

Earth Observation Micro-satellite Design Optimization Using Satellite Simulator

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ABSTRACT

With the more demanding performances and more limited resources available, obtaining an optimized engineering design is the necessity for design engineers. Therefore, the objective of the research is to develop method for optimizing satellite design. The satellite design phase concerned in the research is in detail design, which mean that the choices for basic configurations of the satellite has been determined. The design case is Earth observation microsatellite, with objective of the optimization is the minimum power consumption from the attitude control subsystem. Doing so, the payload duty cycle, and therefore, the image coverage can be increased. In order to perform the optimization that involve attitude control subsystem, a high-fidelity modeling tool, which in this context means the attitude dynamics module of the satellite simulator used. The module calculate the satellite orientation at any time, and the torque required to perform the camera pointing operation, which is the base for power consumption calculation. The result shows that the simulator can support the selection of the satellite optimal configuration by providing evidence of minimum power consumption. It is also find that due to full acces level, the self-made simulator as used in the research has good potential to be used in the optimization case with search algorithm.

Keywords: *Design Optimization, Earth Observation Micro-satellite, Satellite Simulator*

Introduction

Previous Satellite Design Optimizations

Satellite design optimization using low fidelity design model has been performed, among others, by Hassan [1], Tan [2], Jafarsalehi [3], and Wang [4]. Hassan [1] performed optimization for telecommunication satellite weight by varying the types satellite components, using Genetic Algorithm. The design constraint is the launcher's weight and dimension envelope. The best configuration found in this satellite design is a telecommunication satellite that use Si solar panel, NiH_2 batteries, pasive thermal system, plasma propulsion, and wave tube amplifiers for all of transponders. Tan [2] performed design optimisation for small (1000 kg) class Earth observation satellite with objectives highest resolution and maximum coverage. The design constraint is the payload's size, weight, and power consumption, as well as the satellite's weight and size, based on the launcher's envelope. The variables are the ratio of propellant, structure, power subsystem, attitude control components, and orbit height, and collaborative optimization method is used to find the best configuration.

Jafarsalehi [3] performed optimisation for small (1000 kg) class Earth observation satellite design with objective of highest resolution, and design constrains of launch envelope and groundstation visibility. The variables include orbit height, propulsion, structure, and solar panels, and the optimum search is done by Genetic Algorithm. Wang [4] also optimized Earth observation satellite design with objectives of highest resolution and maximum coverage, with constrain of launch envelope. The design models is aranged web-like structure connected by their coupled variables, called all-at-once (AAO) model, and solved with collaborative method. The variables include orbit height, propulsion, structure, and power subsystem.

Satellite design optimization using high fidelity design model has also been done in subsystem level by Boudjemai [5], Zhang [6], and Kim [7]. In satellite system level design, such work has been done by Wu [8] and Hwang [9]. Boudjemai [5] used finite element analysis software and Genetic Algorithm to optimize the structure of the satellite automatically. Zhang [6] used solid modeling software and Genetic Algorithm to automatically design the satellite components placement, for the required satellite's center of gravity and inertia. Kim [7] used own-built satellite attitude control simulator and Genetic Algorithm to optimize the attitude control system of KITSAT-3 micro-satellite. The resulted design is the KITSAT-3 attitude control with minimum response time.

Wu [8] used commercially available concurrent engineering software iSIGHT, that integrate finite element for the high fidelity model of satellite structure, and Matlab for designing the satellite attitude control, power suply,

and thermal subsystems. The optimum solution is solved using collaborative optimization method, and the aim of the design was to optimize the satellite performance at system level, i.e. image resolution and swath/ coverage.

Hwang [9] developed satellite design models in AAO method, with one of the node as a high-fidelity model, i.e. the satellite orbit and attitude propagator. The propagator also calculates the sun angle with respect to the satellite solar panel, so that the electrical power supplied to the satellite can be calculated. Determining the ground station location, the propagator can calculate the satellite downlink data rate, which is a function of the angle between groundstation line of sight with the satellite antenna. The optimization is done using gradient method, to get the best satellite solar panel and antenna angles for maximum amount of data downlinked in 1 month operation.

Research Objectives and Methods

System level optimization involving high-fidelity design model may become the future in satellite design. However, the approach using commercially available softwares is considered expensive for micro-satellite developer. Meanwhile, the AAO approach requires high ability in mathematics and programming. Therefore, the research proposed the method of optimizing satellite design in two steps, i.e. at system level, using low fidelity design model to get the satellite basic configurations, and then continued using high fidelity model to further optimize the design.

In this research, the system design for the intended micro-satellite has been done [10], as well as the system level multi-objectives optimization [11]. The optimization yield 5 possible design options (pareto), in which, further selection may be performed to get the best design. Several high-fidelity models can be selected, such as finite element model for the design of structure subsystem as in [8], to minimize weight, or orbit propagator with Sun model for the design of power subsystem as in [9], to maximize operation duration.

Attitude control system is crucial in Earth observation satellite, since it needs stable and accurate pointing to produce good quality images. In microsatellite, the limited power supply capacity causes the operation of attitude control system limited only during imaging operation. The system design requirement defined that the imaging operation has to be done at minimum 30% of the orbit time [10]. Therefore, during the rest of the time, the satellite can be set at hibernation mode, in which the attitude control system can be switched-off.

A satellite orbit and attitude dynamics simulator might calculate, in high-fidelity, the power consumption for satellite attitude control. In this research, the variables is satellite moment of inertia, which is different for each configuration, and the satellite control operation modes. The objective

of the optimization is to find satellite configuration with potential of highest satellite imaging operation duration due to its power availability.

The Earth Observation Satellite Configuration

The satellite mission is to obtained images of Earth surface with the highest quality possible (in object recognition), as much as possible. These means a satellite that could accomodate imaging system with highest resolution and widest swath.

The typical micro-satellite design constraints are the maximum dimension of 60x60x80 cm, and maximum weight of 100 kg. The satellite configuration chosen is a box-shaped satellite for maximizing base area utilization, with middle plate to allocate te satellite components. The sattelite imaging payload are placed on the base, so that the length of the lens could be utilized the full height of the satellite. The satellite has body-mounted solar panels occupying the intire four lateral sides. Another design constraint is the maximum downlink datarate that the satellite could perform is 200 Mbps, and the satellite could only perform direct downlink operation mode.

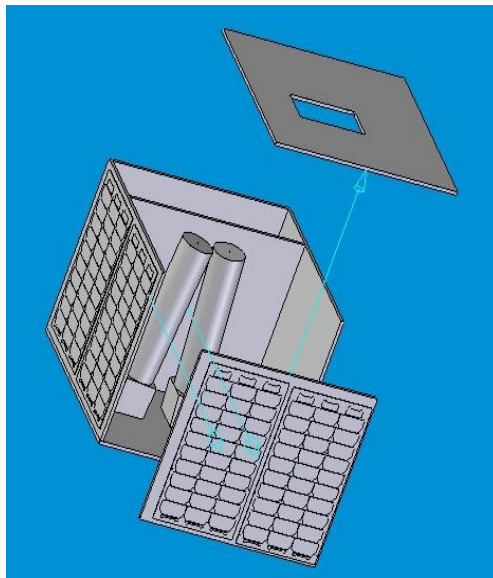


Figure 1: The micro-satellite structure showing its solar panels and 2 camera imagers

The pareto result for optimizing the satellite configuration with respect to highest resolution and maximum image swath is the 5 configurations in table 1 [11].

To accommodate the satellite pointing requirement, it is equipped with 3 reaction wheels and 3 associated gyros, placed in its 3-axis. It is also equipped with star sensor for absolute pointing knowledge. The satellite's power budget analysis from the low fidelity model, i.e. statistics of LAPAN's satellite, shows that the attitude control system (ACS) consumed 29% of the total power consumption [10]. Such consumption is the 2nd highest after the consumption of the satellite's data transmission system. Therefore, the impact from optimizing the ACS power consumption will be significant for the satellite total performance.

Tabel 1 : Optimal satellite configuration recommended by MOPSO

No	Resolution (m)	Swath (km)	Power production (Whr)	Dimension (cm)	Weight (kg)
1	6	50	144,1	60 x 60 x 58,6	80,5
2	7	75	137,6	60 x 60 x 55,9	76,4
3	11	150	155,4	60 x 60 x 63,2	85,5
4	12	175	144,5	60 x 60 x 58,8	80,4
5	13	200	135,3	60 x 60 x 55,0	76,0

Attitude Control Power Optimization

The Satellite Dynamic Simulator

LAPAN-ITB satellite dynamic simulator consist of 4 modules, as illustrated in Figure 2. The first module of the simulator is an orbit propagator. Given the orbit parameters and initial position, the module will calculate the satellite position at any time point. Since no propulsion system installed in the satellite, orbit maneuver is not accommodated in the module.

The second module is a space environment model. Since the simulation is mainly concern in attitude control, the environment to be developed means magnetic flux that the satellite may experience at any position given by the orbit propagator module.

The third module is a satellite model, which simulate the operation status of its 3 reaction wheels and 3 magnetic torquers, based on attitude control mode selected. The known attitude and angular rate knowledge

simulated star sensor and gyros in the satellite, The module also calculates the power consumption of the attitude control subsystem.

The fourth module is attitude dynamics, which calculate the new attitude (angles) based on the attitude control components operation. The input of the module includes satellite moment of inertia. For operation that does not involved external torque (magnetic torque), the new attitude is feedback to the satellite module, or else it feedback to the environment module, before brought to satellite module.

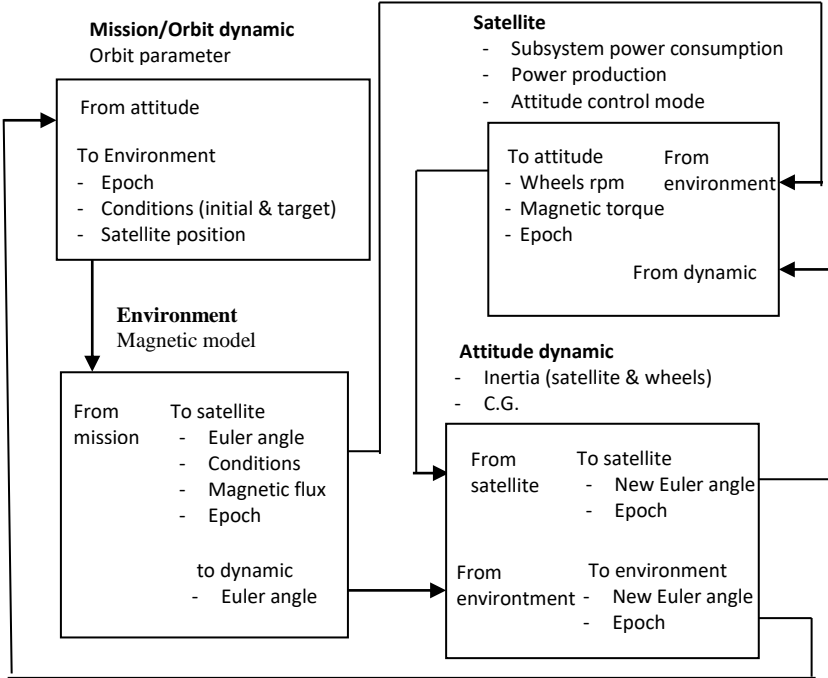


Figure 2: The satellite dynamic simulator schematics

For the case performed in this research, i.e. no external torque, the governing equation of the attitude dynamics for satellite with 3 orthogonal reaction wheels is :

$$\begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{xy} & I_{yy} & I_{yz} \\ I_{xz} & I_{yz} & I_{zz} \end{bmatrix}_S \begin{bmatrix} \dot{\omega}_x^s(t) \\ \dot{\omega}_y^s(t) \\ \dot{\omega}_z^s(t) \end{bmatrix} = \begin{bmatrix} \omega_x^s(t) \\ \omega_y^s(t) \\ \omega_z^s(t) \end{bmatrix} \times \left(\begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{xy} & I_{yy} & I_{yz} \\ I_{xz} & I_{yz} & I_{zz} \end{bmatrix} \begin{bmatrix} \omega_x^s(t) \\ \omega_y^s(t) \\ \omega_z^s(t) \end{bmatrix} + \begin{bmatrix} I_{rw} & 0 & 0 \\ 0 & I_{rw} & 0 \\ 0 & 0 & I_{rw} \end{bmatrix} \begin{bmatrix} \omega_x^{rw}(t) \\ \omega_y^{rw}(t) \\ \omega_z^{rw}(t) \end{bmatrix} \right) \quad (1)$$

Superscripts in the angular rate (ω) denote the rotating bodies; ‘s’ for satellite and ‘rw’ for reaction wheel.

The implementation of the simulator is done in Matlab-Simulink. The validation test of the attitude dynamics part of the simulator was done on [12]. The validation, among others, involved varying the inertia of the satellite starting from no cross product inertia (cylindrical type) to significantly high percentage of cross product inertia, and running 1 reaction wheel in open loop mode. The tests show phenomena as govern by Equation (1), which no nutation occurs in cylindrical type inertia and grow as percentage of cross product inertia increase.

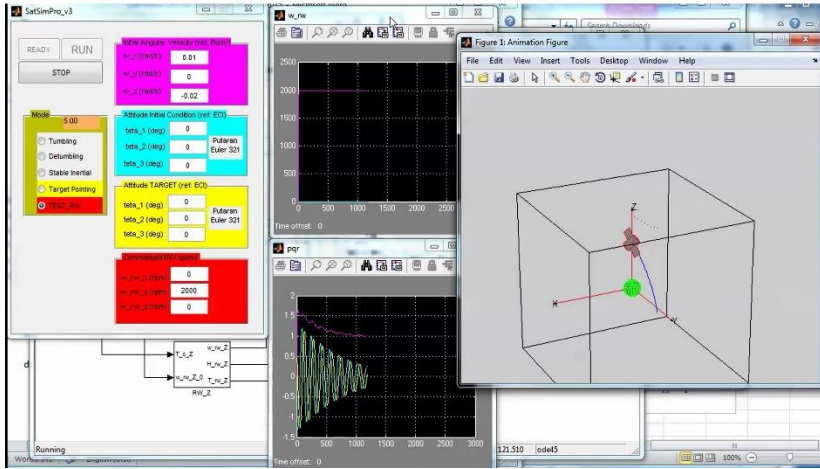


Figure 3: The satellite simulator showing case of angular momentum absorption

The Simulated Cases

The input variables in the attitude dynamic simulation, among other, is the satellite inertia. Based on the satellite mass and dimension in Table 1, the moment of inertia of the satellite is calculated, as listed in Table 2. The cross product inertia is set for 2% of the major axis inertia as the typical configuration in LAPAN's micro-satellite [13]. Other input is the inertia of the satellite reaction wheels, which is selected to be 0,0049 kg.m².

Table 2: Moments of inertia of the satellite preliminary design optimal configuration (kg.m²)

Configuration	Ixx	Iyy	Izz	Jxy/Jxz/Jyz
1	4,72	4,72	4,83	0,14
2	4,28	4,28	4,58	0,13
3	5,41	5,41	5,13	0,16
4	4,73	4,73	4,82	0,14
5	4,20	4,20	4,56	0,13

The reaction wheel's power consumptions is modeled by semi-empiric formulation:

$$W_i = \int_0^{t_a} \left[\frac{30}{0.02} I_{rw} \dot{\omega}_i^{rw}(t) + \frac{6}{6000} \omega_i^{rw}(t) \right] dt \quad (2)$$

The power consumption depends on the torque given to accelerate, and to maintain the wheel's rotation. The wheel's control electronics modeled with simple PID controler. The constants in Equation (2) use the typical value of microsatellite reaction wheels, which at maximum power consumpton of 30 W, may give 0.02 Nm torque to the wheel [13]. The power required to overcome the friction in the wheel, or to maintain the wheel's speed, is modeled to be propotional to the speed. The typical microsatellite reaction wheel has maximum speed of 6000 rpm, which the power needed to overcome the wheel's friction at such speed is assumed to be 6 W.

Since the satellite switched-off its attitude control system during hibernation mode, the attitude maneuver required to conduct imaging operation started with detumbling mode. As shown in Figure 4, during hibernation mode, the satellite may arbitrarily rotate in its 3 axis (tumbling). The mode is activating the satellite's 3 reaction wheels (closed-loop with the gyros) to stop the rotation in all axis.

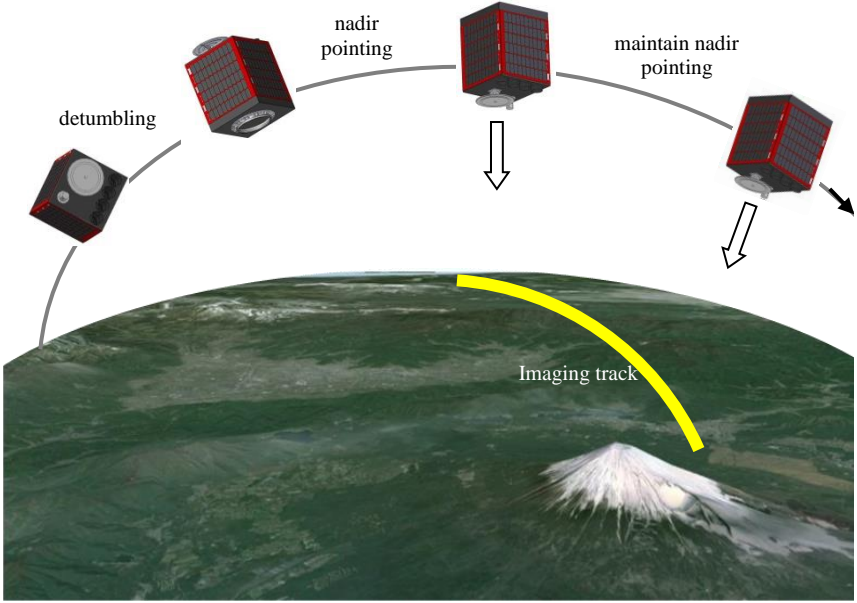


Figure 4: Attitude maneuver for imaging operation

At the end of detumbling maneuver, the satellite camera might point to any arbitrary direction as illustrated in Figure 3. Therefore, the next maneuver is to make the satellite's camera points to nadir. Here, the simulation assumed the satellite has to performed large angles rotation, i.e. 120° in X (roll) axis and then 80° in Z (yaw) axis.

The last maneuver in the imaging operation is maintaining nadir pointing, so that the camera can make highest resolution images. The maneuver is to rotate the satellite of 0.06 deg/s in Y axis.

Results and Discussions

Detumbling Maneuver

The initial angular velocity of the satellite in the detumbling maneuver is assumed to be 1.1 deg/s at X axis, 1.7 deg/s at Y axis, and 2.8 deg/s at Z axis. In real satellite operation, such number is considered high for the operation mode selected (need angular momentum dumping). However, the purpose of this exercise is to show significant differences in the reaction wheels responses. The results from detumbling simulation, i.e. satellite angular rate and reaction wheels rpm, history are plotted in Figure 4 and Figure 5.

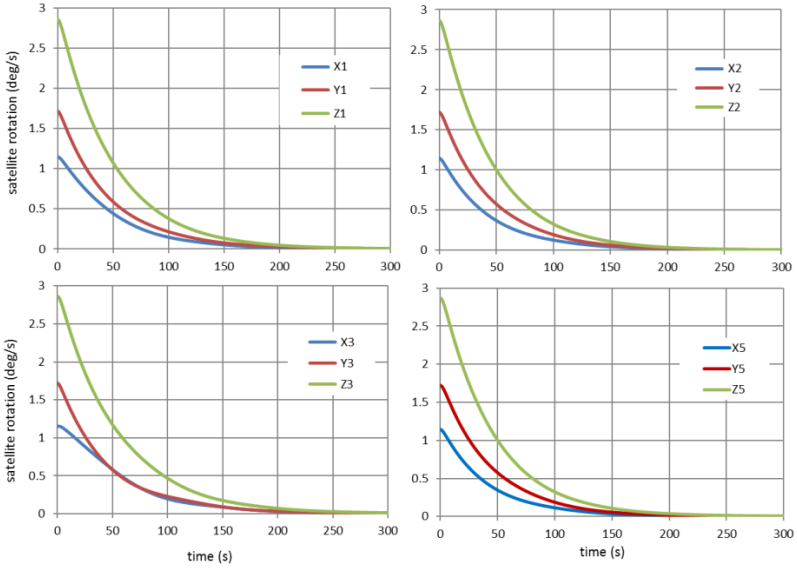


Figure 4: Satellite angular rate on detumbling maneuver for configuration 1, 2, 3, and 5

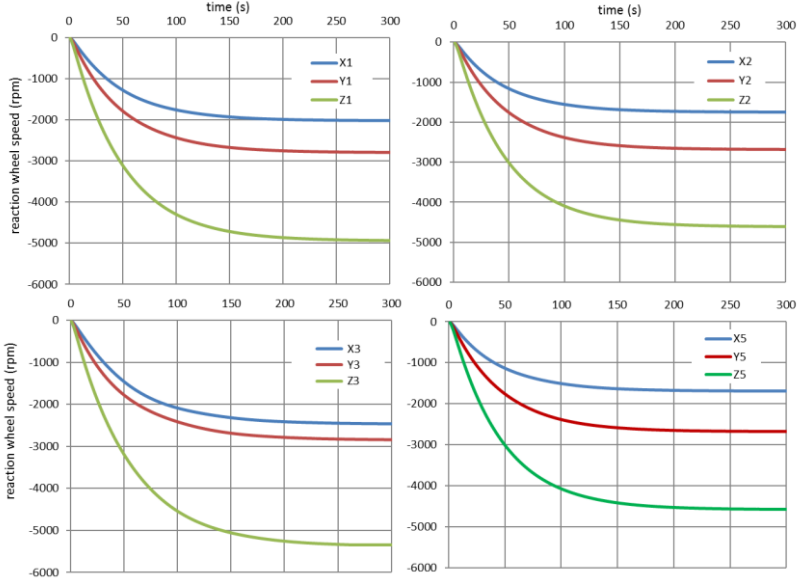


Figure 5: Reaction wheel speed in detumbling maneuver for configuration 1, 2, 3, and 5

From the detumbling simulation, it is shown that all satellite configuration can complete the maneuver in less than 250 s (configuration 5 not shown for display efficiency). Figure 4 show that the satellites angular rate history in Y axis is exactly the same for all configurations. Meanwhile in X and Z axis, the rate for satellite configuration 2 and 5 decay the faster, and satellite configuration 3 decay the slowest.

Figure 5 show that satellite configuration 5, which has the smallest inertia out of the four configuration displayed, is shown to require the smallest reaction wheel rpm to stop the satellite rotation. Meanwhile, configuration 3, which has the largest inertia out of the four, is shown to require the highest reaction wheel rpm to stop the satellite rotations.

The simulated attitude control power consumption (Figure 6) shows that the power consumption for configuration 2 and 5 is almost similar and the lowest. The highest power consumption is in configuration 3. This trend confirms the inertia comparison of each satellite configuration (Table 2).

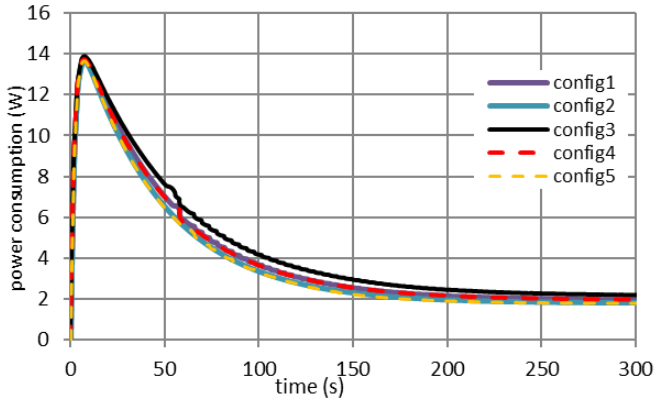


Figure 6: Attitude control power consumption in detumbling maneuver

Nadir Pointing Maneuver

The results from nadir pointing attitude maneuver simulation are shown in Figure 7 to 9. The rotation history shows that all configurations can finish maneuver at 200 seconds (the initial angles is the last pointing given by last maneuver). The rotation in Y axis is not commanded but performed by the system due to transfer of angular momentum by the satellite cross product inertia. Figure 7 shows that satellite configuration 2 took less undershoot angle in X and Y axis at time 150 seconds. Other than that, the angle profiles are very similar.

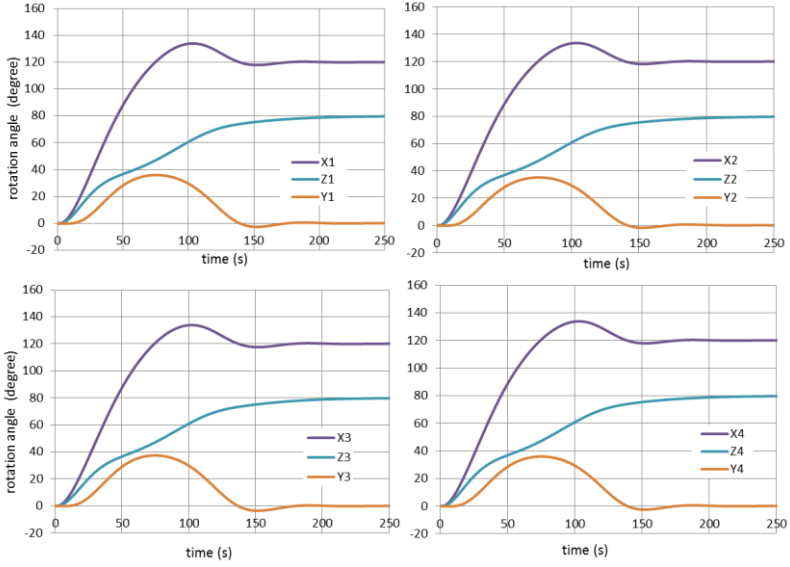


Figure 7: Satellite angle on nadir pointing maneuver for configuration 1, 2, 3 and 4

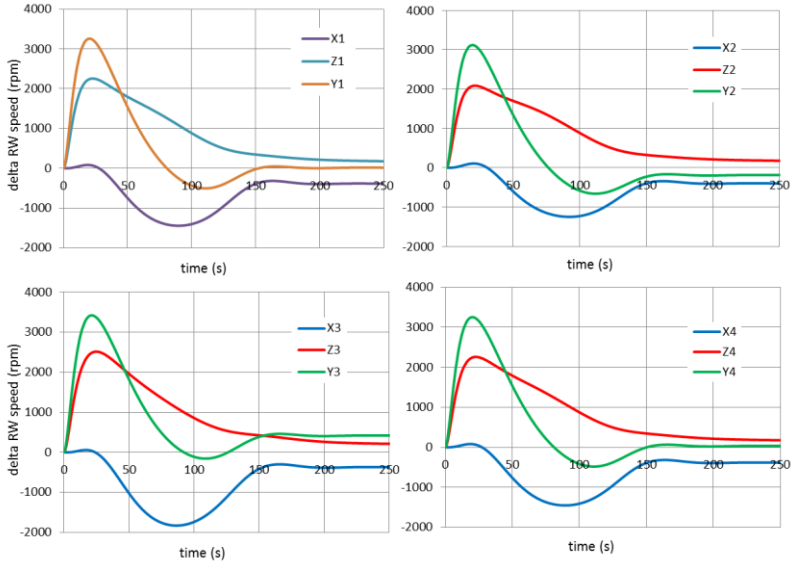


Figure 8: Reaction wheel speed in nadir pointing maneuver for configuration 1, 2, 3, and 4

Even though the satellites angle history look very similar, the reaction wheels performed quite different for each configuration. Figure 8 shows the reaction wheels speed that needs to be added from the wheels' speed at the end of detumbling maneuver. Even though configuration 2 need the least Y wheel rpm during the 1st 75 seconds of attitude maneuver, configuration 1 and 4 need the least rpm afterwards (almost zero after 150 second). The figure also shows satellite configuration 2 need the least X wheel rpm to perform the compensation rotational. Satellite configuration 3 need the most wheel rpm to perform the maneuver. The configuration also needs positive rpm in Y axis reaction wheel starting at 120 second until steady state.

Figure 9 shows the additional power consumption (from the last maneuver state) needed by the attitude control subsystem to perform the nadir pointing rotations. The sudden high power consumption in the 1st 20 seconds of the maneuver is to built-up necessary torque to rotate the reaction wheels at the beginning of the maneuver. The consumption, however, still below the power limit defined for the attitude control system, and therefore, confirm the attitude control system design is feasible. The plot shows that configuration 3 need the most power for the maneuver.

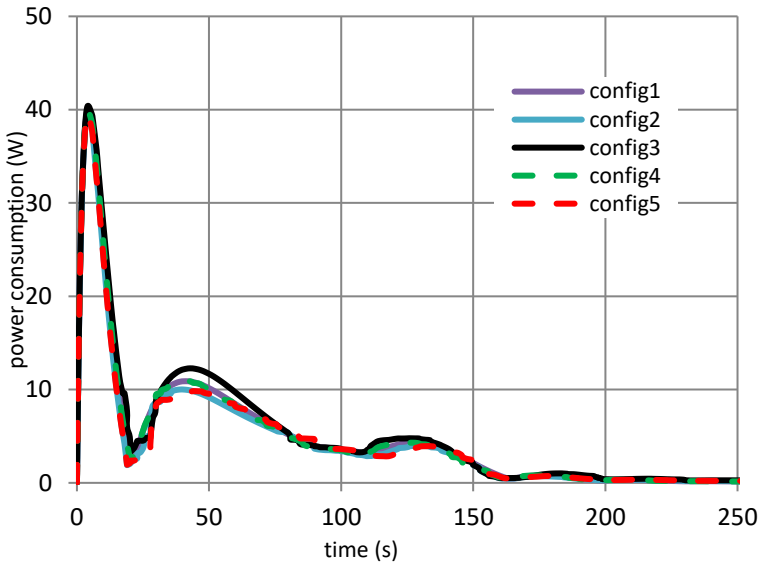


Figure 9: Attitude control power consumption in nadir pointing maneuver

Nadir Keeping Manuver

In order to keep nadir pointing during imaging operation, the satellite only needs to increase (assuming a polar orbiting satellite flying from North to

South) the rotation rate of Y axis reaction wheel's by about 10 rpm. Therefore, power consumption differences are not significant for each configuration, and can be regarded as the power needed to maintain the satellite wheels's rpm from the previous maneuver (detumbling). The imaging operation is assumed to be done for 10 minutes.

Table 3: Power consumption of the satellite attitude maneuver (Wh)

Mode	Config 1	Config 2	Config 3	Config 4	Config 5
Detumbling	0,292	0,296	0,343	0,315	0,292
Nadir pointing	0,449	0,415	0,489	0,446	0,417
Nadir keeping	0,338	0,311	0,378	0,338	0,305
Total	1,079	1,022	1,21	1,099	1,014

Table 3 shows the power consumption (in Watt-hour) from each attitude maneuver mode of the for satellite imaging. The table show that the lowest power consumption is by satellite configuration 5, i.e. satellite with image resolution of 13 m and swath of 200 km.

From Table 1, it is known that configuration 5 also has the lowest power production capacity. Therefore, using configuration 5 as the baseline, the increase in the power consumption and production are measured, as tabulated in table 4. The table show that in configuration 4 and 5, the percentage increase in the power consumption is less than the increase in power production, due to the larger area available for solar panel. Configuration 2, however, show different trend where the increase in power consumption is less than those of production. Therefore, 2nd best in power consideration is satellite configuration number 2, which means should higher resolution is desired for some reason, the choice is the satellite with image resolution of 7 m and swath of 75 km.

Table 4: Power production and consumption comparison

% higher	Config 1	Config 2	Config 3	Config 4	Config 5
Consumption	6,4	0,8	19,3	8,4	0,0
Production	6,5	1,7	14,9	6,8	0,0

The simulations show that the total time needed to prepare imaging operation (achieve nadir pointing) is 450 seconds or 7.5 minutes. The power consumption plots (Figure 6 and 9) show that the system can be further optimized to have shorter transient time, simply by increasing the gain in the PID. Such changes will not change the total energy consumption but will increase wattage consumption profile. With the large margin currently exist

in the wheel's power consumption (maximum 30 W per wheel), the transient time is potentially be reduced in half.

In the case when attitude control system design feasibility is in concern, for example exceeding power limit to get the desired transient time etc., the attitude control hardware parameter in the simulator can be easily modified. Therefore, if needed, the design variables can be extended into choices of attitude control hardware parameter.

Since the simulator is built in Matlab environment in academic institutions, it can be easily adapted for the implementation of optimizing algorithm in the design process (not restricted by commercial proprietary).

Conclusions and Further Work

LAPAN-ITB's satellite simulator, in this case its attitude dynamics module, has been shown to be an effective tools in design optimization. It is able to provide support for the best configuration decision making out of 5 configurations obtained from multi-objectives pareto. The effectiveness of the simulator as optimizing tools is even higher in the case where large input parameter variations, in this case is moment inertia, exist. For example the case choosing between of deployable or body mounted solar panel or between solid plate and iso grid structure, where the solution may not be intuitive.

The satellite simulator has been shown to be potentially useful for sizing the attitude control components and deciding on control parameters/algorithm. Therefore, using the simulator, such parameter may be included for the future research in satellite design optimization.

Since the simulator can be easily adapted, future research may involve the implementing optimization algorithm in the simulator's code. Potential collaborators are welcomed.

Acknowledgement

The authors wish to thank Mr. Satriya Utama of National Institute for Aeronautics & Space (LAPAN) on the discussion in the modification of the satellite simulator. The authors also wish to thanks Faculty of Mechanical and Aerospace Engineering, ITB for funding this research.

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