Capstone Project

Optimized Sailing Trajectories

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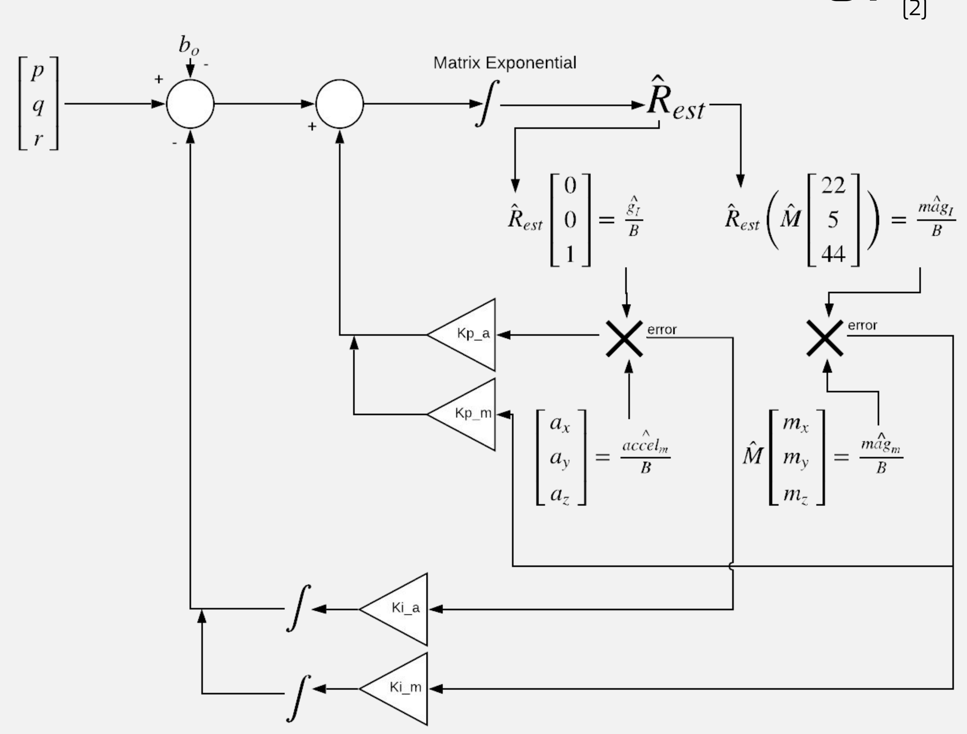
Objective

Effective sailing requires a depth of on-board experience and practice using proven techniques. Improving one's technique can be difficult to do while out on the water. Our group built an affordable sensor system for sailors and hobbyists to provide feedback on the optimal trajectory based on current conditions.

Primary Operations:

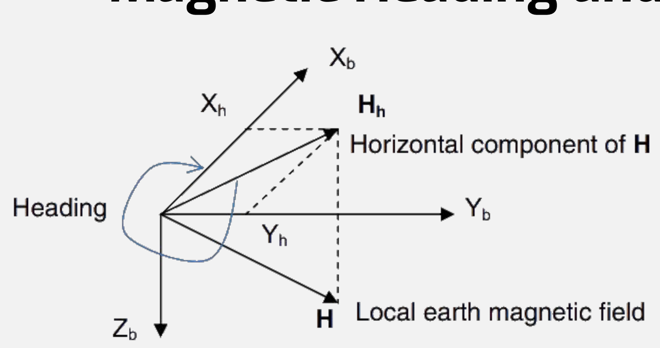
- Determine GPS location, velocity, course over ground
- Calculate a triad of wind vectors
- Use IMU for roll, pitch, and tilt-compensated compass heading
- Provide feedback on the boom angle
- Relay all information via Bluetooth Low Energy to a phone

Attitude Estimation Methodology [2]



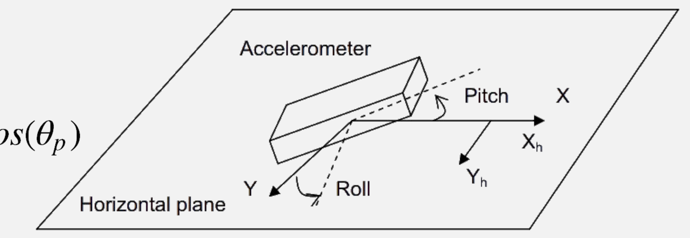
- Direction Cosine Matrix (DCM) calculated from integrated gyroscope data
- Inertial magnetometer and accelerometer vectors are rotated into the body frame
- Error is calculated as the cross product between body measurements of accelerometer and magnetometer with their corresponding rotated inertial vectors
- 'Kp' parameters control rotation rate error, 'Ki' parameters control bias error

Magnetic Heading and Tilt Compensation



$$H = arctan(\frac{Y_h}{X_h})$$
$$H = (\ H < 0\ )?\ H + 360 : H$$

$$X_h = X_m cos(\theta_p) + Z_m(\theta_p)$$
$$Y_h = X_m sin(\phi_r) sin(\theta_p) - Z_m sin(\phi_r) cos(\theta_p)$$

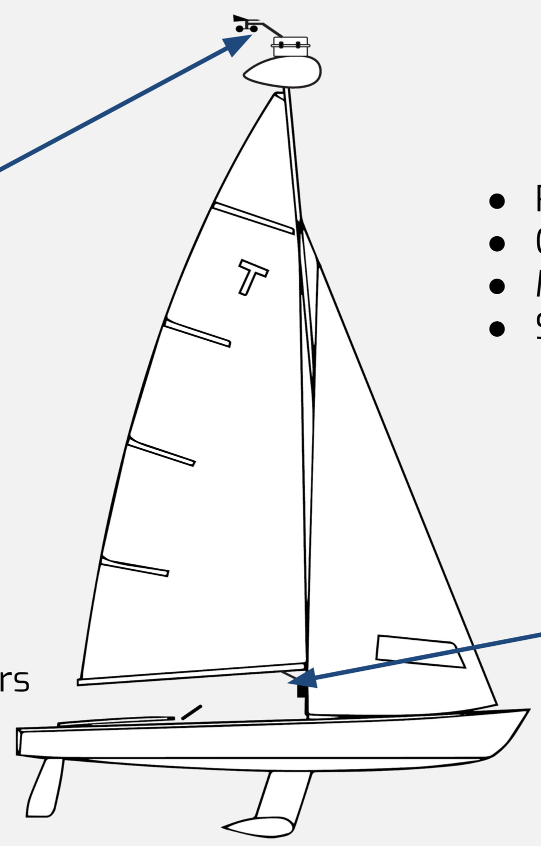


[3]

- Readings from magnetometer axes Xh, Yh are used for magnetic orientation
- Roll and pitch affect magnetometer readings in the horizontal plane
- After the magnetometer is aligned with the accelerometer, tilt correction is done using current roll and pitch

A Bluetooth Network of Sensor Packages

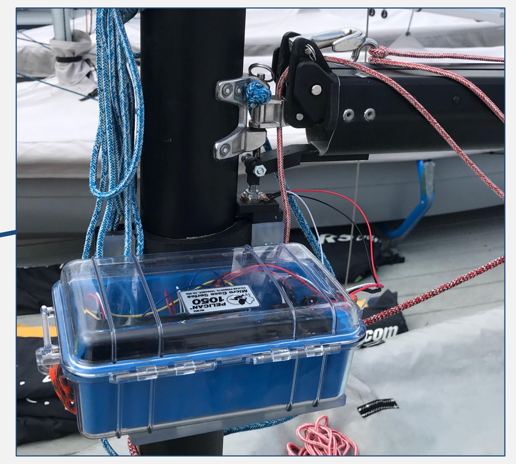
Boat Implementation on RS Quest



Boom Package

Bluetooth Master to Mast Package
Bluetooth Slave to Phone

- Receives data from the Mast Package
- Checks and filters all data
- Measures angle of the boom
- Sends all mast and boom data to cell phone

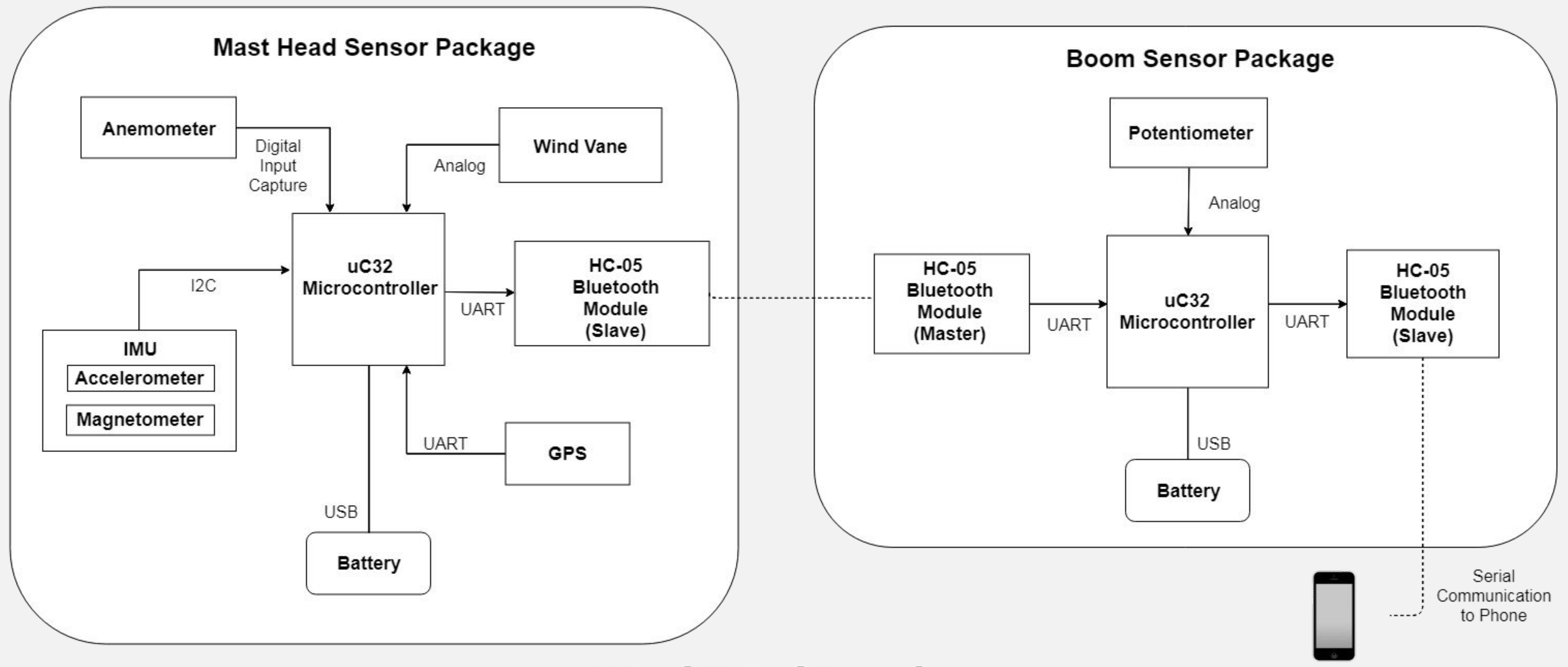


Mast Head Package

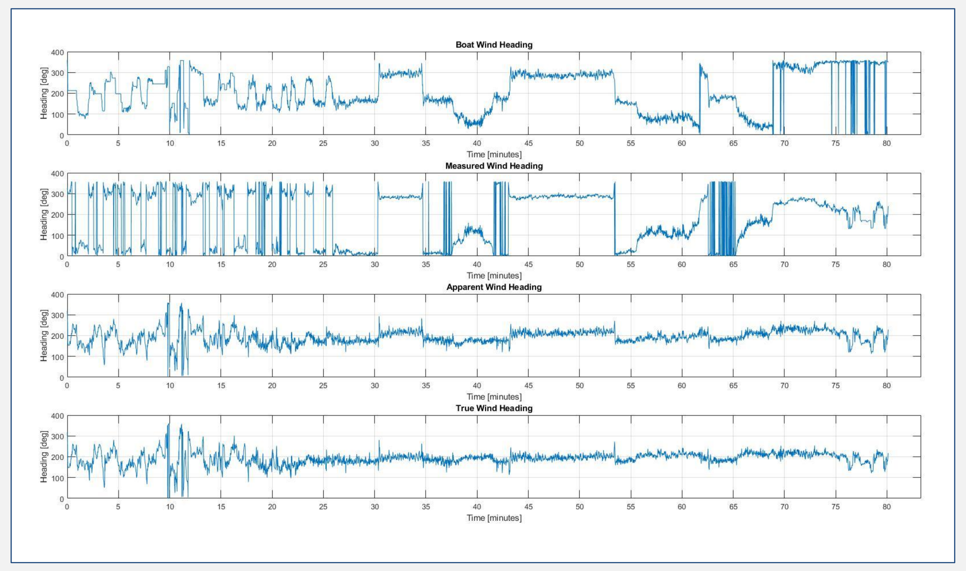
Bluetooth Slave to Boom Package

- Handles and collects data from most sensors
- Connects to Boom Package via Bluetooth
- Transmits custom NMEA packet with embedded sensor data

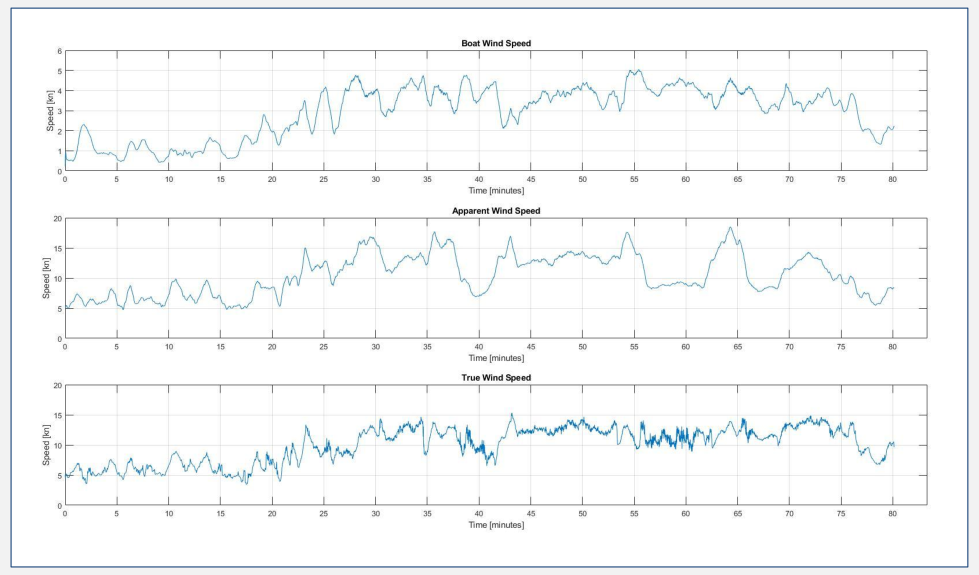
System Block Diagram



Wind Triad Results



Wind Headings



Wind Speeds

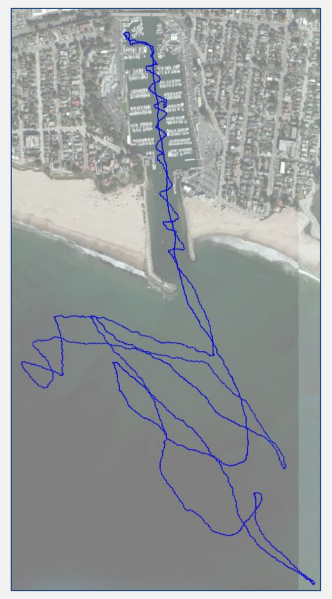
- Any moving object induces a relative wind opposing its velocity (boat wind)
- True Wind = Apparent Wind (from anemometer and wind vane) - Boat Wind (due to boat velocity)
- Noise is introduced by the motion of the boat along with wind's unstable nature
- To yield more practical results, noise is dampened by a weighted moving average

Phone Application

Bluetooth Master to Boom Pkg

- Receives all sensor data from Boom Package
- Uses online data with live sensor data to calculate optimal sailing path
- Displays optimal path and sensor data to user

GPS Results

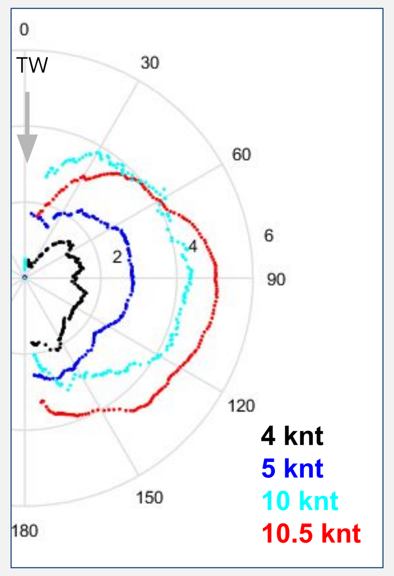


- In addition to position information, the GPS is used to gather speed and course over ground, necessary for computing true wind speed and direction
- The GPS packet format, NMEA, provided a template for our custom bluetooth data packet

Example Custom Packet:
$GNOST,1,3658.0442,-12200.2109,3.31,13.00,0.30,261.81,2.10,213,204122*57

VMG Polar Speed Results

- Velocity Made Good (VMG) polar speed plots are a common metric for determining a boat's optimal speed for a specific point of sail
- Data from different true wind speeds and headings were used in post-processing to determine this VMG polar plot for the RS Quest sailboat
- These results match the common butterfly shape of VMG plots, where boat speed is zero into the wind, fastest at a beam reach, and slowing dead down wind



Conclusion

Over the course of this project, members of this team developed methods for getting reliable data from unreliable conditions. Much of the data had to be manipulated via parsing, fit functions, and filtering. Data processing was done in real time and with regard to an appropriate package output frequency to the mobile phone application. Matlab post-processing was done to mimic processing done by the phone app, and to provide insight on possible improvements to the system. Sensor packages were successfully constructed and repeatedly tested in both controlled and real environments. Testing yielded good results that improved throughout consecutive test runs. Future work would involve further data collection as well as more complex and condensed sensor packages.

Acknowledgments

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References

[1] Ardakani, H. Alemi, and T. J. Bridges. "Review of the 3-2-1 euler angles: a yaw-pitch-roll sequence." *Department of Mathematics, University of Surrey, Guildford GU2 7XH UK, Tech. Rep* (2010).

[2] Elkaim, Gabriel Hugh. "Batch Misalignment Calibration of Multiple Three-Axis Sensors." *12th International Workshop on the Algorithmic Foundations of Robotics (WAFR 2016).* 2016.

[3] *Using LSM303DLH for a Tilt Compensated Electronic Compass.* STMicroelectronics, Aug. 2010.