Mesh Networks for Simultaneous Localization and Communication

ECE 4011 - Senior Design Project Proposal

Section A05, Team 1961C

Advisor: Ma, Xiaoli

Abraham, Kevin
Bennani, Yassine
Molugoori, Sai
Nicholson, Keenan
Nicholson, Norris

Submitted: 28 November, 2018

Contents

Executive Summary

Sailboat regattas are a series of competitive boat races conducted by schools, clubs, organizations, and other event conductors. The duration of each race (in collegiate regattas) ranges from 20 to 40 minutes, with 6 to 10 races in each regatta [13]. Traditionally, spectators stand on the shore and watch as boats race around a course on the water. However, these races are difficult to observe from shore and would greatly benefit from real time tracking. The cost of individual GPS modules for each boat combined with a reliable method of transmission can be prohibitive. To solve this problem, we propose a mesh network of radios that use distance measurement techniques to discover the location of each boat in the water. Each boat will have a node attached: a self-contained unit containing the radio, internal antenna or external antenna connection, and other required electronics. The node will be secured to the mast in an easily accessible location along with the external antenna (if not equipped with an internal antenna). There will also be a base station that will contain equipment for hosting a web app over Wi-Fi, offloading visual processing of the map to client devices. The web app will offer spectators a convenient way to watch the race and know the position of the boats. The app can also be used by race committee to check for any misconduct between boats. By tracking boats in this way, the cost per boat will be reduced to $40. For a twelve boat regatta, this will cost a total of $480.

Mesh Networks for Simultaneous Localization and Communication

█████Introduction

Team 1961C is developing a mesh network solution for simultaneous localization and communication. It is a cheaper method for mapping boats participating in sailboat regattas, as well as other device localization applications. The end result will be a web app to view the map and self-contained units on boats containing electronics such as radios, antennas, PCBs, etc. The team requests $700 of funding to accomplish this.

1.1. Objective

The objective of Team 1961C is to develop a solution for real-time tracking of all the sailboats participating in a regatta. The created map will show the location of the boats throughout the race for the audience and race committee to see. The solution will use a mesh network of radios which can use distance measurement techniques to pinpoint the location of each boat on the water. This information will be relayed back to a base station using the same network. There will be at least two base radio towers with known locations, which will enable the base to determine the position of the boats using different methods depending on location of the boats. For boats in the triangulation area (i.e. within range of at least 2 towers), the base can directly triangulate the location of the node. For boats outside this range, each node must measure the distances between itself and at least three nearby nodes and transfer it to shore using the mesh network. This data can be processed by the base station to determine the location of each node.

1.2. Motivation

Sailboat regattas are difficult to observe since the races take place around buoys ~100m offshore. Creating a real-time map of all the sailboats will make it easier for the audience to see as well as for judges to determine racecourse violations. Using mesh networks for this task is a more affordable option compared to using GPS modules plus a method of transmission, and will provide similar accuracy [14]. The Georgia Tech sailing team could utilize this system, along with other schools, clubs, and organizations that conduct regattas. Additionally, this technology could be used to track other competitive events where the course is obscured or difficult to see. Other applications beyond sports events would also benefit from low-cost mesh-based localization.

1.3.   **Background**

The basic technology supporting this method of localization is Time of Flight distance measurement. Variations on this technology have been used as far back as the mid twentieth century with the advent of DME (Distance Measurement Equipment) for use in the aviation industry [9]. DME operates in the VHF band (200 MHz) and is accurate to within 600 ft.

Another prominent technology which uses a variation of Time of Flight distance measurement is the GPS system, although click synchronization is a key component in its accuracy [4].

In recent years, systems operating in the GHz bands have begun to surface for use in factories and warehouses in order to track materials. These systems are the direct foundation for the node based tracking system proposed here for use with regattas. Reference

As it relates directly to tracking vessels on a regatta course, most modern systems use GPS combined with either a VHF transmission system or a cellular module. These systems are optimized for offshore regattas on larger boats. The aim of Team 1961C is to develop a system optimized for use on smaller boats in local water at a much more reasonable cost [16].

■■■ Project Description and Goals

Team 1961C will focus on creating a prototype system consisting of at least three nodes and two base stations. The prototypes will be tested using three C420 sailboats owned by the Georgia Tech Sailing Club at Lake Lanier [3]. Each of the nodes will be attached to the mast of one of the sailboats. The two base stations will be positioned on shore at least 300 feet apart.

For the project to be successful, the system (three nodes and two base stations) will need to accomplish the following tasks:

- Track the position of each node within 7 feet of their actual location

- Communicate this information to shore

- Present the position of each node to a user using a locally hosted web app

- Each node should cost less than $40 (the baseline price for a GPS system that accomplishes the same function) [5]

- Each base station should cost less than $50

Furthermore, each node should be a self-contained unit that houses all of the processing hardware, transmission systems, and power sources. The base stations should also be self-contained, except they should be able to be powered using a long term power source (such as AC power or a high capacity battery)

▰Technical Specifications

Project Element	Category	Specification
Radio Systems	Localization	Positional accuracy of within 7 feet or better
		Position measurement rate not less than once every three seconds (for entire fleet)
		Each node must be individually identifiable
	Communication	Communication range between two nodes not less than 300 feet
		Communication range between a node and a base station not less than 400 feet.
		Sufficient data throughput to outpace fleet-wide localization measurements
		Nodes must be able to relay messages for other nodes if a direct link between a node and a base station cannot be made
	Network	System must operate with as little as one (1) node and up to a maximum of twelve (12) nodes
		System must operate with as little as two (2) base stations (provides they are positioned such that boats can only sail to one side of them) and up to a maximum of three (3) base stations (for full position triangulation on both sides of the station formation)
Node Module	Enclosure	No larger than 8"x5"x5"
		No heavier than 3 lbs
		Water resistant to a depth of 25 feet for up to 5 minutes

Project Element	Category	Specification
		Must be easy to disassemble for charging
	Antenna	Must be securely mounted to the enclosure (inside or out)
	Power	Must be rechargeable in less than 6 hours
		Battery system must last for not less than 4 hours total time, with not less than 2 hours of active position tracking
		Must be able to withstand temperatures up to 130 °F and down to 40 °F for up to 8 hours
	Interface	Must have internal buttons and indicators to distinguish between applicable operation modes.
		Must be controllable via the base stations using the radio interface
Base Station	Enclosure	Must affix to the top of a tripod or other lifting device
		Excluding the tripod or lifting device, must be no larger than 10"x6"x6"
		Excluding the tripod or lifting device, must be no heavier than 5 lbs
	Antenna	Must be securely mounted to the enclosure (inside or out)
	Power	Must be capable of switching between external 120VAC input and internal battery (if equipped)
		Internal battery (if equipped) must be rechargeable in less than 6 hours, and last for not less than 8 hours, with not less than 6 hours of active position tracking
		Must be able to withstand temperatures up to 130 °F and down to 40 °F for up to 8 hours

Project Element	Category	Specification
	Interface	Must host a wifi network for user devices to connect to
		Must host a web app to allow user interactions
		Must contain settings relevant to the regatta including but not limited to: • Defining the base station's exact location • Starting and stopping races • Enabling lower power modes for the nodes
		Must present a map to clients so that they can see the location of each node (boat) in real time

▮▮▮Design Approach and Details

4.1. Design Approach

▮▮▮Radio Transceiver

The radio transceiver for this project will likely be the DW1000 by DecaWave [5]. This module was chosen in order to streamline the overall project design. It is specifically designed for warehouse inventory management and comes equipped with a Time of Flight distance measurement unit that is compatible with other modules of the same time. Additionally, the DW1000 allows the radio to be used for communication as well, however it needs an external microcontroller to give it each instruction. Three DWM1000 modules (DW1000 modules with an added on-board antenna) have been acquired and breakout boards allowing them to be connected to a breadboard have already been designed and fabricated. Module testing and vetting will occur over the next few weeks [6].

Antennas

The DW1000 radio transceiver needs an external antenna. Omni-directional antennas such as loop or dipole antennas are required on the nodes. These antennas will be used to find other nodes around the sailboat to acquire data and form a mesh network. However, a directional antenna is preferred on the base stations (similar to a Yagi-Uda or a end-fire array antenna with a high half power beamwidth). This is because a base station on the shore will only need to communicate in the direction of the race course, not the beach.

Microcontrollers

A 32-bit ARM core microcontroller will be used to control each node [1, 17]. These will interface directly with the DW1000 and the onboard power management hardware. The microcontroller will be responsible for implementing the mesh communication network, determining distances between nodes and base stations (with hardware support from the DW1000), and controlling low power modes as commanded by the network.

An ESP8266 will be used to control each base station due to its Wi-Fi capability [8]. It too will interface directly with a DW1000 module, however the base stations will also be responsible for additional calculations. Additionally, the ESP8266 will host a Wi-Fi network and present all relevant information to the user using a web app. The app itself will be directly hosted using HTML, CSS, and JavaScript. WebSockets will serve as the primary communication method between clients using the web app and the ESP8266. No proofs of the user interface are available at this time.

Both microcontrollers are compatible with the Arduino IDE and will be programed in C. This will allow much of the transmission and localization code to be reused between systems.

▮▮▮ Power Supply

The power being supplied to all the electronics in each node will likely be from 18650 battery cells [7]. The 18650 cells are cheaper and more thermally and volumetrically efficient, and have a higher charge cycle count (~1800 times).

▮▮▮ Algorithm

The localization algorithm will convert the numerous direct Time of Flight distance measurements between individual nodes (and base stations) into a cohesive map of the race course. MATLAB simulations will be executed in order to test and debug this algorithm before deployment. One of the most likely "problem areas" with this algorithm will be accounting for an overconstrained system (where there are too many distance measurements between too many nodes). It will likely use probability to determine a "best guess" of each node's location given all of the overconstrained possabilities. See *Appendix B* for diagrams relating to localization situations that this system will have to deal with.

If the chosen transceiver module proves to be insufficient, other modules will be considered instead. The radio and distance measurement systems may be split into two individual radio systems instead, allowing for a more customized system overall. If the localization algorithm becomes a problem, then directives will be added to each node in order to rank the estimated accuracy of each measurement. This way, the localization algorithm can use only the most accurate measurements in order to avoid an over constrained system.

At this point, the specific localization algorithm details have not yet been determined. Additionally, the process by which the nodes will communicate with each other is still in the early stages of development.

███████Critical Path Tasks

One major critical path task is evaluating the power consumption, range, and accuracy of the chosen radios. This task must be completed before we can move forward with the process. We have chosen to address this by purchasing a few parts early in the process so that evaluation is not hindered. Another major critical path task is the initial hardware design, as the software development is entirely dependent on the specifics of this task. We have chosen to address this by moving this task as early as possible in the process, and structuring it so that the information that is needed for software development is available within the first week of the task. The rest of the critical path involves software development-testing iterations. Since access to the testing site may not be available at all times, we have planned out testing times to pace our software development workflow.

4.2.   Codes and Standards

The IEEE 802.15.4 standard defines the operation of low-rate wireless personal area networks, which our communications fall under [11]. The radios we choose must adhere to this standard. Thus, we have chosen a commercially available radio transceiver which already conforms with these standards.

The IEC 60529 standard defines solid and liquid ingress protection [12]. Our finished product must be able to achieve at least an IP58 rating, since there is a risk of complete immersion in water if the boat capsizes. This will influence the enclosure that we choose/design.

4.3.   <u>Constraints, Alternatives, and Tradeoffs</u>

We originally intended to use standard D-Cell batteries, however, the 18650 batteries have more voltage and much better current capabilities when used in parallel [7]. If the 18650 cells are being used in a pack, when one cell goes bad the rest of the pack will still function with minimal damage. If a slimmer battery is required and parallel performance is deemed unnecessary, a flat-style lithium-ion battery, such as the 785060 2500mAh battery pack can be used [10].

Each node needs to be capable of measuring the distance to another node within radio range. Measuring inter-node distance can be done with hardware support from the radio module. This limits our choice of radio, but allows for a more accurate solution with minimal software overhead. Measuring inter-node distance can also be done entirely in software. This can be done with any radio, but comes at the cost of decreased accuracy. We chose to implement distance measurement using hardware support from the radio.

Some sort of user interface is necessary to view the generated data. One option is to run the UI directly on the base station. Either the processor must be powerful enough to support the UI without affecting triangulations, or another processor must be added. Both of these options would increase cost significantly. Another option is to have the base station host a server, to which client devices can connect to. The base station only has to process a stream of data, which puts minimal load on the processor. The visual processing can be offloaded to the client device (smartphone, tablet, laptop, etc). We chose the client-server approach to implement the UI [15].

▮▮▮ Schedule, Tasks, and Milestones

In *Appendix A*, our GANTT chart shows the list of tasks, task assignments, estimated completion of each task, as well as accomplished tasks. Critical path tasks include evaluating the chosen radios, initial hardware design, and software development-testing iterations. Since access to the testing site may not be available at all times, we have planned out testing times to pace our software development workflow. Milestones include first testing (week of Feb 18/25), final testing (week of Mar 25), and final demo (month of April).

▮▮▮ Project Demonstration

6.1.   Physical Validation

Each physical attribute of the enclosure and base station will be measured and compared to the requirements listed in Section 3 as prototypes are developed. Physical requirements will be kept in mind throughout the design process, and checked continually. For portions of the project that will result in physical results (the node case in particular), physical reviews will be conducted with each iteration design.

Components such as the radio systems, node modules, and base stations will be tested individually based on the criteria listed in Section 3 to ensure compliance with requirements throughout the design and testing process.

6.2.   System Validation

The total system will be tested at Lake Lanier Sailing Club (LLSC) using the Georgia Tech Sailing Club's available C420 sailboats. At least three nodes will be attached to the masts of their respective boats, and the base stations will be positioned on shore. Either a GT Sailing Raceteam practice will then take place, or the boats will be sailed as if a regatta was taking place. Each node will be tracked and the data sent to the base stations, which will relay the information to the user interface. All aspects of the system will be judged and compared to the requirements listed in Section 3. This event will happen within a month of the final Capstone presentation, and will serve as our primary demo of performance and project completion.

Marketing and Cost Analysis

7.1.   Marketing Analysis

This product will appeal to groups seeking fast, low cost relative positioning information for nodes that will be confined to a certain area. Functionally, the product will produce similar results to a constellation of GPS receivers with a messaging interface. A suitable comparison would be the BARTUN® Vehicle tracker, which can continuously track its location via GPS and relay it to a cloud service as long as GSM/GPRS access is available [2]. This proposed product will be considerably cheaper per device, and will not have the GSM/GPRS reliance, allowing for more realistic device tracking for well-defined regions.

A real-world example is tracking sailboats in a fleet race, where it can be challenging to see locations of boats from shore. Other applications include but are not limited to warehouse forklift tracking, small aerial drone localization, indoor robotic tracking, and other sport applications.

Compared to the competition, this proposed product will be cheaper, relying on local positioning rather than expensive GPS receivers, and utilizing a contract-less local communication network, removing the need for expensive GPRS packages and SIM card contracts [14]. This allows for, and benefits from, larger-scale device deployment, where many devices are tracked concurrently and relative to each other.

This product will be marketed as a localization solution, with at least two base stations and a node being the minimum required components. Additional base stations and nodes can be added to expand the usability and utilization of the system, as the buyer sees fit.

7.2. <u>Cost Analysis</u>

█████Parts and Materials

The system will be composed of one node and two base stations. Both nodes and base stations will require a radio transmitter, suitable antennas, a microcontroller and a power supply. Each base station will also require a Wi-Fi transceiver. Additionally, we will need wires and cables for inter-components communication. Finally, the system will require packaging and mounting parts. The table below shows the costs of each item.

Item	Cost
Radio Transceiver	$24.40
Node Antenna	$5.99
Node Microcontroller	$1.59
Node Power Supply	$5.00
Node Total	$36.98
Base Antenna	$30.00
Base Microcontroller	$6.95
Base Power Supply	$30.00
Base Total	$66.95
Cables/Wiring/Misc.	$10.00
Packaging/Mounting	$15.00
System Total (1 node, 2 bases)	$195.88

█████Total Development Hours

Five engineers will complete the design and development of the nodes and bases stations. The total hours for the project per engineer (per semester, not including class times) are included in the following table.

Task	Engineer-Semester Hours
Weekly Meeting	50
Reports	20
Research	8
Presentation	3
Fabrication	15
Assembly	5
Testing	5
Total	106

Total Development Costs

Given a salary of $55,000 per year per engineer and 106 hours of work we can estimate an amount of $8,000 for the labor. Additionally, we need to plan for unexpected expenses as they usually occur.

Development Component	Cost
Parts	$195.88
Labor	$8,000
Unexpected Expenses	$2,000
Total Development Costs	$10195.88

The selling price of the system (1 node and 2 base stations) will be $180. Additionally, it is possible to buy either an individual node for a price of $40 or a base station for $80. We will provide

significant discounts on high quantity purchases. These prices are very similar to the prototype costs listed above, however when translated to full production, economics of scale would reduce the production cost, thereby increasing profit margin.

███Current Status

By the time this report was submitted, tasks A-G have been started, and tasks A, B and F are completed, as seen in the GANTT chart in *Appendix A*. Task C ("Program MCUs for radio testing") has been started and is 80% complete. Tasks D and E are awaiting tack C, and are both 60% done. By the end of the weekend (Dec 2.), task G will be complete, along with tasks D and E if everything goes according to plan. Currently we are on track and on schedule based on the plan defined by the chart in *Appendix A*.

References

[1] Atmel, "8-bit AVR Microcontroller with 4/8/16/32K Bytes In-System Programmable Flash,"
8-bit AVR Microcontroller with 4/8/16/32K Bytes In-System Programmable Flash.
Atmel, 2009.

[2] BARTUN, "BARTUN Vehicles GPS Tracker," *BARTUN Vehicles GPS Tracker*. BARTUN,
2018.

[3] "Club 420," *Pro Opti Sailboats – Optimist Sailboats from Zim Sailing*. [Online]. Available:
https://www.zimsailing.com/club-420.html. [Accessed: 20-Nov-2018].

[4] D. Kalman, "An Underdetermined Linear System for GPS," *THE COLLEGE
MATHEMATICS JOURNAL*, vol. 33, no. 5, pp. 384–390, Nov. 2002.

[5] DECAWAVE, "DW1000 Product Overview," *DW1000 Product Overview*. 2015. DW1000
802.15.4-2011

[6] DECAWAVE, "DWM1000 Product Overview," *DWM1000 Product Overview*. 2015.
DW1000 802.15.4-2011

[7] EM3, "Lithium-ion Battery DATA SHEET ," *Lithium-ion Battery DATA SHEET* . 2010.
LIR18650 2600mAh

[8] Espressif Systems, "ESP8266EX Datasheet," *ESP8266EX Datasheet*. 2018.

[9] "Federal Radionavigation Systems," National Technical Information Service, Springfield,
VA, rep., 2001.

[10] Hunan Sounddon New Energy, "785060 Product Specification," *785060 Product Specification*. 785060 2500mAh

[11] "IEEE Standard for Local and metropolitan area networks--Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)."

[12] "Ingress Protection IEC 60529 IP," *SST*, pp. 1–2.

[13] "International 420 Class Rules," *World Sailing Class Association*, 2017.

[14] L. Quaglietta, B. H. Martins, A. D. Jongh, A. Mira, and L. Boitani, "A Low-Cost GPS GSM/GPRS Telemetry System: Performance in Stationary Field Tests and Preliminary Data on Wild Otters (Lutra lutra)," *PLoS ONE*, vol. 7, no. 1, May 2012.

[15] Mildred Moy, "Approaches to Building Client/Server Applications," *Government Technology: State & Local Government News Articles*, 30-Sep-1995. [Online]. Available: http://www.govtech.com/magazines/gt/Approaches-to-Building-ClientServer-Applications.html. [Accessed: 24-Nov-2018].

[16] SICK, "Efficient solutions for Warehouse and Distribution," *Efficient solutions for Warehouse and Distribution*. SICK.

[17] "Teensy 3.2 & 3.1 - New Features," PJRC. [Online]. Available: https://www.pjrc.com/teensy/teensy31.html. [Accessed: 22-Nov-2018].

Appendix A

	Activity	Assigned to
A	Assess component options (radio, MCU)	Team
B	Purchase components for testing (radio, MCU)	Norris, Kevin
C	Program MCUs for radio testing	Keenan, Kevin
D	Evaluate power consumption, range, accuracy	Sai, Yassine
E	Assess antenna setup options	Sai, Kevin
F	Complete Project Proposal / Updated PSF	Team
G	Design Notebooks	Team
	Winter Break	
H	Oral Proposal Presentation	Team
I	Revised Proposal	Team
J	Revised PSF to Advisor	Team
K	Define PCB requirements (dimensions, mounting hole and connector locations)	Norris, Keenan
L	Design initial hardware (PCBs, enclosures, mounts)	Kevin, Yassine
M	Test enclosed units for shock/water resistance	Sai, Keenan
N	Program MCUs for distance measurement, communication	Norris, Kevin
O	Conduct initial real-world tests (Lake Lanier)	Team
P	Revise hardware design (if necessary)	Sai, Kevin
Q	Improve software based on feedback from tests	Yassine, Keenan, Norris
R	Conduct final real-world tests (Lake Lanier)	Team
S	Improve software (small changes, if necessary)	Team
T	Design Notebooks	Team
U	Final Presentation	Team
V	Capstone Design Expo	Team
W	Final Project Demonstration	Team
X	Final Project Report	Team
Y	Final Project Summary	Team
Z	Website	Team

Week Of — November (5, 12, 19, 26), December (3, 10, 17, 24, 31), January (7, 14, 21, 28), February (4, 11, 18, 25), March (4, 11, 18, 25), April (1, 8, 15, 22, 29)

Appendix B

Unconstrained system constrained
by environmental factors **OK**

System constrained by three
known node locations **OK**

System overconstrained by disagreement between nodes

GUESS