Piezoelectric Vibrational Sensor for Sail Luffing Detection on Robotic Sailboats

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Abstract Current robotic sailing relies on sensing wind direction and moving the sails to a position that is appropriate for that relative wind angle. The research to date shows that a correctly tuned sail in the classic wing shape is essential for maximum speed over water. This paper relates research on sensors used to determine when sail trim is incorrect. With improper sail trim, the sail luffs. This luffing produces turbulence which reduces the efficiency of the sail. By instrumenting the sail with sensors to detect when sails begin to luff, the robot can determine when the sail is improperly trimmed and, potentially, take corrective action.

1 History & Current Technology

With traditional, sailing vessels, the helmsman monitors the shape and position of the sail to ensure it performs at peak efficiency. With RC, sailing models, the radio controller maintains line of sight with the model and tunes sail position based on what he or she sees. Autonomous sailing vessels remove the human operator and that human ability to observe and react to changes in the sails. The ability to adjust sail trim is a crucial aspect of the competitive sailing that had been in place and proven effective for more than a century.

Most robotic sailboats approximate where the sail should be with respect to the measured wind angle [9, 1, 4]. This is frequently done with trigonometric functions or a simple ratio between sail actuator position and sail position and proves to be reasonably effective in many situations. This falls short by assuming:

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- Wind data is accurate and correctly reflects the real world situation.
- The function or method used to set the sail is correct.
- The position of the sail actuator represents the location of the sail.

If the sail winch line is re-tied or is tangled to a different length, the wind sensor rotates, or the sail is replaced with one with slightly different dynamics, the sail will not be truly, correctly trimmed by current methods. By adding a feedback loop to the current sail trimming method with a sensor on the sail that can determine wen the sail is not operating at peak efficiency, fault-tolerance and accuracy of the sail control system is increased. One attempt at this was performed in [5]. While their data mining approach is more based on the physical dynamics of the vessel, it is still tied to the specific system studied and requires extensive test time.

Sails form the shape of a wing. With flexible sails, inefficiencies most frequently manifest in a phenomena referred to as “luffing.” This is when the sail material deforms off the shape of the wing. Sails Generate lift which propels a boat forward due to a difference in pressure[12]. Bernoulli’s principle states air moving across a curve moves faster has a lower pressure. Therefore, the air on the outside of a sail has a lower pressure than the air on the concave curve of a sail, creating lift which moves the boat forward [3]. If, for a moment, this pressure differential is reversed or becomes too small, the flexible material comprising the sail will be pushed over into the lower pressure creating a movement called a luff where the shape of the wing collapses [12]. This deformation reduces the efficiency of the sail by making the shape of the sail deviate from that of a wing and slows the vessel. If the onset of luffing is known, its occurrence can be used to help control the speed and forces on the robot, a technique used by the Portuguese Man-of-War jelly fish with its sail to keep from getting torn apart while catching prey [6]. A sail that is positioned too far in or out will luff. Ideally, the sail should be let out until it begins to luff, then pulled in until it ceases to luff. The onset of luffing can be detected with a piezoelectric vibration sensor.

2 The Sensor

The sensor chosen was the Minisense 100 [11] by Measurement Specialities. This sensor weighs under .4 grams, and is light enough to be placed on sails. The sensor was connected to the data collection device by 36 gauge magnet wire. The enamel insulation prevents shorting and the wire is flexible so the sail can still form the necessary wing shape. The sensor itself consists of a thin strip of piezoelectric ceramic, terminated by a small weight of .3 grams. This is an inertial mass, so when the sail luffs, the piezoelectric strip of the sensor moves, sensing the sail luff.

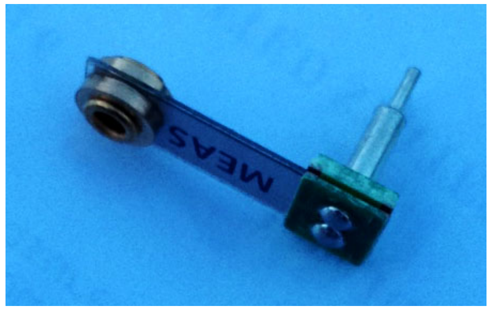

Fig. 1 The Minisense 100 piezoelectric vibration sensor. The brass, metal cylinder is a weight that makes the flexible band made of a piezoelectric ceramic flex. This flexion is what is sensed by the sensor.

2.1 Piezoelectric Sensor Response

Piezoelectric materials produce a voltage in response to an applied stress [7]. Practically, this means that the act of deforming them creates an electric potential. The voltage is directly proportional to the stress applied and can be described by the equation: $D = \frac{Q}{A} = dT$ found in [7] where D is the dielectric displacement, $\frac{Q}{A}$ is the charge per unit area, and T is the stress. Therefore, a deformation of the sail where it returned to its initial position should result in a net voltage of zero. Deformations in either direction, not returning to the initial position, would result in non-zero voltages.

2.2 Sensor Output

Piezoelectric materials exhibit a very characteristic, peaked response when moved [13]. The faster the material accelerates, the higher the voltage output. This is logical since the stress applied is proportional to the voltage produced. The stress equation is: $T = \frac{F}{A}$ where F is the force applied and A is the aria over which the force is applied. Substituting Newton's Second law: $F = ma$, makes the correlation between acceleration and voltage clear. When the sensor is not actively deforming (accelerating), it produces no voltage. Therefore, to detect luffing, the output at any instant is not as important as the peaks in recent time. Because of this property, the output from the sensor is expected to have peaks. These peaks are directly proportional and caused by the acceleration of the sail when it luffs.

3 Experimental Setup

To minimize the number of variables, a sail (luff of 1054 mm) was constructed out of thin BoPET (Biaxially-oriented polyethylene terephthalate) polyseter film. The sail was first designed in SailCut CAD [8]. The mast and boom were fabricated from commercially marketed, half-inch, balsa wood dowels. The boom was attached to the sail with tightly tied string.

Fig. 2 Sail attached to the roof of the car.

The sail was then placed atop a car roof. A car was used because its forward motion produces a steady stream of air of laminar flow. The car was driven at a constant speed of 16 kilometers per hour in a straight line in a flat parking lot on a low wind day. Therefore, all air can be considered to hit the sail parallel to the direction of travel of the car. The sail was placed approximately 30 cm off the centerline of the car. The mainsheet was secured along the centerline of the car. This meant the sail was close hauled and formed an angle of 30° with the car's centerline when correctly trimmed.

To place the sail atop the car, it was secured upright in a stable base made of 30 cm x 15 cm x 5 cm wood. A press fit hole was drilled for the mast, and the base was then restrained to the top of the car. A webcam pointed up toward the top of the sail and provided real time images to determine whether the sail was actually luffing or holding a wing shape. Position identifiers were drawn on the sail. By monitoring the position of these markers, the sail could be classified as luffing or not. This data was used to compare what the luffing sensor sensed and to establish a correlation between a luffing sail and the output of the sensor when the sail is luffing.

Two sets of six trials were performed. In the first, control set of trials, the mainsheet was pulled in until the sail no longer luffed. This simulates a sail holding a good, wing shape. In these trials, the sail position markers did not shift more than .5

cm in the full size, video footage. If center of the sail markers moved more than this, the sail was classified as luffing. For the second set of trials, the sail was effectively "in irons," and luffed. The main sheet was secured loosely so the sail could luff without the mainsheet coming tight. With the wind coming from directly in front of the sail and no tension on the main sheet, the sail luffed violently.

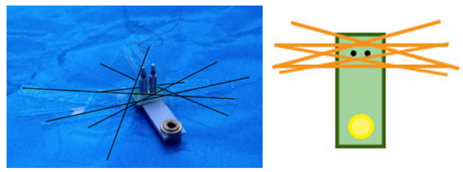

Fig. 3 Schematic diagram of the mounting of the sensor on the sail. The lines represent tape affixing the sensor to the sail.

The sensor was affixed to the sail with cellophane tape made into an x shape. This was done to securely hold the sensor base to the sail while allowing the weighted end to achieve maximum flexion when the sail luffed. The wires were routed across the sail with tape to keep them from getting tangled and to ensure give so if they were pulled, they would not break. Wires were connected to the sensor with wrapping followed by solder to ensure a good connection. Hot melt glue insulated these connections.

Data from the sail luffing sensor was collected with an Arduino. Data from the webcam was collected with a windows laptop using VLC [14] and VirtualDub [2]. The sensor was connected an analog pin so the Arduino handled the analog to digital conversion. This created one problem: modern piezoelectric ceramics generate quite high voltages from the stresses the sensor experienced. Therefore, the analog to digital conversion in the Arduino saturated on the peaks both when the sail was luffing and when it was holding shape. A human could see the difference from when the sail was luffing and when it wasn't, but this was computationally difficult to extract. Therefore, a diode was placed in between the sensor and ground. This kept the analog to digital conversion from flooding when the sail was holding shape. This had the additional benefit of making the average value of the sensor output increase when luffing occurred because there was no longer a direct connection between the sensor and ground. With this change, the averaged output of the sensor changed when the sail began luffing, as expected. The voltage output by the sensor was printed by the Arduino to the serial port. This was then picked up by the computer using MegunoLink Pro. This is software that manages the serial connection to the Arduino and simplifies much of the data handling. In MegunoLink Pro[10], a timestamp from the computer's clock was placed on each line of data collected and the resulting data was written to a plain text file. Since this time was the same as the time recorded during video capture from the webcam, the data from the Arduino and web-cam was synchronized.

4 Results

The sensor's output noticeably changes when the sail begins luffing. Five trials each were performed for the sail luffing and the sail under trim. Sensor data was recorded from the Arduino in Analog-to-Digital Units (ADU) ranging from 0 to 1024. The average sensor output when the sail was holding its shape was 510.7 ADU. When it was luffing, the average value rose to 656.3 ADU. This trend can be seen in the example data from two trials in figures 4 and 5 and in the averages from the individual trials presented in the table.

Test:	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average
Luffing	682.4	649.7	640.8	653.9	654.8	656.3
Holding Shape	461.2	536.4	500.6	532.5	523.1	510.7

Table 1 Averages of the values in each luffing and non-luffing test Data is in Analog-to-Digital Units.

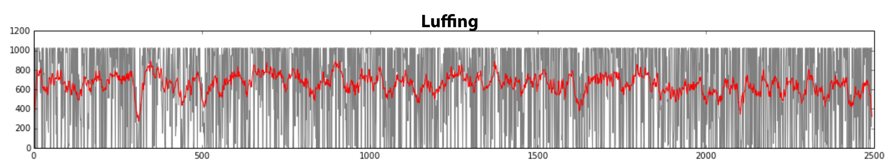

Fig. 4 Plot of the sensor output as the sail luffs in the wind. The y axis is Analog-to-Digital Units and the x axis is milliseconds.

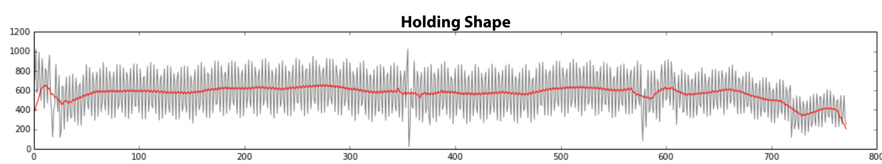

Fig. 5 Plot of the sensor output while the sail holds its shape. The y axis is Analog-to-Digital Units and the x axis is milliseconds.

To further validate the that the sensor output was useful and accurately depicted the physical state of the sail, in two trials, the main sheet was adjusted during the test so the sail went from luffing to holding its shape and back. One of these transitions can be seen in figure 6. The sensor output clearly changed as the sail went from luffing to not luffing and back. In short, the sensor output was correctly correlated to the state of the sail.

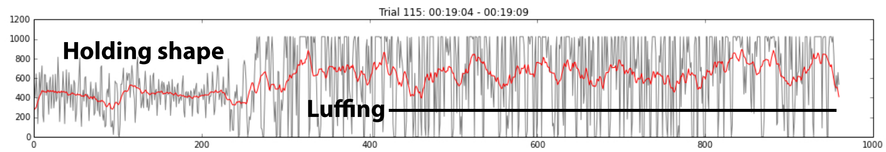

Fig. 6 Plot showing the sensor output when the sail goes from holding its shape to luffing. The sensor output rises as the sail luffs.

5 Conclusions and Future Work

Placing piezoelectric vibration sensors on a sail and testing their response in luffing and non-luffing situations allows the state of the sail (luffing or not luffing) to be determined. In the future, work should be done to integrate luffing sensors into a control system to establish closed loop control of sail position. Further, piezoelectric vibration sensors should be compared to other ways of sensing sail luffing such as accelerometers to sense the movement of the sail when the luffing event occurs and pressure sensors to sense the change of pressure that causes the sail to collapse in shape.

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