Objective Function:

\[ F(P) = \sum_{Y \in \Psi} P(Y) F_Y(P) \]
Simulations

- Data taken from RADISH data set, discretized into 188 cells.
- Cells were found using ‘region growing’ technique.
- Second site is divided into 937 cells using a constrained Delaunay triangulation.
- The robots must maintain periodic line-of-sight constraints.
- Tested for different number of robots and comparison with existing algorithms are provided.
Results
Mobile Robot Implementation

- Team of 2 mobile robots: the Serf and Sideswipe autonomous platforms.
- The inter-robot communications were handled using the Player software.
- The environment was automatically discretized into 52 cells using a constrained Delaunay triangulation.
- Stationary target.
- Robots successfully searched the entire area in less than three minutes while regaining connectivity at most every 30 seconds.
Map and Robots
Conclusions

• MIPP problem with periodic connectivity have been discussed.
• Online, scalable algorithm have been proposed.
• Better than existing algorithms in most of the cases, for similar situations.