INERTIAL NAVIGATION SYSTEM FOR GUIDANCE AND CONTROL OF UNDERWATER VEHICLE

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Abstsract

In this paper the problem of enhancing the performances of a small work class ROV (DEO Phantom2) has been considered. In particular, the installation and testing of a low-cost solid state, six degrees of freedom, inertial device on small work class ROV is described. Inserting a PC in the operator/vehicle loop, IMU data can be used by an automatic control system thus making feasible to achieve high performances when executing position and motion control tasks..

1 Introduction

Unmanned underwater vehicles (UUV) have acquired an increasing importance in field like the exploration and exploitation of the underwater environment and have become a key tool in many activities like environmental data gathering, coastal zones monitoring, construction and surveying of offshore structures etc. The increasing technological demands, the need of reducing the costs of the underwater activities and safety requirements call for robotics systems with enhanced performances in terms of manouvering capability and autonomy. At this regard, the possible intervention areas are to augment the vehicle autonomy, so to reduce the activity of human operator (in case of ROV) or of the control mission (in case of AUV), to supply vehicles with the capability to adapt to environment changes and to equip vehicles with more sophisticated control systems which could guarantee high performances in positioning and motion tasks.

In this paper, the problem of enhancing the performances of a small work class ROV (DEO Phantom2) has been considered. To guarantee accurate performances on tasks like trajectory following and station keeping, accurate position and attitude information are required [3],[4],[5]. At this scope, the utilization of a low-cost solid state 6DOF inertial device that combines three gyros and three accelerometers has been considered. In this paper, suitable alignment procederes and navigation equation have been analyzed so to correctly update vehicle position and attitude information from data coming from the inertial measurement units (IMU). Furthermore, an artificial horizon has been syntetized which result of great help to the operator in the guidance the ROV. An other important utilization of IMU data, opportunely fused with other onboard sensors, is in the identification process of vehicle's model parameters the estimation of which results essentially in the offline testing of the performances of developed guidance and control systems.

The present work is framed in a more comprehensive project, a two years National Italian Research Project, sponsored by the Italian Ministry of University and Scientific and Technological Research, on Navigation, Guidance and Control systems for underwater vehicles. In particular, the project aims at the realization of a (semi-)automatic guidance system by introducing a PC in the operator/vehicle loop which assists the operator reducing its operative burden. Both the data analysis and the guidance of the ROV are currently accomplished by human operators, whose performances are affected by expertise, concentration and weariness (see [1] and [2]). The development and implementation of (semi-)automatic systems and procedures may therefore represent an important factor in reducing the complexity, the duration and the cost of missions, as well as in increasing the reliability of the collected information. In particular, it is possible to fuse sensors, eteroceptive (for example, CCD camera, sonar) and proprioceptive (for example: inertial sensors) ones, supplying the operator with a more fruitful information enhancing its situation awareness. A friendly man machine interface (MMI) will allows the operator to easily drive the vehicle from a PC console.

The paper is organized as follow: section two outlines the vehicle/PC system main components, in section three an introduction to the inertial navigation systems is given together with a description of the adopted navigation equations and of the alignment procedure. In section four experimental results are shown and conclusions are reported in section five.

2 System Description

The general scheme of the system is depicted in figure 1.

The Remote Operated Vehicle we consider is a Phantom S2 made by Deep Ocean Engineering. The vehicle's standard equipment consists of a magnetic compass, a depth sensor and a CCD camera with two halogen lamps. Four thrusters (two horizontal ones and two vertran ones) provide for the vehicle motion by actuating four degrees of freedom. In its original configuration, the ROV is manually governed through a console by a human operator.

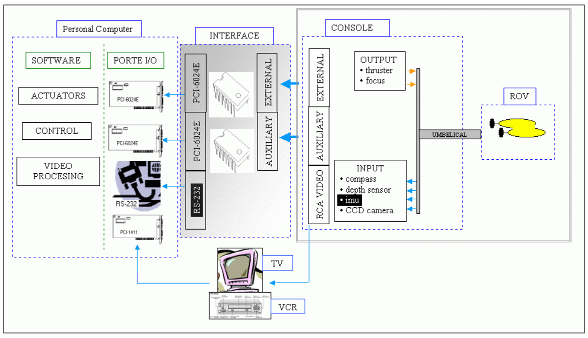

Figure 1: General system scheme

The guidance system of the ROV has been completely redesigned, by introducing a PC (PentiumIII866MHz) in the loop between the human operator and the vehicle thus allowing to implements automatic control and guidance strategies. Visual information coming from an on-board CCD camera and from compass and depth sensors is displayed on the console; control actions can be either implemented by a human operator acting on the thrusters from a virtual console (see figure) or by a control signals commanded directly by the PC.

In addition, a solid state Inertial Measurement Unit (IMU) has been mounted onto the vehicle, in order to get proprioceptive data on linear accelerations and rotational speed around three orthogonal axes.

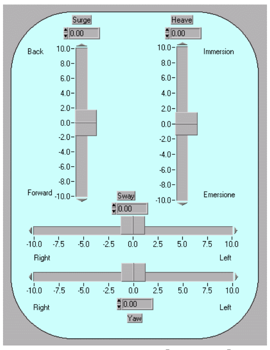

Figure 2: Virtual console

The adopted inertial measurement unit is a low-cost six degree inertial device based on micro-machined technology. It combines three angular rate sensors consisting in vibrating plates that utilize the Coriolis effect to output angular rate independently of acceleration and three accelerometers based on Micro-Electro-Mechanical System (MEMS) that use differential capacitance to sense acceleration. An internal DSP provides for suitable signal processing, so to compensate for internal deterministic error, as well as for offset and scale factor errors. Its external case dimension are 3”x3.75”x3.25” and its weight is 475 g. An analog output and two RS232 digital outputs are present. Digital data may be requested via serial command or transferred continuously. Low power consumption and high start-up speed make this device suitable for ROV applications.

3 Strapdown Inertial Navigation System

Inertial navigation systems have been widely used in aerospace applications [6],[7] but have been scarcely utilized in robotics [8],[9],[10] and UUV fields the main reason for that being the cost impact of these units. In the recent years, due to the significant advances in the technology of solid state inertial sensors, the development of inertial navigation systems, has been characterized by a gradual move from stable platforms to the so called *strapdown systems*, which combine low price with sufficient reliability. In the case of stable platforms, sensors are mounted on a stabilized platform, so to maintain constant the directions of the accelerometer’s input with respect to an Inertial Reference System or, depending on the specific application, to an Earth Reference System. In the strapdown systems, sensors are directly connected with the vehicle. These devices, are composed of two main elements: the gyroscopic and accelerometer block which are strictly connected to the vehicle by rigid suspensions; a processing unit is added which performs corrections to compensate for vehicle vibrations, temperature increase, etc. Strapdown devices performances are dependent on the motion of the platform they are mounted on, which, in our case, is an underwater vehicle. This makes a substantial difference with respect to devices of the first category, whose stabilized platform remains nominally fix with respect to the adopted reference system.

IMU measurements have to be suitably combined and processed in order to enable navigation to take place. Different reference systems can be adopted to refer the measurement acquired from the accelerometers and the gyroscopes. Adopting the local Navigation reference system, which has its origin at the location of the navigation system, and axes aligned with the direction of North, East and the local vertical (down), the navigation equations necessary to calculate velocity and position by a strapped-down device are the following:

$$\dot{\mathbf{v}}_e^n = \mathbf{f}_e^n - \left[2\omega_{ie}^n + \omega_{en}^n\right] \times \mathbf{v}_e^n + \mathbf{g}_l^n \qquad (1)$$

$$\mathbf{f}_e^n = C_b^n \mathbf{f}^b \qquad (2)$$

where $\dot{\mathbf{v}}_e^n$ and $\mathbf{v}_e^n$ are, respectively, the vehicle acceleration and velocity vector with respect to the Earth fixed reference system (origin at the center of the Earth and axes fixed with respect to the Earth) expressed in the Navigation reference system; $\mathbf{f}^b$ and $\mathbf{f}_e^n$ are the force measured by the accelerometers in the vehicle's Body frame, that is the orthogonal axis set aligned with the roll, pitch and yaw axes of the vehicle, and in the Navigation reference system, respectively; ω_{ie}^n is the Earth angular velocity expressed in the Navigation reference system while ω_{en}^n is the angular velocity of the Navigation reference system with respect to the Earth reference system; $\mathbf{g}_l^n$ is the local gravity acceleration vector, which includes the effect due to the Earth angular velocity. Finally, C_b^n is a direction cosine matrix, which transform force vectors measured in the vehicle Body reference system into the Navigation reference. C_b^n can be determined from the angular velocity terms measured by the gyroscopes in the local reference frame, which form the antisymmetric matrix Ω_{nb}^b by solving the following equation:

$$\dot{C}_b^n = C_b^n \Omega_{nb}^b \qquad (3)$$

Given the actual IMU working conditions that is a latitude of approximately 44° and a navigation speed limited to 30 knots, the navigation equation (1) has been simplified neglecting the second right term in (1) and the effects of the Earth angular velocity. Thus, the computed navigation equation has the form:

$$\dot{\mathbf{v}}_e^n = \mathbf{f}_e^n + \mathbf{g}_l^n \qquad (4)$$

where **g** is the gravity acceleration.

The performances of an inertial navigation system are characterized by a time dependent drift in the accuracy of the position and attitude estimates it provides. The rate at which the navigation errors grow is governed predominantly by the accuracy of the initial alignment, constructive defects in the inertial sensors and by the dynamics of the actual trajectory followed.

Initial alignment procedure essentially consists in the determination of the orientation of the accelerometers axes with respect to the designated reference system. When referring the alignment to the Navigation reference system it is necessary to know the direction of the local vertical and of the geographic North. To detect the direction of the geographic North by means of the adopted IMU's gyroscopes is not possible, as their accuracy is too low. To overcome this system limitation, it is either possible to use another sensor or to choose conventionally the North. Adopting this second solution, the calculation of the c_{ij} elements (see [11]) of the direction cosine matrix C_n^b, which relates the vehicle's Body reference system and the Navigation reference system, has to be suitably modified. In particular, the modifications affect the terms of the first raw whose equations are the following:

$$c_{11} = \sqrt{\frac{c_{33}^2}{c_{33}^2 + c_{31}^2}} \quad c_{12} = 0 \quad c_{13} = -\sqrt{\frac{c_{31}^2}{c_{33}^2 + c_{31}^2}} \qquad (5)$$

Alternatively, a different way to calculate the direction cosine matrix may be used. In this case, additional data coming from the IMU are employed: the roll (φ) and pitch (θ) angles values that are internally computed and can be read from the serial port. Adding external information about the yaw (ψ) angle, calculation of C_n^b, can be performed as follows:

$$C_n^b = \begin{bmatrix} c\psi\, c\theta & s\psi\, c\theta & -s\theta \\ -s\psi\, c\varphi + c\psi\, s\theta\, s\varphi & c\psi\, c\varphi + s\varphi\, s\theta\, s\psi & c\theta\, s\varphi \\ s\psi\, s\varphi + c\psi\, c\varphi\, s\theta & -c\psi\, s\varphi + s\theta\, s\psi\, c\varphi & c\theta\, c\varphi \end{bmatrix} \qquad (6)$$

where s and c represent, respectively, the sine and cosine function.

4 Experimental Tests

Experimental tests have been performed on the IMU both to test its performances and to verify the validity of the implemented navigation algorithm.

To exclude possible noise sources, tests have been performed on the IMU both before and after mounting it onboard the Phantom, not noticing any appreciable difference. The experimental conditions of the data reported in the following were: IMU at rest, positioned with its Z-axis in the vertical position and a plywood board placed underneath the IMU basis so to smooth possible vibrations transmission from the floor. With this configuration, the linear accelerations on the x and y direction, as well as the three angular velocities values, were expected to be practically zero.

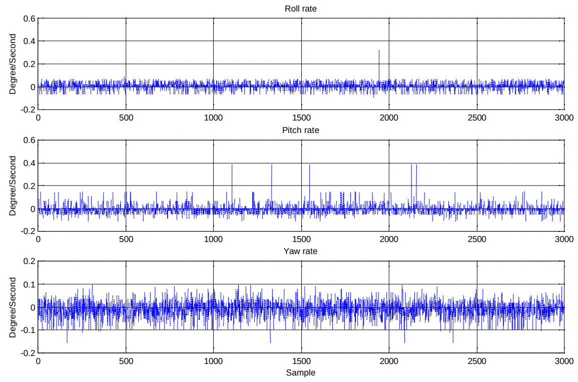

Fig .3. Angular rate components. Experiment conditions: IMU at rest positioned with its Z-axis in vertical position.

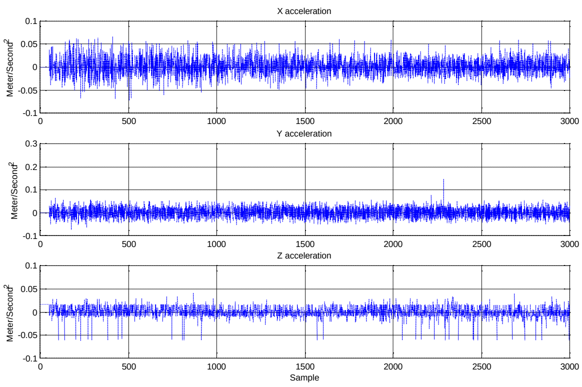

Fig 4. Acceleration components. Experiment conditions: IMU at rest, positioned with its Z-axis in vertical position.

Fig. 3 and 4 show the angular rate and the acceleration data, respectively. Sampling rate was set at 50 Hz. Means and standard deviation values have been computed on the previous data as reported in table 1. Since accelerometers resolution is 0.005 G, the analysis of the acceleration components shows accordance with the expected data. Since the gyroscopes resolution is 0.05 °/s angular velocity values are within the expected range, except that, if its standard deviation is compared with the datasheet random walk errors, it results to be one order greater.

Tab .1.

	mean value	standard dev.	Norm
ω_x [°/s]	5.5338e-003	3.1069e-002	
ω_y [°/s]	-5.6312e-003	4.0030e-002	1.3041e-002
ω_z [°/s]	-1.0380e-002	3.5759e-002	
a_x [m/s]	1.4584e-003	1.9886e-002	
a_y [m/s]	1.5111e-003	2.5041e-002	1.6194e-002
a_z [m/s]	-1.6058e-002	1.2145e-002	

From a further data analysis, an estimate of alignment errors has been performed. Different parameters values have been calculated depending on the adopted procedure for the computation of the direction cosine matrix (see section III).

In particular, the misalignment errors $\delta\alpha$ and $\delta\beta$, in the first case can be estimated to have values around 0.29 °, while in the second case these values can be reasonably estimated to be 0.1 °. The misalignment with the North direction $\delta\gamma$, given the assumption made in section III, could be referred to the compass resolution that is of 3°.

Whiteness tests on data errors have been performed with positive results for the accelerations data. On the contrary, tests performed on the angular rate components around Y and Z-axes showed that, in these cases, the errors can not be considered white. Depending on the adopted IMU operational mode, different navigation algorithms have been tested, whose main difference consists in the computation of the direction cosine matrix as described in section IV. Moreover, the use of quaternion in the navigation algorithm, as alternative to the direction cosine matrix, has been tested, but no substantial improvements in the performances have been reported.

Depending on the operational mode set, IMU will output, along with the angular rate and the acceleration information, also the stabilized pitch and roll angles. The IMU uses the accelerometers to provide long term stability to keep the rate gyro drift in check. A comparison of the internally computed values of pitch and roll angles with those computed by integration of the angular rate, confirmed the better reliability of the first. In figure 5, values of roll and pitches angles resulting from the inertial units and the computed yaw angle values are reported. It can be noticed that, even if the platform is keep at rest, the nonzero mean value of the velocity components gives rise to a drift error that, in the example, resulted to be approximately 0.6° over a period of one minute. This drift, over a period of two hours has showed to be practically constant.

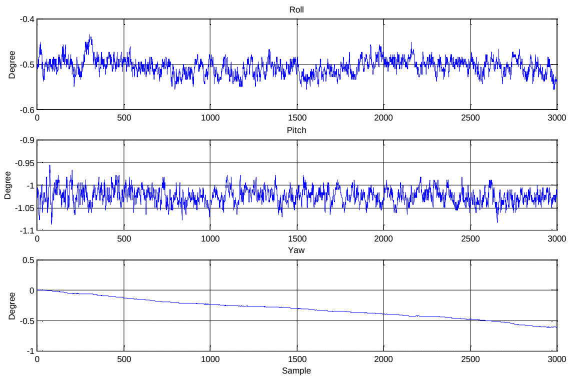

Fig 4. Roll, pitch and yaw angles. Experiment conditions: IMU at rest, positioned with its Z-axis in vertical position.

A similar behavior can be observed in the position and velocity data obtained by successive integration of the acceleration measurements. Given to the high drift values it can be concluded that, without the application of suitable filtering algorithms, the use of the adopted IMU device for positioning task is not recommended.

Filtering algorithms, which are currently under study, should limit the drift errors thus extending the period of time over which data can be considered significant.

Moreover, occasional realignment procedures based on external information will be necessary to overcome long-term drift.

5 Conclusions

The realization of a (semi-)automatic guidance system for a low-cost work class ROV class-has been realized by introducing a PC in the operator/vehicle loop. A solid state Inertial Measurement Unit (IMU) has been mounted onto the vehicle, in order to get proprioceptive data on linear accelerations and rotational speed around three orthogonal axes. Installation and testing procedures of the inertial unit have been described and discussed. More testing are scheduled to fully verify IMU performances after its definitive mounting onboard the vehicle. Further analyses are necessary in order to characterize the dynamic models for the IMU rate and acceleration drift errors so to operate opportune data filtering. Once the error characteristics of the platforms will be well understood, to further improve the accuracy of the inertial system, the use of additional sensors will be considered, as a common approach, for the its occasional realignment.

IMU data, opportunely fused with other onboard sensors, will be essential in the of identification process of vehicle's model parameters.

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