# Simultaneous Collaborative Mapping and Reasoning in Dynamic Unstructured Environments

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***Abstract*— Robots are expected to operate in dynamic environments, such as teaming up with human or searching for specific targets. In such cases, robots are required to perform collaboration environmental mapping and semantic reasoning . This abstract proposes a novel probabilistic framework for simultaneous collaborative mapping and reasoning (SCMR). For each mission, robots first apply heterogeneous sensor fusion model to detect humans and separate them from the static environment. Then, the collaborative mapping is performed to estimate the relative position between robots and local 3D maps are integrated into a globally consistent 3D map. Next, by leveraging the transformation relationship among the robots, collaborative dynamic reasoning can accurately analyze each person's motion by sharing observations from neighboring robots. The experiment is conducted in a rainforest with moving people. The results show the accuracy, robustness, and versatility of 3D map fusion and human uniqueness reasoning in multi-robot missions.**

## I. Introduction

The human-robot teaming has garnered significant attention in recent years [1]. In static unstructured environment, the author considered multi-robot localization and collaborative mapping in RT-DUNE Workshop 2018 [2]. In more challenging dynamic environment, it is crucial that the multi-robot systems could analyze the dynamic human motions, and further reason their uniqueness [3]. On the other hand, accurate static mapping also requires the detection and filtering of dynamic objects in the environment. Then, robots can plan their motion by considering the motion of people. This abstract considers these two problems jointly and provides simultaneous collaborative mapping and reasoning (SCMR) as a possible solution.

The key novelty of this work is the mathematical modeling of the overall SCMR problem and the derivation of its probability decomposition. Specifically, by detecting and filtering out dynamic people in the environment, the robot can achieve more accurate relative positioning and global mapping. In addition, collaborative dynamic reasoning can accurately analyze each person's motion by sharing observations from neighboring robots and identify the unique people.

## II. Distributed Collaborative Map Fusion

The objective of this abstract is to develop a framework for collaborative mapping and reasoning that simultaneously estimates the global map and the uniqueness of all detected human. The system architecture is consisted of three modules: *multimodal environmental perception, static environmental mapping*, and *dynamic environmental reasoning*.

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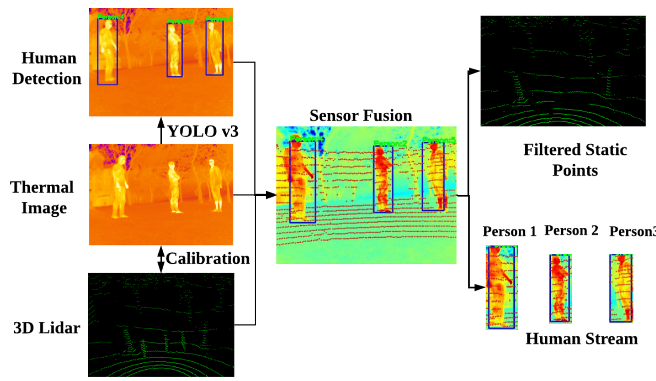


Fig. 1. Robot environmental perception results of fusing thermal image with 3D Lidar, static world and dynamic human are separated in the night forest environment.

### A. Single Robot Level

In single robot level, each robot performs multimodal environmental perception. The heterogeneous sensors carried by each robot are calibrated and integrated. The object detection & tracking algorithms [4] are executed to separate the static point cloud and human stream in two parallel processes, as shown in Figure 1. Then, each robot performs static environmental SLAM given the input of filtered static point cloud, while conducts human uniqueness reasoning conditioned on the estimated single robot pose.

### B. Multi-Robot Level

For multi-robot level, each robot communicate with neighboring robots to share local 3D maps, human states and unique role estimated by single robot. The multi-robot systems first perform collaborative static mapping, estimating relative position between all robots and global 3D map. Then, the global uniqueness is estimated conditioned on relative position between all robots, human states and single robot unique roles. The objective is to estimate fused global map $M_t$, set of relative transformation $T_{r,R_r}$ and uniqueness of human $I_t$ under a fully distributed network, given local maps $m_t^{(r,R_r)}$, human states $g_{1:t}^{(r,R_r)}$, and single robot human uniqueness $i_t^{(r,R_r)}$ from neighboring robots $R_r$.

$$p(M_t, T_{r,R_r}, I_t | m_t^{(r,R_r)}, i_t^{(r,R_r)}, g_{1:t}^{(r,R_r)}) \tag{1}$$

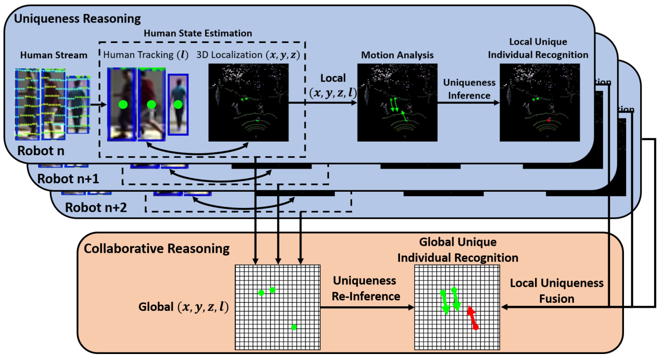


Fig. 2. The schematic diagram of collaborative reasoning. The blue part is the uniqueness reasoning on each robot, and the brown part is the collaborative reasoning based on the observation and inference result from every single robot.

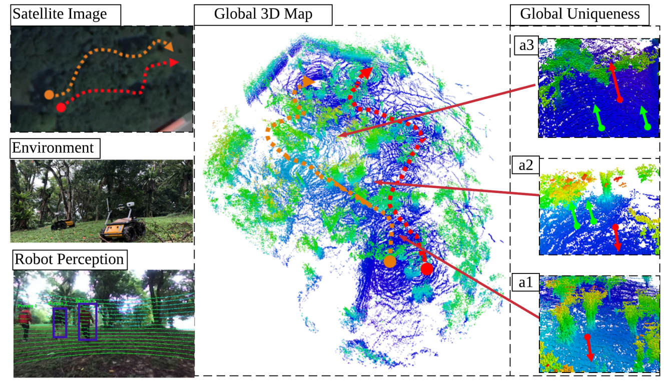


Fig. 3. The result of the simultaneous collaborative mapping and reasoning in a daytime rainforest environment. Left: an overview of the environment setting and robot perception result. Middle: collaboratively generated 3D global map. Right: collaborative reasoning results in three scenarios.

Robot $r$ receives the local maps $m_t^{(R_r)}$, human states $g_{1:t}^{(R_r)}$ and preliminary human uniqueness $i_{1:t}^{(R_r)}$ from all the nearby robots $R_r$. Then, the problem is factorized into collaborative static mapping and collaborative dynamic reasoning. By applying chain rule and conditional independent theory, (1) can factorized and simplified into (2).

$$
\begin{aligned}
&p(M_t, T_{r,R_r}, I_t | m_t^{(r,R_r)}, i_t^{(r,R_r)}, g_{1:t}^{(r,R_r)}) \\
&\propto \underbrace{p(M_t, T_{r,R_r} | m_t^{(r,R_r)})}_{\text{Collaborative Static Mapping}} \cdot \underbrace{p(I_t | T_{r,R_r}, i_t^{(r,R_r)}, g_{1:t}^{(r,R_r)})}_{\text{Collaborative Dynamic Reasoning}} \qquad (2)
\end{aligned}
$$

The principal advantage of the factorization comes as follows. Firstly, it benefits from utilizing Maximum a Posterior (MAP) probability for robots relative transformation estimation and global map estimation. Secondly, global uniqueness human reasoning can be performed given the estimated relative transformation of collaborative mapping, it can help to improve the decision process of the system and reduce the need for communication bandwidth.

## III. Experimental Results

As shown in Figure 3, the human-robot team operates under a dense forest canopy, which is a fully dynamic and unstructured 3D environment that contains trees, slopes and moving people. The mission is to collaboratively map out the full 3D environment and simultaneously estimate the uniqueness of people. The two robots started moving from a nearby place, while robot **1** (red trajectory) turned left and went uphill and robot **2** (orange trajectory) turned right and went downhill. People moved in the environment in different directions and speeds.

The overall results of collaborative mapping and reasoning is provided. It can be found from the satellite image that it is a dense rainforest, and it is difficult to see the ground from the top view. Real images also verify the complexity of the environment from a human perspective. Experiment is carried out immediately after the rainstorm, and the robot is operated in muddy terrain. The middle image shows the final merged global map at the end of the operation. The global map reconstructs the entire unstructured environment in detail with high precision. It is worth noting that while dynamic objects are moving around in the environment, we are still able to build an accurate 3D static map based on multimodal context-aware frameworks. The foundation behind the global map is to accurately estimate the relative position between the robots, which is also the basis for collaborative reasoning. The left three images show the collaborative dynamic reasoning results on the global map. The dots and arrows show the 3D position and motion of each person. The red dot denotes the recognized unique person from comprehensive human motion analysis.

## IV. Conclusion

This abstract presents a method for simultaneous collaborative mapping and reasoning in GPS-denied and dynamic unstructured environments. We have designed a new framework to provide theoretical formulas and system implementations for collaborative static mapping and dynamic reasoning. Explicitly environmental mapping is addressed by developing a collaborative static mapping process. The robot judges each person's uniqueness by analyzing each person's movements and comparing them with each other. In summary, the proposed collaboration system provides a new perspective for sensing and adapting to dynamic unstructured environments, which compensates for the limitations of individual robot perception, mapping, and reasoning.

## References


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