Collaborative Simultaneous UAV Exploration and Mapping In GPS Denied Environments Using a Relative Framework

by

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MECHANICAL ENGINEERING

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1 Problem Statement

After a disaster such as an earthquake or fire, buildings are often left structurally unsound. Sending in a human team to inspect the building can unnecessarily put human lives at risk. This project seeks to minimize the problem by sending in a swarm of intelligent unmanned aerial vehicles (UAVs), able to map a building, scan for damaged structures, and identify the source of a fire to determine the level of damage and whether or not it is safe to send in humans.

Recent advances in GPS-denied navigation (cite relative nav paper) make it possible for UAVs to safely and accurately localize themselves in GPS degraded environments without colliding with obstacles, making indoor exploration and mapping possible.

Because UAVs inherently have a very short battery life span, the optimization of search routes is imperative to their success in exploring and mapping an area. They must also be able to collaborate in their efforts to map and scan the building to quickly deliver results to a ground station. There are many mapping algorithms that work excellently with a single UAV, but collaborative, simultaneous mapping with UAVs is a not as developed. Leveraging multiple UAVs simultaneously mapping an area and meshing the data into a single map will greatly decrease the time it takes to survey and map an area. This will make it more feasible for UAVs to quickly survey a building in an emergency and get the information to first responders without risking human lives.

The objective of this proposed research is to develop a method that leverages multiple UAVs by optimally plans their search routes, and efficiently meshing data from the on-board sensors of the UAVs into a single, human-readable map.

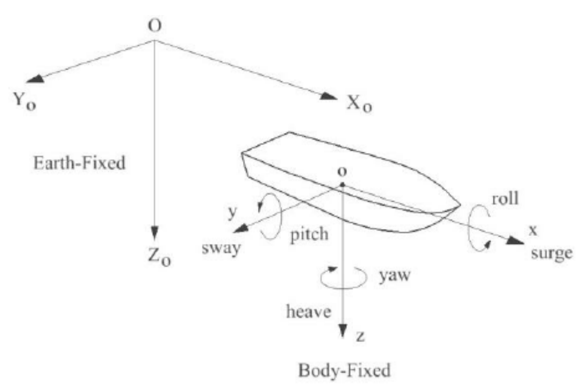

Figure 1: Definitions of reference frames and ship motions (surge, sway, heave, roll, pitch and yaw)

2 Background

There are many approaches to the mapping problem for UAVs which can be split up into different categories

2.1 Sensors

The sensors mounted on the UAVs greatly affect how they are able to map their environments. Monocualar cameras have been around the longest and are the most lightwieght, but are hardest to use in mapping a 3 dimensional environment. A newer technology that greatly increased the potential of 3D perception of cameras are stereo cameras. Made up of two cameras set up side by side, this type of camera allows for easier depth extraction from images. These cameras work much better than monocular cameras, but are still limited in their ability to reliably extract depth information from a camera. In the last several years, RGBD (RGB Depth) 3D cameras have emerged. these cameras are much better at reliably extracting depth information from the scene. Rather than just a stereo pair, RGBD cameras have a standard RGB (color) camera, a stereo pair of IR (Infrared) cameras, and an IR Projector, these all work together to produce a high resolution color image with an associatedd depth for each pixel in the image. These cameras have already had a significant impact on robotics and autonomy applications (Cite someting here). Until recently, however, these cameras have had a very large form factor compared to monocular and stereo cameras, making it hard for these cameras to be used on small UAVs. Intel, one of the industry leaders in RGBD camera technology, recently released a line of small lightweight, very capable RGBD cameras. The Intel RealSense D435 is the camera that will be used on this project.

Another type of sensor that should be noted is 3D and 2D scanning LiDAR sensors. Rather than return an image, these sensors are able to return a 360 degree representation of the environment. These sensors are very powerful, especially the 3D sensors, but as of writing this, due to the size of these sensors, it is infeasible to carry one on the size of UAV that will be used on this project. There are some smaller 2D scanning LiDAR sensors that are more feasible to use and one will likely be used for obstacle avoidance for this project.

2.2 Data Structures

There are different approaches to the way the data is stored and used in mapping. Voxels - 3d pixels used for reconstructing and representing environment in 3D space. Either very data heavy or low resolution depending on size of them, limited area representation Octomaps-Scale with detail, allow for more detail in detailed areas and less data usage in large open areas or closed areas [1] Pointclouds- very dense, by default LiDAR and RGBD cameras return these, not ideal for 3D maps, but can be good for 2D ones

2.3 Algorithms

(maybe combine this section with data structures) SLAM - Simultaneous Localization and Mapping works well, better with few landmarks (is this the only way for this to work?) Occupancy grid mapping- more dense, uses above items

2.4 Planning

Address the questions: What have others done? Why is it important? What are the challenges?

Example looks like this In 2009, Garratt et. al. [**?**] detailed a shipboard landing method for autonomous collective pitch helicopters that used a digital IR camera and a laser range finder pointed at a spinning mirror to supply data for estimating the relative position and motion of the ship deck. Flight test results showed that their system was able to estimate the relative roll and pitch angles, as well as height distance between the helicopter and the simulated ship deck to a high degree of accuracy. Their results however only demonstrated the capabilities of their measurement and estimation system and did not demonstrate the actual ability to execute a successful landing maneuver.

From this brief survey of the current research, it can be seen that although various and significant contributions have been made in the field of autonomous shipboard landing, there is still great opportunity for continued research. The research I would like to propose I believe would help to move some of the current research from the simulation and simplified use case, to real-world application.

3 Research Objectives

To successfully complete this proposed research, the following objectives will be accomplished:

- Build up a simulation environment that models and controls generic quadrotor UAVs with appropriate sensors and an environment to be explored
- Develop (or implement) Optimal planning algorithm that decides where the UAVs need to go to fill area with loop closure to mesh maps
- implement the best approach to mapping the area that will be human readable and provide sufficient information for action
- Develop a way for the UAVs to share map information so that the maps can be meshed together
- Implement the solution in hardware on actual quadrotors and explore and map a GPS denied environment
- Perform flight test demonstrations and gather test data to showcase the effectiveness of the solution that has been developed.

4 Proposed Research

To address the research, a multi-phase approach will be used. Research will commence by first setting up simulation environment in ROS Gazebo to allow for frequent testing without needing to rely on hardware every step of the way. Once the environment is set up, the project will be broken into three milestone hardware demonstrations:

4.1 Phase 1

The first demonstration will be flying a single UAV in a GPS-denied environment to collect data and map the area. To complete this demonstration, an algorithm will need to be developed or implemented to plan the path in 3D space based off of a CAD model or blueprints of the area. This path will need to be able to change on the fly based on unexpected obstacles and changes from the initial plans. Although using a good odometry algorithm is essential to the success of this project, there are other students who are focusing on that aspect.

The next focus of this will be to implement a mapping algorithm on the UAV that works in a relative frame work

4.2 Phase 2

The second phase of the project will be to get a single UAV to fly multiple paths in the same environment. These paths will need to be optimized to cover the desired search area and overlap enough to provide sufficient loop closure to be able to mesh the maps together in post processing.

4.3 Phase 3

The third and final phase of the project will be to get multiple UAVs flying simultaneously in the same environment and meshing the maps of them into a single map. This will require more effort on the path planning to make sure the paths can be flown simultaneously, then something clever will be done to make the meshing of the maps as close to real time as possible.

To address the problem at hand, a multi-phase approach will be used. Research work will commence by first identifying a suitable and somewhat generic controls framework that can be used to accomplish a vision-based shipboard landing. This framework will then be implemented and tested in simulation using MathWorks® MATLAB and SIMULINK. To keep things simple to begin with, a proportional integral derivative (PID) controller will be implemented for the Quadrotor UAS. The Extended Kalman Filter (EKF) will be used to generate state estimates for the UAS, and will be augmented to take in additional measurement inputs from the vision system in order to generate estimates for the ship deck attitude and relative position. Once functional in simulation, tests will be performed to evaluate the performance and limitations of the vision-based landing approach.

The first augmentation to a standard vision-based landing method that we would like to research is operating in low-light or total darkness. This stage of the research will require different sensor and landing marker combinations to be evaluated and tested. Of current interest is using an infrared (IR) camera and IR markers. In 2015 Wilson [**?**, 1] successfully used an IR-sensitive camera to track IR beacons along the trailing edge of a leading aircraft's wing and around the rim of a drogue that the leading aircraft was towing behind (see Figure 2). It was shown that the IR beacons could easily be seen and tracked by the IR vision system in a wide range of lighting conditions. Wilson's results also showed that he was able to obtain good relative position estimates between the leading and following aircraft using

Figure 2: Infrared markers as seen through RGB and IR cameras [**?**].

the same IR markers. Building on Wilson's findings, we would like to see how a similar IR vision and marker system could be implemented to enable autonomous shipboard landing in dark and lighted conditions.

Brigham Young University, and specifically the MAGICC Lab, has a strong background in the field of Relative Navigation for UAS [**?**]. Though the shipboard landing problem is significantly different than the relative navigation work that has been previously performed here, successful shipboard landing requires a form of relative navigation, and can likely draw on some of the relative navigation work that has already been done. In the current relative navigation problem, measurements between the static surroundings and the dynamic UAS are taken to estimate the relative position and velocities of the UAS. If we now flip the problem by assuming that the UAS is pseudo-stationary (i.e. its movement is small and its position is known thanks to GPS), we would like to explore the possibility of taking similar measurements to estimate the state of the dynamic surrounding (i.e. the ship deck). In the current relative navigation problem, an accurate estimate of the UAS' state is aided significantly by measurements from an on-board IMU. Similarly, we would like to research the contribution that a ship-based IMU can offer to enable a more robust shipboard landing solution.

Though much of this proposed research will begin in simulation, the resultant methods and solutions that are discovered are planned to be implemented in hardware flight tests. Testing in hardware will require a quadrotor UAS to be procured and assembled, and will also require a ship deck motion emulator to be fabricated. The UAS will be comprised of standard hobbyist equipment for the airframe and propulsion system, and the ship deck emulator will similarly be fabricated using off-the-shelf components. Autopilot capabilities for the UAS will be enabled through the use of a ROSflight flight controller paired with an on-board computer that will run the autopilot control loops in Robot Operating System (ROS). The ship deck emulator is planned to have its own GPS receiver and IMU unit. Communication of sensor measurements and/or state estimates from the ship deck emulator to the UAS are planned to be communicated over a local WiFi network. At all times during flight test operations the UAS will be controllable through a ground-station computer, and a safety pilot will be present to take manual control of the UAS at any moment. When satisfactory results from flight demonstrations are obtained, the data will be collected, analyzed, and presented in the form of a formal Thesis.

5 Anticipated Contributions

As a result of this research, there will be an improved understanding of how robust maritime landing can be achieved for real-world applications and conditions. Specifically, it is anticipated that this work will demonstrate the contributions that an IR vision system and shipboard IMU can make in helping to ensure a soft and safe landing. Although there are many shipboard landing methods that have already been developed, this proposed research seeks to extend and add to current methods to a degree that is new and unique. Maritime landing in darkness, and landing with ship deck IMU data, are both areas that appear to be absent in the current literature. Good results coming out of this research would open opportunities for possible journal or conference paper publications, and would also pave the way to further research opportunities for future students.

References

[1] A. Hornung, K. M. Wurm, M. Bennewitz, C. Stachniss, and W. Burgard, "OctoMap: an efficient probabilistic 3D mapping framework based on octrees," *Autonomous Robots*, vol. 34, no. 3, pp. 189–206, apr 2013. [Online]. Available: http://link.springer.com/10.1007/s10514-012-9321-0