The AUSS FIREfly: A Distributed Sensing and Coordination Platform for First-Year Engineering Education

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This paper describes an embedded computing and sensing system developed to serve the needs of the Autonomous Unmanned Systems Stream (AUSS), a two-semester sequence at the University of Maryland that provides first-year students with an inquiry-based introduction to concepts in engineering and autonomy. AUSS is part of the UMD First-year Innovation and Research Experience program (FIRE), a campus-wide initiative that provides course-based undergraduate research experiences for first-year students. FIRE aims to propel students towards planning, conducting and reporting research that is relevant to the scientific community. To serve its educational mission, the AUSS needs to equip incoming freshmen with the necessary technical capabilities to pursue engineering research in autonomous systems. The AUSS FIREfly is a robotics kit designed to be a training tool and a research platform. Each device is assembled and programmed by an individual student, exposing the builder to topics such as circuit design, information theory, and computer science. Once completed, the FIREfly uses onboard infrared transceivers to emulate the photic system of a firefly, supporting group-led experiments in multi-agent synchronization. The devices are also designed to serve as nodes in a distributed sensor network when equipped with additional measurement modules such as airspeed probes. This paper presents the design features of the AUSS FIREfly system within the context of the challenges faced by a first-year research education experience. It presents student experience evaluations from the first cohort of AUSS students and describes two FIREfly student projects as case studies.

I. Introduction

Autonomous robotic systems will operate in crowded environments populated by manned and unmanned vehicles, posing a number of technical and regulatory challenges. Despite myriad commercial opportunities in autonomous unmanned systems, the basic components of educational training in this area are still undefined. The AUSS was created as a pilot program to introduce first-year students at the University of Maryland to the field through a research-based course experience. It is part of the FIRE program on campus, which operates twelve faculty-led research streams that span a wide range of academic disciplines. Each stream is a two-semester sequence through which 35-40 students formulate and execute research with broad relevance and impact beyond the classroom while engaging with the scholarship of each discipline. These goals can be challenging when serving first-year students and the course must provide sufficient technical training for students that come from a wide range of backgrounds before meaningful involvement in research is possible.

This abstract describes an embedded computing, sensing and control platform designed to meet the training requirements of the AUSS while serving its broader research agenda. The AUSS FIREfly is an electronics assembly and programming kit that uses three 8-bit microcontrollers and a set of infrared (IR) components for line-of-sight communication. Additional modules allow the FIREfly devices to function as small sensor platforms and as mobile robot controllers.

In Section II, the educational and technical challenges faced by the AUSS are discussed as a motivation for creating the AUSS FIREflies. A brief background on electronic firefly analogs is also provided. Section III describes the design features of the AUSS FIREfly board and how each supports the needs of the AUSS. Section IV presents student evaluations of the FIREfly learning experience with a focus on core learning outcomes. Section V describes two ongoing student projects based on the FIREfly platform. The first uses the FIREfly as an electronic test bed for multi-agent synchronization algorithms. The second study uses the sensing and communication capabilities of the FIREfly to develop and validate a model of gust propagation. Section VI concludes by describing the expected

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results from both case studies. The contribution is (1) a robotics-based curriculum designed to support a research-based engagement for first-year students in engineering; (2) learning outcomes from the first, Spring 2016 cohort of students; and (3) a presentation of student-led multi-agent synchronization trials and an empirical gust-propagation model developed using the FIREfly system.

II. Background

Undergraduate involvement in research has been linked to positive outcomes beyond the development of technical skills that range from degree retention [1] to positive feelings [2]. The FIRE program at the University of Maryland provides a number of course-based undergraduate research experiences (CUREs) throughout campus. A CURE has all the appearances of a lab-based course but is fundamentally distinct in how it combines an emphasis on the scientific method, discovery of new knowledge, impact beyond the classroom, collaboration, and a structure that recreates the inherently iterative nature of scientific research [3].

Pioneered in Spring 2016, the AUSS has had success in empowering first-year undergraduates to propose and conduct meaningful research in autonomous unmanned systems. This paper describes the design of an embedded sensing and computing platform that served as the launching pad of the AUSS syllabus and approach during the first five months of 2016.

Unlike a traditional lab-based robotics course with predetermined methodologies, objectives or known outcomes [4,5], the AUSS syllabus emphasizes the process of scientific discovery by encouraging students to formulate and refine their own research topics in autonomous systems. The initial portion of the course provides a minimal level of technical training along with a dose of practical engineering reality to so that initial research proposals do not begin within the realm of science fiction. Inspired by the Conceive-Design-Implement-Operate model of education [6,7], the training phase of the AUSS syllabus guides students through the complete life cycle of a research project. Students quickly gain a basic set of knowledge, skills and attitudes by participating in a nominal research thrust before formulating their own research topic.

We chose to investigate firefly synchronization as the initial training and research activity of the group, because of ongoing research activities in Paley's Collective Dynamics and Control Laboratory. Firefly synchronization is an example of collective behavior in nature where multiple individuals have been observed to synchronize their flashing [8]. An electronic firefly would only need light-emitting diodes (LEDs) and is a simple electro-mechanical device that can be built by first-year students. At the same time, the interaction between these devices allows a range of emergent behavior to be studied. The device is also designed to be expandable with different modules so the onboard optoelectronic components can also serve as homing beacons or optical modems as part of more sophisticated mobile robots. This aspect allows the same training module to serve as the computing platform for subsequent projects that students propose.

Previous electronic firefly projects were built using discrete electronic components to investigate specific synchronization models [9,10]. We chose to design an electronic firefly that is modular and easily reprogrammable so a variety of synchronization algorithms may be implemented. Validating previously proposed firefly models from literature provided students with opportunities to find and utilize academic resources, whereas experiments with new algorithms allow them to innovate and create new results.

III. The AUSS FIREfly Curriculum

A. Learning Outcomes and Course Organization

The main objective of the FIREfly curriculum is to prepare students with different levels of experience to formulate and conduct research in autonomous systems. The following learning outcomes were identified for the FIREfly curriculum:

1) Understand key concepts in autonomy (Knowledge)
2) Understand basic programming principles and skills (Knowledge, Skill)
3) Develop embedded electronics design and assembly capabilities (Knowledge, Skill)
4) Be able to synthesize and implement algorithms found in existing literature (Skill)
5) Gain confidence to conduct research in autonomous systems (Skill, Attitude)

Outcomes (4) and (5) are considered particularly important to preparing students to become independent researchers. In addition to technical skills, students need to both understand and implement algorithms in existing literature so they can propose and evaluate their own research activities. Building confidence in this capability completes the Performance Pyramid applied to learning by Spady [11], recreated in Fig. 1:

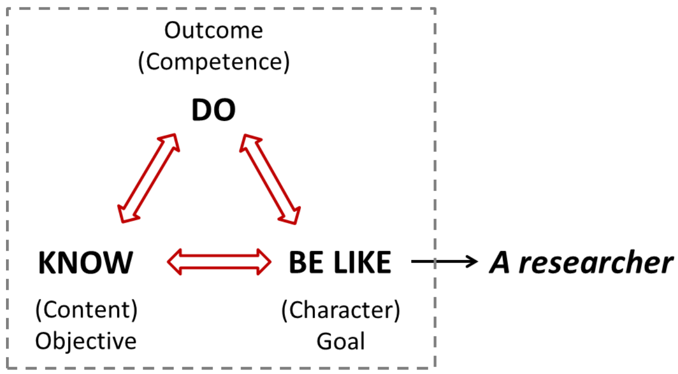

Figure 1: Performance Learning Pyramid adapted from Spady [11]

The Performance Learning Pyramid casts *Content*, *Competence* and *Character* as key factors of successful performance of a role. In other words, the FIREfly training curriculum needs to support students as they acquire knowledge, perform tasks with that knowledge, and thereby gain the confidence to conduct themselves as confident and successful research professionals in future projects.

The 4-week FIREfly curriculum is organized around a series of weekly instructional labs that are complete, self-contained lesson in electronics assembly, programming, and an additional topic related to embedded systems. Students demonstrate increasingly challenging examples of the learning outcomes identified by building and testing small stand-alone modules at the end of every week. This sequence of increasing challenge allows students to build an understanding of new concepts based on preceding lessons, a strategy consistent with existing literature on multi-disciplinary course development as describe by Sharma et al. [12]. Each of these smaller modules is designed to combine and connect with the others, forming a complete FIREfly device and supporting collection of testing tools. Fig. 2 summarizes the FIREfly curriculum that forms the first month of the course.

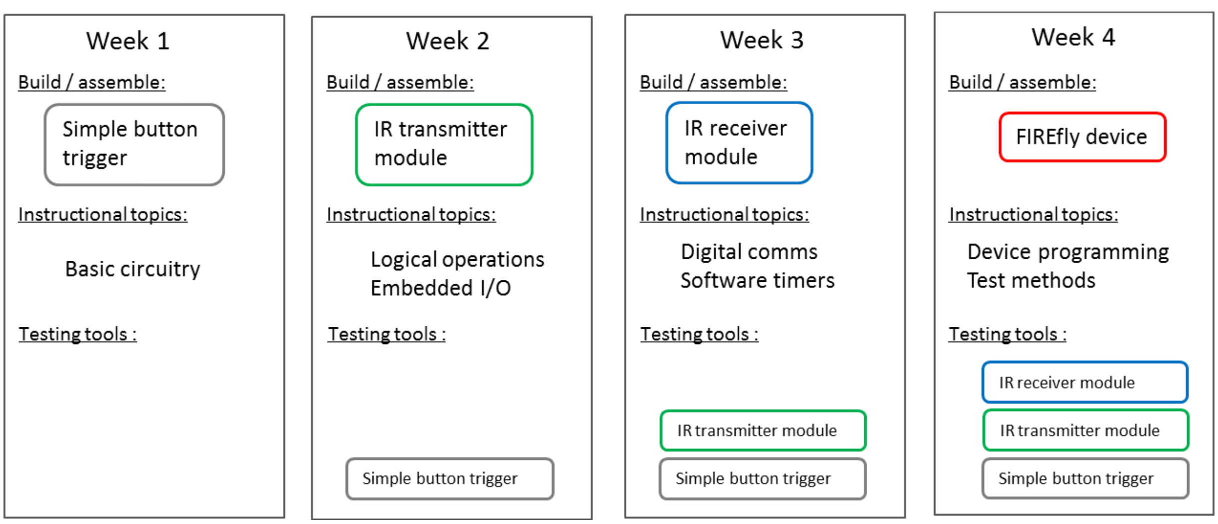

Figure 2: FIREfly training and module assembly schedule, weeks 1-4.

B. Hardware Configuration

The AUSS FIREfly uses three 8-bit microcontrollers on two boards. This modular approach means each processor and its accompanying firmware software is relatively simple. Each microcontroller forms the core of a sub-system that serves a clearly defined role within a sense, think and act framework. Two smaller microcontrollers serve as IR message transmission and receiving/decoding modules, leaving one main processor to execute higher-level tasks. This approach allows each sub system to serve as the subject of weekly instructional lab modules, each a complete lesson in electronics assembly, programming and a related topic in embedded computing. Students assemble and test smaller versions of each module over the course of three weeks, improving their soldering and programming skills as they progress.

The FIREfly device consists of a printed circuit board with all the components and the Adafruit Mini Metro. A set of stackable headers connect both boards, providing power and data connections between the two boards and any additional modules. Fig. 3 provides an overview of the complete system.

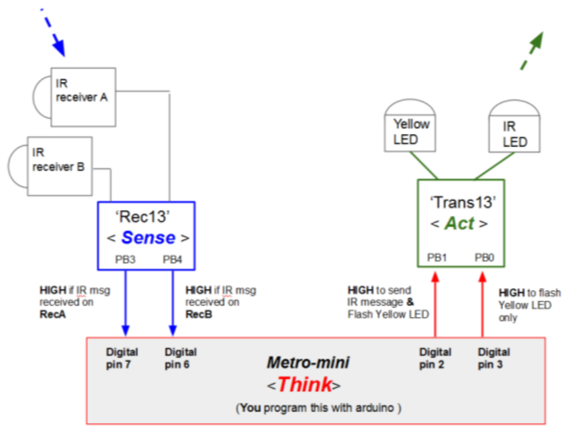

Figure 3: FIREfly system overview (from AUSS training manual)

The Rec13 unit is programmed to recognize a specific IR message using two receiver units on each side of the device. These provide a basic direction-finding capability with two I/O pins connected to the main board. The main processor board uses another two I/O pins as triggers for the Trans13 module, which flashes yellow visible LEDs and transmits the specified IR message using the appropriate carrier frequency. IR transmitters and receivers are tuned for a 38kHz carrier frequency, making the system compatible with most commercial remote controls. The main FIREfly board was created using Fritzing [13], which is a simplified, open-source prototyping tool intended for hobbyists. The board design and complete device are shown in Fig. 4.

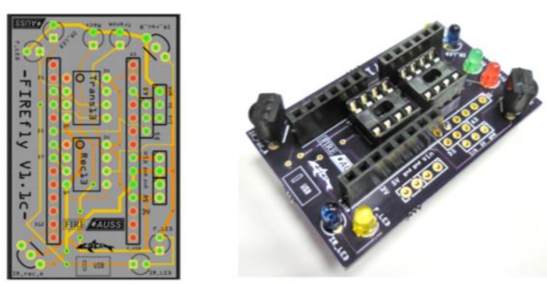

Figure 4: AUSS FIREfly version 1.1c

C. Accommodating Students with Different Levels of Experience

The FIRE program serves students from all majors. As such, the AUSS syllabus accommodates students with a wide range of experience in programming and electronics. It enables students with no prior experience to develop their own autonomous agent while still offering challenges to those with embedded electronics experience. The hardware configuration of the FIREfly system was chosen with this challenge in mind. Two pre-programmed Atmel ATtiny13 interface with the IR components and implement a simple communications protocol. The main processor board is a

Mini-Metro development board manufactured by Adafruit industries. It is powered by an Atmega328, which runs an Arduino bootloader [14].

For most students AUSS is their first experience with writing software; the Arduino environment is well suited as an introduction to programming. By offloading the communication functions to the ATtiny13s, transmitting and receiving messages may be abstracted to two digital input / output lines. Existing functions in Arduino allows all students to successfully create their own simple automata. More importantly, the ATtiny13 sub-processors also allowed more advanced students to explore embedded programming beyond the limitations of the Arduino environment. Students are challenged to upgrade the communications modules using AVR libc for the Atmel family of 8bit processors. These students are introduced to bitwise operators and the concept of event-driven programming with interrupts. This level of engagement results in a functionality upgrade to the IR receiver module. The most adventurous are offered a bonus AVR ASM software assignment that teaches the basics of the AVR assembly language. On the other end of the spectrum, sample code created in a graphical programming environment for the Arduino environment (Ardublock) is also offered for students overwhelmed by the need to write software. In Spring 2016, all students completed their FIREfly successfully without using Ardublock.

IV. Student Evaluations

Skill-based learning outcomes are measured through the successful completion of key tasks and assessments. By the end of the initial 4-week sequence, all students are familiar with the core concepts of autonomy and are able to build individual FIREfly devices and use them to implement synchronization algorithms. Student feedback is used to gauge how well the FIREfly platform achieved the learning objective of developing student confidence to formulate and conduct novel research. This section presents results from a short questionnaire that students completed after their experience with the FIREfly curriculum in Spring 2016.

A. Student experience distribution before FIREfly curriculum

Students assessed their own capabilities in the core skills through an intake survey, grading themselves on a scale of 1-5. A response of 1 indicated the student has no experience and is intimidated by the concept; 3 indicated no experience but with a willingness to learn; and 5 indicated the student is very experienced. These responses are summarized in Fig. 5 for the 22 participants who completed the survey. Many incoming students (10 of 22) had no prior experience in software when they enrolled in the AUSS; some students considered themselves to have actual experience with implementing algorithms from scholarly literature and with embedded electronics.

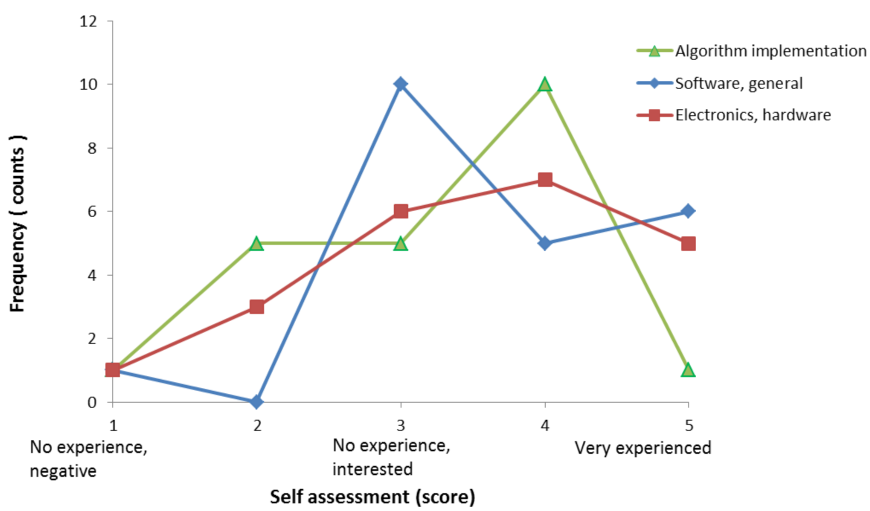

Figure 5: Student self-assessment of ability prior to starting the FIREfly curriculum.

B. New information offered by the curriculum

One of the key challenges faced by the FIREfly curriculum is the range of backgrounds that students bring with them. The instructional lab modules were designed to balance clear instructions for content for inexperienced students while still delivering enough advanced content to keep more experienced students engaged. To assess the success of these efforts, students were asked to evaluate how much they learned from the FIREfly curriculum beyond their prior knowledge. The survey asked students to rank their programming skills, embedded electronics capabilities and their ability to implement algorithms in existing literature on a scale from 1-10, with 1 indicating the course provided the student with a complete lack of new information, 5 indicating enough of the material was new and engaging, and 10 indicating everything in the FIREfly curriculum was new and exciting information. These results indicate that, on average, AUSS students found the syllabus provided enough new content to remain engaging while also catering to a range of academic backgrounds and prior skills.

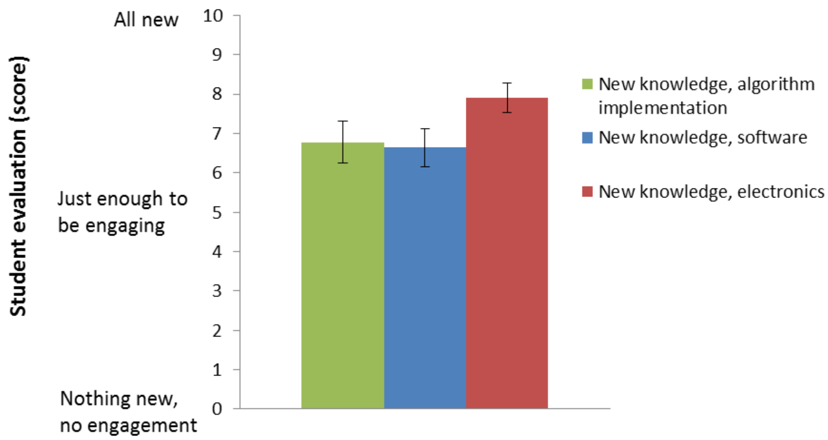

Figure 6: Student perceptions of additional knowledge gained through the FIREfly curriculum

C. Impact of FIREfly syllabus on confidence levels

In addition to technical skills, the FIREfly training sequence seeks to inspire students with a sense of confidence in applying their knowledge to research problems. the Students were asked to self-assess their confidence in skills across the same three technical aspects on a scale of 1-5 (5 being very capable) before and after the FIREfly sequence. This analysis captures the individual difference in these scores which is important as as students began the class with different academic backgrounds, experience, and levels of confidence. The statistics of these individual differences are summarized in Fig. 7.

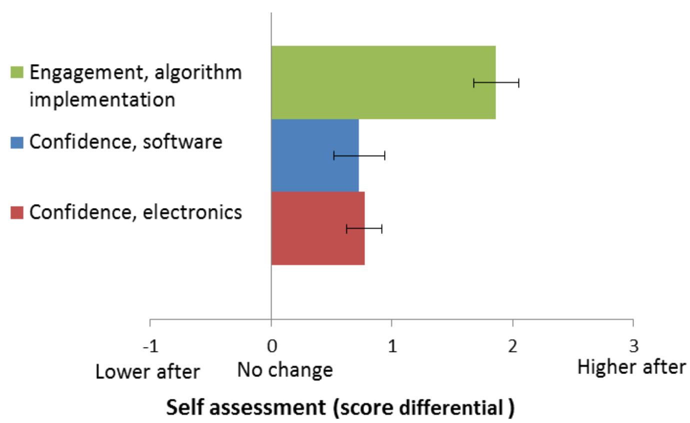

Figure 7: Reported impact on student confidence levels through scoring differences before and after FIREfly project

V. Student Projects Based on the FIREfly Platform

The FIREfly system is designed primarily to be a training tool, but has also supported the research agenda of the AUSS. This section describes two student projects in which the FIREfly system was used to conduct research in multi-agent synchronization, and gust modelling for unmanned aerial vehicles.

A. Multi-agent Synchronization

Each student in the AUSS built and programmed a FIREfly device to develop and evaluate bioinspired synchronization algorithms for small autonomous robots. Certain firefly species have been observed to synchronize their flashing across large groups and two models [8] were used as starting points for this study. These models provided simple behavioral guidelines for each agent and encouraged students to engage primary literature as part of an open-ended programming assignment. Each student wrote their own algorithm based on group-wide standards, resulting in a diverse population of FIREflies with small variations in response time and cycle period across the group due to individual differences in implementation. Fig. 8 shows one of the student-built populations assembled for testing. Basic trials with the IR system showed that each FIREfly in the test space was able to communicate with every other one.

Figure 8: Spring 2016 semester test group

A group of students used a numerical simulation of the FIREfly communication system to generate a set of expected results. A synchronicity metric based on the disparity between lit and unlit agents was developed with a value of 1 indicating perfect synchrony. This simulation has been used to evaluate three models with a population of 20 FIREflies; the phase-advance model and the reset-advance/delay model are implemented according to the observations made by Buck [8]. The third model is an integrate-and-fire (IAF) algorithm that is commonly used to simulate neurons [15] adapted for use with the FIREfly system. FIREflies were initiated at random points in their cycle and an all-to-all topology was used. The final synchronicity score for 100 test runs are tabulated and shown in Fig. 9.

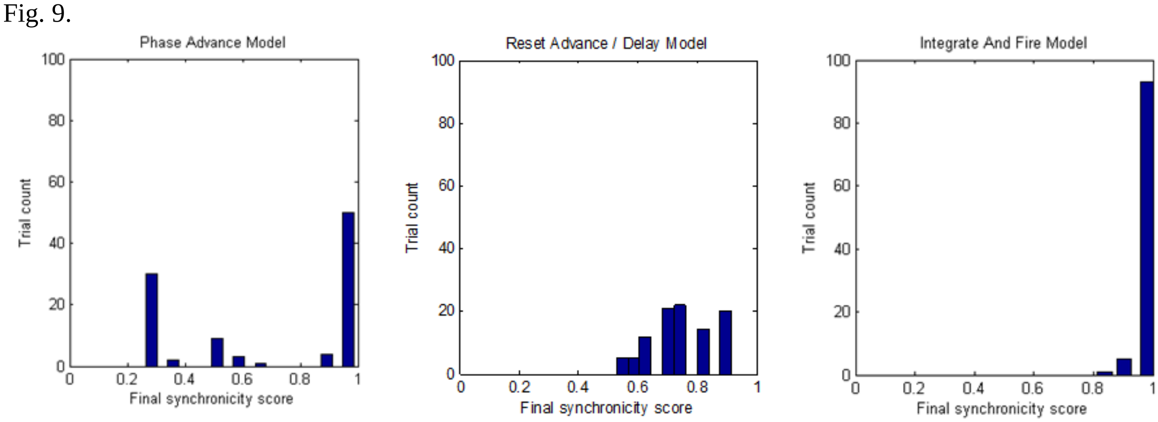

Figure 9: Synchronization results for three numerically simulated algorithms

These simulations suggested that a Phase-Advance model used would only result in a high level of synchronization about half the time and a low synchronicity score would be encountered very often. These trends were observed in experiments as FIREflies programed with behavior tended to synchronize in groups that began the trial in similar points of their cycles. The Reset Advance/Delay model performed similarly, offering better both in simulation and in experiments. The IAF model performed well, resulting in near-perfect levels of synchronicity for 85% of the trials. This trend was also observed in experiments and demonstrations where FIREflies always reached group-wide consensus when programmed with the IAF algorithm. These student-led tests represent a novel implementation of the models proposed by Buck [8]. Development of a data collection system for quantitative validation is ongoing.

B. Gust Propagation and Disturbance Information Transmission

Coordinating multiple autonomous aerial vehicles is more challenging in changing flow conditions and recent work has shown the potential for improving adaptation to gusts by using onboard flow measurements [16]. Cooperative platforms that use measurements to predict the effect of incident gusts on a group of spatially distributed platforms could provide stability and control advantages for individuals. A number of FIREfly devices were equipped with flow-measurement modules and used as gust-detection platforms that track flow disturbance and information propagation throughout a test area. Test data was used to develop a propagation model for a discrete gust-front travelling through an indoor test volume.

A set of eight Dyson blower-style household fans were used to generate a flow-field. An actuated shutter screen allowed a discrete gust to be generated and measured downstream. A flow-measurement module on each FIREfly detects a passing gust and the IR system communicates this information throughout the group. This provides a set of transit time data that is used to develop an empirical gust propagation model. The FIREfly experimental setup for a two-sensor experiment is shown in Fig.10

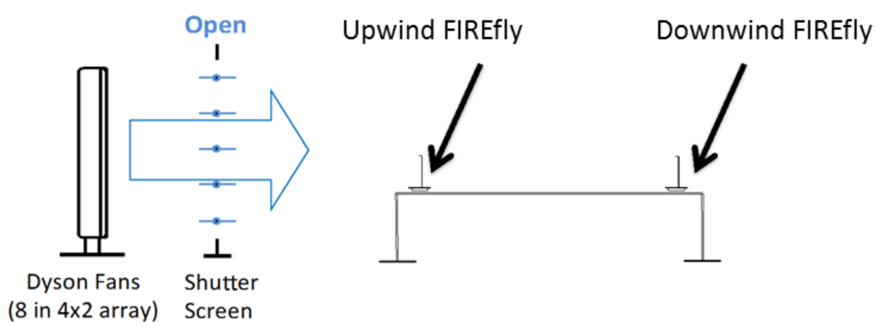

Figure 10: Experimental overview

Test data was first used to develop a baseline model for gust-front position as a function of time. A gust velocity decay law for the test setup was approximated with a polynomial fit and used to predict gust positions as shown in Fig. 11. Numerical integration of the wind velocity profile provides a model of gust front position as a function of time. The model is simple enough to be implemented on an embedded processor such as the FIREfly and could be used to provide neighboring platforms with information such as impending gust severity and arrival time. The model was evaluated using test conditions outside the calibration data, showing good agreement within 10% as shown in Fig. 12.

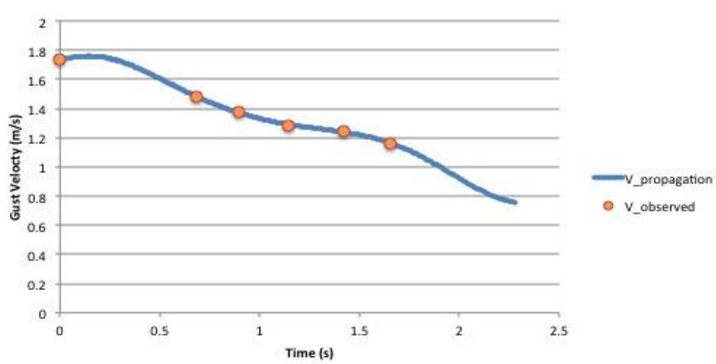

Figure 11. Gust velocity decay model

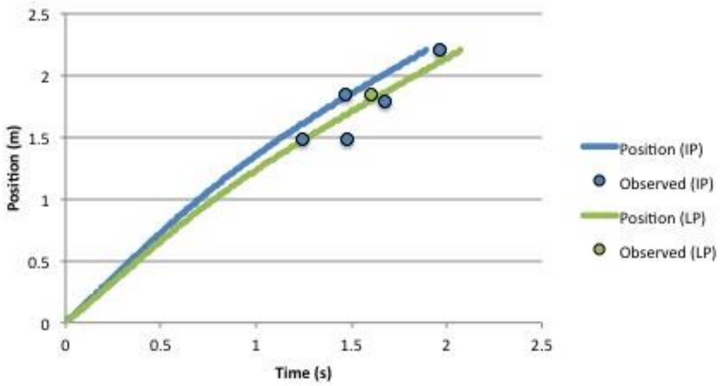

Figure 12. Gust-front position model validation

VI. Conclusions and Ongoing Work

Key design features of an electronic firefly system have been described in the context of research-based engineering education for first-year students. A set of learning objectives have been identified that serve the goals of a course-based undergraduate research experience. Learning outcomes based on knowledge and skill were continually assessed through in-lab assignments, and student evaluations indicate that the curriculum has succeeded in achieving qualitative learning outcomes. A modular approach to hardware design offers optional development environments that accommodates and engages students with different levels of prior experience. Integrating exercises in which students are guided through the synthesis and implementation of algorithms presented in existing scholarly literature have resulted in a positive impact on student attitudes. The FIREfly device has also served as a training tool for embedded systems and has supported to two student-led research projects. A population of FIREfly devices has qualitatively verified three firefly synchronization algorithms and supported the development of a gust propagation model for use on cooperative aerial vehicles. Preliminary results have been reported along with ongoing work.

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