EKF-SLAM for First Responder Urban Mapping

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***Abstract*—This paper explores the application of robotics and autonomy to enhance the safety and effectiveness of first responders in urban firefighting scenarios. The focus is on developing rapid situational awareness inside burning buildings using structural and heatmapping SLAM to aid in locating people, identifying hazards, and planning routes. The research investigates Human-Robot Collaboration (HRC) and the use of heterogeneous robot teams (UGVs and UAVs) to leverage complementary strengths. Key themes include variable autonomy, Meaningful Human Control (MHC), and the design of effective user interfaces for situation awareness and cognitive load management. Challenges such as environmental factors, communication reliability, robot robustness, human factors, ethical considerations, and system integration are addressed. The proposed method involves an agile, object-and-heat detecting robot utilizing EKF-SLAM to rapidly map building structures. The evaluation will assess the speed and quality of data acquisition and its usefulness for decision-making.**

# Introduction

Fires, including urban structure fires and large wildfires, continue to pose a significant threat to human life. Furthermore, these events are exacerbated by climate change and urban development [1]. The inherent dangers of firefighting – exposure to extreme heat, toxic environments and gasses, structural hazards, and other unpredictable hazards – place immense physical and psychological threat on first responders, highlighting an area with critical need for safety and operational effectiveness [2]. Robotics and autonomy has emerged as a field showing immense promise in offering tools for first responders to augment and increase their response time and efficiency in time-sensitive life-critical scenarios [1].

The motivation for this work comes from the potential to significantly reduce firefighter injuries, fatalities, and risk while simultaneously making them more effective at saving lives and protecting property. More specifically, this work will focus on **developing rapid situational awareness inside burning buildings** before firefighters commit to entry. By mapping rooms, hazards, hotspots, and entry/exit ways before and during entry to a building, firefighters can use that information to find people more quickly, quickly route and re-route accessways, and deal with hazards in more efficient manners.

Early robotic applications typically involved simple remote control, but the field has rapidly advanced towards sophisticated Human-Robot Collaboration (HRC) and manned/unmanned teaming (MUMT) that allows humans and robots to function more akin to teammates [3]. This approach leverages the complimentary strengths of each: robots can provide endurance, precise sensing, and ruggedness while humans give better situational awareness, decision-making, adaptability, and ethical judgements [3]. This work is specifically targeting HRC for **rapid indoor reconnaissance** in building fires using structural and heatmapping SLAM.

In a traditional or more lengthy research approach, this work would further evaluate sensing strategies, interaction models, evaluation techniques, sensor fusion, and route planning/augmentation between the robot and its human teammates. Due to time and resource constraints, this project is constrained to a mostly literary analytical review, proposed improvements on the state of the art, and a simplistic EKF-SLAM simulation [4]. Metrics for success include: the speed and quality of robot data acquisition, usefulness of the data for decision-making, and the ease of implementation. See Table 1 for a comprehensive list of deliverables and Figure 1 for an outline of the proposed method, which is also detailed later in this proposal.

1. Project Deliverables

| ***Output Deliverables*** | ***Type*** |
| --- | --- |
| Accuracy per sim run per error rate | Metric |
| Speed per sim run per error rate | Metric |
| Output data/map usefuleness | Metric |
| Final Report | Report |
| Simulation Code | Code |
| Simulation Demo | Code/GIF |
| Final Presentation | PPT |

# Related Work

The literature on HRC in firefighting spanning 2020-2025 covers multiple disciplines, from robotics, to AI, and disaster management. Key themes across disciplines are extracted and used to guide and inform our approach: robotic platforms and roles; interaction paradigms and collaboration models; human-robot interface (HRI) design; key common challenges; and evaluation approaches.

Recent work utilizes diverse platforms, primarily Unmanned Ground Vehicles (UGVs, often tracked for robustness) [5] and Unmanned Aerial Vehicles (UAVs/drones) [6]. UGVs excel at payload delivery (water/foam suppression, sensors, tools) [4] and ground interaction (manipulation via arms) [1], while UAVs provide rapid aerial reconnaissance, mapping, and access to difficult areas [7]. Tasks assigned include reconnaissance/surveillance, search and rescue (SAR), hazard detection (flames, heat, gas), suppression support, logistics, and prevention (hazard mapping and disaster planning). A significant trend is the use of *heterogeneous teams* (UAV-UGV collaboration) to leverage complementary strengths [7], influencing our proposed method towards hybrid human/multi-robot systems. Platform specialization based on environment (wildland vs. indoor vs. industrial) is also evident.

Interactions are moving beyond simple teleoperation [4] towards supervisory control, shared autonomy, and particularly *variable autonomy* [3]. Variable autonomy dynamically adjusts robot independence, aiming to optimize performance, manage operator workload, and crucially, enable *Meaningful Human Control (MHC)*. MHC ensures human moral responsibility for autonomous actions through traceability and tracking [3].The conceptualization is shifting from robot-as-a-tool to *robot-as-a-teammate*, emphasizing shared goals, trust, communication, and transparency within Human-Robot Teams (HRTs). Multi-robot/swarm coordination is also a growing area. Furthermore, it is very common for telemetry and GPS signals to be lost or intermittent indoors, increasing the need for enhanced SLAM and autonomy capabilities [8] [9]. These findings strongly suggest that future systems should incorporate adaptive autonomy and focus on building effective team dynamics, forming the basis of our proposed interaction model.

Effective user interfaces are critical in high-stress firefighting environments. Key aspects include clear information visualization (real-time data, sensor feeds, maps) [5], exploration of immersive displays (VR/AR) for enhanced SA [8], intuitive control methods (traditional controllers, multi-modal inputs like speech/gaze [9], natural language processing), and adaptive interfaces [10]. Crucially, interfaces must support *Situation Awareness (SA)*, promote *agent transparency/explainability* (understanding robot state/intentions), and minimize *cognitive load* on firefighters. The literature highlights the need to prioritize cognitive load management and transparency/explainability. In other words, firefighters should be able to trust and verify the information their robotic teammate is giving them, so the human on-the-loop can make the best tactical decision possible.

Significant hurdles across all domains remain. *Environmental challenges* include extreme heat, smoke, water, dust, and complex terrain [11].*Communication reliability* is often compromised by signal degradation due to urban hazards, environmental impacts, and bandwidth limits [12]. *Robot robustness* (hardware resilience, power/endurance) is essential but can be difficult to achieve. *Human factors* like trust calibration, SA maintenance, cognitive workload, and training needs are also very important. *Ethical considerations* (responsibility/accountability, bias, privacy, safety, job displacement) are increasingly recognized as important impacts also [3]. *System integration* into existing workflows and cost are practical barriers [13]. These challenges are interconnected, requiring holistic solutions. The growing emphasis on ethics underscores the need for proactive ethical design. Existing literature, while advancing capabilities, often struggles to bridge the gap between prototypes and operationally robust systems, highlighting the need for rigorous, realistic evaluation.

Systems are evaluated using simulations (e.g., Unity) [5], lab experiments [14], and crucial field tests/demonstrations with end-users. Metrics include task-specific measures (accuracy, precision, trust, time-on-station, speed, area covered), HRI metrics (SA, workload, trust, usability), safety metrics (collisions) [6], and emerging MHC metrics (traceability scores, intervention rates, ethical adherence).Evaluations in lab settings always have limitations and must be reinforced by representative field testing and validation.

# Preliminary Methods

Our proposed method involves an agile, object-and-heat detecting robot that enters the structure of interest at a given point. Following this, the UGV attempts to map the structure as quickly and accurately as possible using EKF-SLAM, with an emphasis on speed over accuracy. The datapoints relayed in turn are mapped and constitute the structural and hazard map for the human firefighters. Accuracy and speed will be assessed among different simple structure layouts and error rates, simulating sensor fusion techniques and sensor layouts.

This method will serve as a proof-of-concept for rapid deployment of small form factor firefighting assistance robots, using EKF-SLAM. Furthermore, this work can be used as a simulation baseline combined with or independent of other work, for future works. For communal ease of use and model robustness, the experimental setup largely consists of Python and libraries including Numpy, Scikit Learn, Pandas, Matplotlib, and custom EKF-SLAM code. Figure 1 includes the group’s approach to solving the problem and implementing the solutions.

Broken out into four major steps, our method is composed of:

1. Creating and modifying EKF-SLAM and simulation code – this includes Github repository(ies) and guidance from key references [17] [8] [4]
2. Set up the simulation environment – create the baseline and testing environment “physical” parameters (building layout, landmarks, etc.)
3. Run experiment iterations – run the experiment at a baseline, and then iterate over sensor error rates, and repeat with different building layouts
4. Evaluate and report results

A diagram of a different method of making a difference

AI-generated content may be incorrect.

1. Preliminary Methods Roadmap.

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