Student Research Endorsement

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Proposal Abstract

Formation-flying satellites are less expensive, quicker to build and more efficient than larger satellites. However, smaller satellites have more restrictions on hardware and formations are susceptible to perturbations. This research will address two key challenges with formation-flying: drift and obstacle avoidance. Using decentralized control methods, individual satellites in a formation will respond to obstacles and drift without a central controller, making them more flexible and robust.

Endorsements

Faculty Sponsor: Formation Flying Satellite missions identified to date include astronomical observations, coherent distributed aperture processing, multi-point Earth observation, communication relaying, etc. This student research proposal is in support of the UVM proposal to NASA "Advances to Increase the Flexibility and Robustness of Precision Formation-Flying Satellites." Ryan is our strongest student candidate to support that research. This research should occur even if the UVM proposal is not funded. This work merits this attention in its own right.

23 FEB 2015 Ronald A. Lessard

Date Signature

Department Chair/School Director:
THIS PROJECT WILL CONTRIBUTE TO THE BODY OF KNOWLEDGE DISTRIBUTED CONTROL IN COLLABORATING ENTITIES. IT HAS MY HIGHEST RECOMMENDATION.

23 FEB 2015

Date Signature

School Student Research Committee Member signature A. Mahdamberov/A 24 FEB 2015

Attach proposal and send to:
Director of Student Research, Office of Academic Research

Advances to Increase the Flexibility and Robustness of Precision Formation-Flying Satellites

I. *Applicant*

- Ryan Whitell
- 195 King St. Northfield Vt, 05663
- Faculty Mentor: Prof. Ronald A. Lessard

- Date of Application: 24 February 2015

II. *Classification of Request*

This application is a request for a 10-week Research Fellowship.

III. *Nature of Project*

- Project Title: “Advances to Increase the Flexibility and Robustness of Precision Formation-Flying Satellites”
- General Field of Study: Electrical and Computer Engineering
- Specific Areas of Study: MATLAB Simulation, Embedded Systems, Decentralized Control Algorithms

IV. *Description of Proposed Work*

Formation-flying satellites (FFS) improve upon the functionality of large scale satellites in flexibility, robustness and cost. Smaller satellites in formation can perform the same tasks of much larger, and usually more expensive satellites. Smaller satellites are quicker to build, less expensive and easier to replace making them economical and efficient. Many space missions, such as future interferometer and imaging expeditions, would require massive, un-deployable space craft, making formation-flying satellites the only realistic option [1]. Formation-flying satellites have an endless amount of applications. A few examples include observing radio frequencies below what is measurable on earth [2], processing of multi-point SAR sensors creating high resolution imagery [3], creating accurate measurements of the earth’s geomagnetic field using multi-point observation satellites [4], and aiding distributed space missions [5].

Individual satellites in an FFS configuration are small and therefore have many design constraints and limitations. Additionally, any multi-point system imposes many unique challenges. For example, FFS configurations will require large amounts of data to be transmitted between units at 100 Mbps or faster [1]. For the required high speed communication frequency range, current transmit/receive devices are too large and draw too much power. Most existing satellites operate in a frequency range that limits the available data rate, as a FFS system would need to operate in the Ka-band (25-27, 31-32 GHz) [6]. Also, flexible and configurable satellites require high performance antennas - electronically scanned arrays are currently being researched as a viable upgrade. Decentralized controllers would contribute the reliance needed in a formation, allowing units to better adapt in case of failure or drift. Formation-flying satellites need to be configurable and support a wide variety of applications. Finally, FFS need to be robust and failure proof as the loss of one unit could affect the entire system.

Currently, formations are initialized in a stable orbit using Hill's equations [7] or other similar initial condition techniques. Orbital deviations caused by differential drag then have to be corrected. Decentralized control of formations is being investigated as a solution to stabilizing formational orbits, as are algorithms that make the most efficient use of fuel when reforming drifted formations. A Stanford University project has made efforts to implement autonomous control architectures utilizing low-level algorithms like formation keeping in combination with high level algorithms that maximize fuel efficiency [8]. However, the low-level formation keeping algorithms are not reliable enough in case of obstacle avoidance and not flexible enough for multiple mission purposes. Decentralized control could improve the flexibility and robustness of multiple team, multiple objective missions. For missions that do not require high precision flying, a more swarm-like formation could be implemented using a decentralized model or a hierarchical model. In both cases, the satellites would act slightly more like a swarm than adhere to a ridged formation. In all cases, each satellite must be responsible for its own drift correction and collision avoidance without the need of a central unit.

V. *Approach and Procedure*

I will be using MATLAB and Simulink to simulate the correct formation of an existing cluster like the Planet Labs Doves. The doves are small formation-flying satellites oriented in a line that scans and takes pictures of the Earth as it rotates [9]. By initially simulating an already known FFS configuration the validity of the MATLAB software can be confirmed. Also, this test should lay the foundational knowledge needed for all following experiments. I will then move onto a theoretical three point formation under ideal conditions. This formation should orbit in any two dimensional three point layout of specified parameters and should be able to reform itself on command. This MATLAB simulation will provide the fundamental model for a real-time simulation using three Parallax Arduino robots. Three robots will be programmed using a decentralized architecture in which each robot will be aware of its own trajectory and of the trajectories of its nearest neighbors. Some background reading must be done initially to familiarize myself with the specifics needed for the Arduino tests. I will then develop algorithms that run the MATLAB simulations in physical real time. The robots will follow on a straight path and adjust themselves to fit the parameters of any three point formation on command. The techniques will utilize the robots' available infrared sensors and position monitoring to simulate satellite awareness. The real satellites position monitoring would be handled via GPS, however for the purposes of this experiment the available sensors and communication abilities on the Arduino robots will be satisfactory. These experiments will set up the conditions for testing the proposed decentralized communication techniques and algorithms to improve the flexibility and robustness of any formation in two key areas: drift and obstacle avoidance.

Drift will be handled in MATLAB by incorporating differential drag into the simulations, and obstacle avoidance will be simulated by introducing a foreign object on collision with any satellite in the formation. In future space missions NASA predicts that space debris avoidance will be a top priority as space becomes more congested [10]. Also, failure of one satellite in formation could become debris that must be avoided, especially in formations containing hundreds of satellites or more. Drift and obstacle avoidance will again be tested on the Arduino robots physically by pushing them off course and by placing objects in collision paths. Correct algorithms should give each satellite the means to adjust itself accordingly without the need of a central controller. These tests will expose the strengths and weaknesses of decentralized control.

VI. Significance of Project

Formation-flying is a new and exciting field. This technology has many applications that are not feasible using existing bulky satellites. In fact, the idea of using teams of many small and simple units to do the jobs of fewer, larger, and more complex units relates to more than just satellites. Teams of small robots are being experimented with right now, such as the Harvard University Kilobots that can currently swarm into shapes and one day may help clean up oil spills [11]. Any swarming or formation flying robots could benefit from decentralized control algorithms. Having individual units able to control themselves to a greater degree increases the overall functionality of the entire team. Upcoming DARPA efforts are focusing on advanced autonomy of unmanned aircraft by decentralized controlling means. Having a human controller able to command more than one aircraft at a time greatly improves UAV effectiveness, survivability and affordability [12]. This of course is only possible through autonomy and decentralized control.

I believe mastery of MATLAB is of utmost importance to an engineer. This project will allow me learn and utilize MATLAB to its full potential. Also, the open source Arduinos are a very popular microcontroller. Being able to effectively program Arduinos is a useful skill. Both the experience with MATLAB and Arduino will be instrumental in my future engineering career. This project also requires a lot of programming, which is a specific area of study I find very interesting. Upon graduation I might pursue a career that has aspects related to software, or software development. This project will give me enough experience to make the proper decision on my future career path. While researching this topic I became very interested in formations and swarms. When this project is completed I will continue to work on it, hoping one day to possibly develop it as a senior project, Master's thesis and beyond.

VII. Personal Qualifications and Endorsements

Previously working with MATLAB in Linear Systems, Electronics, and Electrical Circuits has given me a strong understanding of the software. The learning curve and implementation of the MATLAB simulation program Simulink should be challenging but very doable. Differential Equations, Discrete Mathematics and Calculus III gives me the math background needed to understand and implement my own working algorithms. I have pre-existing knowledge of satellite motion from Physics I and II, having learned Newton's laws of universal gravitation. Through writing this proposal, I have become familiar with Hills' equations. I have a hobbyist programming knowledge in C++ and Objective C, which will help when working with MATLAB and Arduino. I have worked with Arduino in Engineering II, and worked extensively with MSP340 Launchpads in Embedded Systems (similar to Arduino). Additionally, Arduino has a massive online open-source community so I should be able to access any and all help I will need.

VIII. Project Timetable

I intend to work 40 hours a week. The project start date will be the week of May 11th and run through August 7th (10 working weeks). After 6 weeks, I wish to take a 3 week break to work a hockey camp in Northfield. Week of:

- **May 11th:** Begin research. Familiarize myself with MATLAB and the Arduino platform. Work on a problem statement with a hand example.
- **May 18th:** Use hand example as a base for simulating three-point formations using MATLAB.
- **May 25th:** Finish MATLAB simulations. Work on a problem statement and hand example for three-point Arduino formations.

- **June 1st:** Use hand example as a base for conduction of three-point Arduino robot decentralized control.
- **June 8th:** Gather knowledge from previous experimentation. Explore the strengths and fix the weaknesses. Set up an outline (problem statements and hand examples) for testing Drift and Obstacle avoidance.
- **June 15th:** Simulate drift in MATLAB.

~ Break ~

- **July 13th:** Simulate obstacles in MATLAB
- **July 20th:** Test the decentralized controller for handling drift and obstacle avoidance using the Arduino robots.
- **July 27th:** Make necessary corrections and tweaks. Fix errors and any unforeseen complications.
- **Aug 3rd:** Finish up testing, finalize report.

IX. Terminal Report

The terminal report will include all simulations and experiments broken down into easily presentable segments: the problem, input/output, hand example, algorithm and testing. Also, the report will recount the project and touch on the successes and any failures or limitations encountered during the ten weeks. The report will be fully exhaustive and publishable.

X. Facilities Involved

I will be using the resources in the U building, more specifically the computers in U209 or the computer labs for MATLAB.

XI. Financial

Equipment Purchases:

- Parallax BOEBot Kit – 3 x \$124.95 = \$374.85
- Arduino Uno R3 – 3 x \$24.95 = \$74.85
- USB Cable – 3 x \$3.95 = \$11.85

Total Overall Cost: \$461.55

XII. References

1. Precision Formation Flying. NASA JPL. http://scienceandtechnology.jpl.nasa.gov/research/ResearchTopics/topicdetails/?ID=60
2. Bentum, M.J. and Verhoeven, C.J.M. and Boonstra, A.J. and Gill, E.K.A. and Veen, A.J. van der*, A novel astronomical application for formation flying small satellites.* In: 60th International Astronautical Congress, 12-16 Oct 2009, pp. 1-8.
3. Stiles, Jim, Nathan Goodman, and SiChung Lin. "*Performance and processing of SAR satellite clusters.*" Geoscience and Remote Sensing Symposium, 2000. Proceedings. IGARSS 2000. IEEE 2000 International. Vol. 2. IEEE, 2000.
4. Slavin, James A., et al. "*Space Technology 5 multi-point measurements of near-Earth magnetic fields: Initial results."* Geophysical Research Letters 35.2 (2008).
5. Barnhart, David J., Tanya Vladimirova, and Martin N. Sweeting. "*Very-small-satellite design for distributed space missions.*" Journal of Spacecraft and Rockets 44.6 (2007): 1294-1306
6. K. P. McCarthy, F. J. Stocklin, B. J. Geldzahler, D. E. Friedman, P. B. Celeste, "*NASA's Evolution to Ka-Band Space Communications for Near-Earth Spacecraft*", SpaceOps 2010, Huntsville, AL, April 25-30, 2010
7. G.W. Hill, "Researches in Lunar Theory," American Journal of Mathematics, Vol. 1, 1878
8. Inalhan, Gokan. Busse, Franz D. and How, Jonathan P. "*Precise Formation Flying Control of Multiple Spacecraft Using Carrier=Phase Differential GPS"* AAS Stanford. 2000
9. Marshall, Will. (2014, March). Will Marshall: Tiny satellites show us the Earth as it changes in near-real time. [Video file]. Retrieved from URL http://www.ted.com/talks/will_marshall_teeny_tiny_satellites_that_photograph_the_entire_planet_every_day?language=en
10. Committee for the Assessment of NASA's Orbital Debris Programs; National Research Council "Limiting Future Collision Risk to Spacecraft: An Assessment of NASA's Meteoroid and Orbital Debris Programs" 2011.
11. Harvard University, "Kilobot Swarm" https://www.youtube.com/watch?v=JmyTJSYw77g
12. DARPA Special Notice "*Collaborative Operations in Denied Environment"* Tactical Technology Office, DARPA-SN-15-20.
13. Robots - http://www.adafruit.com/products/749