Planning and Optimization for Multi-Robot Planetary Cave Exploration under Intermittent Connectivity Constraints

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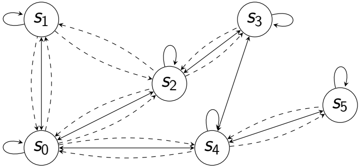
DARPA Subterranean Challenge

Plan Requirements

Synthesize a behavioural plan Π that

- sends robots to frontiers to perform exploration
- periodically updates the base station about the progress
- distributes the plan itself to robots



Mobility-communication network $\mathcal{N}$

Plan

Plan $\Pi = (\Pi_t, \Pi_c)$ consist of two components

- trajectory collection $\Pi_t = \{s_0^r s_1^r \ldots s_T^r\}$
- communication collection $\Pi_c = \{(t, r, r', b)\}$

Cost $C(\Pi)$ of plan $\Pi = (\Pi_t, \Pi_c)$

$$C(\Pi) = \sum_{r \in R} \sum_{t=0}^{T-1} \bar{C}_t(s_t^r, s_{t+1}^r) + \sum_{(t,r,r',b) \in \Pi_c} \tilde{C}_t(s_t^r, s_t^{r'}),$$

$\bar{C}_t(s, s')$: *mobility cost*
$\tilde{C}_t(s, s')$: *communication cost*

Information-Consistency

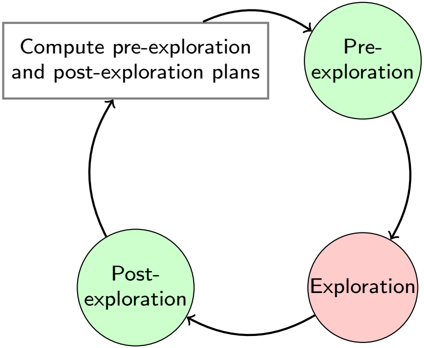
Information-Consistency: robots remain idle until received plan

Definition

Let a subset of robots $R_m \subset R$ be *master robots* that have knowledge of information m at time $t = 0$. A plan $\Pi = (\Pi_t, \Pi_c)$ is *information-consistent* if:

- A robot without information m does not move;
- A robot without information m does not send information

Plan Decomposition



Plan Decomposition

Problem (Pre-exploration planning)

Devise an information-consistent multi-robot plan $\Pi = (\Pi_t, \Pi_c)$, *using the base station as master, such that*

$$-C(\Pi) + \sum_{s \in S_f} \begin{cases} \mathfrak{R}(s,k), & \text{if } \sum_{r=1}^{R} 1_s(s_T^r) = k, \\ 0, & \text{otherwise,} \end{cases}$$

is maximized.

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is maximized.

Problem (Post-exploration planning)

Devise an information-consistent multi-robot plan Π*, using* R_m *as master robots, such that the base station receives information* b *for all* $b \in R_f$*, and such that*

$$-C(\Pi)$$

is maximized.

Intermittent Connectivity Problems

The intermittent connectivity problem is to maximize an objective whilst satisfying intermittent connectivity constraints.[1]

Inputs: Network $\mathcal{N}$, master robots R_m, initial positions s_0^r, connectivity constraint $(\texttt{src}, \texttt{snk})$, optimization objective, time horizon T.

Output: Information-consistent plan $\Pi = (\Pi_t, \Pi_c)$ that satisfies the intermittent connectivity constraint.

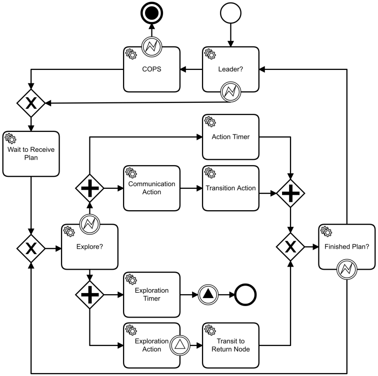
COPS: Python stack solving intermittent connectivity problems.[2]

[1] Klaesson et al. 2019. Intermittent connectivity for exploration in communication-constrained multi-agent systems.

[2] COPS available at https://github.com/FilipKlaesson/cops

Plan Executive: Business Process Model Notation

Symbol	Action
	Start Event: Starts a process.
	End Event: Ends a process.
	Terminate End Event: Terminates all processes.
	Error Boundary Event: Triggered if an task error occurs.
	Signal Throw Task: Throws a specific signal.
	Signal Catch Event: Catches a specific signal.
	Exclusive Gateway: Proceeds with first input-process.
	Parallel Gateway: Breaks one process into multiple processes, and merge multiple processes into one process by waiting for all input-processes.
	Service Task: Performs a task when triggered by a process.



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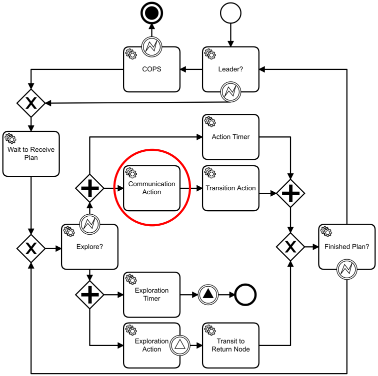


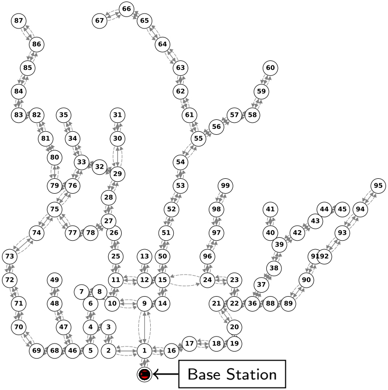
Detail: Communication Action

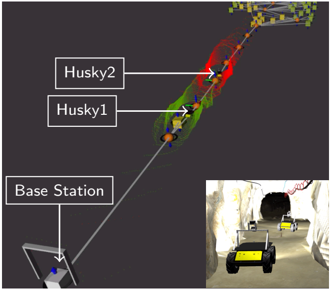
Distinguish between *internal* communication among robots within a location and *external* communication across communication edges.

- $\texttt{PreIntCom}(t, r) = \{(t, r_1, r_2, b) : r \in \{r_1, r_2\} \wedge s_t^{r_1} = s_t^{r_2} \wedge r_2 = l_t^{s_t^{r_1}}\}$
- $\texttt{ExtCom}(t, r) = \{(t, r_1, r_2, b) : r \in \{r_1, r_2\} \wedge s_t^{r_1} \neq s_t^{r_2} \wedge r \in L_t\}$
- $\texttt{PostIntCom}(t, r) = \{(t, r_1, r_2, b) : r \in \{r_1, r_2\} \wedge s_t^{r_1} = s_t^{r_2} \wedge r_1 = l_t^{s_t^{r_1}}\}$

Simulation setup

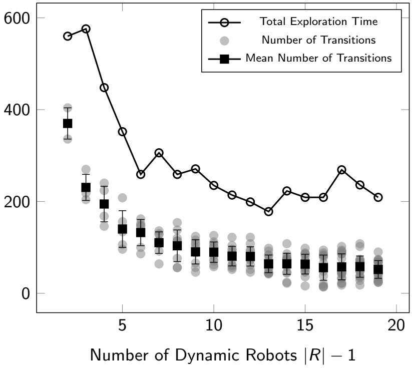
- COPS Simulation
  - Discrete graph
  - Explore scalability properties
- High-Fidelity Simulation
  - Integrated with full autonomy stack

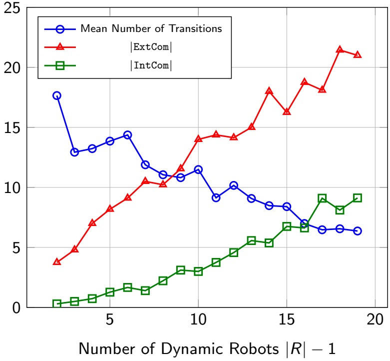




COPS Simulation

Results


Total Exploration Time
Number of Transitions
Mean Number of Transitions
600
400
200
0
5
10
15
20
Number of Dynamic Robots $|R| - 1$


Mean Number of Transitions
|ExtCom|
|IntCom|
25
20
15
10
5
0
5
10
15
20
Number of Dynamic Robots $|R| - 1$

Conclusion & Future Work

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- Information-consistent plans ensure feasible information distribution
- Communication protocol minimize low-bandwidth communication
- BPMN plan executive
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Future work

- Adding redundancy to the plan to cover robot failure
- Consider transition time when planning to allow for significantly varying transition times