Graduate Research Plan Statement

Title: Collaborative Autonomous Control for Firefighting Robots in Hazardous Wildfire Environments.

Introduction: Wildfires represent one of the most dynamic and dangerous natural disasters. Wildfires are becoming more common as human-induced warming increases frequency, severity, and risk of wildfires [1]. Firefighters operating in these environments not only have to battle the blaze but also work meticulously to prevent its spread by establishing containment zones. This often involves digging lines, also called handlines, to separate the fire from the rest of the forest. Currently, the US faces wildland firefighter shortage [2], and this lack of sufficient resources and personnel to combat wildfires directly jeopardizes the safety of US citizens. To combat this and reduce human exposure to dangerous situations, this research proposes the development of an autonomous robot control system designed to work collaboratively with working personnel in dangerous and dynamic environments like wildfires.

Objective: To design, develop, and evaluate an autonomous control for a robot, focusing on cooperative capabilities, danger assessment, navigation through forest terrains, and strategic handline excavation route determination.

Intellectual Merit: The proposed blending control function, which fluidly transitions between assistance and full authority based on situational demands, represents a novel approach in the field of human-robot interaction. By designing a system that prioritizes human safety over strict adherence to commands, this research pushes the boundaries of how we conceptualize and implement robotic obedience in dynamic environments. The introduction of a feedback system that assesses real-time wildfire dynamics can offer a blueprint for similar applications in other unpredictable environments, broadening the scope of autonomous robotics applications. This project is emblematic of the benefits of interdisciplinary research, merging insights from robotics, wildfire behavior, and firefighting practices to create a holistic solution.

Research Plan: *(1) Determining Safety for Both Robot and Firefighters in Wildfire Environments*: I would start by identifying potential hazards in wildfire settings, specific to both the robot's operational integrity and the firefighter's well-being. Considering factors such as high temperatures affecting robot components, fire trajectories threatening firefighters, and communication disruptions between human and machine, I will develop a dual set of safety metrics that cater to both the robot's operational health and the firefighter's safety. This might include metrics like thermal thresholds for the robot and safe distance parameters from active fire zones for firefighters. I plan to equip the robot with an extensive array of sensors, such as infrared to measure heat, cameras, and accelerometers to detect unusual movements (e.g., falls). I will use CNN to identify forest fires using infrared black-hot camera imagery [3] and assess its efficacy on the forest floor. Should the robot detect significant danger through the system, it will be able to communicate this. To test this system, I'll first simulate a forest fire in a virtual environment to validate the core functionalities and accuracy of the safety detection mechanism. Next, in a controlled setting, I will reproduce various wildfire conditions to evaluate hazard detection and safety decision-making. Based on the observed interactions, I will then refine the protocols and algorithms. *(2) Forest Terrain Navigation and Defining Optimal Handline Excavation:* Through utilizing sensors, LIDAR, or other cameras, I will create a real-time local map of forest environment. After developing the safety determining system, I will calculate the optimized route based on our map and determined safety parameter. I will use model predictive control [4] with the addition of our safety variable to develop motion planning capabilities. The algorithm will be able to reroute and reoptimize itself as the local map actively changes (trees falling, fire spreading, etc.) in real-time. I will test this algorithm by modeling a burning forest environment and putting obstacles for it to navigate in the simulation then in real-life. The obstacles will be moved as the robot goes through the test to simulate the changing forest environment. Through talking to firefighters who work with wildfires, I will assess the most common and difficult obstacles for robots to navigate and use them in my testing. After seeing its performance, I will improve our predictive model until it gives me reliable motion planning. *(3) Development of Adaptive Command Compliance and Safety-centric Controls:* I will begin by designing a control algorithm that variably follows commands based on real-time safety evaluations. When a person issues an order for a specific digging pathway, the robot should attempt to follow this command as closely as possible, but it should also optimize for safety and optimal path factors. One of the successful approaches to model this control system involves using a Markov decision process that depicts the interplay between the human and the robot [5]. By leveraging inverse reinforcement learning, I can capture an abstract representation of human behavior [5], which will be instrumental in determining how much authority the robot should have. Furthermore, to address the unpredictability inherent in human decisions, potentially arising from complex task specifications or imperfect interfaces, I plan to employ stochastic strategies [5]. Before real-world testing, I will run simulations to test the algorithm's response to various scenarios, measuring its balance between command adherence and safety prioritization. Then, I will deploy the control in real-world settings (controlled, initially) to evaluate its performance. Data from its response to commands will be used to refine the control algorithm, focusing on areas where safety may have been compromised or commands were not adequately followed. *(4) Simulation:* Given the inherent dangers and unpredictability of wildfires, real-world testing of our safety parameters and controls presents substantial challenges. In this context, the Unified System for Automation and Robot Simulation (USARSim) emerges as an optimal simulation platform. Originally developed for modeling search and rescue robots, USARSim boasts an array of maps, with the added flexibility to craft custom scenarios [6]. It has the capacity to replicate odometry, range, camera, and touch sensor readings [6]. USARSim's ability in fire modeling is unique as most other tools don’t have this capability. In 2006 Robocup, it simulated a complete burning building [7]. This shows its potential to be able to be applied to simulating forest fires. Another unique feature of USARSim is its noise regulation capability [7], enabling us to simulate challenging conditions, such as smoke-obscured terrains. The simulator's compatibility with a Matlab Toolbox enhances our ability to modify the simulation [6] to address additional aspects of wildfires that USARSim might not originally have been designed for. Moreover, its GPL licensing [7] ensures easy accessibility. Leveraging my personal background in 3D animation and game development, I find USARSim particularly compelling as it’s built on a popular video game engine, Unreal Engine, which I am familiar with. My background in 3D art design will significantly enhance our customization capabilities, ensuring we maximize the benefits of this simulation tool. Furthermore, my professional experience at Oshkosh Corporation, where I developed simulation-based tests for autonomous vehicles in line with DARPA requirements, equips me with the proficiency to ensure accurate and effective testing. *(5) Real-Life Testing:* Based on our results from simulation, we can optimize both the placement and quantity of sensors. While the primary focus of this project is the control system, I will design a rudimentary driving rig approximately one foot in length with wheels suitable for forest terrains and a basic suspension system to navigate minor obstacles like small branches and rocks. It will also be equipped with a compact computer and LiDAR, cameras, temperature sensors, and others. ***(6)** Resources:* For this research Ufuk Topcu from Univeraity of Texas Austin will provide all resources and funding for this proposal.

Broader Impacts: The advancements in robotic controls for challenging environments hold promise for a broader spectrum of societal applications. Beyond the confines of wildfires, the technology's principles can be extended to aid in other disaster scenarios, such as earthquakes, hurricanes, and floods. For instance, equipped with these sophisticated robotic systems, disaster response units could more efficiently perform rescue operations, deliver crucial supplies, or conduct post-disaster structural assessments. Moreover, this research's innovations could be pivotal in areas like infrastructure maintenance and hazardous site inspections, where robots could work in environments deemed too risky for humans. Overall, by refining and deploying these robotic controls, we have the potential to reshape how society approaches and manages high-risk situations, enhancing safety and efficiency.

References: [1] Matthew W. Jones et al. *Climate Change Increases the Risk of Wildfires* 2020. [2] Jason Steinmetz *Wildland Firefighter Resources Shortage in the United States; is a national endorsement process the solution* 2019. [3] Rahmi Arda Aral et al. *Wildfire Classification Using Infrared Unmanned Aerial Vehicle Data with Convolutional Neural Networks* 2023. [4] Ali Mohandes et al. *A Motion Planning Scheme for Automated Wildfire Suppression* 2014. [5] Murat Cubuktepe et al. *Shared Control with Human Trust and Workload Models* 2023. [6] Aaron Staranowicz et al. *A survey and comparison of commercial and open-source robotic simulator software* 2011. [7] Stephen Balakirsky *USARSim: a robot simulator for research and education* 2007.