EXPERIMENT ON THE APPLICATION OF A CUBE TYPE GYROSCOPE-FREE INERTIAL MEASUREMENT UNIT ON LAPANS RUM PAYLOAD-TEST ROCKETS

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Abstract

This paper discuss the application of a Gyroscope Free Inertial Measurement Unit (GF-IMU) for rocket. A GF-IMU is an inertial measurement unit that uses only sets of accelerometers to compute both translation and rotational of a vehicle, which in this case was a rocket. The elimination of gyroscope caused the system to be much cheaper (low-cost), compared to conventional inertial measurement unit.

A cube type GF-IMU was used as a case study. The system were implanted in a payload test rocket (Roket Uji Muatan, RUM). The rocket was launch in August 2009 as part of student payload rocket competitions held by Indonesian National Institute of Aeronautics and Astronautics (Lembaga Penerbangan dan Antariksa Nasional, LAPAN).

The GF-IMU data were transmitted during flight and recorded on the ground station. Analysis were conducted to obtain the rocket translational and rotational accele-rations by processing the data. The experience on manufacturing, transmitting, recording and processing data from GF-IMU on rocket application were described in the end his paper.

1 General Introduction

The objective of this research was to verified the performance of a cube type GF-IMU on a rocket flight to measure both translation and rotation acceleration. This experiment will also be a milestone on expanding the use of GF-IMU, especially on developing a low-cost control system for rockets.

The GF-IMU subjected in this research were the cube configuration proposed by Park [1]. This cube type GF-IMU will be described briefly in section 1.1, including the underlying equation to derive translational and rotational acceleration from its data. The rocket use for the experiment was the LAPAN RUM Payload Test rockets, which will be described in section 1.2.

Section 2 in this paper will described the GF-IMU system manufacture process for application in LAPAN RUM rocket. Section 3 will discuss the data obtained from the experiment, how it was processed and the general analysis. Section 4 will list the concluding remarks of the experiments, including some future works suggestions.

1.1 Cube Type GF-IMU

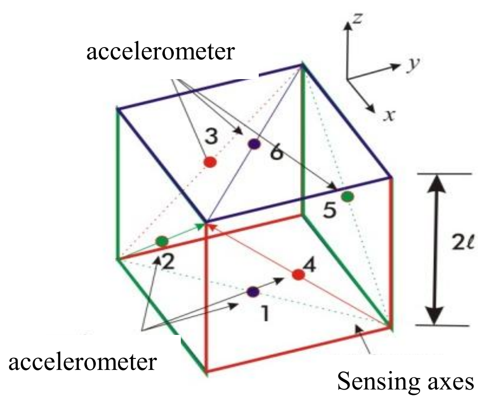

Fig. 1 Cube Type GF-IMU

The Cube Type GF-IMU proposed by Park [1] uses six accelerometers, placed at the center of each six cube faces, and sensing direction along the respective cube face diagonal in such a way that the six sensing direction forms a regular tetrahedron (see Figure 1).

The equation use to obtain rotational and translational acceleration ($\dot{\omega}$ and f_b) of the cube frame of reference (as shown also in Figure 1), could be presented as follows [1]:

$$\dot{\omega}_{ib}^{b} = \frac{1}{2l^2} J_1 A \tag{1}$$

$$f^b = \frac{1}{2} J_2 A + l \begin{bmatrix} \omega_{ib2}^{b}\omega_{ib3}^{b} \\ \omega_{ib1}^{b}\omega_{ib3}^{b} \\ \omega_{ib1}^{b}\omega_{ib2}^{b} \end{bmatrix} \tag{2}$$

Where *2l* is the cube length, while A is the vector of accelerations measure by each accelerometers, and J_1 and J_2 is the configurations (cube) matrix, which are described as follows:

$$A = \begin{bmatrix} A_1 & A_2 & A_3 & A_4 & A_5 & A_6 \end{bmatrix}^T \tag{3}$$

$$J_1 = \frac{l}{\sqrt{2}} \begin{bmatrix} 1 & -1 & 0 & 0 & 1 & -1 \\ -1 & 0 & 1 & -1 & 0 & -1 \\ 0 & 1 & -1 & -1 & 1 & 0 \end{bmatrix} \tag{4}$$

$$J_2 = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 & 0 & 0 & -1 & -1 \\ 1 & 0 & 1 & -1 & 0 & 1 \\ 0 & 1 & 1 & 1 & 1 & 0 \end{bmatrix} \tag{5}$$

Equation (1) – (5) could be use to solve both rotational and translational accelerations, thus it could substitute the use of the conventional IMU combinations of accelerometer and gyroscope. However, this method would require an additional integrations step to obtains rates and positions.

1.2 LAPANs RUM Payload Test Rocket

In this paper, the application of the cube-type GF-IMU for rockets was tested using the RUM rockets (see figure 2), a payload-test rockets, developed by the Indonesian National Institute of Aeronautics and Astronautics (LAPAN) [6].

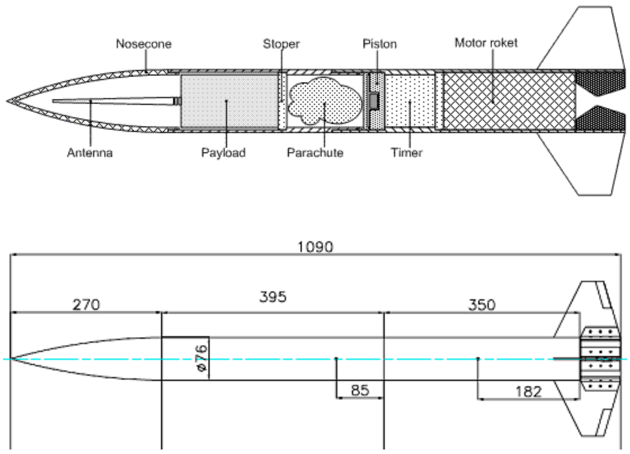

Fig. 2 LAPANs RUM Rockets (courtesy of LAPAN.go.id)

The dimensions and specifications of this rocket are described as follows:

Parameter	Unit	Value
Total Length	[m]	1.09
Body Length	[mm]	76
Total Weight	[kg]	4.6
Thrust	[kgF]	30
Operational Height	[m]	800-1500
Shock Burning	[g]	10
Body Material	-	PVC
Propellant	-	composite

With its low-cost characteristics, the cube-type GF-IMU is suitable to measure both the translation and angular rate of this rocket. The GF-IMU was placed in the payload modules, which was equipped with parachutes. The rocket flight mission is described in section 4.1.

1.3 LAPANs RUM Payload Rocket Competitions Rule and Procedures

The research in this paper uses the Annual Payload Rockets Competitions to test the cube-type GF-IMU. The competition was held by Indonesian National Institute of Aeronautics and Astronautics (Lembaga Penerbangan dan

Antariksa Nasional, LAPAN). It was a supervised student-team competition on designing and constructing a payload system (and thus, not the rocket) for LAPANs RUM Rockets (described in section 1.2).

The designed payload system must meet the competition limitations and requirements, which summarized as follows [6]:

- Payload consist of sensors that must include sensors to measure air humidity, temperature and pressure during flight. The payload should also have an accelerometer system as an inertial measurement unit. No gyroscope were allowed
- Sensors Baud rate at 9600 bps.
- Flight data should be obtained during flight using radio transmitter-receiver, provided by the competition committee. This obtained during-flight data and the data post-processing analysis will be the main subject of scoring.
- The payload system should be fit in the payload module of LAPANs RUM Rockets (cylinder), with dimensions as follows:
    - Diameter : 67.0 mm
    - Length : 207.9 mm

The cube-type GF IMU was then proposed for by this papers author supervised team. It was proposed mainly to overcome the competitions no gyroscope rules, while still could be able to measure both translation and angular accelerations of this rocket. Nevertheless, it was also aimed to impress the judges to win the competitions.

The RUMs rockets were launch from Pandansimo beach in Yogyakarta, Indonesia. It flight a parabolic trajectory at initial elevation of 70^o. At 10 second after the launch, the piston component (see Figure 1) will operates, separated the payload module from the rest of the rockets. The parachutes deployed, and the payload slowly descent to the ground. Figure 3 describe briefly the rockets flight mission.

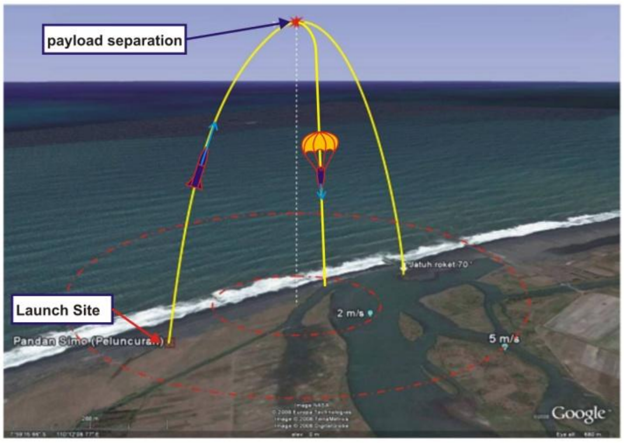

Fig. 3 LAPANs RUM Rockets designed trajectory

2 GF-IMU System Constructions

The GF-IMU was connected with a telemetry system in order for the ground station to received data immediately during the flight. The data, consist of the six acceleration measurement from each accelerometers, was then processed after the flight.

This chapter will describe the concept, materials, manufacturing process and calibrations in constructing the GF-IMU system for the rocket payload.

2.1 Payload Concept and Design

The cube-type GF-IMU was a part of the payload sensors system, which work together during the rocket flight with the air relative humidity, temperature and pressure sensors. The main concept of this payload system was described in the following figure:

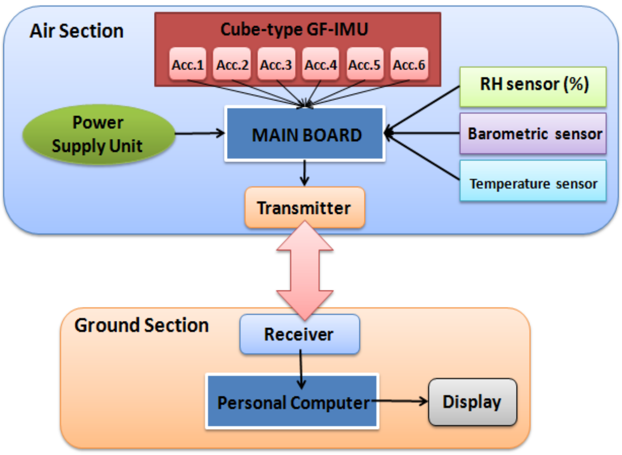

Fig. 4 Rocket Payload Concepts

As the rocket payload module compartment were cylinder, the payload was also a cylinder base with mainly aluminum structures. It consist of four level, with the cube-type GF-IMU placed in the second, described together with the already finished payload system, as follows:

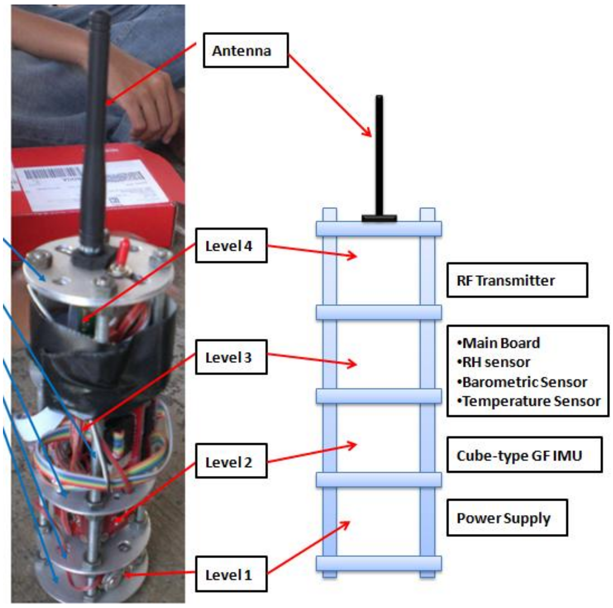

Fig. 5 Payload System Details

The lowest level of this payload was where the power supply (i.e. batteries) placed, which supply power for the entire system. The transmitter antenna was placed in the top level.

2.2 Cube-type GF-IMU Design

The cube-type GF-IMU system used in this research consists of six two-axis ADXL321 accelerometers with specifications as follows:

- Low power consumption 840 μW
- Small package
- Fast Responses.
- Small and Thin (4 mm × 4 mm × 1.45 mm LFCSP package)
- 3 mg resolution
- 2 axis accelerometer, +/- 18 G

It should be noted that the system actually only require single-axis accelerometers, therefore only one axis of the ADXL321 accelerometers were tapped. Each accelerometer were place in a square PCB, with cables extended from it, which will be connected to the transmitter circuit board, at the fourth level (see section 2.1).

Aluminum cube were use to construct the GF-IMU cube, with length of 3 cm. Accelerometers PCB were glued on each side of the aluminum cube structure, as shown in Fugure 6.

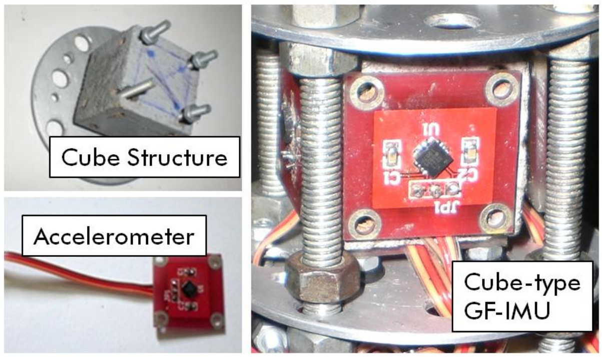

Fig. 6 cube-type GF IMU Construction

These accelerometer outputs would be in voltage unit, tapped via an analog-digital converter than converted into RS232 level signal, before it transmitted to the recorder on ground. Next section explains the calibrations of the signal obtained into an acceleration unit (in g or m/s)

2.3 Gravitational Calibrations

The manufacturers already provided equations to converts the accelerometers output into acceleration unit. However, since there were six accelerometer, pointing in various directions from gravity (or, earth surface), calibrations works needs to be conducted. These calibrations were conducted after all six accelerometers have been installed forming the cube-type GF-IMU, and have been put in the rocket payload system, as explained in previous section.

Gravity was used as the control parameter of the calibration process. The GF-IMU system in the payload structure was placed in several positions on a flat surface, where each accelerometer measurements was done for two attitudes from the surface, 45° and -45°.

The output of each accelerometer for each position, and the acceleration that should be measured (based on gravity), were tabulated as follows:

Acc.	measured	1st position (-45°)	2nd position (+45°)
1	Output	504	530
	G*	-g/√2	+g/√2
2	Output	505	530
	G*	-g/√2	+g/√2
3	Output	506	525
	G*	-g/√2	+g/√2
4	Output	507	528
	G*	-g/√2	+g/√2
5	Output	499	523
	G*	-g/√2	+g/√2
6	Output	501	527
	G*	-g/√2	+g/√2

* acceleration 'should be' measured

Furthermore, the result could be presented in figure 7, as follows:

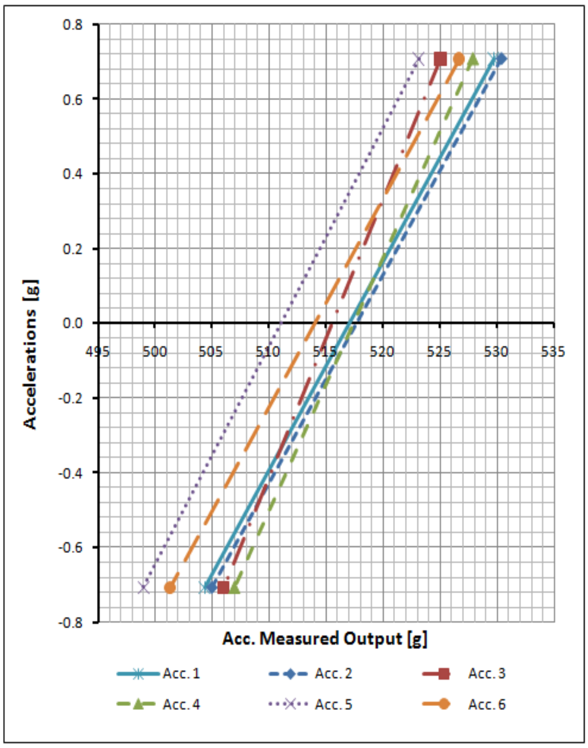

Fig. 7 Accelerometer Output Reference

While assuming the linearity of each accelerometer, these results will be the reference for data calculations, detailed in chapter 3.

3 GF-IMU Experiments and Analysis

There were two experiments conducted for this research, which were vibrations test, and the rocket launch experiments. In the end of this chapter, the data analysis will be explained.

3.1 Vibrations Test

This vibration test was conducted in the vibration laboratory facility in the Faculty of Mechanical and Aerospace Engineering, ITB. This test was part of the payload system test which includes data acquisition system and structural rigidness.

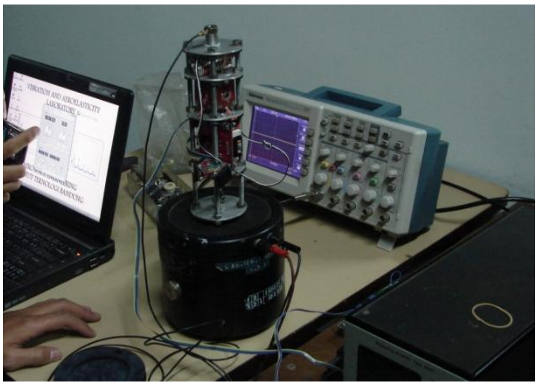

Fig. 8 Vibration Test Setup

The test was conducted using a 3g exciter, which would give a vertical vibration of six times gravity. The vibration was conducted two times for medium and high vibration the exciter could gives.

Since the GF-IMU system only subjected by a single axis, vertical accelerations, only the 'sides' accelerometer (2-3-4-5) would measure it. It should be noted that in the test, the payload system was placed up-side down, so the gravity would be measured as positives. The output results, and the accelerations converted from it, are presented in the following graphs for each 'sides' accelerometer.

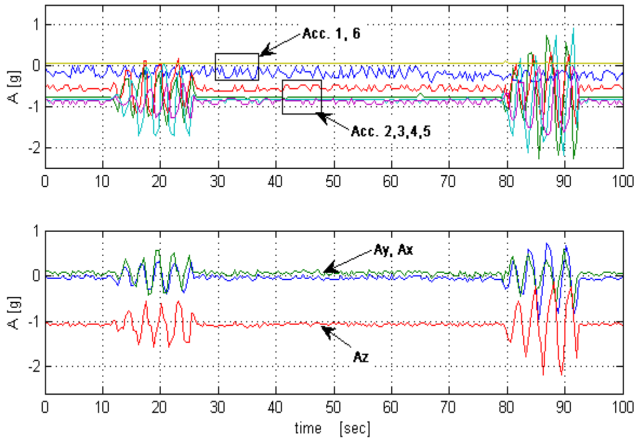

Fig. 9 Vibration Test Measured Accelerations

The figure above indicate the reliability of the cube-type GF-IMU system, which result measured accelerometer confirm the exciter setting by .

As it could be observed in figure 9 that even though the payload only subjected by single axis accelerations, the ‘sides’ accelerometers (2,3,4,5) did not measure the same value. This could indicates either there was some small rotation motion, or could also be difference in accelerometers resolutions errors. Observations during this vibration test confirm that the payload system did wobble, which could induce a rotation motion. Using the cube-type GF-IMU equation in section 1, this rotation motion parameters could be extracted, as follows:

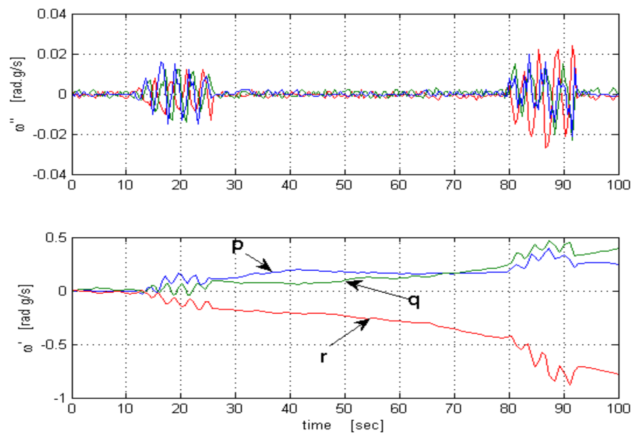

Fig. 10 Vibration Test Measured Rotational Accelerations

While the payload system might rotate a little bit, figure 10 shows that accelerometers resolution was indeed contains some error. This could be observed from the rotation speed between two vibration. It shows some certain values, while in the reality during the test, the payload only wobble when the vibration induced.

The last conclusions would be considered in the flight test data results, especially data related to the rotations motion. It should also be noted that errors in an inertial measurement unit typically would increase logarithmically with time.

3.2 Rocket Launch and Flight

The LAPANs RUM Rocket, carrying the payload system described before, was launch together with other rockets from each competing team. It was launch according to the procedures explained in section 1.3 without any significance disturbance, both technical and environments. The following figure shows the launching of author supervised team, next to other rockets.

Fig. 11 LAPAN RUMs Rockets Launch Off

The flight last about eight seconds from the launch, before separation of payload module. The payload module itself could not be retrieved as it fall to the ocean.

During flight, all data were tapped. They were processed after the competition for the team presentation in the next day. The data tapped, and the flight data resulted, are presented in the following figure.

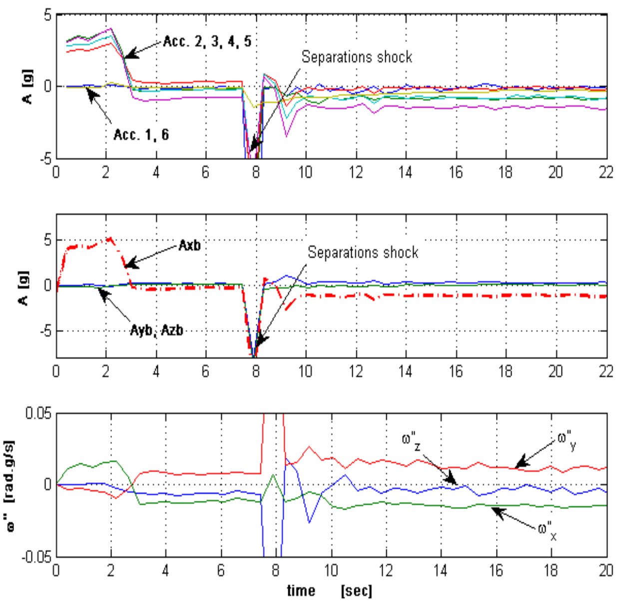

Fig. 12 Flight Test Measured Accelerations

The flight data result shows a good agreement with the observation during flight. The sudden change of accelerations almost certain indicates were the separations process, which used pistons, happened, at about 7.5 – 8 second after launch. The result also shows significant variation of accelerations happen on the body X-axis, which confirm the acceleration caused by the rocket motor, with maximum 5 g accelerations. After the separation shocks, the body X-axis acceleration became relatively constant at -1g, which could indicates that the rocket free-falling with gravity, with 90^{o} pitch attitude, resulting from the use of parachute. This last analysis, however, could not be confirmed in the trajectory reconstruction (see figure 14). Instead, the trajectory shows a somewhat random trajectory after the separations, which was actually not possible in the real world.

To reconstruct the rocket trajectory, the flight data require to be transformed, from body axis reference, into the earth axis. The transformation matrices for this purposes could be derived from the second integrations of the rotational accelerations, which produce the attitude angle (Euler angles). The rocket position and attitude are presented in the following figure, along with the rocket trajectory, compared with the 'supposed' to be values for a parabolic trajectory.

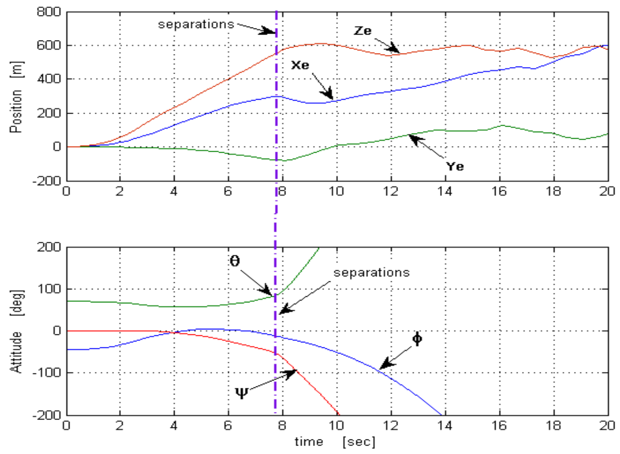

Fig. 13 Measured Position and Attitude

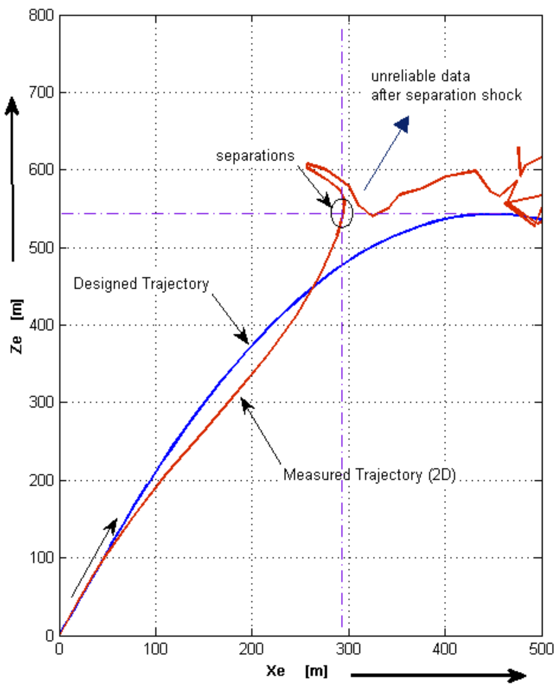

Fig. 14 Flight Trajectory (2-Dimensional)

Figure 14 only shows the 2-dimensional trajectory, which was the designed trajectory, assuming no cross wind or other disturbances occurs. However, the cube-type GF-IMU could actually measured flight parameters in 3-dimensional. It could be observed from the 3-dimensional trajectory, shown in figure 13 below, that the rocket sway more than 50 meters to its left side during its flight. This motion was also confirmed with the flight videos.

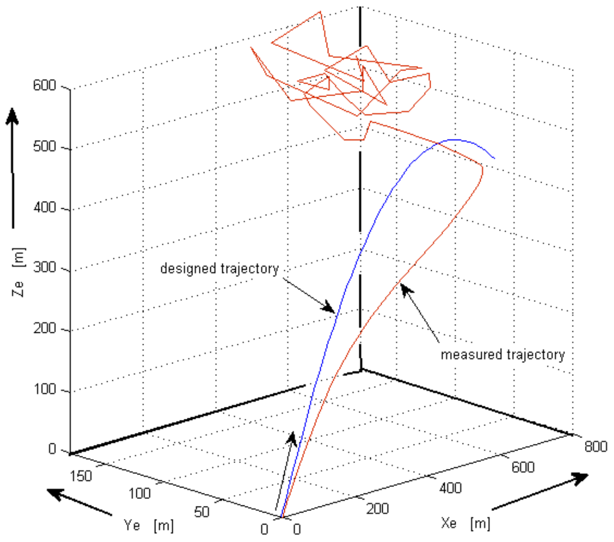

Fig. 15 Flight Trajectory (3-Dimensional)

As mentioned before, after separations, the trajectory recorded became somewhat random, which did not confirm the rocket flight reality, and actually was not physically possible. This error might result from the same reason in the vibration test. As it could be observed in Figure 13, after the separations, the rocket attitude were wildly increased.

The reason for this was when the separation occur, all accelerometer shows a sudden high reading, resulting from the separation shocks. This error, while it happen only in a short time, result a never ending logarithmic increase in attitude. Furthermore, with errors in attitude, the body-earth reference transformation matrices would also error, and in the end resulting a random trajectory, after separations, as shown in Figure 14 and 15.

4 Concluding Remarks

On the applications of the cube-type Gyroscope Free Inertial Measurement System for a simple rocket (LAPANs RUM rocket), there could be listed several concluding remarks, as follows:

1. The cube-type GF-IMU make a fine substitution for a gyroscope function. The construction, as well as the data calculations involved, was fairly simple.
2. More than one sensors involved, however, was a downside, since it would require more complicated calibrations process. This was true especially for the calibrations after the accelerometers were combined into a cube type GF-IMU system. A standardize calibrations process for this matter is mandatory.
3. Another condition that would produce error is the precision of the accelerometer positions. Not only the cube structure that require to be symmetric, the angle of each accelerometer, which is 45^o on each side, also have to be perfects. A standard tolerance need to be developed for this matter. Park [1] also gives some suggestion for this.
4. As several error might occur, a filter algorithm might became important. Filho [2] suggest the use of Kalman Filter to reduce errors in calculations.
5. Similar with other Inertial Measurement Unit, the cube-type GF-IMU also has a logarithmic characteristics of error. For a rocket applications, this could be fatal, since rockets are likely to endure sudden change of accelerations. In the example in this paper shows that matter with a random measured trajectory, after the LAPANs RUM rocket payload module endure the separation shocks.
6. The results shown in this paper were confirmed only by observations during flight. For a better analysis in the future, a gyroscope might be use for data redundancy, to have comparison data for another inertial measurement system.

References

[1] Park S, Tan C-W. Research Reports, GPS-Aided Gyroscope-Free Inertial Navigations Systems. California Partners for Advanced Transit and Highway, University of California, Berkeley, 2002

[2] Filho E A M, Kuga H K, Neto A R. Integrated GPS/INS Navigation System Based on a Gyroscope-Free IMU. *Brazilian Conference on Dynamics, Control and Their Applications* (DINCON 2006), Guaratinguata, SP, Brazil, 2006.

[3] Filho E A M, Kuga H K, Neto A R

[4] Park S, Tan C-W, Park J. A scheme for improving the performance of a gyroscope-free inertial measurement unit. *Sensors and Actuators A: Physical*, Volume 121, Issue 2, 30 June 2005, Pages 410-420
[5] Astronic System Project Team, Laporan Lomba Muatan Rocket (Rocket Payload Competition Reports), Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung, 2009
[6] ______. Lomba Muatan Roket 2009: Payload Meterologi, Panduan Peserta *(Participant Guide, Rocket Meteorology Payload Competition).* Indonesia National Institute of Aeronautics and Astronautics (LAPAN), 2009

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