Speed acquisition system for reaction wheel of LAPAN-A3 Satellite using field programmable gate array module

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Abstract. Reaction wheel is one of the important components in satellite attitude control by employing torque to satellite through command, resulting in the change of the angular momentum (or angular velocity) of the satellite. LAPAN-A3, the third-generation satellite built by LAPAN, utilizes three systems of reaction wheel placed on three coordinate axes. The system consists of two parts; electric motor and wheel drive electronic (WDE) to adjust the motor’s motion by reading input from control center. This research will implement the measurement of reaction wheel system by using field-programmable gate array (FPGA) as the processor. The outcome of this study is expected to obtain more accurate results and lower transient delays in acquiring the speed of wheel than that of generated input signal from PC.

1. Introduction
LAPAN-A3, also known as LAPAN-IPB, is the third satellite built by LAPAN, in collaboration with Institut Pertanian Bogor (IPB), after LAPAN-A1/LAPAN-TUBSAT and LAPAN-A2/LAPAN-ORARI. It is the first Indonesia’s remote sensing satellite [1], launched on June 22nd 2016 from Sriharikota Space Center, India, with ISRO’s PSLV rocket launcher.

In the same way as its direct predecessor LAPAN-A2, the assembly, integration, and test of LAPAN-A3 was conducted in Indonesia. Its remote sensing main mission is supported by a 4-band Line Scan Imager (LISA) [2], which consists of red, green, blue, and near infrared (NIR) spectral bands, and a Space Digital Camera (SpaceCam), providing data of growing season, such as planting season, fertilization, harvest season, and crop yield forecast. LAPAN-A3 is also equipped with Automatic Identification System (AIS) signal receiver to track and monitor vessel movements in polar orbit.

Many types of actuators have been used for the satellite attitude control such as magnetic torquer, momentum wheel, reaction wheel, control moment gyro and thrusters, etc [3]. The satellite bus of LAPAN-A3 utilizes the same attitude control actuators as in LAPAN-A1 [4] and LAPAN-A2 [5] which is comprised of four pairs of reaction wheel (RW) and three air coils, with horizon sensor [6] and star sensor [7] as complementary. Reaction wheel itself has been widely used in spacecraft attitude control system to carry out high precision control, e.g. directing the antenna for sending image or AIS data to ground station. The wheel conveys torque command from electromagnetic torque emitted by the attitude control system.

RW consists of two parts; reaction wheel assembly (RWA) and wheel drive electronics (WDE). Reaction wheels operate by accelerating a wheel in one direction and thereby forcing the satellite to
rotate in the other direction [8]. In principle, RWA is comprised of brushless direct current (BLDC) and load mass with certain moment of inertia mounted on the motor shaft or wheel. WDE is an electronic component actuating BLDC on RWA so the wheel rotates according to the desired torque or angular momentum [9]. Performing tests on satellite apparatus is vital before initiating satellite integration. This series of tests is a part of component-level verification in satellite development phase [10].

This paper measures the speed of reaction wheel using a field-programmable gate array, an integrated circuit that can be programmed directly by users after manufacture. FPGA consists of programmable logic blocks distributed by interconnecting 'wire' (routing channels) that can be reconfigured according to user requirements [11]. FPGA is widely used by electronic developers because of its advantages in cost efficiency, customized architecture that adapts to algorithms, and heavy computing at high speed. Recent advances in FPGAs have made hardware-accelerated computing a reality for many application domains, including image processing, digital signal processing, data security and communications [12].

2. System design

This project is intended to optimize WDE output read by signal measurement device. User input commands through personal computer (PC) in the form of rotation per minute (rpm) which will be executed by the motor, namely -9000 rpm, -6000 rpm, -3000 rpm, -1000 rpm, -500 rpm, -200 rpm, -100 rpm, -50 rpm, +50 rpm, +100 rpm, +200 rpm, +500 rpm, +1000 rpm, +3000 rpm, +6000 rpm, and +9000 rpm. The positive sign indicates clockwise gyration and the negative sign denotes otherwise.

From the sixteen frequency values, four inputs are needed; three ports of frequency option (this will give eight different selections) and one for spin direction. The input is sent via serial communication between PC and microcontroller. Microcontroller reads the given value and direction, passing them in parallel afterwards to FPGA through nine GPIO headers. FPGA processes the inputs and delivers them (as seen as Sense A, B, and C sensors) to WDE and measuring instrument such as oscilloscope (figure 1).

2.1. Microcontroller system design

Serial communication system between microcontroller and FPGA is needed to send data [13]. This system utilizes the pins available on the ATMega 128 microcontroller which uses three pins for sending desired frequency signal, one pin for reset, and one pin for determining the signal in clockwise or counter-clockwise whirl. The signal transfer from the microcontroller to the FPGA is parallel. If the three pins for sending the desired frequency signal is active, then the signal sends 9000 rpm; if all three pins are off, then the signal sends 50 rpm. For the provision of signal sending can be seen in table 1.
Table 1. Conditions for signal transfer.

| Pin 1 | Pin 2 | Pin 3 | Frequency Inferred |
|-------|-------|-------|-------------------|
| Off   | Off   | Off   | 50                |
| Off   | Off   | On    | 100               |
| Off   | On    | Off   | 200               |
| Off   | On    | On    | 500               |
| On    | Off   | Off   | 1000              |
| On    | Off   | On    | 3000              |
| On    | On    | Off   | 6000              |
| On    | On    | On    | 9000              |

2.2. FPGA system design

Microcontroller provides inputs of control signal to FPGA, such as reset RST, motor rotation SW_W, and eight frequency selections SW. The FPGA system consists of three subsystem modules; CLOCKDIV yields new frequency value from clock divider approach based on 50 MHz internal clock [14]. FSM (finite state machine) contains state machine to generate A, B, and C sensor that differs 60 electronic degrees with each other, and tb_sensewde as testbench integrates all subsystems.

Figure 2. Data flow diagram of FPGA system design.

Figure 3. FSM for clockwise (upper) and counter-clockwise (lower).
Clock divider in CLOCKDIV is a circuit that receives input frequency $f_i$ to produce output frequency $f_o$:

$$f_{out} = \frac{f_{in}}{n}$$

where $n$ as an integer. The module affects a counting variable which will be incremented by one on each rising edge clock, then returning to initial number of zero after reaching the desired integer obtained from the formula above and converting frequency in rpm unit to hertz.

The state machine for sensors is defined on the motor datasheet [15] where each sensor has six states [16] to change its signals (temp signal to store temporary sensor signal) for either clockwise or counter-clockwise rotation, in addition of idle state for initializing all signals and variables during reset.

**Figure 4.** Flowchart of CLOCKDIV module.
3. Simulation

**Figure 5.** Simulation result of CLOCKDIV module with 111 input.

Figure 5 depicts clock divider process in CLOCKDIV module. When the input is 9000 rpm or 111 in the form of port, the process counts to its stored integer 27777 for every 50 MHz or 20 ns and yields new desired frequency after reaching that value.

**Figure 6.** Simulation result of reset condition.

**Figure 7.** Simulation result of clockwise direction.

**Figure 8.** Simulation result of counter-clockwise direction.
For FSM module, starting from figure 6, reset condition initializes all signals and variables and will not produce any output albeit changes occurring on input. After disabling reset, the next state of either clockwise or counter-clockwise takes place superseding idle state. If the control signal designates motor to rotate clockwise, the state shifts in S1-S2-S3-S4-S5-S6 order with respective signal changes in A, B, and C sensors; otherwise, shifting occurs in S1-S6-S5-S4-S3-S2 sequence. Following the process, when reset is reactivated, idle state ensues; registers are initialized and no process follows.

Table 2 has given correct output frequencies for particular input frequency and direction.

| Input (rpm) | Sensor | Output Period (ns) | Output Frequency (Hertz) | Input (rpm) | Sensor | Output Period (ns) | Output Frequency (Hertz) |
|------------|--------|--------------------|--------------------------|------------|--------|--------------------|--------------------------|
| 9000       | A      | 6666599            | 150                      | 9000       | A      | 6666597            | 150                      |
|            | B      | 6666599            | 150                      |            | B      | 6666597            | 150                      |
|            | C      | 6666597            | 150                      |            | C      | 6666599            | 150                      |
|            | A      | 9999994            | 100                      |            | A      | 9999990            | 100                      |
| 6000       | B      | 9999990            | 100                      | 6000       | B      | 9999994            | 100                      |
|            | C      | 9999996            | 100                      |            | C      | 9999994            | 100                      |
|            | A      | 19999992           | 50                       |            | A      | 19999994           | 50                       |
| 3000       | B      | 19999993           | 50                       | 3000       | B      | 19999997           | 50                       |
|            | C      | 19999997           | 50                       |            | C      | 19999992           | 50                       |
|            | A      | 59999998           | 50/3                     |            | A      | 59999994           | 50/3                     |
| 1000       | B      | 59999994           | 50/3                     | 1000       | B      | 59999991           | 50/3                     |
|            | C      | 59999998           | 50/3                     |            | C      | 59999993           | 50/3                     |
|            | A      | 119999988          | 25/3                     |            | A      | 119999995          | 25/3                     |
| 500        | B      | 119999992          | 25/3                     | 500        | B      | 119999992          | 25/3                     |
|            | C      | 119999995          | 25/3                     |            | C      | 119999992          | 25/3                     |
|            | A      | 299999994          | 10/3                     |            | A      | 299999996          | 10/3                     |
| 200        | B      | 299999992          | 10/3                     | 200        | B      | 299999990          | 10/3                     |
|            | C      | 299999992          | 10/3                     |            | C      | 299999992          | 10/3                     |
|            | A      | 599999995          | 5/3                      |            | A      | 599999996          | 5/3                      |
| 100        | B      | 599999996          | 5/3                      | 100        | B      | 599999996          | 5/3                      |
|            | C      | 599999995          | 5/3                      |            | C      | 599999992          | 5/3                      |
|            | A      | 119999996          | 5/6                      |            | A      | 119999992          | 5/6                      |
| 50         | B      | 119999992          | 5/6                      | 50         | B      | 119999994          | 5/6                      |
|            | C      | 119999994          | 5/6                      |            | C      | 119999994          | 5/6                      |
4. Verification result

![Compilation result](image)

**Table 3. Output frequency measurement for every input.**

| Input Direction | Input Frequency (RPM) | Sensor Frequency (Hz) | Steady State (µs) |
|-----------------|-----------------------|-----------------------|-------------------|
|                 |                       | A        | B      | C     | A       | B       | C       |
| Positive        | 9000                  | 150     | 150   | 150   | 200     | 200     | 200     |
| Positive        | 6000                  | 100     | 100   | 100   | 100     | 100     | 100     |
| Positive        | 3000                  | 50      | 50    | 50    | 37.5    | 37.5    | 37.5    |
| Positive        | 1000                  | 16.67   | 16.67 | 16.67 | 200     | 200     | 200     |
| Positive        | 500                   | 8.33    | 8.33  | 8.33  | 1000    | 1000    | 1000    |
| Positive        | 200                   | 3.33    | 3.33  | 3.33  | 100     | 100     | 100     |
| Positive        | 100                   | 1.67    | 1.67  | 1.67  | 2000    | 2000    | 2000    |
| Positive        | 50                    | 0.83    | 0.83  | 0.83  | 1000    | 1000    | 1000    |
| Negative        | 9000                  | 150     | 150   | 150   | 0.4     | 0.4     | 0.4     |
| Negative        | 6000                  | 100     | 100   | 100   | 20      | 20      | 20      |
| Negative        | 3000                  | 50      | 50    | 50    | 100     | 100     | 100     |
| Negative        | 1000                  | 16.67   | 16.67 | 16.67 | 200     | 200     | 200     |
| Negative        | 500                   | 8.33    | 8.33  | 8.33  | 1000    | 1000    | 1000    |
| Negative        | 200                   | 3.33    | 3.33  | 3.33  | 400     | 400     | 400     |
| Negative        | 100                   | 1.67    | 1.67  | 1.67  | 500     | 500     | 500     |
| Negative        | 50                    | 0.83    | 0.83  | 0.83  | 2000    | 2000    | 2000    |

The highest delay-time transient response, 2 ms, is found on A, B, and C sensors when the output frequency is -50 rpm and +100 rpm and all output signals show negative result of overshoot transient response. It is significantly lower than the highest delay-time on Septanto’s paper [18], 10 ms, which is 5 times slower, using CPU as input signal generator.

5. Conclusion

Wheel speed acquisition with FPGA has been successfully implemented and verified; it provides 0% of error on output signals without overshoot transient response and 5 times faster of highest delay-time compared from previous work [18]. A highly accurate output signal of speed acquisition will result in precise component-level verification of reaction wheel, confirming that acquisition system using
FPGA delivers improved outcome. Recommended further work will include arbitrary and limited ranged input frequency values for better component-level verification.

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