A Rover and Drone Team for Subterranean Environments: System Design Overview

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***Abstract*—This abstract provides a concept overview of a rover and drone team for the exploration of subterranean environments that is currently under development. Recently, significant advances have been made in the field of autonomous robotics. These advances span from high-level semantic scene understanding to low-level efficient optimization. Through the utilization of these advances, autonomous robotic platforms are starting to leave the research laboratories and beginning to permeate novel environments. One such example of a novel environment is a subterranean tunnel, which presents not only commercial applications (e.g., the utilization in tunnel infrastructure monitoring) but also safety critical applications (e.g., the fast and efficient response to a tunnel collapse). The safety critical applications in subterranean environments provide many novel challenges for the robotics community (e.g., robust navigation in highly dynamic environments in the case of a robotic first response to a cave collapse).**

I. INTRODUCTION

Unfortunately, so long as there is subsurface mining, there is the possibility of a mine collapsing. These catastrophic failures are not only dangerous for the miners trapped inside but also for the rescue personnel attempting to help. For example, consider the Sago Mine disaster of 2006 [7], which was caused by a methane explosion. The high methane gas levels made it such that rescue personal could not enter the mine for 12 hours after the explosion. This delayed response resulted in 13 miners being trapped in the mine two days and ultimately a casualty total of 12.

This motivates the need for for methods that ensure the safety of both parties (i.e., the miners and the rescue personnel). One such alternative is to leverage the recent advances in the robotics community. This idea can be traced back back to the 1990's with the Numbat [9] platform, which is a remotely controlled mine rescue robot. This idea was later extended by the Ground Hog [11] platform, which allows for autonomous mapping of subterranean environments.

This work — although the work present within is only an initial system design overview — aims to extend upon the work presented above by allowing for the cooperative mapping of subterranean environments through the utilization of both an unmanned ground vehicle (UGV) and an unmanned aerial vehicle (UAV). In this concept of operations, an autonomous ground vehicle will be utilized for mapping the environment, and the autonomous aerial vehicle — which will be equipped with a thermal imaging camera — will be utilized to detect signs of life while under the authority of the ground vehicle.

The rest of this paper is organized in the following manner. First, an overview of the system design is presented. In this section, an overview of the hardware and the algorithmic implementation is discussed. Next, the discussion progresses to initial results generated in a subterranean environment. Finally, some concluding remarks and future work are discussed.

II. SYSTEM DESIGN OVERVIEW

This section details a system overview of initial prototypes for an UGV, named Badger, and an UAV, named Canary, for the exploration of subterranean environments.

A. Hardware

1) The Badger: The Badger is built upon the ClearPath Robotics® Husky platform. Placed on top the Husky platform is a custom electronics enclosure that houses the main computer and power distribution hardware. The main computer on-board the Badger is an x86-64 motherboard with an Intel Core i7-7700 3.6 GHz CPU and a Nvidia GTX 1050 Ti GPU.

To enable perception and localization, the Badger will be equipped with a variety of sensors. TO facilitate SLAM, a 2D Hokuyo UTM-30-LX-EW Laser Scanner with 270 degree field of view (FOV) and 40 Hz scan rate and is utilized in conjunction with a a Dynamixel MX-64 smart servo and slip ring to enable full rotation of the unit and 3D point cloud generation. The spin rate and orientation are still currently being optimized, but the FOV will be tailored to capture the ceiling of the tunnel. Additionally, to enable drone tracking and the potential for RGB-D SLAM, a FLIR 5MP Blackfly-S camera with a fisheye lens is located directly above the Lidar facing upward. Through the utilization of this camera, fiducials on the Canary and a ranging radio link (Time Domain Pulson P-410 radio), the Badger will be able to localize the Canary. Finally, that Badger is equipped with a 9 degree-of-freedom (DOF) ADIS 16488 inertial measurement unit (IMU).

2) The Canary: To enable extended operation time, the Canary will only be equipped with three sensors: a 9 DOF IMU (ADIS 164899), a ranging radio (Pulson P-410), and an a dual thermal/visual imaging camera (FLIR Duo). There is a 915 MHz communication link between the Badger and Canary based on the open-source mavlink protocol and potentially a shared ROS instance between the drone and rover. The IMU will keep the Canary platform stable and in conjunction with a micro-controller will be utilized to control the Canary via outer-loop commands sent from the Badger. LED fiducial markings (i.e., colored and illuminated diffusion spheres to avoid camera saturation) will be tracked via computer vision along side a ranging radio link between the Badger and the Canary will be used to localize the Canary with respect to the Badger through the use of a relative navigation filter.

Fig. 1: Initial prototype unmanned aerial vehicle (Canary)

B. Navigation and Localization

1) The Badger: To utilize this sensor payload for state estimation on-board the roving platform, a factor graph based sensor fusion framework is adopted [3], as depicted in Fig. 2. Specifically, the incremental smoothing and mapping (iSAM [5]) framework will be adopted to allow for real-time state estimation, which will be realized the Georgia Tech Smoothing and Mapping (GTSAM) library [2]. An additional benefit of this framework is that it allows for the efficient incorporation of robust optimization techniques (e.g., switchable constraints [10], and dynamic covariance scaling [1]), which is critical in highly dynamic and cluttered environments.

2) The Canary: To minimize the computation burden on the Canary, the localization of the platform will be calculated on-board the Badger. This will primarily be realized through visual tracking of the Canary's fiducials (i.e., light-emitting diodes (LED)) with the vertically facing fisheye camera on the Badger.

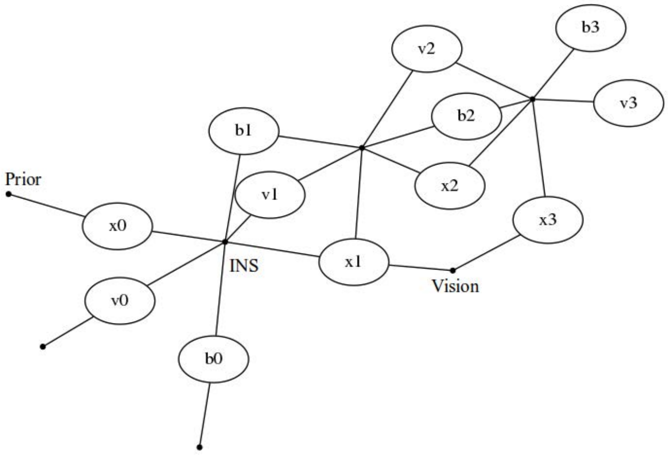

Fig. 2: The proposed navigation solution will be implemented as a factor graph, in which the set of desired states is composed of sensor biases, the platform's pose, and the platform's velocity.

C. Autonomy

Autonomous motion planning and control of the Badger and Canary presents a number of interesting challenges. Since the purpose of the Canary is to augment the search capability of the Badger, it is important that the motion of the Canary, relative to the Badger, is performed in such a way that the Badger maintains good observability of the Canary at all times. Otherwise the information being gathered from the Canary will have high uncertainty and will not be beneficial. At the same time, however, the robots are trying to map their environment and look for targets with the Canary's thermal camera, such as survivors in a disaster, so they must plan their maneuvers to explore efficiently and effectively. The motion planning of the Badger can be modeled as an optimization problem where the observability of the Canary and the information gain about the environment are both factors in the planning algorithm's performance index. The expected information gain about the environment can be maximized by planning the motion of the sensing platforms based on mutual information contours, such as in [4].

In this research, however, the Canary is an extension of the Badger's sensing capabilities, rather than an independent agent, working as a member of a distributed team with the Badger. Information gained from it for mapping, as a remote sensing platform, must be transformed back into the frame of the Badger, and since the two are not rigidly attached, accurate estimation of the Canary's pose, relative to the Badger is critical. Planning the Canary's motion to maintain good observability can be performed by using methods similar to those of "Opportunistic Navigation" [6]. Rather than searching for opportunities to gain information and maintain good observability from the ambient environment, the motion of the Canary and the Badger can be controlled to purposefully benefit the estimation performance, since they are exchanging information between each other.

III. PRELIMINARY TESTING

Final project demonstrations will be conducted the West Virginia Memorial Tunnel Complex, a $\frac{1}{2}$-mile long 28-foot high underground research and training facility. Initial testing has been conducted at WVU, where the Berkeley Localization and Mapping (BLAM) [8] library has been utilized. This library is an open source factor graph-based implementation of simultaneous localization and mapping (SLAM) that utilizes GTSAM [2].

IV. CONCLUSION

The need for robots to operate autonomously in subterranean tunnel environments has not only commercial applications (e.g., automated tunnel inspection), but also safety-critical applications (e.g., first response to a tunnel collapse). In an initial step to enable research in this field, this paper details the development of a rover and drone duo that are under development for subterranean environment exploration. Within this duo, the ground rover will be utilized for environment mapping and the localization. The drone will host a thermal imaging camera to identify and locate signs of life to provide assistance to first responders.

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