Development of a Low Cost Inertial Measurement Unit for UAV Applications with Kalman Filter based Attitude Determination

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***Abstract*— This paper presents the development of an inertial measurement unit (IMU) specially designed for unmanned aerial vehicles (UAV) applications. The design was intended to be a low cost solution of high performance for robotic applications using 3-axis accelerometers and 3-axis gyroscopes MEMS sensors. We present simultaneous sampling to avoid the loss of orthogonality of the inertial measurements due to multiplexed data acquisition commonly used in low cost IMUs, as well as anti-aliasing processing. The IMU was implemented in two boards to separate the sensors from the processing hardware in order to be able to use it with different sets of sensors. The sensor fusion algorithm for attitude determination is based on the Kalman Filter. As testing process, the IMU was installed in a 2-DOF helicopter and the results were compared with those obtained from the encoders for the pitch and roll angles. We also present the results of the IMU installed in a T-REX 450 scale helicopter inside a motion analysis laboratory, using a custom-design safety stand that supports the helicopter allowing only its rotational 3-DOF (roll, pitch and yaw movements). Those demanding experiences tested the IMU performance under true UAV conditions and the results exhibited a maximum RMS error of 4°.**

I. INTRODUCTION

The field of Unmanned Aerial Vehicles (UAV) has experienced a vertiginous growth in recent years. UAV have enormous potential to be used in different areas, ranging from civil applications to homeland security applications, all of which have helped to its development. These vehicles can be used to check the status of high voltage electric transmission lines, search for lost people on harsh environments, rescue and environmental research.

A lot of UAV projects share a common starting point, they all begin with a remote controlled device and then convert it to an autonomous platform. Among the challenges that need to be faced is the development of an inertial measurement unit, which is required to report the inclination and heading of the vehicle, among other important variables. This information is crucial to perform control over the vehicle, which, for example, can be used in a helicopter to achieve good hovering flight condition.

Additionally, thanks to the availability of inertial sensors (accelerometers and gyroscopes) fabricated using MEMS technology, low-weight low-cost IMUs can be developed. Therefore, this is a great time to perform research in this area, which not only means to come up with new systems, but also to tune these inertial units and suit them to the requirements of high-performance applications. Previous works have presented hardware and software developments for IMU [1][2][3]. Our contribution is oriented to a low cost product designed for UAVs using commercial off-the-shelf components.

The objective of this work was to develop a low-cost IMU for AUV applications as well as the design of test experiments under true UAV conditions in a laboratory framework. The attitude determination algorithm is based on the Kalman Filter. The ideas of modularity, antialliasing, low weight, fast dynamics, and simultaneous sampling are some of the key factor that we took into account in the design, as it is explained in Sec. II. In Sec. III it is shown the hardware implementation, whereas in Sec. IV and Sec. V we show the experiments developed using a 2-DOF helicopter and a scale helicopter inside a motion analysis laboratory.

II. IMU CONCEPTUAL DESIGN

The IMU was designed for UAV applications whose characteristics represent a challenging environment for an strapdown IMU [4]. This applications usually present fast dynamics, vibration due to the propeller engines, a wide variety of disturbance and simultaneous movements in all its 6-DOF. The following fundamentals of the design allowed to counteract those problems and to improve the performance of the IMU to be used in multiple types of UAVs. The high level block diagram of the IMU is shown in Fig.1

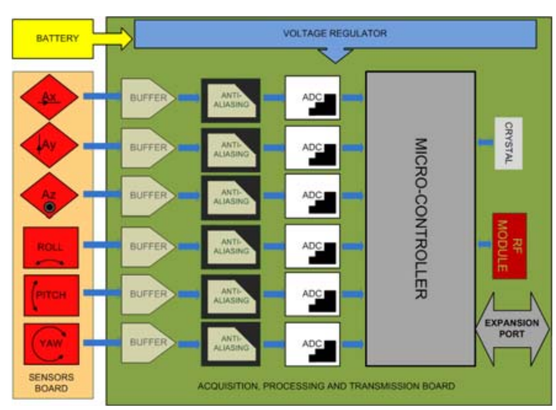

Fig. 1. IMU Block Diagram

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A. *Modularity*

The device was separated into two boards: a sensor board and a processing board. This modular design allows to use the processing board with different sensors without the necessity of major changes. Depending on the types of trajectory of the specific UAV, certain types of sensors would exhibit better performance than others.

B. *Voltage buffers*

This simple and commonly used stage allows the use of the board with different sensors, while guaranteeing no charge effect from the processing board to the sensor board.

C. *Antialliasing filters*

Studies were performed in order to determine the main frequencies components of the gyroscopes and accelerometers signals when they are mounted on an UAV such as a scale helicopter. Antialliasing is always important, but the results indicated that filtering is an important part of the signal conditioning in order to avoid high vibration interference in the attitude determination results.

D. *Simultaneous Sampling*

In low cost IMUs multiplexed sampling is typically used because it is the most common method found in microcontrollers. This method could work for slow dynamic systems; however, for fast dynamics, as it is in the case for UAVs, it leads to a loss of orthogonality in the inertial measurements and the consequential misaligned-like results. The idea with this design was to implement simultaneous sampling by using an ADC for each acquisition channel, while the microprocessor is in charge of the synchronization and data communication of the ADCs. The processing requirement here is that the adc-microcontroller system should be able to process all the data before the next simultaneous acquisition of the values given by the 3-axis accelerometers and the 3-axis gyroscope, which are 6 channels of data processing. If a 3-axis compass is included it would be 9 channels.

E. *Microcrontroller*

If the attitude determination algorithm is going to be hosted by a computer on the ground, the microcontroller should only be in charge of the simultaneous sampling and the wireless communication coordination. If the case is for an on-board processing of attitude estimation, the microcontroller will receive a lot more processing tasks. This paper presents the first case, using a Propeller® microcontroller from PARALLAX, which has 8 processing cores (called cogs). These cogs are a great advantage for the management of simultaneous processing.

F. *Wireless Communication*

Both Xbee and Bluetooh communication systems were tested. Experience shows that Xbee tends to lose packages after a certain threshold of transmission rate while Bluetooth does not. However, in terms of distance, Xbee has a better performance. The most suitable method depends on the the type of UAV.

III. HARDWARE IMPLEMENTATION

Considering all of the factors given in the previous section, a set of low cost commercial chips were selected and evaluated. The first prototype was implemented in a DIP format, as shown in Fig.2 and Fig.3, for the processing board and sensor board. Two sensor boards (**T1** and **T2**) were implemented in order to perform several tests with different sensors and sensibilities. Both sensor boards are based on Freescale® accelerometers and Invensense® gyroscopes. **T1** has 120°/sec gyroscopes and 1.5g accelerometers, whereas **T2** has 500°/sec gyroscopes and 6g accelerometers.

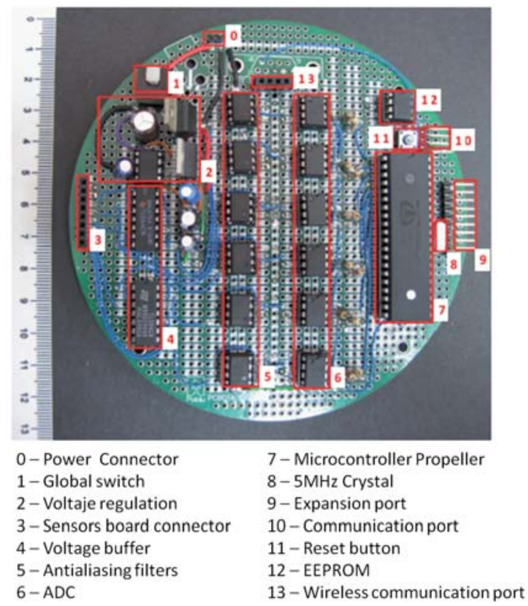


Fig. 2. Processing Board

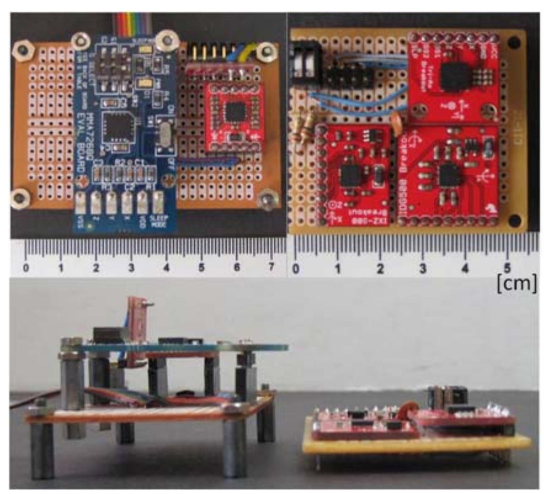


Fig. 3. Sensors boards. T1 (left) and T2 (right)

A. *Sensors Calibration*

There are two parameters that need to be determined in order to express the signals from the accelerometers in [g] units, and the signals from the gyroscopes in [°/s] units. These are known as the voltage bias and the scale factor (SF), as it is shown in the calibration Eq. 1

$$Ycalibrated = SF * RawSignal - Bias \quad (1)$$

Therefore, the problem can be restated as the optimization of the RMS error between the calibrated signal and an appropriate reference. Computing this error for convenient values of the pair (SF, B) generates a surface as it is shown in Fig.4. The best possible calibration is achieved when the calibration parameters are taken at the minimum of that surface.

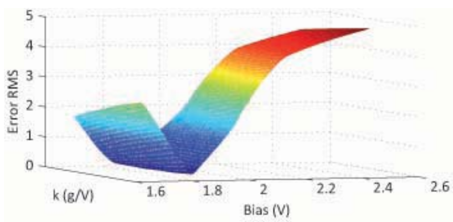


Fig. 4. Calibration Device

This method requires that the true values be available, which means that an IMU of proved performance is required. If there is not availability of such unit, a calibration instrument can be used as the one shown in Fig.5.

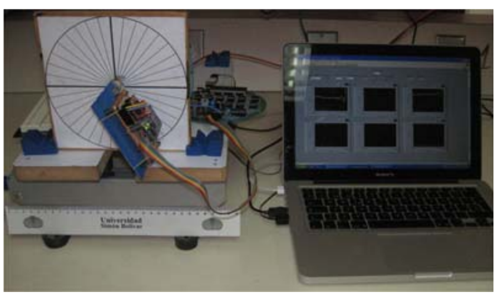


Fig. 5. Calibration Device

This process was performed with **T1** and **T2** for each single axis for a total of 6 calibrations.

B. Weight of the first prototype

It is well known that an important requirement for UAVs instrumentation is low weight. This prototype weights 120g., which is low enough for our testing UAV platforms without any other processing component. Based on the next design, it is expected to achieve less than 40g. with a second prototype using surface mounted components as well as a reduction of 70% of its physical dimensions.

IV. 2-DOF Test using a Quanser® Platform

The first evaluation was performed installing the IMU on a 2-DOF helicopter commercial platform by Quanser commonly used for research projects. The test set up is shown in Fig.6, where it can be seen that the processing board is located in the center of the structure, while the sensor board is on the back of the helicopter for best accommodation. Both sensors and processing boards are able to rotate with the platform. This platform can move in pitch and yaw angles while it is computer controlled.

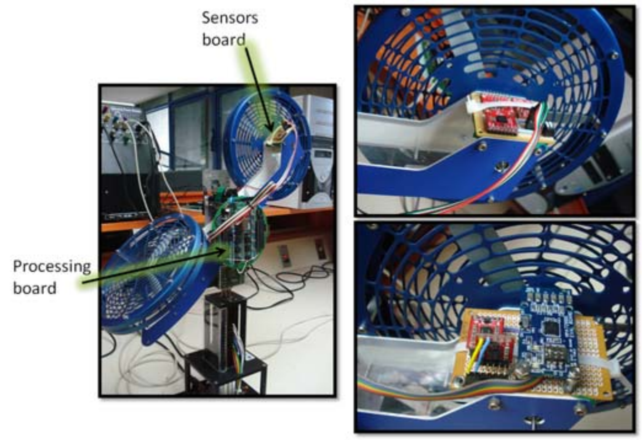


Fig. 6. IMU Block Diagram

Pitch and roll are measured by using the platform encoders (12bits, 1KHz), while simultaneously and independently the 3-axis accelerations and 3-axis angular velocities are measured by the IMU. Fig.7 and Fig.8 show the results for pitch and yaw angles respectively. Notice in Fig.7(a) the difference between the pitch calculated exclusively from the accelerometers data through tilt equations, i.e. the raw result without sensor fusion, and the result provided by the Kalman Filter. Then, Fig.7(b) compares the KF result with the Quanser encoders for pitch angle. Fig.7(c) and Fig.7(d) show the same difference for pitch angular velocity between the gyro-based raw calculation and the KF vs. encoders.

The yaw angle results are analyzed in Fig.8. In the case of the yaw angle, we must notice that counting on only the gyroscopes it is not possible to estimate the yaw angle without the well known time-dependent drift. In the case of roll and pitch, the gyroscopes are fused with the accelerometers information, but in the yaw case, that is not possible because accelerometers do not measure any quantity related to yaw. Having explained all this, it is clear that the estimation of the yaw needs the aid of another kind of sensor, as a 3-axis compass, to avoid the drift. A compass is not included in the presented IMU for this moment, but the effect of its correction was computed using the encoder information as compass. Fig.8(a) shows the results without correction, while Fig.8(b) shows the results with the correction. Fig.8(c) and Fig.8(d) show the estimation results for yaw angular velocity using raw values and the KF.

Even though the sensor board was located near the propellers of the 2-DOF helicopter, the overall result in the comparison between the IMU and the Quanser platform instrumentation exhibited good performance with an error under 4° RMS.

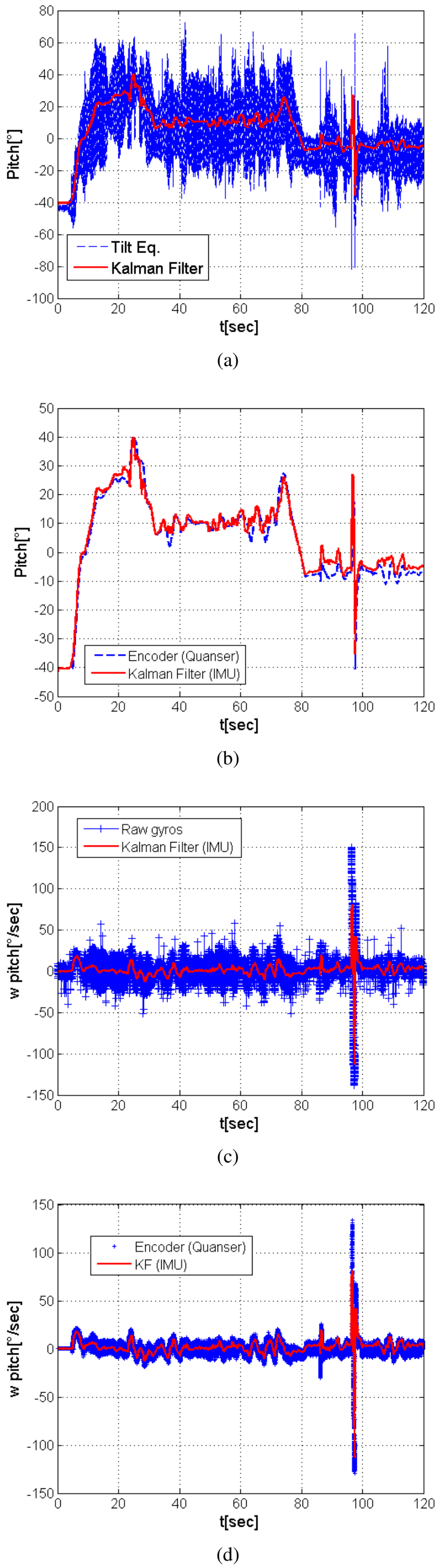


Fig. 7. Results for Pitch Angle. Encoders Quanser vs. IMU Kalman Filter

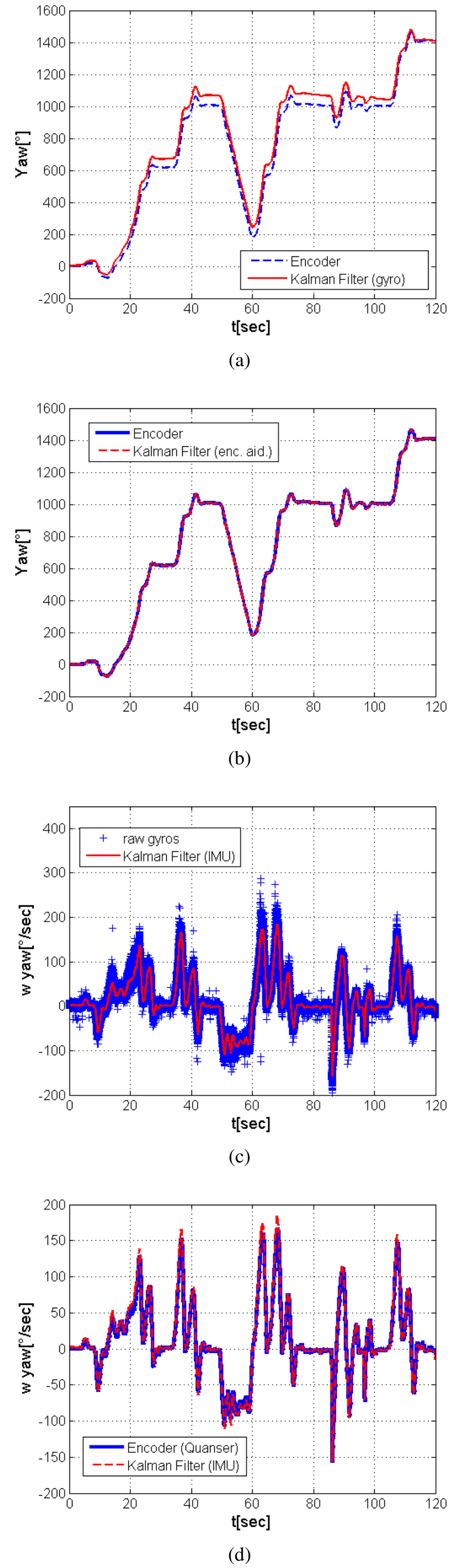


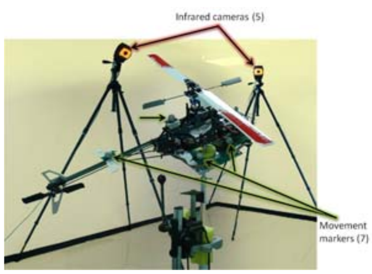
Fig. 8. Results for Yaw Angle. Encoders Quanser vs. IMU Kalman Filter

V. 3-DOF Test with a Scale Helicopter

A more challenging test was performed with a T-REX 450 scale helicopter inside a motion analysis laboratory. This lab allows to track the position of several markers inside a test space using a set of 5 infrared calibrated cameras. Those markers were installed on the scale helicopter as well as the IMU (processing board + sensors board) as shown in Fig.9

The objective is to compare the result given by the IMU in attitude determination (roll, pitch and yaw) with the measurements of the motion lab. The cameras work at 200fps while the IMU works at 514Hz. An elaborate process of synchronization and interpolation is needed in order to compare both sources of signals.

(a) IMU installation on the scale helicopter

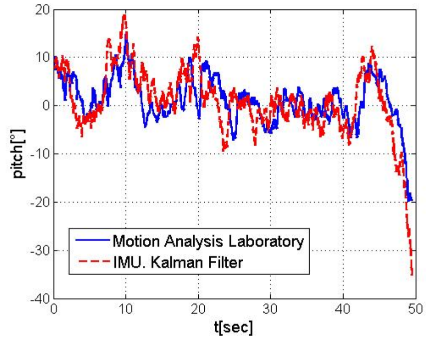


(b) Movement markers

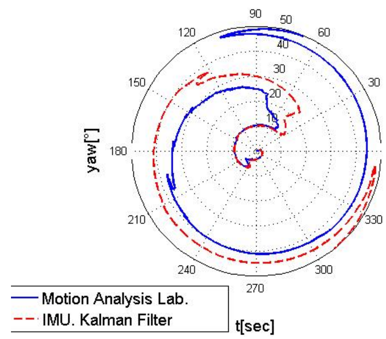
Fig. 9. Set up of the IMU and helicopter at the motion analysis laboratory

Localization by external cameras have been used for UAVs indoor experiments, however the use of a motion analysis laboratory for assessing and onboard IMU performance has not been implemented. Through this method it is possible to evaluate the IMU by comparing it with a totally different source of information, instead of the classical comparison with another IMU previously tested and calibrated.

The experiments were carried out using a safety stand that supports the helicopter allowing only its rotational 3-DOF with minimum inertial effect. The results are presented in Fig.10 for roll, pitch and yaw angles. The pitch angle given by the motion analysis lab and its calculation from the IMU data is presented in Fig.10(a). A similar comparison is presented in Fig.10(b) and Fig.10(c) for yaw and roll angles, respectively. It is important to note that after a few seconds the yaw angle loses accuracy due to the drift; a fact that should be corrected by another sensor. Fig.10(d) shows the difference between the roll estimation from raw sensors without any fusion method and the result obtained by the Kalman Filter.



(a)



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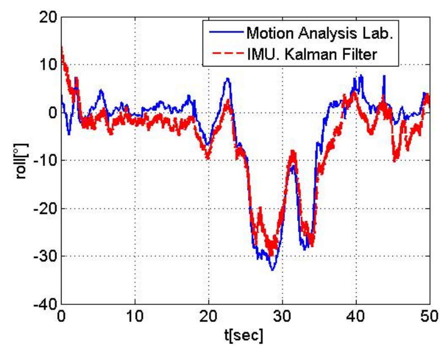
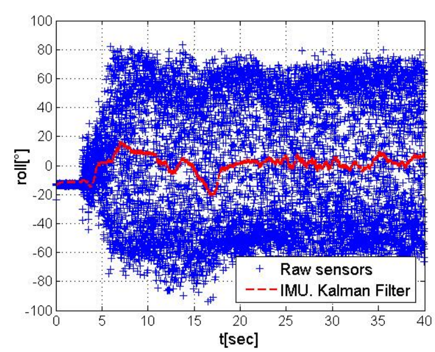


(c)



(d)

Fig. 10. Attitude determination results for a scale helicopter: IMU vs. Motion Analysis Laboratory

VI. CONCLUSIONS

The development of a low-cost IMU for UAV applications was presented in this paper. The design is based on the ideas of modularity, antialliasing processing, low weight and simultaneous sampling to avoid loss of orthogonality of the inertial measurements. The general block diagram and implementation were presented showing both the sensor and processing boards.

The IMU attitude determination performance was tested under true UAV conditions through two experiments: (1) Comparison with encoders of a 2-DOF helicopter platform, and (2) Comparison with the infrared cameras measurements of a motion analysis laboratory using a T-REX 450 scale helicopter. The angle estimation error was under $4°$ RMS.

This IMU prototype will be redesigned using surface mountain components for a final low-cost product of less than 40g with a performance suitable for UAV applications. Future work will be also focused on the translational variables calculation and the addition of a GPS and a compass.

REFERENCES

[1] Samuel Fux, André Noth, Samir Bouabdallah and Janosch Nikolic: *Development of a Planar Low Cost Inertial Measurement Unit for UAVs and MAVs*. Swiss Federal Institute of Technology Zurich ETH, Autonomous Systems Lab, Prof. Roland Siegwart (2008)

[2] Grewal, M.S.; Henderson, V.D.; Miyasako, R.S.: *Application of Kalman filtering to the calibration and alignment of inertial navigation systems*. IEEE Transactions on Automatic Control, vol. 36, No. 1, pp. 3–13, (1991)

[3] Gebre-Egziabher, D.; Hayward, R.C.; Powell, J.D.: *Design Of Multi-sensor Attitude Determination Systems*. IEEE Transactions on Aerospace and Electronic Systems, vol. 40, No. 2, pp. 627-649, (2004)

[4] David Titterton y John Weston: *Strapdown Inertial Navigation Technology*. IET Radar, sonar, navigation and avionics series 17, AIAA (American Institute of Aeronautics and Ast; 2da Edición, (2005)