Autonomous UAV Navigation in an Indoor Environment for Warehouse Inventory Recording

Project Description

Overview. In this project, I plan to investigate techniques that will enable unmanned aerial vehicles (UAVs) to autonomously explore an indoor environment. While UAVs are currently used extensively in outdoor environments for various applications, including wildfire monitoring [1], agricultural surveying [2], and traffic management [3], ***their use in indoor applications have been fairly restricted, owing mainly to the difficulty to maneuver them in smaller indoor spaces and the inability to use critical functionalities, such a GPS-based navigation system.*** Nevertheless, there are many indoor applications where UAVs could provide a safe, reliable and resilient means to perform operations that are dangerous for humans. For example, ***UAVs could be used for searching for survivors inside a building following a disaster scenario, for reconnaissance operations inside chemical plants to detect toxic chemicals following accidents, for determining the health of engineering structures such as trusses and beams inside a building, and for inventory management within extreme indoor environments such as cold storages***. To use UAVs in such indoor environments, there are several challenges that need to be addressed, including localizing the UAV without using a GPS, maneuvering the UAV to avoid collisions with obstacles, especially within tight indoor spaces in the presence of turbulence caused by the UAV rotors, and controlling the UAV to autonomously follow a prescribed flight path to complete its operation. To gain a better understanding of these issues, in this project, ***I will investigate techniques to address the problem of autonomously maneuvering a UAV to find a collision-free flight path to cover an indoor environment. I plan to use the results of this research toward implementing an indoor warehouse inventory management system using a UAV where the UAV autonomously flies in front of a shelf-like structure constructed in our lab, and uses its camera to systematically capture images at every rack in the shelf to report the inventory data back to a base station.*** My work in this project will build upon the background research on robotic coverage done in the CMANTIC robotics lab at UNO [5] and my experience on autonomously navigating a UAV called the Parrot AR Drone 2.0 [4] that is available in the lab. The results of this project will help to provide a better understanding of issues in autonomous indoor navigation of UAVs toward deploying them to aid humans in extreme indoor environments.

Background. One the main challenges in robotic exploration is to cover an initially unknown environment while avoiding collision with obstacles whose locations and geometries are not known *a priori*. To solve the coverage problem in a structured manner, a ***coverage path planning algorithm is used to determine a set of waypoints in the environment that the robot should travel to so that it is able to cover every portion of the free space of the environment*** using its sensor, such as a vacuum, camera, landmine detection sensor, etc. Researchers have proposed several algorithms to solve the robot coverage problem. Choset *et al.* [6] proposed one of the earliest and most successful techniques to solve the robot coverage problem in a two-dimensional (2-D), planar environment using a technique called *Boustrophedon Cellular Decomposition (BCD)*, where the environment is dynamically divided into polygon-shaped cells by the robot as it covers the environment; each cell is then covered using back-and-forth sweeping motions, such as a seed spreader algorithm [7]. Other approaches for robot coverage include depth-first spanning tree algorithm [8] and a multi-robot dispersion–based algorithm [9]; but these methods have limitations of not being able to guarantee complete coverage, owing to leaving some cells uncovered due to sensor noise, robot localization error or randomness of the approach. Researchers in the CMANTIC robotics lab have developed techniques for coverage of an initially unknown environment using multiple robots while guaranteeing complete coverage of the free space in the environment [10, 15, 16, 17, 18]. While most of the above techniques have been implemented using wheeled, ground robots in a 2-D planar environment, relatively few researchers have reported techniques for robotic coverage techniques using UAVs. Recently, Rekleitis et al. [11] described techniques for aerial survey of farmlands using UAVs, based on the Boustrophedon cell decomposition technique. To the best of our knowledge, this project is one of the first attempts to develop techniques for autonomous coverage by UAVs for indoor environments. Recently, a system to capture and process data in an indoor warehouse using a UAV has been proposed, but the UAV does not determine its coverage path autonomously [12]; rather it is controlled manually by a human to avoid obstacles and fly to suitable locations to acquire required inventory data using its camera. ***Indoor navigation of a UAV presents some unique challenges due to absence of a reliable indoor navigation system like GPS, limited sensor range of UAV, and kinematic constraints of UAVs such as the ability to fly at a certain speed, and/or at a certain angle in tight spaces.***

As preparation for my project, ***I have already implemented algorithms on the Parrot AR Drone 2.0 UAV in the CMANTIC robotics lab*** for performing basic aerial maneuvers autonomously, such as take off, landing, maintaining constant altitude (hover), moving sideways and forward. I have also developed software that runs on a desktop computer that can be used to control the UAV maneuvers remotely using WiFi commands, as well as to receive the navigation and image data from the UAV's sensors. ***I have taken a course on robotics at UNO*** and implemented a robotic coverage algorithm using the Boustrophedon cell decomposition technique for a ground robot called the e-puck. These experiences have given me a solid grounding in the fundamental technology I will be using for my project and will help me focus on the research aspects of the project.

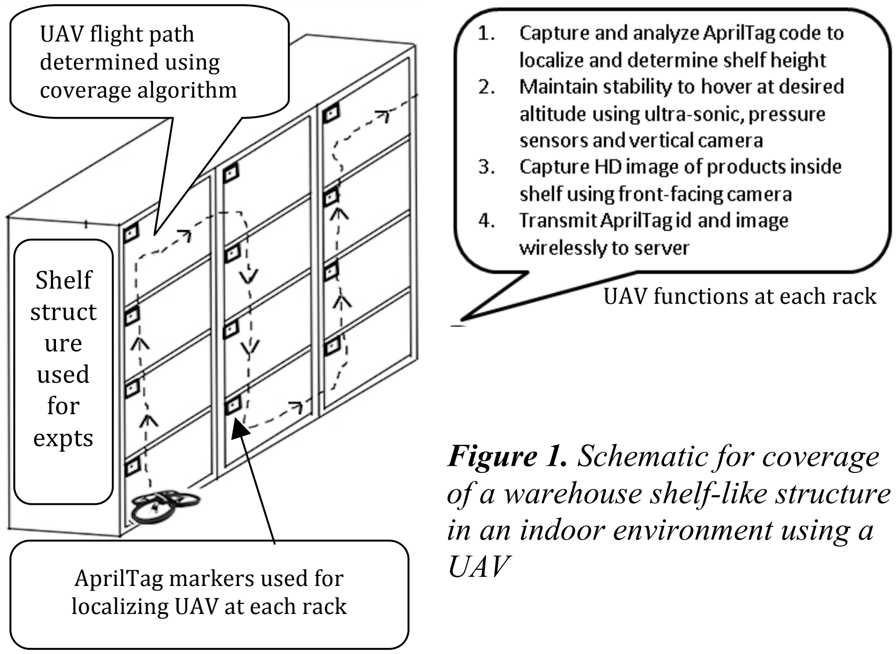

Figure 1. *Schematic for coverage of a warehouse shelf-like structure in an indoor environment using a UAV*

Research Plan

The main research question that I plan to investigate in this project is the following; How can we enable autonomous exploration of an indoor environment by a UAV by developing a novel 3-D coverage algorithm that guarantees complete coverage of the environment and is also resilient to deviations in the UAV's flight path while doing the coverage? The algorithm should be able to maneuver the UAV on its calculated flight path while avoiding obstacles, prevent repeatedly flying over previously covered areas, and enable the UAV to start/end the mission at the same location. My proposed approach will not need continuous human attention to operate the UAV. ***I plan to evaluate my proposed approach in an indoor warehouse-like environment*** constructed inside the CMANTIC lab, where the UAV will autonomously fly in front of warehouse shelves, and acquire inventory data (e.g., image) from items placed on the shelves using its camera. Potential benefits of my research include improving the time required for inventory management, as well as reducing risks for humans to manually analyze the stock placed at difficult locations, such as tall shelves.

Activities to be undertaken. My main concept to address the UAV-based coverage problem in an indoor environment will be to decompose the three-dimensional (3D) free space that the UAV could fly in into suitable cells by developing an extension of the Boustrophedon cell decomposition (BCD)[13] algorithm for a 3D space. I will then investigate a coverage algorithm that finds a collision-free path through these cells to completely cover the set of cells. The final step will be to implement the coverage algorithm on the UAV to navigate it along the prescribed coverage path. Further details about each of these steps are given below:

<u>Cell Decomposition Phase.</u> Before starting the coverage, a map containing a layout of the indoor environment that differentiates obstacle and free space will be provided to the UAV. For example, in a warehouse-like environment, the obstacles would be shelves and the free space would be the aisles between shelves. The BCD algorithm will be used on this map to divide the free space into polygon-shaped cells; the union of such cells will cover the free space in the environment. To find a connected path through these cells, I will represent the cells as a graph structure called a Reeb graph [14], where each polygonal cell is represented as a graph node, and the boundary between two adjacent cells is represented as a graph edge. Next, to find a path that covers all the nodes in the Reeb graph, I will investigate using the Chinese Postman problem to determine an Eulerian path [14], which passes through every connecting cell at least once.

<u>Online Coverage Phase.</u> Online 3D coverage will be done by generating up and down sweeping motions along the Eulerian path calculated in the previous step. The up-down motion is similar to a seed spreader motion. The important parameter for a seed spreader algorithm is the coverage footprint of the UAV, which measures the distance between consecutive sweep lines in up-and-down motion. In a warehouse stock coverage problem, the coverage footprint would be the width of the shelf in a rack. I will determine a suitable distance between the UAV's camera and the shelf so that the entire shelf width can be captured by camera's image since the UAV flies in front of the shelf. The resultant trajectory is generated as a set of waypoints forming sweep lines along the boundary of racks. These waypoints would be converted to control commands for an UAV to make it scan the stock shelf-by-shelf along the boundary of the racks.

UAV Implementation Phase. After developing the coverage algorithm, the final step of my project will be to implement it on the AR Drone 2.0 UAV platform. For localizing the UAV in the indoor environment, I will use an AprilTag-based system [19] that is being implemented for the AR Drone UAV in the CMANTIC robotics lab. The principal challenge that I expect to encounter in this phase is that, due to turbulence from walls and floor of the environment, it is often difficult to make a UAV hover at fixed location or follow a prescribed flight path accurately. Consequently, the UAV will most certainly deviate from the trajectory calculated by the coverage algorithm. To mitigate these errors in the UAV's flight path, my plan is to use a Proportional-Integrative-Derivative (PID) controller [20] that has been used extensively in literature and to practice quickly maneuvering a UAV back on its course as soon as it deviates off-course. If the UAV ventures into critical regions (e.g., very near to a shelf), it would have to be maneuvered aggressively back to a safe location. On the other hand, if it deviates slightly off-course but remains in a safe region (e.g., going at a distance or angle where the camera image is lost or distorted), the UAV could be maneuvered less aggressively. The PID controller has been shown to be effective in adjusting the maneuver speed while reducing the energy (battery) expended by the UAV for the maneuver operations. I will implement the PID controller on the AR Drone 2.0 UAV platform, integrate it with the coverage algorithm, and investigate techniques to adjust the parameters of the controller to suitably maneuver it in the environment.

The complete system will include a control interface running on a base station (desktop machine) through which a user will be able to control basic functionality of the UAV, such as launching, emergency landing, etc. The UAV will also periodically transmit the information collected by it (e.g., images of items on racks, location of racks encoded in the AprilTag id) using WiFi, back to the base station for analysis by humans. For this I will extend and integrate the user control program that I have already developed in Fall 2015 to interact with the UAV coverage algorithm.

Research Contribution to Student Objectives and Discipline

I have started in the Computer Science Master's program at UNO in Fall 2015 and have familiarized myself with basic UAV and robotics technology. This project will give a solid grounding in applying a robotics coverage algorithm on a UAV and will be used as a foundation for my Master's dissertation. Currently, UAVs are mainly used for outdoor applications; they are very seldom used in indoor applications due to the challenges of maneuvering in tight spaces while not using GPS data. ***Solving the research issues in this project will help us to gain a better understanding of the problems of maneuvering UAVs in indoor environments and would take UAV technology closer to being used to aid humans in search and rescue operations in dangerous and extreme indoor environments.***

Future Directions. ***The proposed solution can be extended to various other applications, such as scanning books placed in racks in a library, checking for valid parking permits on vehicles in campus parking lots, etc.*** In the future, I plan to extend the coverage algorithm to handle shelves of different dimensions (height and width) in a warehouse environment; the coverage algorithm would then have to dynamically adjust the UAV's path and its distance from the shelf suitable for capturing the image. Another practical, future extension of this project could be to handle initially unknown obstacles (e.g., forklifts) in the UAV's coverage path by detecting them with the UAV's camera and adapting the UAV's coverage path on-the-fly to avoid them.

Student and Faculty Roles. The student will implement and test the techniques and algorithms related to the proposed project. Dr. Raj Dasgupta, Professor, Department of Computer Science, College of IS&T at UNO will be the faculty mentor for this research. He will supervise the research and hold weekly meetings with the student to review progress and results, provide direction for the research, and suggest additional readings. As part of the meetings, the student will present the research findings in the form of oral presentations; code reviews will be done for all code written.

Timeline

June 2016 to August 2016	Develop algorithm for offline-planning phase using general warehouse layout; construct a small shelf-like environment in CMANTIC robotics lab and perform basic UAV flight tests (takeoff, landing, hovering in the environment).
September 2016 to November 2016	Develop algorithm for online-coverage phase; implement coverage algorithm on UAV in lab environment; flight tests to determine appropriate distance of UAV from shelf for seed spreader algorithm; demonstrate UAV coverage of shelf structure using seed spreader algorithm.
December 2016 to February 2017	Develop and implement PID controller for stabilizing UAV; integrate PID controller with coverage algorithm; perform experiments to fine-tune parameters of PID controller.
February 2017 to April 2017	Integrate coverage algorithm with PID control with UAV control from base station; test and debug as required; prepare project report, acquire detailed results and submit conference paper.

Budget Justification

The CMANTIC Robotics lab at the College of Information Science and Technology will provide the Parrot AR Drone UAV and associated supplies to support the research on this topic. A total of $5000 is requested to support the research on this proposal. The following is the breakup of the estimated budget:

Cost Distribution	Budget
Student summer stipend from June 2016 – August 2016 for a total for 480 hours (40 hrs./week over 12 weeks)	$4500
Shelf hardware for constructing small warehouse-like environment inside lab	$350
UAV repair and spare parts such as rotor blades, sensors, etc. (UAVs get damaged easily when they crash.)	$150
Total	$5000

References

[1] Connie Phan and Hugh H.T. Liu. "A Cooperative UAV/UGV Platform for Wildfire Detection and Fighting" in *2008 Asia Simulation Conference,* Toronto, Canada.

[2] *Yanbo Huang, Steven J. Thomson, W. Clint Hoffmann, Yubin Lan, Bradley K. Fritz* "Development and prospect of unmanned aerial vehicle technologies for agricultural production management" *International Journal of Agricultural and Biological Engineering,* USA, 2013.

[3] Srinivasan, S., and Latchman, H., "Airborne Traffic Surveillance Systems – Video Surveillance of Highway Traffic", submitted to *ACM 2nd International Workshop on Video Surveillance & Sensor Networks*. (http://www.list.ufl.edu/publications/atss_acm_04.pdf)

[4] Parrot S.A. COPYRIGHT © 2015, http://www. http://ardrone2.parrot.com .

[5] CMANTIC Lab, College of Information Science & Technology, University of Nebraska at Omaha, http://cmantic.unomaha.edu .

[6] Rekleitis, New, Rankin, Choset "Efficient Boustrophedon Multi-Robot Coverage," in *Annals of Math and AI*, 2008.

[7] R. Mannadiar and I. Rekleitis, "Optimal coverage of a known arbitrary environment," in *Proc. of IEEE Int. Conf. on Robotics and Automation*, Anchorage, AK, May 2010, pp. 5525–5530.

[8] Stuart J. Russell and Peter Norvig, (1995), "Artificial Intelligence – A Modern Approach" Prentice-Hall, New Jersey.

[9] M. Batalin and G. Sukhatme, "Spreading Out: Dispersion-based coverage using multi-robot systems,"

[10] K. Hungerford, P. Dasgupta and K. R. Guruprasad, "A Repartitioning Algorithm to Guarantee Complete, Non-overlapping Planar Coverage with Multiple Robots," *Distributed Autonomous Robots and Systems (DARS)* 2014.

[11] A. Xu, P. Virie, and I. Rekleitis, "Optimal complete terrain coverage using an un- manned aerial vehicle," *in Proceedings of the 2011 IEEE International Conference on Robotics & Automation*, 2011.

[12] Drone Scan, ©DroneScan cc 2014, http:// http://www.dronescan.co

[13] H. Choset, "Coverage of known spaces: The boustrophedon cellular decomposition," *Autonomous Robots*, vol. 9, pp. 247–253, 2000.

[14] J. Edmonds and E.L. Johnson, "Matching Euler tours and the Chinese postman," *Mathematical Programming*, vol. 5, pp. 88–124, 1973.

[15] K. R. Guruprasad, Z. Wilson and P. Dasgupta, "Complete Coverage of an Initially Unknown Environment by Multiple Robots using Voronoi Partition," *2nd International Conference on Advances in Control and Optimization of Dynamical Systems (ACODS),* Bangalore, India, 2012.

[16] Z. Wilson, T. Whipple and P. Dasgupta, "Multi-robot Area Coverage using Dynamic Coverage Information Compression," *8th International Conference on Informatics in Control, Automation and Robotics (ICINCO),* 2011, pp. 236-241.

[17] P. Dasgupta, T. Whipple, and K. Cheng, "Effects of Multi-Robot Team Formation on Distributed Area Coverage," *International Journal on Swarm Intelligence Research (IJSIR)*, vol. 2, no. 1, 2011, pp. 44-69.

[18] K. Cheng and P. Dasgupta, "Coalition game based distributed coverage of unknown environments using robot

swarms," *International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS'08),* Estoril, Portugal, 2008, pp. 1191-1194.

[19] Edwin Olson, “AprilTag: A robust and flexible visual fiducial system,” Proc. International Conference on Robotics and Automation (ICRA) 2011, pp. 3400-3407.

[20] R. Siegwart, I. Nourbaksh and D. Scaramuzza, “Introduction to Autonomous Mobile Robots”, MIT Press, 2^{nd} edition, 2011.

GRACA Mentor Support Letter

To whoever it may concern

Student's Preparation

This letter is to support the project titled "Autonomous UAV Navigation in an Indoor Environment for Warehouse Inventory Recording" by Venkat Garlapati. Venkat is a graduate student in the College of Information Science & Technology at UNO, where he is a currently working towards his Masters in Computer Science degree. He has worked under my supervision in the CMANTIC Robotics lab for the past 5 months in the area of using autonomous navigation techniques for maneuvering Unmanned Aerial Vehicles (UAVs), which is the topic of his proposed GRACA project. During this period, he has gained very good experience in the topics of his proposed project by writing software programs for autonomously controlling the Parrot AR Drone UAV from a base station (remote computer desktop). He has also taken a graduate course in robotics with me in Fall 2015 where he implemented a robotic coverage algorithm within the Webots robot simulator, for a ground robot, as part of the course project. Venkat plans to use the experience gained from these topics for research on coverage in indoor environments using UAVs, in his GRACA project. With his preparation and experience, I am very confident that Venkat is adequately prepared to conduct research on the topic.

Degree of Collaboration

Venkat will implement and test the techniques and algorithms related to his proposed GRACA project. As the faculty mentor, I will supervise the research and hold weekly meetings with him to review progress and results, provide direction for the research, and suggest additional readings. As part of the meetings, Venkat will present the research findings in the form of oral presentations; code reviews will be done for all code written. Venkat will submit the final project report and results originating from this research at the end of the project for my review for potential publication in conferences and/or journals.

Relation to Other Ongoing Projects

Venkat's GRACA project is not funded by existing grants in the CMANTIC Robotics Lab and his GRACA project is a new direction of research in the lab. The results from his GRACA project will be integrated in future extra-mural grants from the CMANTIC Robotics Lab.

Please do not hesitate to contact me if you any further questions about this support letter.

Sincerely,

Raj Dasgupta 1/19/16

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