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Low-Cost Underwater Navigation Systems by Multi-Pressure Measurements and AHRS Data

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***Abstract*—This paper deals with accurate navigation for underwater remotely operated vehicles. A feasibility study for a multi-pressure device to be mounted on an ROV is presented. The device can provide accurate estimates of a ROV orientation and angular speed. It is based on the well-known total pressure principle, also used in a Pitot tube, and allows reconstruction of static and dynamic pressures, which in turn provide good estimates of the ROV's orientation and rotational speed, respectively. An appealing feature of the proposed device is its ability to provide accurate estimates even for low-speed movements.**

Keywords: Remotely Operated Vehicle, Inertial Measurement Units, Inertial Navigation Systems, Attitude Heading Reference System

I. Introduction

Standard methods for autonomous underwater navigation require the availability of several sensors onboard a Remotely Operated Vehicle (ROV), such as an electronic compass, a Inertial Measurement Units (IMU) and a pressure sensor. Onboard electronic compasses generally consist of three independent magnetometers, providing measures along orthogonal axes, and are essential for the determination of the magnetic North. Local magnetic interferences or anomalies may produce inaccurate North estimation, which may prevent effective autonomous navigation even when their duration of only for a small time interval. As it is known a six-degree IMU is a device measuring linear and angular body accelerations, and generally consists of the combination of a 3-axis accelerometer and a 3-axis gyroscope. Using the acceleration signals acquired by the IMU, by means of a simple double time integration, it would be possible to determine linear and rotational displacements. Unfortunately, Inertial-based Navigation Systems (INS) are affected by similar problems due to the sensor accuracy, precision and drift, often highly dependent on environmental parameters (mainly temperature and pressure). Moreover, the presence of sea currents can generate almost constant velocity displacements undetectable by simple use of IMU signals. For underwater navigation, the pressure sensor is a useful instrument for indirect determination of depth, since pressure under the sea surface is mainly a function of the water column above the pressure sensor, and thus from simple relations it is possible determine its depth. Clearly, also the reliability of depth estimation depends both on the precision and the accuracy of the pressure sensor, the environmental conditions. The realization of a reliable INS requires the use of high performance sensors, which are generally very bulky and expensive. Therefore, small sensors have to be used to obtain small ROV. Micro-ROV, the smaller ROV class (<3 kg), are used as an alternative to a diver, specifically in places where a diver might be unable to physically enter. Micro-ROVs have been also employed in the field of underwater geophysics [1] to map magnetic anomalies in volcanic or hydrothermal areas, often rich in rocks made of ferromagnetic minerals. However, for a homogeneous mapping of a study area, an efficient autonomous navigation system it would be desirable. Although MEMS sensors have many advantages in terms of cost and size, their accuracy and precision, are generally insufficient for the implementation of a INS. To improve the MEMS based INS, several calibration and filtering methods, have been proposed, together with sensors and noise modeling. Novel calibration methods consisting of linearity calibration and wavelet signal processing, was proposed in [2], in order to enhance the accuracy and performance of a MEMS inertial sensor module. In order to estimate a vehicle's orientation, it is possible to use a given depth measure, MEMS-AHRS (Attitude Heading Reference System) to reduce drift and bias of MEMS sensors. Depth measurement methods are more accurate and robust than IMU and magnetic field, which increases the performance of orientation estimate [3].In order to improve the accuracy of the orientation estimate we performed a data fusion based on filter adjustment techniques (EKT and Adams). The algorithm is robust to estimate the orientation and depth [4]. A possible solution is to use GPS, IMU MEMS and pressure sensors to measure the depth, DVL (Doppler Velocity Log). Then, through the filtering technique and fusion EKF, data return the position of the vehicle, with a few meters of error after a hour dive [5], [6], [7]. However this method is unable to reconstruct exactly the initial state. An algorithm useful in reconstructing the initial state is UKF (Unscented Kalman filter) that investigates the non-linear model for finding the starting orientation, MEMS drift and bias [8], [9], [10].

In this paper the feasibility analysis of an INS is presented, which can provide accurate estimates of a ROV position also when GPS information may be shortly unavailable. The proposed INS combines data of an IMU sensor, a set of pressure sensors, and of a GPS. It is based on the well-known total pressure principle, also used in a Pitot tube, an instrument employed for macroscopic velocity measurement within a fluid. By means of this, static and dynamic pressures are reconstructed, which in turn are exploited to improve a ROV's orientation estimation and its speed estimate, respectively. The information provided by the INS relies only on data locally available to a single ROV, but it can also be integrated with data communicated by neighboring other devices or vehicles, such as described in [11]. Furthermore, geometrical correlation of sensor data on the surface of the ROV allows vector reconstruction of the marine currents, the orientation and the position displacement of the ROV. By applying data filtering on the IMU, barometer and GPS, it will be possible to reconstruct the evolution of the system, and any of the filter parameter corrections. An appealing feature of the proposed INS is its ability to provide good estimates of the orientation and speed of the ROV even for low-speed movement.

A. Theoretical Background

In the field of fluid mechanics, with the term total pressure of a fluid it is defined as the sum of the dynamic pressure and the static pressure taken from the fluid at a precise point of its motion field at a precise instant of time:

$$p_{tot}(x,y,z,t) = p_{st}(x,y,z,t) + \frac{1}{2}\rho \left|v\right|^2 (x,y,z,t) \qquad (1)$$

The static pressure and the dynamic pressure have be measured at the same instant of time. This condition is a major problem for the measuring instruments that base their operation on the total pressure definition.

Stevin's law states that the pressure exerted by a column of fluid with constant density ρ in a point of depth z (distance from the free surface of the fluid, ie the surface of the liquid which is in contact with the external environment air) is in direct proportion to depth increases z ($z < 0 \in \Re$) and the average value of the Earth's gravitational field $g \approx 9.81$ m/s:

$$p_r = -\rho g z \qquad (2)$$

When p_r is the relative pressure.
The equation also implies that the equipotenzali surfaces in the case of ideal fluid are also isobaric surfaces. Since the surface of the liquid column is exposed to atmospheric pressure p_0, then the Stevino law can be written in terms of absolute pressure:

$$p_a = -\rho g z + p_0 \qquad (3)$$

When p_r is the absolute pressure.

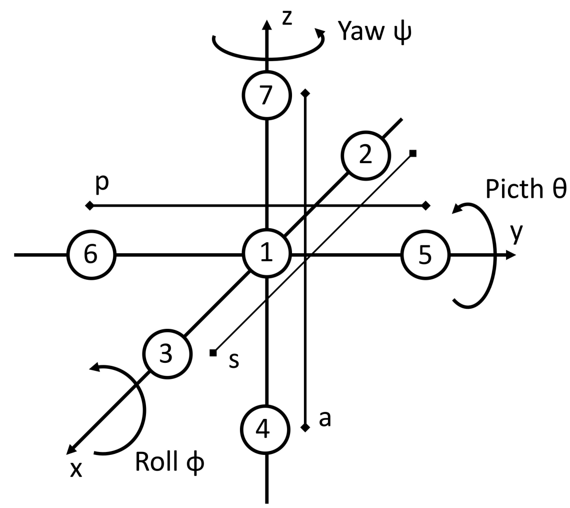

Fig. 1. Sensors available

II. Pressure - Attitude Heading Reference System (PAHRS) and Pressure-based Navigation Sistem (PNS)

In this chapter we will set itself the goal to understand if the new pressure MEMS sensors can be of support for the attitude estimates and speed of a robot submarine. It will address this issue by obtaining the absolute uncertainty of the system that you want to study. The innovation that could make this system is to have additional information about the motion of the vehicle and the surrounding environment (for example marine currents), combine elements as to movement and data from IMU, INS, AHRS, pressure sensors, PAHRS and PNS to build systems autonomous navigation.

A. Description of the System

The system that we want to study, bases its operation on the total pressure definition. It is equipped with seven pressure sensors, arranged in pairs on orthogonal axes and on the origin of the axes.

The sensor at the origin of the axes has the task of measuring the static pressure. It is placed in a involcro with sockets of special fluid that greatly attenuate of the sensor the dynamic pressures. The static pressures are calculated using the measurement of the static pressure, of sensor 1 (of Fig.1), and the buoyancy information of the AHRS and PAHRS. They depend on the distances between the sensors lying on the same axis (this distance for simplicity imposes symmetrical with respect to the origin of the axes) and by a dependent rotation matrix from the alignment of the body (from the roll and Picth angles).
The other six sensors have the task of measuring the total pressures on the faces of the body, they are directly exposed to the external environment allowing you to directly measure the dynamic pressures.

B. Operating Conditions

The points in which are installed the seven pressure sensors are distant from each other, this would seem to render the system useless, pressures are not measured at the same point (the distances between the sensors depend on the size of the body) in the same instant of time (use of microcontroller systems for measurements). In order for the system to work, the total pressure should remain constant in the range of motion of the fluid (that should apply the Bernoulli equation in his first or at least second statement). Since the measuring system does not excessively perturb the flow field around, this approximation is acceptable. You can make the system more efficient plotting of calibration curves. The time problem is solved using fast microcontrollers capable of reading the measurements and filter signals in short times of the order of microseconds. The identified commercial sensors allow to be able to operate up to 300 meters deep, they have a built-in temperature sensor useful to be able to perform the correction of the measurements (the sensors can vary its characteristic function of the temperature, also the density of water depends the temperature and the amount of salts dissolved in it).

C. Uncertainty of PAHRS

The uncertainty of the PAHRS depends on the depth value measured, from the uncertainty of the pressure sensor in determining the depth, the distances between the sensors and the uncertainty of the distances between the sensors. We proceed for simplicity with the discussion assuming constant density water along the vertical and the total pressure measurements filtered so as to remove the component due to the dynamic pressure and provide the only static pressure measurement. In these conditions you can apply Stevin's law represented by the equation 3 to determine the depth in which are located the sensors, you can obtain the relationship between the measured depth and attitude angles:

$$z_6 - z_5 = s\sin(\phi) \tag{4}$$

$$z_3 - z_2 = p\sin(\theta) \tag{5}$$

$$z_4 - z_7 = a\cos(\phi)\cos(\theta) \tag{6}$$

by formulas 4 5 you are obtained attitude angles:

$$\phi = \arcsin(\frac{z_6 - z_5}{s}) \tag{7}$$

$$\theta = \arcsin(\frac{z_3 - z_2}{p}) \tag{8}$$

the third equation 6 can be used to get a feedback on the goodness of the measures:

$$z_4 - z_7 - a\cos(\phi)\cos(\theta) = 0 \tag{9}$$

We calculate the absolute uncertainty of previous reports by entering the data provided by the manufacturers, uncertainty

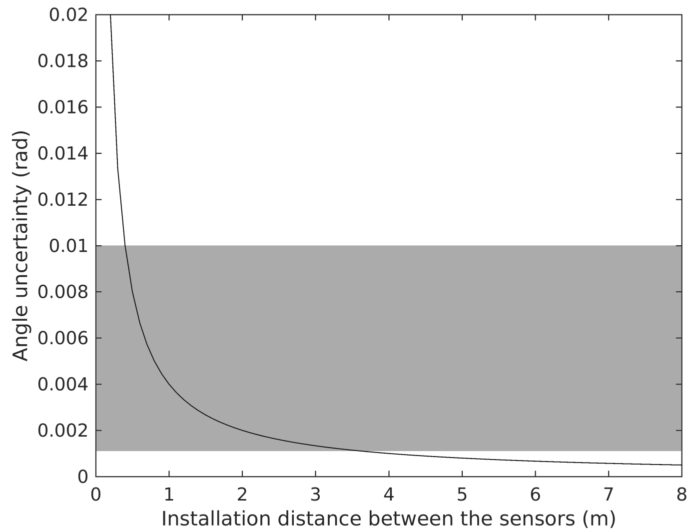

Fig. 2. Angle uncertainty as a function of the installation distance of the sensors, the gray area is the uncertainty range of the inclinometers based on MEMS technology.

of the depth measurement $\triangle a = 2$ mm and uncertainty of the distace between sensor measurement $\triangle b = 10^{-2}$ mm:

$$\triangle\phi = \arcsin\left(\frac{\triangle z_6 + \triangle z_5}{b} + \frac{(z_6 - z_5)\triangle b}{b^2}\right) \tag{10}$$

$$\triangle\theta = \arcsin\left(\frac{\triangle z_3 + \triangle z_2}{b} + \frac{(z_3 - z_2)\triangle b}{b^2}\right) \tag{11}$$

In the fig:2 is possible to note that placing the sensors at a greater distance PAHRS the system has a lower uncertainty. It should be remembered that the measures can be considered usable if the uncertainty takes on smaller values:

$$\frac{\triangle z_6 + \triangle z_5}{z_1} < r \tag{12}$$

$$\frac{\triangle z_3 + \triangle z_2}{z_1} < r \tag{13}$$

$$\frac{\triangle z_4 + \triangle z_7}{z_1} < r \tag{14}$$

whith $0 < r < 10^{-1}$

In the fig:3 is possible to note the minimum depth in order to have confidence in the measures.

D. Uncertainty of PNS

The uncertainty of the PNS depends on the measured pressure values, from the uncertainty of the pressure sensors, from the density of water and from the uncertainty of the density of the water. Using the definition of total pressure 1 for obtained the law in which the difference between total pressure and static pressure are proportional to the square of the speed of the macroscopic form (the static pressure and

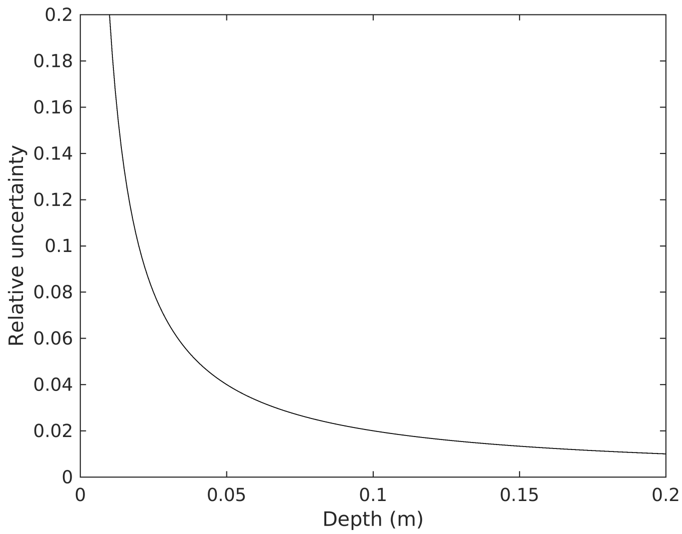

Fig. 3. Relative uncertainty as a function of the depth of the sensors

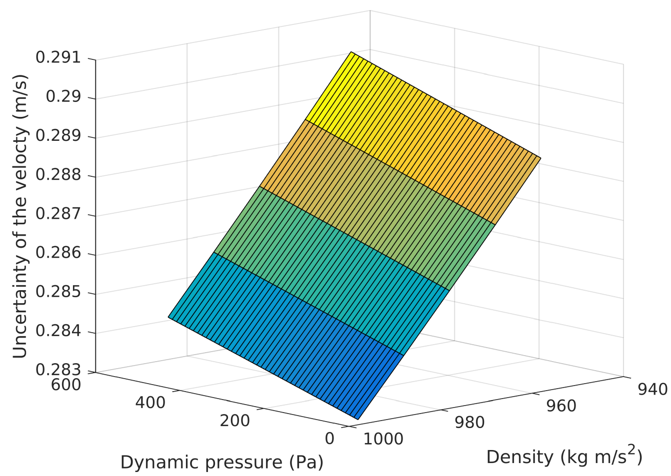

Fig. 4. Uncertainty of the velocity as a function of the density and dynamic pressure measurement

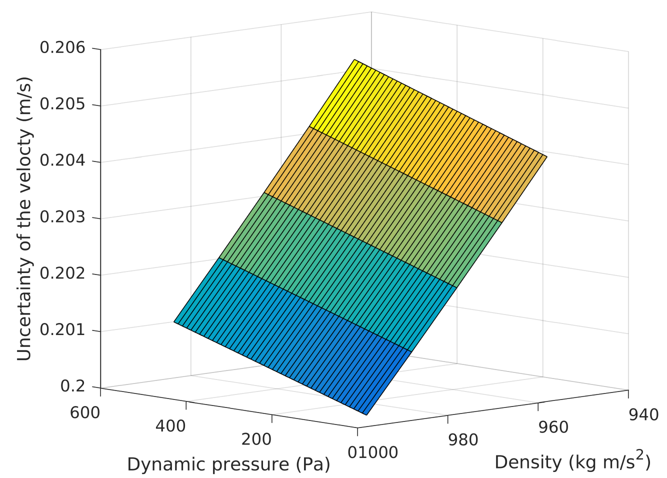

Fig. 5. Uncertainty of the velocity as a function of the density and dynamic pressure measurement

the total pressure to be measured at the same instant of time), then:

$$v_n = \sqrt{\frac{2(p_{tot_n} - p_{st_n})}{\rho}} \tag{15}$$

whith $1 \leq n \leq 6$. We calculate the absolute uncertainty of previous reports by entering the data provided by the manufacturers, uncertainty of the pressure measurement $\triangle c = 2 \times 20$ Pa and uncertainty of the density of whater $\triangle d = 1$ kg/m^3:

$$\triangle v = \sqrt{\frac{2(d\triangle c + c\triangle d)}{d^2}} \tag{16}$$

to follow the uncertainty speed graph is shown fig:4, be noted that the uncertainty is strongly influenced by the value of the density (theoretical variation of the density of water for the range in which the liquid state is present in nature) with respect to the dynamic pressure measurement (theoretical pressure change for speed range from 0 to 3 m/s).

In addition to derive the static pressure of the affected sensor you should be used the following equations worse estimate speed even further:

$$p_{st2} = p_{st1} - \frac{s}{2}\sin(\theta)\rho g \tag{17}$$

$$p_{st3} = p_{st1} + \frac{s}{2}\sin(\theta)\rho g \tag{18}$$

$$p_{st4} = p_{st1} + \frac{a}{2}\cos(\phi)\cos(\theta)\rho g \tag{19}$$

$$p_{st5} = p_{st1} - \frac{p}{2}\sin(\phi)\rho g \tag{20}$$

$$p_{st6} = p_{st1} + \frac{p}{2}\sin(\phi)\rho g \tag{21}$$

$$p_{st7} = p_{st1} - \frac{a}{2}\cos(\phi)\cos(\theta)\rho g \tag{22}$$

To reduce the uncertainty you might be using the two lying pressure measurements on the same axis, as they do in PAHRS system. In this way, it vanishes the constant multiplier 2 in the calculation formula of the speed and consequently the calculation of the uncertainty in that:

$$p_{tot}6 - p_{st}6 = \frac{(p_{tot}6 - p_{tot}5) - p\sin(\phi)\rho g}{2} \tag{23}$$

to follow the new uncertainty speed graph is shown fig:5, be noted that the uncertainty is significantly decreased compared to the first case of fig:4.

In this case it is not useful to calculate the relative uncertainty since the atmospheric pressure ensures the reliability of the measures as it is of four orders of magnitude compared to the full scale of the MEMS pressure sensor taken as a reference.

III. Conclusion

In this article the uncertainty study of a pressure sensor underwater system MEMS arranged as in fig:1 was addressed, in order to assess its ability to estimate attitude and speed.

From the analysis made on the PAHRS you are obtained currently with commercially available sensors to obtain an uncertainty on the lower attitude estimation with respect to a commercial IMU or AHRS (about $7 \times 10^{-2}\ ^\circ = 1.22 \times 10^{-3}$ rad), the sensors placed on the same axis they must be at least 4 meters between them. If the sensors sell seats at a greater distance of 4 meters, the system becomes more accurate of the IMU or AHRS systems. The PAHRS system still maintains a high accuracy up to 2 meters distance between the sensors, wanting to decrease the distance better not fall below 0.5 meters in which uncertainty has the value of 8.7×10^{-3} rad $= 0.5\ ^\circ$.

From the analysis made on the PNS you are obtained currently with commercially available sensors is obtained an uncertainty on the estimate of the speed of the robot or of a marine current that affects it by 0.2 m/s. The density of water is the physical quantity that has the most influence on the measuring system, due to the change in density the largest error that can be made is 10^{-2} m/s, knowing the external temperature and the concentration of salts dissolved in water can reduce the uncertainty of the density and compensate for this error.

In both systems so the main problem is the resolution of the sensor that can detect up to 20 Pa, to remedy this technological problem you can use the technique of oversampling or place multiple sensors and then filter the signal with a moving average filter or estimator BLUE average, these topics will be covered in the next job.

Acknowledgment

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