Design and Calibration of an Innovative Ultrasonic, Arduino Based Anemometer

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Abstract— **A precise estimation of wind intensity and direction is important for many applications. Authors, thanks to a consolidated experience in marine robotics, are building a sail propelled marine drone for a sustainable monitoring of wide sea areas. In particular, sail propulsion assures a near to infinite autonomy since limited energy demand of on board electronic can be assured by renewable sources such as solar cells. However, to correctly manage a sail system, a correct estimation of wind intensity and its direction is essential. Conventional anemometers make use of delicate mechanical moving parts, are therefore not suitable to work autonomously in difficult environments such as the marine one. Commercial ultrasonic anemometers represent a valid alternative but their cost, weight and size need to be optimized for the proposed application which is a cheap, light and relatively small drone. In this work the authors redesigned both acoustic and electronic system to meet the required specifications. Innovations have been suggested in terms of materials, components and introducing a smart measurement algorithm that allowed the authors to simplify the design, construction and calibration of the instrument. Finally, the system has been tested and calibrated in a wind tunnel, introducing a simple and effective calibration algorithm able to drastically reject disturbances arising from interference between mechanical system and the wind flow under measurement.**

Keywords— *ultrasonic sensor, low cost application, marine robotics, sustainable robotics, mechatroniscs, arduino based system;*

I. INTRODUCTION

There is a concrete industrial interest for the development of sustainable marine autonomous vehicles for exploration and monitoring of wide environmental sensitive areas.

Sail propelled autonomous vehicles should be a very attractive solution in terms of autonomy, which is quite infinite considering that limited power requests by on board electronics, rudder and sail actuators (needed to control the system), should be covered by renewable sources such as solar cells[1]. In terms of environmental impact sail propulsion involve the absence of any emission, noise, pollution, harmful interaction of moving parts with living beings. Even unavoidable energy exchanges associated to propulsion are limited to drag forces exchanged by the hull with surrounding water and by sails with the wind. Also in case of shipwreck, which is not a statistically remote event for autonomous vehicles in harsh marine environments, sail propulsion assures the absence of fuel and potentially dangerous components. However potentially toxic components are still present, such as accumulators, but their size and possible environment damage are extremely limited, thanks to the use of solar panels and an electromechanical system with low energy consumption.

So, it should be concluded that a Sail ASV (Autonomous Surface Vehicle) is a sustainable vehicle having sustainable construction, usage, and end of life impact on the surrounding environment. Unfortunately sail propulsion requires a good real time estimation of wind direction and intensity as stated by many works in literature [2],[3]. Although studies concerning techniques to reduce the dependence of the navigation from wind estimation [4] were made, it has confirmed the need to equip ASV vehicles with compact, reliable and effective anemometers.

In this work authors, starting from a typical sensor layout (see Fig. 1) often adopted by commercial ultrasonic anemometers[5][6][7], designed the system to be smaller, lighter, and cheaper in order to be installed on a small ASV as the Ifremer Vaimos[3] or on the model boat designed and assembled by groups of university students to participate to international robotics competitions as perhaps one of the most famous, the WRSC[8]. In particular, detailed features of the autonomous sail vehicle proposed by the students should be the object of a dedicated paper at IEEE-EEIC 2017 conference[9].

The system has completely redesigned with a complete mechatronic approach influencing the following aspects:

- Industrial low cost components: cheap piezo for automotive applications, open source (Arduino based) low cost boards for the prototyping.

- Structural and Manufacturing Optimization: the design of the structural frame of the sensor has been redesigned to

conform to requirements in terms of cost, weight, modal response, resistance to corrosion, easy prototyping and manufacturing.

- PLSS (Phase Locking Servo Sensor): an innovative, robust and algorithm for signal treatment with a low computational load which allows a good noise rejection as well as the implementation on cheap computing platform.

- CFD (Acronyms of Computational Fluid Dynamics) simulation and Calibration in wind tunnel: size, weight and cost reduction induce the development of a sensor affected by repeatable non linearity, that an accurate calibration based both on CFD simulations and experimental tests in wind tunnels can compensate in a relatively simple way.

Looking at the current state of art the second (Structural Optimization) and the fourth topic (CFD) of the above mentioned list are often described in studies concerning the so-called problem of aero-elasticity: modal behavior of large structures is excited by wind generated forces [10] where ultrasonic sensors are widely used for measurement of exciting air currents. It's interesting to notice that for most of these applications the instrument is supposed to be rigid respect to low frequency vibrations affecting the structure, while in the proposed applications aero-elastic vibrations of sails transmitted to the light tensile structure of mast and stays should produce a wide spectra of exciting forces[11],[12]. For this reason, sensor has to be relatively rigid respect to vibrations. Also in this case the mass of the sensor should not be negligible respect to the one of the coupled structure producing cross-coupling interactions. For this reason for the proposed application the sensor should be optimized to be also relatively light reducing potentially negative interactions with the structure to which is attached as visible in the example of Fig. 2. In this sense the carried optimization is interesting respect to proposed commercial sensors [5-7] which are mainly proposed for "static" applications such as meteorological stations.
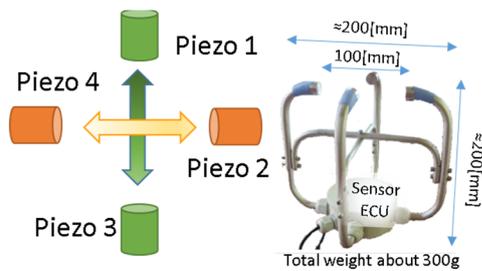

Fig. 1: layout of the proposed sensor

Also for first (low cost components) and third (innovative PLSS) points of the above mentioned list are strictly correlated: as example to reduce the cost from a minimum of 150€ which was considered extremely cheap in to 2007 [13] to no more than 15-20€ authors have to use both as emitter and receiver piezo elements with a very limited frequency response that are often used for low cost automotive applications using low cost commercial micro-controller such as the ones of the Arduino series that as example, have been used for low cost meteo stations[14]. It's quite obvious that starting from limited

performances both in terms of sensing elements and computational power authors have to really invent a very simple, application oriented algorithm, the PLSS to find a feasible engineering compromise.
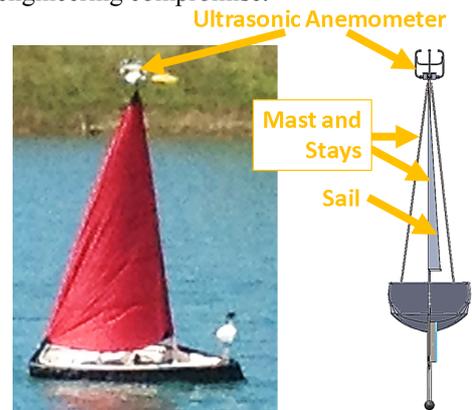

Fig. 2: placement of the proposed anemometer on the autonomous sail boat build by the students of the university of Florence[9]

II. INDUSTRIAL LOW COST COMPONENTS

System uses piezo elements MCUSD14A40S09RS usually adopted for low cost automotive applications. Each sensor has a narrow cone of emission and very narrow bandwidth (see fig. 3 limiting the operations to the center frequency (40 KHz).

Also each piezo element has to be used alternatively as emitter and receiver since as visible in the scheme of Fig. 1, the proposed algorithm (further explained in section IV of this work) is substantially based on measurement and comparison of the fly time in different sense and direction of the an ultrasonic signal alternatively produced and received by each element of the two couples of piezo used to measure both Cartesian components of the wind speed.

These limitations have been exploited in the design of the proposed estimation algorithm to make possible the implementation on a low cost, Arduino™ Based board.
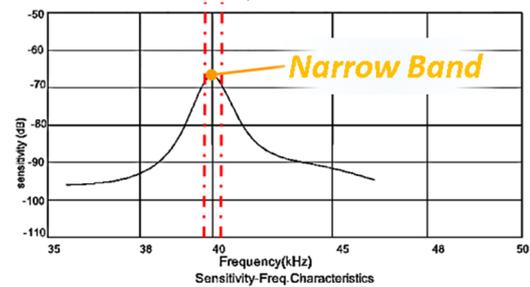

Fig. 3 the adopted piezo elements

III. STRUCTURAL OPTIMIZATION

Aero-elastic vibrations of the sensor frame can produce disturbances in the speed estimation. Also, weight and cost reduction are influenced by the way in which the sensor frame is assembled. For these reasons, authors designed a stiff structure made of hard anodized aluminum pipes, whose first eigenfrequency (about 90Hz) is far higher respect to the first

expected to the expected frequency response of the sensor that was designed (including internal software filtering) to be able to appreciate wind dynamics with a maximum frequency bandwidth of 10Hz. Hard anodized aluminum was chosen for the construction since it is a cheap, light and relatively rigid material being the ratio γ_m (1)between elasticYoung Modulus E and the density ρ almost equal to the one of a typical stainless still like AISI 416.

$$\gamma_m = \frac{E}{\rho} \begin{cases} (Al.Alloy)\,AA7075 \Rightarrow \gamma_m \approx 26*MN*kg^{-1}*m \\ (S.Steel)\,AISI\,416 \Rightarrow \gamma_m \approx 25.5*MN*kg^{-1}*m \end{cases} \quad (1)$$

Fig. 4 shows an example of performed modal analysis: it's interesting to notice that the first two symmetric modes and their effect on the two measurement directions in terms of relative motions able to influence the performed measurements. It's also interesting to notice that at end of the optimization procedure the total weight of the system including electronic board is about 300g, which is quite lower respect to the corresponding mass of comparable commercial solutions (typically from one to four Kg).
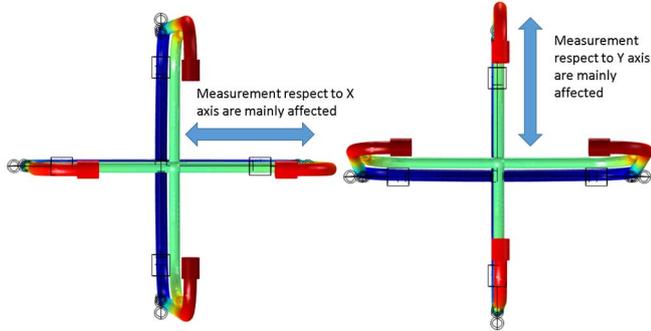

Fig. 4: shape of the two first symmetric modes of the structure (about 90Hz)

IV. PLSS ALGORITHM

As visible in the scheme of figure 1 the sensor is composed by two couple of piezo elements each devoted to the measurement of wind velocity along a Cartesian axis. As visible in the scheme of Fig. 5, if the fluid is moving with a speed v_f respect to sound source, the resulting absolute propagation speed of the ultrasonic wave v_p should be the vector sum (2) , being v_s the corresponding sound speed in air calculated according (3):

$$\overline{v}_p = \overline{v}_s + \overline{v}_f \quad (2)$$

$$v_s = \sqrt{KRT} \quad (3)$$

Being in (3) T the temperature of the fluid, K and R, are respectively the isentropic expansion factor and the gas constant.
By measuring the fly-time of an ultrasonic signal in both senses of the same i-th direction is possible to calculate the difference Δt_i between of the fly-time measured in opposite sense of the same direction i, being l_i the distance between the two piezo (each alternatively working as transmitter and receicer) the same direction(4):

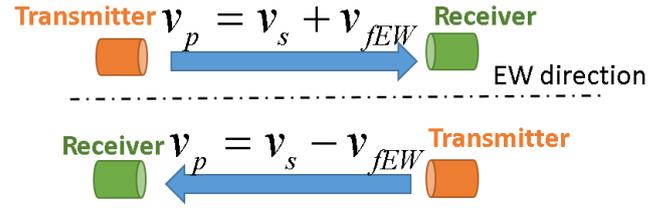$$\Delta t_i = 2\frac{l_i}{v_{fi}} \Rightarrow v_{fi} = \frac{2l_i}{\Delta t_i} \quad (4)$$

Fig. 5:wind speed measurement, principle of operation

By applying a differential measurement of the fly time (4) in both Cartesian directions briefly called S-N and E-W, it's then possible to calculate both estimated modulus v_{f*} (5) and direction β_* (6) of the wind speed.

$$v_{f*} = \sqrt{v_{fSN*}^2 + v_{fEW*}^2} \quad (5)$$

$$\beta_* = \tan^{-1}\left(\frac{v_{fSN*}}{v_{fEW*}}\right) \quad (6)$$

Considering the distance l_i (about 0.1 m) the sound speed (340m/s), and the desired sensitivity of the system (about 1kmh), delays of about 0.1-0.2µs has to be appreciated.

PLSS (Phase Locking Servo Sensor) is a time sharing detection algorithm which is used to perform a robust and smart estimation of differential delays produced on each measurement axis by the relative speed of the air.

In particular, the conceived anemometer required the design and realization of a custom analog/ digital electronic module. It includes a specific ultrasonic transducers front-end, an analog signal conditioning section followed by the analog to digital domain conversion, an appropriate numerical processing and the extraction of the output parameters: wind speed and angle of incidence.
The designed anemometer operation requires the use of 4 ultrasonic transducers. These devices must operate in independent pairs, and each pair have to alternate TX (transmit)/ RX(receive) function between the two transducers. This goal is obtained by the use of analog switches, to provide a simplified interface with a single TX input and a single RX output and controlled with 2 address signals that allow the selection of the direction and the orientation (N-S, S-N, E-O, O-E).
A transmitter unit provide 40 kHz pulses with a bandwidth of few kHz to match the low bandwidth of the low-cost transducers designed for this application. the pulses are transmitted at 1 kHz rate, rotating continuously between the transducers in the four cardinal directions N, E, S, O.
To minimize the needed computational resources, the envelope of each measured signal is evaluated and processed by an analogic circuit. In this way, the implemented algorithm on the micro-controller has to simply track the four time delays associated to envelope curves related to the two directions and two orientations, which has proved to be quite invariant respect the main operating condition as the wind direction and

amplitude, temperature, injected random disturbances. The tracking algorithm is briefly described in the flowchart of Fig. 6.

The name of the proposed algorithm PLSS (Phase Locking Servo Sensor) derived from the adopted tracking techniques which is substantially based on closed loop of analyzed envelope signals. The received signal is amplified by 2 low noise (5 nV/sqrt(Hz)) operational amplifiers, is band pass filtered around the transduces center frequency (40 kHz) with an active 6° order filter, and then sent to a specific envelope detector.

The output of the envelope detector is then connected to the Input Capture unit of the processing unit.
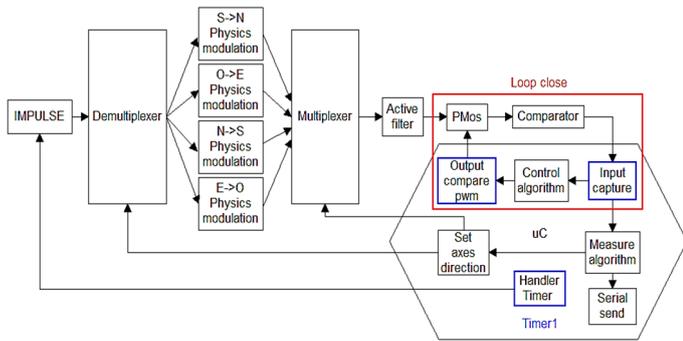

Fig. 6: flowchart of the proposed PLSS algorithm

The digital section has been based on the widespread "Arduino" platform, an open-source electronics device extremely easy to use, not expensive, and with a large library core and support that facilities writing programs.

V. CALIBRATION AND EXPERIMENTAL VERIFICATIONS

In the proposed sensor, to reduce the overall encumbrances, the distance between piezo elements is reduced to only 100mm. Since the diameter of proposed piezo elements is about 10mm aerodynamic shadowing effects are not negligible and have to be identified in order to be compensated by the calibration of the sensor[9].
For this reason, the sensor was tested in the Wind Tunnel of the CRIACIV laboratory in Prato (Fig. 7), a structure of University of Florence, were was possible to verify the sensor response respect to different wind conditions (amplitude and direction). The sensor has been calibrated to work in a wind range of from zero to 50km/h. Under these conditions, accuracy for estimated velocities was lower than 2 km/h. Also the accuracy of wind direction estimation was lower than 2°.
Fig. 7 shows a picture of the full scale tests performed on the CRIACIV wind tunnel with the prototype anemometer mounted on a position controlled platform that make possible a continuous regulation of the incoming wind direction.
Some results concerning the calibration of the sensor and the comparison between raw and calibrated sensor outputs with different input wind speeds and directions are shown in Fig. 8.
It's interesting to notice that the raw unfiltered output of the sensor respect to different input speed is affected by a multiplicative disturbance which substantially depends only from the incoming direction of the wind. This phenomena is quite common also on commercial products and it's typically described in literature [15] as "shadowing effect" since it's mainly caused by the interaction of the incoming flow of air with the structure of the sensor.
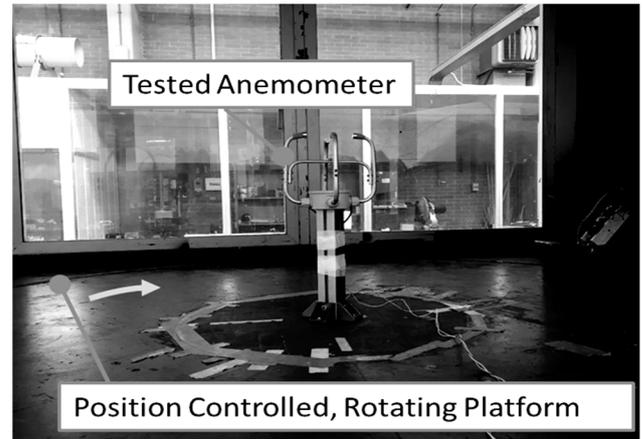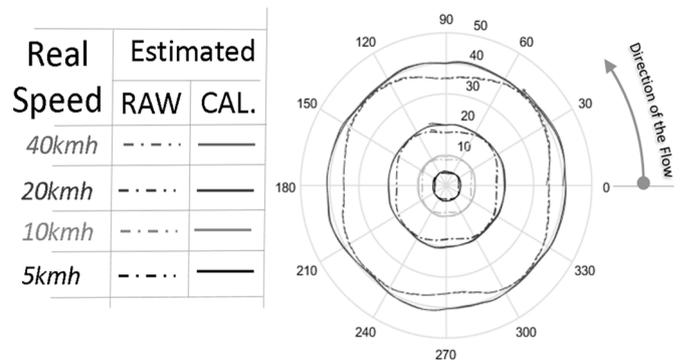

Fig. 7:CRIACIV wind tunnel

Fig. 8: Polar diagram representing the response of the sensor as a function of wind intensity (5-10-20-40kmh) and direction (0-360°with 2048 divisions)

For this reason, authors introduced an on line compensating function able to correct this natural distortion of the sensor output whose main structure is described in Fig. 9: the signal is preliminary processed by a Kalman filter and a running mean digital filter in order to obtain a preliminary "raw" estimation depured from random measurement noise, of both module and direction of the wind (variables indicated as "raw" in figure 9).
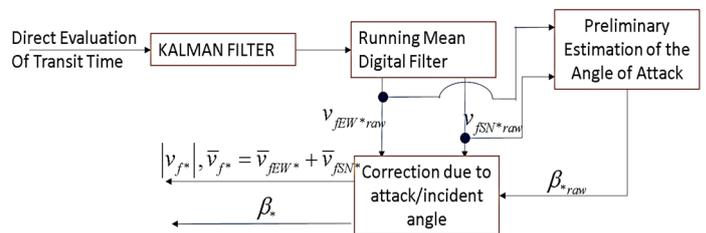

Fig. 9: sensor output filtering and calibration

Once preliminary raw values are evaluated further correction of the shadowing effect is performed through a simple tabulated relationship. As visible in figure 8 results of filtered/corrected response of the sensor is compared with the raw one: it should

be clearly noticed that the response of the calibrated sensor is associated to quite low errors, as also visible in Fig. 10:it's clearly noticeable that repeated measurements produce an absolute error between real and estimated wind directions which is lower of 1kmh considering both different wind directions and intensities. Measurement are repeated considering incoming directions of the wind from 0 to 90 degree since the response of the sensor is typically periodic respect to this angular interval.
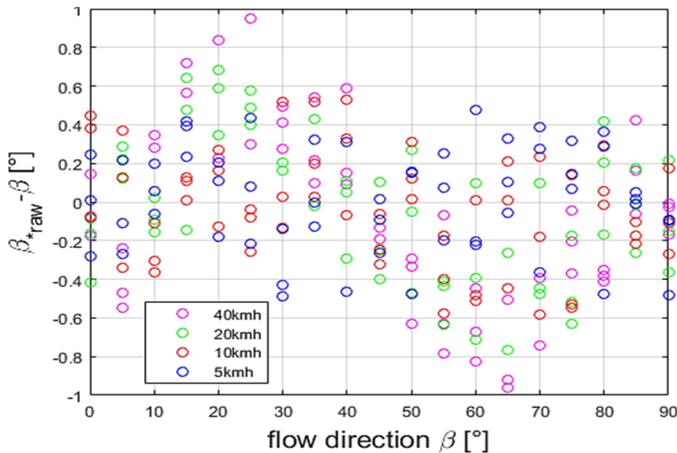

Fig. 10: statistical distribution of wind direction estimation errors as function of incoming wind speed and direction

Also in figure 11 it's represented the distribution of estimated error in terms of modules wind intensity for different wind intensities and directions. Also in this case errors are limited to about 1kmh.
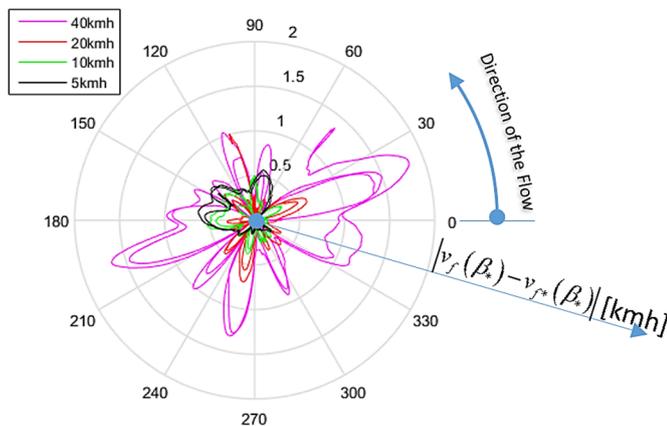

Fig. 11: statistical distribution of wind direction estimation errors as function of incoming wind speed and direction

This particular behavior of the sensor has been investigated by authors performing some CFD (Computational Fluid Dynamics) simulations with Comsol Multiphisics™.

In particular, as visible in figures 12 and 13, when the attack angle of the incoming wind is about 0° respect to a piezo transducer, there is a strong interaction that produce a strong shadowing effect: in the region between the two piezo transducers the local speed of the fluid is much lower respect to

the mean one, as a consequence the performed speed measurement should be necessary underestimated.

On the other hand, when the incoming flow is inclined of about 45° respect to transducers the resulting speed field in the region between piezo sensors, it's quite uninfluenced and local speed values are almost equal to nominal ones. As a consequence the measurements performed with angle of attacks of about 45° are almost exacts suffering of limited or null shadowing effects.
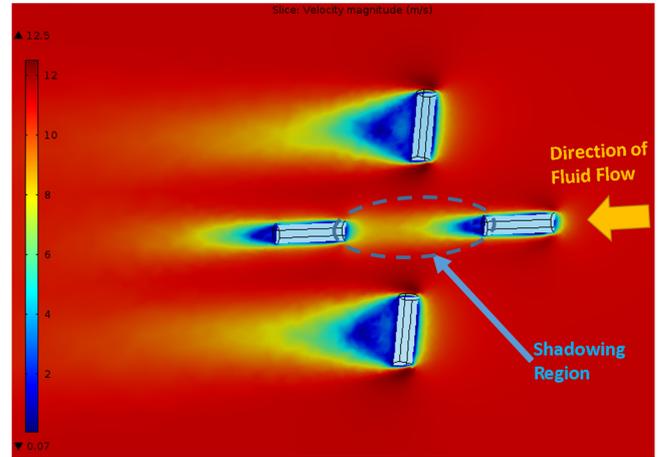

Fig. 12: calculated air speed field considering the interaction between sensor structure and incoming flow, with an attack angle of 0°
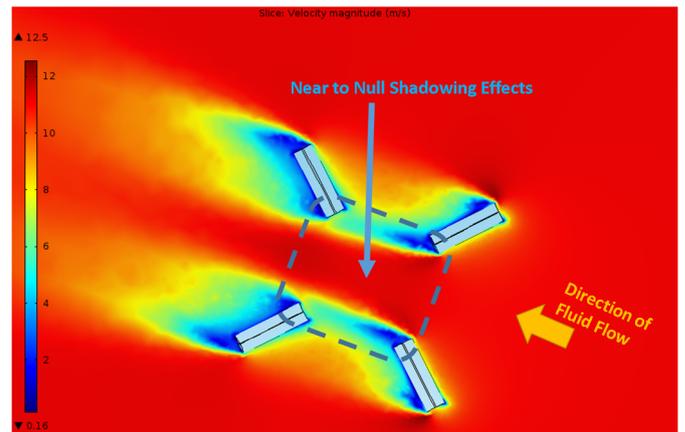

Fig. 13: calculated air speed field considering the interaction between sensor structure and incoming flow, with an attack angle of 45°

VI. PRELIMINARY TESTING ACTIVITIES WITH SENSOR IN THE LOOP

As previously said in the introduction the sensor has been designed also to be integrated on an autonomous sail boat, assembled by students of university of Florence [9]. Further experimental activities have regarded the capability of the sensor to be successfully integrated in an autonomous vehicle which will be the object of dedicated work.

However, it's important to notice that this integration has been successful, the sensor has been installed on the autonomous boat in order to provide a fundamental feedback for the navigation (estimated wind direction and intensity).

As example, in Fig. 14 it's shown a typical mission profile in which the autonomous boat of university of Florence is able to perform multiple closed points around four known waypoints. This test could not represent a validation of sensor precision since the real direction of the wind is not verified with another reference instruments. However, this test represents an important validation of sensor response respect to desired functionality since the autonomous boat propelled only by a sail have to know wind direction to properly regulate its trajectory. This is a very important result, also considering the low speed intensity (3kmh) of the wind which is far near to expected resolution of the sensor (1kmh).
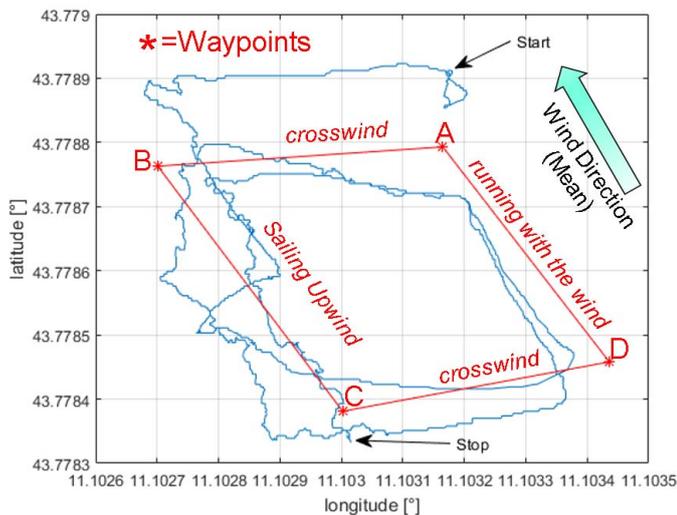

Fig. 14: sensor in the loop, the sensor installed on an autonomous sail boat is able to perform multiple closed paths around four assigned waypoints (mean wind speed of 3kmh)

CONCLUSIONS AND FUTURE DEVELOPMENTS

In this work, a low cost planar anemometer which is an essential component of sustainable, low cost marine sail drones, has been presented. Experimental results clearly show the feasibility of the proposed solution and this is quite interesting results also considering the previous limited experience of author which was limited for the marine sectors to the design of underwater vehicles [16][17][18].

Further developments of the activity should be focused on a better design of the sensor aiming to further improve miniaturization and usability of the proposed sensor respect to proposed application.

ACKNOWLEDGEMENTS

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