On efficient and robust coordination of multirobot systems

Alberto Quattrini Li
Computer Science and Engineering
University of South Carolina
Outline

• Multirobot coordination overview and taxonomy
• Multirobot exploration problem
  – Semantic information
  – Communication constraints
• Discussion
Multirobot systems

Warehouse management
Source: [Girdhar et al., 2012]

Service robotics
Source: [Wąsik et al., 2015]

Precision agriculture
Source: ibtimes.co.uk

Environmental monitoring
Source: wonderfulengineering.com

Surveillance
Source: xsens.com
Multirobot coordination

• Obstacle avoidance

• Formation control

• Task planning and allocation

Source: [Navarro et al., 2009, DARS]
Source: [Parker et al., 2012, RoboCup]
Multirobot coordination

• Many benefits
  – Efficiency
  – Robustness

• But also some drawbacks
  – Higher complexity
  – Higher communication demands
Multirobot coordination can be broadly defined as behaviors, techniques, and approaches that *limit negative interaction* between robots and *provide positive effects on the overall performance* of the system.
Multirobot coordination taxonomy

• By system’s characteristics [Dudek et al., 1996, Auton Robot]
  – Number of robots
  – Communication capabilities (range, bandwidth, ...)
  – Collective reconfigurability

  – Single- vs multi-task robots
  – Single- vs multi-robot tasks
  – Instantaneous vs time-extended assignments

• By communication constraints [Banfi et al., 2015, AAMAS ARMS]
  – Continuous connectivity
  – Periodic connectivity
  – Recurrent connectivity
EXPLORATION PROBLEM CASE
Multirobot exploration system: a system of multiple robots are deployed in an unknown environment with the aim of building its map.
Decision-making process

- **Exploration strategies**: select interesting locations
- **Coordination methods**: assign interesting locations to robots
Exploration strategy and coordination methods

• Information from metric maps
  – Distance of the frontier [Yamauchi, 1998, AGENTS]
  – ...

• Several methods for building semantic maps have been proposed (e.g., [Pronobis et al., 2010, Int J Robot Res])

• Despite the great effort in constructing semantic maps, the study of their use for exploration is still limited (e.g., [Stachniss et al., 2008, Ann Math Artif Intel], [Wurm et al., 2008, IROS])
Semantically-Informed Coordinated Multirobot Exploration

- We designed and developed a multirobot exploration system for search and rescue that is able to exploit semantic information having some *a priori knowledge* given by human rescuers.

Search for victims in big rooms

Source: wikimedia.org

R. Cipolleschi, M. Giusto, A. Quattrini Li, F. Amigoni
“Semantically-Informed Coordinated Multirobot Exploration of Relevant Areas in Search and Rescue Settings”

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“Semantically-Informed Coordinated Multirobot Exploration of Relevant Areas in Search and Rescue Settings”
Exploration strategy

• **Criteria**
  - \( A(p) \), amount of free area beyond frontier location \( p \)
  - \( d(p,a) \), distance between \( p \) and current location of robot \( a \) (Euclidean distance)
  - \( b(p,a) \), battery level of robot \( a \)
  - \( S(p) \), relevance of \( p \), according to the semantic label of \( p \) and *a priori* knowledge on victims’ locations
  - \( ND(p) \), number of doors where \( p \) is located

• **MCDM strategy**
  [Basilico and Amigoni, 2011, Auton Robot]

\[
S(p) = 1 \quad p \in B
\]
Coordination method

- Consider semantic information to determine the optimal number of robots to send to a candidate location

  \begin{enumerate}
  \item For each robot $a$ and each location $p$, compute $u(p,a)$
  \item Find $(p^*,a^*)$ that maximizes $u(p,a)$, allocate $p^*$ to $a^*$ and eliminate $a^*$
  \item Eliminate $p^*$, only if the number of robots already allocated to $p^*$ is equal to the maximum number of robots allocable to $p^*$
  \item Goto step 2
  \end{enumerate}

- MRv2: variation of MRv1, where the utility of $p^*$ is discounted after each allocation
Experimental results

Results in indoor-like environment

Results in mall-like environment

→ The semantically-based coordinated multirobot exploration system compared to a state-of-the-art multirobot exploration system covers
→ More relevant area at the end of the given time interval, even in the presence of a non-perfect semantic mapping system
→ The relevant area is explored faster
Communication-constrained exploration problem

Given
• an unknown two-dimensional, continuous, and bounded environment
• a base station in a fixed position
• \( m \) mobile robots equipped with a finite range sensor

Find a set of robot poses over time so that
• the environment is *explored* efficiently
• the communication with the base station is guaranteed when new information is gathered: *recurrent connectivity constraint*
Planning scheme – Main contributions

- **Asynchronicity**: replan as soon as a given number of robots is ready
- **Configuration**: the optimal subset of frontiers such that connectivity to the BS is guaranteed
  - objective: maximize utility collected from frontiers (NP-Hard)
    \[ U(f) = \frac{g(f)}{\min_{j \in R} d_{p_j}} \]
    - techniques: ILP and approximation algorithm
- **Deployment**: given a configuration, assign a robot to each location therein
  - objective: minimize total traveled distance (easy)
Optimal configuration – ILP

• Observation: a connected configuration with \( n \) vertices must induce a connected sub-tree with \( n-1 \) links

• Preprocessing phase to account for non-ready robots

\[ y_f \text{ takes value 1 iff frontier } f \text{ is chosen} \]
\[ x_{ij} \text{ takes value 1 iff arc } (v_i, v_j) \text{ is chosen} \]

\[
\begin{align*}
\text{maximize} & \quad \sum_{f \in F} U(f)y_f \quad \text{s.t.} \\
& \quad \sum_{(i,j) \in C} x_{ij} \leq |R| \\
& \quad \sum_{(i,j) \in \delta^-(S)} x_{ij} \geq y_f \quad \forall f \in F, \forall S \subseteq V \setminus \{\text{BS}\}, f \in S
\end{align*}
\]
Optimal configuration - Approximation algorithm

• Basic idea: exhaustively enumerate all the subsets of frontiers (S_1, S_2, ..., S_F) with cardinality upper bounded by a given δ and try to connect them with the BS

• We exploit an optimal algorithm for the Steiner Tree problem with fixed number of terminals (at most δ+1) to connect a given subset of frontiers S_i with the BS

• Take the best Steiner Tree (in terms of utility) with at most |R| links

• Approximation guarantee of \( \min\{|R|, |F|\} / \delta \) in polynomial time for fixed δ
Experiments

Simulations

TurtleBots 2

Imagine human rescuers that send a team of autonomous robots in a collapsed building to get a preliminary idea of the situation through cameras.
Experimental results

![Graphs showing experimental results](image)

- Explored area [%] vs. Elapsed time [steps]
- Time not in communication [s] vs. Elapsed time [steps]

- Line styles and colors correspond to different conditions:
  - APX1
  - APX3
  - APX6
  - APX9
  - APX12
  - Utility0.5
Summary

• Semantic information can improve the overall performance of the multirobot system

• Frequent replanning can offer a good situational awareness without significantly limiting the explored area

• Leveraging on the knowledge from the application domain allows the method to be computationally efficient
Open problems

– Heterogeneous systems

– Communication uncertainty

– Recovery mechanisms
Thank you!
albertoq@cse.sc.edu
https://sites.google.com/site/albertoquattrinili/