SPACE SYSTEM TRADE-OFFS
TOWARDS SPACECRAFT
SYNERGISMS

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INTRODUCTION

Sputnik 1 was launched on 4 October 1957 by the Soviet Union (Russia). Since then satellite technology has been evolving rapidly for a few decades. However, satellite design has remained similar in the recent years. Therefore, space innovative concepts become desirable to anticipate the emerging demand/cost of near and long term space missions. Other factors of concern are the increasing system complexity and weight. A synergetic system design could be an attractive approach for future spacecraft to cope with their demands. Synergism for spacecraft describes the linking or merging of different subsystems in order to achieve a better overall performance, e.g., reliability, mass saving or even for enabling a certain mission. Therefore, using the existing subsystems in an integrated subsystem to replace not only the conventional system design but also the traditional design approach is of particular interest herein. The earth-pointing satellites need a number of subsystems to accomplish their missions. Table 1 shows the typical conventional subsystems of earth-orientated satellites. Spacecraft synergisms could be envisaged by couplings of those conventional subsystems. A wise choice would be to concentrate on one of the most crucial and costly subsystems onboard. Hence, synergisms for the spacecraft attitude control system emerge as the prime research topic of interest [Renuganth1].

This inaugural lecture is divided into five major parts. In this first part the vital research area is established based on the international space research needs. The second part discusses the current Malaysian space scenario. The third part presents the fundamental science of the core space research area undertaken herein. The fourth part presents all the treated conventional spacecraft systems towards the innovative spacecraft systems. The final part concludes this inaugural lecture.

Table 1 A Typical Satellite Subsystems

SATELLITE	
PLATFORM	**PAYLOADS**
• Electrical Power System (e.g., batteries, solar arrays, etc.) • Attitude Control System • (e.g., reaction wheels, thrusters, magnetotorquers, etc.) • Thermal Control System (e.g., heat pipes, heat sinks, radiators, etc.) • Navigation System (e.g., star sensors, GPS, gyroscopes, etc.) • Onboard Computer	• Communication System (e.g., transponders, antennas, etc.) • Observation System** (e.g., optical cameras, radar, etc.) • Scientific Experiments** (e.g., environmental probes, sensors, etc.) ** Mission dependence

MALAYSIA SPACE TECHNOLOGY STATUS

The aerospace sector has been identified as one of the major contributors to the nation's wealth since the early 1990s. The turnover of the aerospace industry hovers around RM 25 billion since 2010. This trend is maintained and gradually increasing as well. However, the aerospace engineering field in Malaysia can still be considered at a developing stage.

There have been serious activities since a decade ago covering the education, research, business, etc. The interest is actually spurred or thrustered through the National Aerospace Blueprint (MiGHT-1997) [MiGHT]. The blueprint identifies key initiatives for transforming Malaysia into a regional and international aerospace nation by the year 2015. The blueprint includes 45 noble recommendations to achieve this clear goal. It is important to note that the recommendations focus primarily on the human capital and aerospace facility investments within the country. In parallel, a roadmap was also drafted together with some policies. The roadmap covers mainly the aeronautical field; whereas the astronautical field (space) is seen as a relatively smaller contributor to the national aerospace annual turnover. It is a fact that the astronautics field has been introduced only some 20 years ago compared to the aeronautical field, which has been around since the Malayan Airways days in the 1950s. In such an infant state, the manned space mission had already been executed without acquiring all the necessary space technologies.

Malaysia has bypassed most mandatory space technology developments and participated in small satellite, medium-satellite and manned space programs through the foreign space facilities. Obviously, there is a huge technological vacuum in the domestic space field. Generally, space research can be divided into two categories, i.e., the space segment and the ground segment. The space segment consists of all the activities related to space sciences (e.g., astronomy, planetary protection, space life sciences, etc.), spacecraft (e.g., satellites and space modules), and rockets. The ground segment consists of all the activities performed in ground stations (e.g., telemeasures, telecommands, etc.). In fact, the ground segment can also be considered as a part of space applications. Figure 1 elaborates on the space activities in Malaysia with respect to a typical classification of space clusters. Note that the manned and unmanned capsules are considered as the integrated rocket parts before their orbit insertions. It is worthwhile to mention that Figure 1 does not consider a direct purchase of space solutions. The outcomes of those R & D activities are Ground Models and Low-Cost Models. The Ground Models refer to the earth-based space solutions, e.g., ground station solutions, laboratory space solutions or space engineering models. The Low-Cost Models refer to those Ground Models that are ready and can be tested in a specific space mission. The Flight Grade Models are space solutions that have clocked operation hours in space. Once the Flight Grade Models are available; the models can then be considered as Commercial Space Models for commercialization.

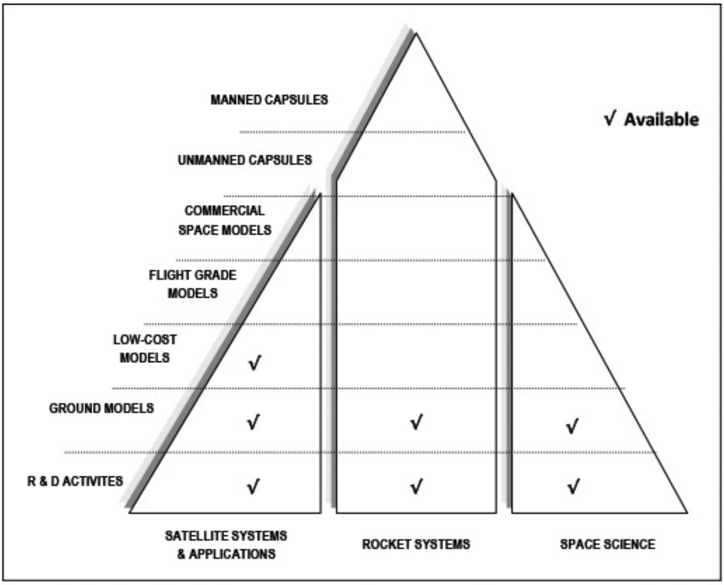


Figure 1 Classification of Space Clusters and Activities in Malaysia. The classification is based on the article contributions mapped using *SCOPUS*

The Unmanned and Manned Capsules concern the human exploration in space. At the moment, R&D Activities, Ground Models and Low-Cost Models can be found in the Satellite Systems and Applications cluster in Malaysia. For the Rocket Systems and Space Science clusters only the R&D Activities and Ground Models are available. Obviously, the Flight Grade Models could not be developed due to the lack of maturity in R&D Activities and Ground Models. It is clear that there are opportunities for improvements in terms of space research and development in Malaysia.

Satellite Systems and Applications

The Satellite Systems comprise of satellites and satellite ground stations. Satellites can then be divided into platforms and payloads. A satellite platform holds all the vital subsystems such as power, communication, attitude and orbit determination and control, thermal and onboard computers. Usually, a platform can be a standard feature for most satellites. On the other hand, payloads (e.g., communication devices, optics, radar, etc.) vary depending on the satellite missions. There are R & D activities concerning the satellite subsystems leading to Ground and Low-Cost Models. However, these activities are mostly concentrated on the satellite integration works, which are practical engineering in nature. They lack a profound satellite subsystem and payload research works, which preclude their reporting in top space journals. Nevertheless, there are space scientific works on satellite subsystems reported in top space journals.

Satellite Applications such as the remote sensing activities (e.g., meteorology, earth observation, etc.) and communication solutions (radio frequency, radar, GPS, etc.) are reasonably active in Malaysia. Many satellite application research works have been reported in a wide range of engineering/science journals. It can be seen that most of the Ground and Low-Cost Models for satellite applications are very specific and localized, e.g., remote sensing softwares and communication solutions. Therefore, it is difficult for these models to be incorporated into the existing satellite systems as Flight-Grade Models. An absence of scientific research efforts concerning the satellite ground stations is also evident at this point. In fact, indigenous ground station solutions can fetch a high commercial value, which can be the driving factor for research in this area.

Rocket Systems

There are basic rocket R & D activities and Ground Models mainly on the solid fuel sounding rockets. The liquid fuel option has been recently proposed as well. Only a very few scientific works on rocket systems are reported in common engineering journals. The R&D activities on other rocket elements such as structures, liquid fuel engines, guidance and control systems, on-board computers, separation systems, docking systems and heat protection systems are not available. Therefore, the rocket related elements such as the ground stations, life support systems, manned and unmanned capsules are not available as well. Thus, any rocket research venture would be desirable. However, such efforts seem to be unlikely at the moment due to the lack of human capital and heavy financial investments.

Space Science

The Ground Models for space sciences are mostly concentrated on the system integration as well (e.g., simple telescope system). Ground Models concerning the space probes and space flight experiments are not available. Most research activities are observation and measurement works related to astronomy, meteorology, and radio sciences. And these research findings have been mainly reported in a wide range of common engineering/science journals instead of top space journals. Crucial profound space science research works can be started mainly on planetary protection (e.g., space debris, meteorites, asteroids, etc.), space weather, and scientific balloons. On the other hand, space science activities related to microgravity conditions such as for life sciences can be enhanced through drop-towers or parabolic flights. However, space life science research works are rather desirable if a country is hosting human space flights.

The Core Space Research Field

The core space research field remains the spacecraft attitude control in this inaugural lecture. However, some other related areas such as the space navigation, space power and space thermal control also will be discussed. The role of an attitude control system (ACS) is to maintain the spacecraft orientation in space, directing communication antennas towards the Earth, retargeting solar arrays facing the sun, and pointing scientific cameras or instruments at objects under investigation. For most earth orientated spacecraft, the ACS is responsible for maintaining a nadir pointing and keep the spacecraft body axes close to the local-vertical-local-horizontal (LVLH) axes (see Figure 2). The ACS consists of three parts: attitude sensors, attitude controllers, and attitude actuators. Determination of the current attitude is carried out by banks of sensors (e.g., earth sensor, star tracker, etc.) that sense relative orientation with respect to other bodies including the sun, earth, stars, and other planets. Rate and acceleration sensors (e.g., gyroscopes) are also employed to sense the spacecraft motion. All these parts are usually integrated in a closed loop attitude control process. There are two basic methods for controlling the spacecraft, i.e., an active control with electrical power and a passive control without electrical power. Only the attitude control methods related to the research herein will be presented. Other attitude control techniques (e.g., based on aerodynamic, solar pressure, permanent magnets, etc.) can be found in the references [Kaplan]. The control method selection depends highly on the spacecraft mission.

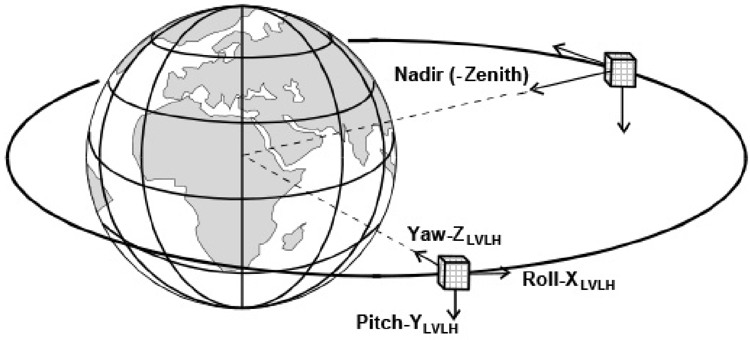


Figure 2 The ACS Ensures the Spacecraft Nadir Pointing

In space, the external disturbance torques T_D perturb the orientation of a spacecraft. As a result, the spacecraft's body axes will no longer be aligned with the local-vertical-local-horizontal (LVLH) reference frame. A rigid body (e.g., flywheel) within a spacecraft rotating at a relatively high-speed Ω_W can stabilise the spacecraft according to Eq. (1). In fact, Eq. (1) remains as the fundamental equation of the core attitude control research works presented herein.

$$\begin{aligned} I_1\ddot{\varphi}_1 + \left(h_2 - \Omega_0\left(I_1 - I_2 + I_3\right)\right)\dot{\varphi}_3 + \left(4\Omega_0^2\left(I_2 - I_3\right) + h_2\,\Omega_0\right)\varphi_1 &= T_{D,1}, \\ I_2\ddot{\varphi}_2 + \left(3\Omega_0^2\left(I_1 - I_3\right)\right)\varphi_2 &= T_{D,2} + \dot{h}_2, \\ I_3\ddot{\varphi}_3 - \left(h_2 - \Omega_0\left(I_1 - I_2 + I_3\right)\right)\dot{\varphi}_1 + \left(\Omega_0^2\left(I_2 - I_1\right) + h_2\,\Omega_0\right)\varphi_3 &= T_{D,3}, \end{aligned} \tag{1}$$

where $\varphi_{1,2,3}$ are the small Euler angles, Ω_0 the orbital frequency, and $I_{1,2,3}$ are the roll, pitch and yaw inertias, respectively. Also, the internal spacecraft bias momentum vector is defined as $h_{2[LVLH]} = [0\ -h_2\ 0]T$. The nominal bias momentum must be significantly large to provide stiffness as well for the roll/yaw plane: $h_2 >> max\ [I_1\Omega_0, I_2\Omega_0, I_2\Omega_0]$.

INNOVATIVE SPACE SYSTEMS

As mentioned in Table 1, a spacecraft or a satellite consists of a platform and a payload at least (see Figure 3). A single platform can adapt different payloads depending on a space mission. Therefore, a satellite platform is mandatory in a space mission.

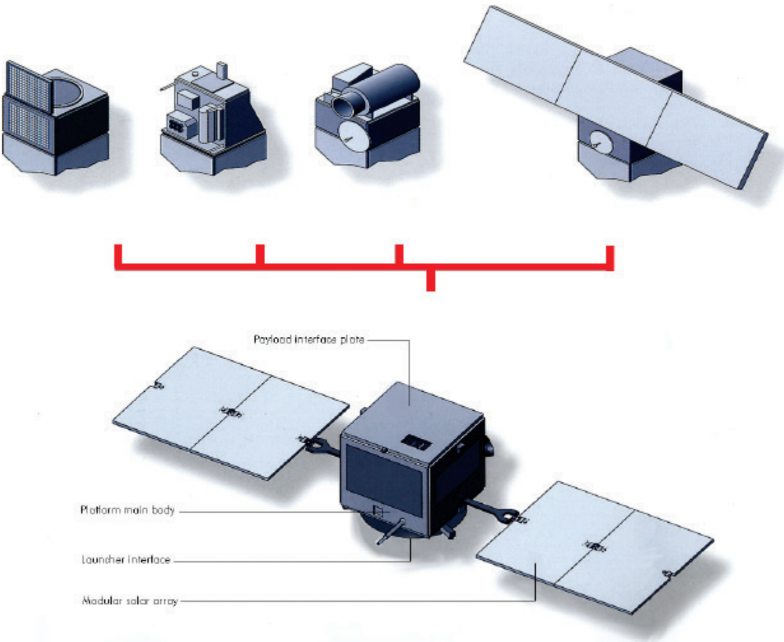


Figure 3 A Satellite: Payloads and Platform

A satellite platform carries all the vital subsystems to ensure a space flight such as the power & photovoltaic panels, flight control and navigation, communication, thermal control, onboard computer, etc. All these conventional subsystems are independently working and managed by an onboard computer.

A typical satellite platform is shown in Figure 4. The research works performed herein are focussing on a satellite platform and its conventional subsystems.

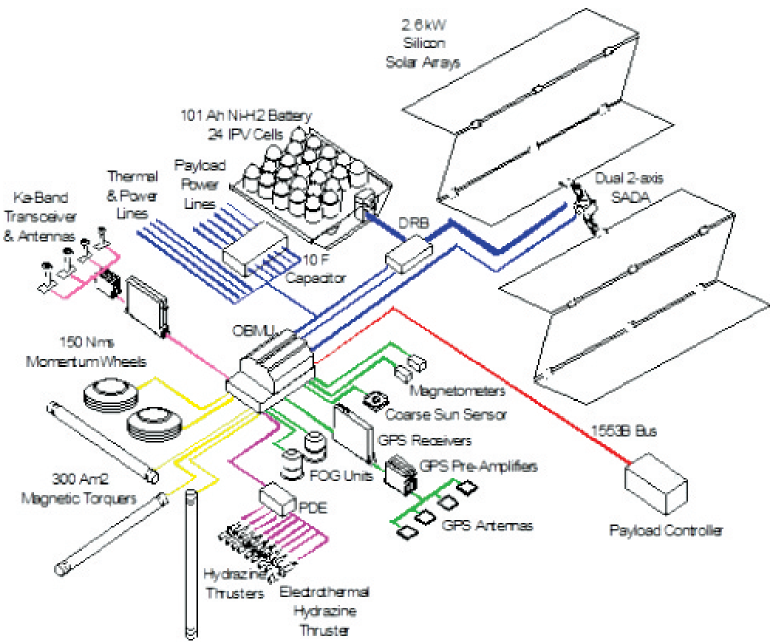


Figure 4 A Typical Satellite Platform

The research works can be clustered into three main areas as follows:

i. Conventional core spacecraft system researches,
ii. Innovative spacecraft synergetic system researches,
iii. Supporting space system researches.

All these main areas will be discussed in great detail together with their control techniques and attitude control performances. Although the focus of this inaugural lecture is on the innovative spacecraft synergetic systems, the conventional and supporting space solutions have also indirectly contributed to the innovative space systems.

Conventional Core Spacecraft System Researches

i. Satellite Attitude Controls with Reaction Wheels

The reaction wheels are the most feasible satellite actuator that can provide high attitude pointing accuracies (0.1- 0.001 deg) [Baizura *et al.*]. The reaction wheel's configuration plays an important role in providing the attitude control torques, which are proportional to the required current. Several reaction wheel configurations as shown in Figure 5 have been investigated in order to identify the most suitable orientation that consumes a minimum power. Such information in a coherent form is not summarized in any publication; and therefore, an extensive literature search is required to obtain these results. The standard reaction wheel control and angular momentum unloading schemes were adopted for all the reaction wheel configurations. Numerical simulations are then performed for all the possible reaction wheel configurations with respect to an identical reference mission to identify a minimum total control torque, which also corresponds to the configuration with a minimum power intake.

The standard PD-type controller is employed for the 3-axis attitude control [Ismail *et al.*]. The control law can be represented as

$$\mathbf{T}_a = -2\mathbf{K}_p\mathbf{q}_e - \mathbf{K}_d\boldsymbol{\omega}_e \qquad (2)$$

where the error quaternion $\mathbf{q}_e$ is the quaternion difference between the commanded quaternion $\mathbf{q}_{cmd}$ and the current quaternion $\mathbf{q}_c$. Whereas, $\boldsymbol{\omega}_e$ is the angular rate difference between the commanded angular rate $\boldsymbol{\omega}_{cmd}$ and the current angular rate $\boldsymbol{\omega}_c$. In order to generate sufficient control torques from the control law, the proportional gain $K_p = \omega_n^2 I$ and derivative gain $K_d = 2\xi\omega_n I$ are to be chosen accordingly. These control gains are the functions of dynamic characteristics, i.e., the natural frequency ω_n and the damping ratio ξ. All the proposed configurations have a similar total attitude pointing accuracy of about 0.001 deg. Nevertheless, the best attitude pointing (<0.001 deg) is achieved in case 1 of four reaction wheels (see Figure 6).

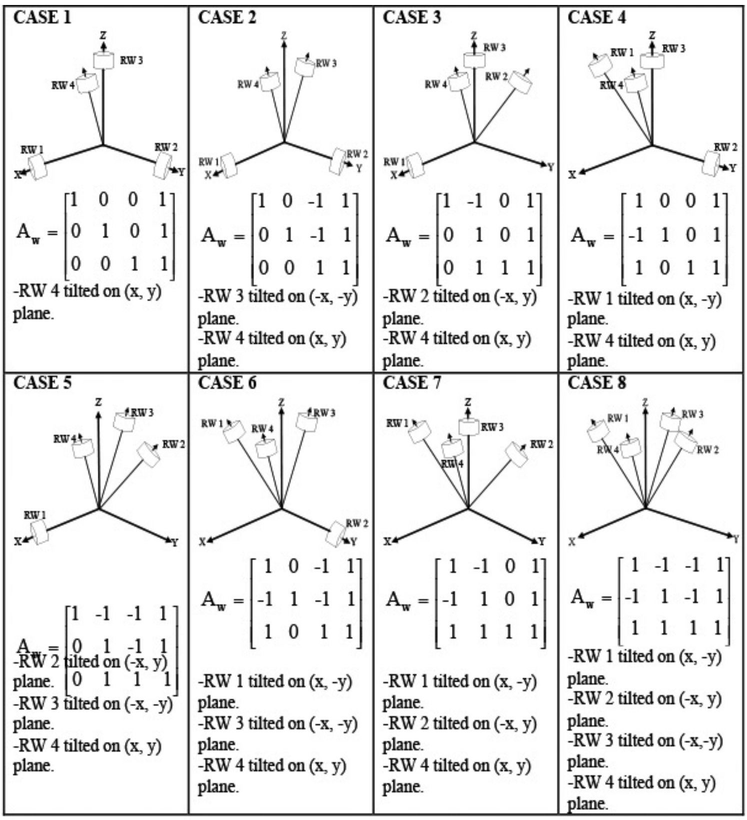


Figure 5 Typical Configuration Matrix of Four Reaction Wheels

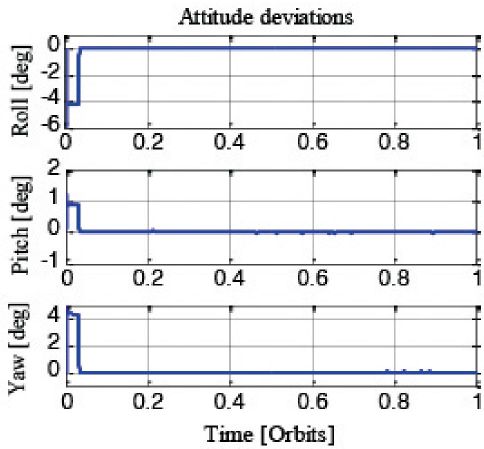


Figure 6 Case 1: The Best Attitude Pointing

Another research undertaken for reaction wheels is the torque delivery enhancement through an optimal control command. The active pointing accuracies achieved were around 0.2 deg as shown in Figure 7. This research was a joint research with the Indian Institute of Technology (Kanpur) [Tewari *et al.*].

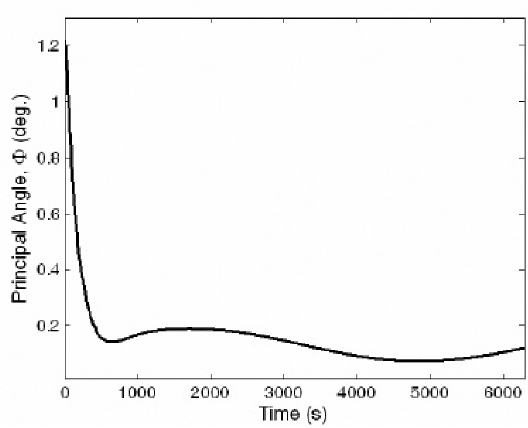


Figure 7 The Attitude Pointing for Optimal Torque Commands

ii. Satellite Attitude Controls with Magnetic Torquers

The interaction between the Earth's geomagnetic field **B** and magnetic dipole moment **M** within the satellite will generate a magnetic torque T as given in Eq. (3).

$$\mathbf{T} = \mathbf{M} \times \mathbf{B} \tag{3}$$

This torque can be used for attitude controlling purposes when it is generated in a desirable amount and direction. This is done by generating a controllable value of magnetic dipole moment within the satellite using an electromagnetic based device called magnetic torque (see Figure 8). The formulation of the control structure was based on the conventional proportional-integral (PI) type. The best achieved attitude pointing with two and three magnetic torquers are between ±0.5 and ±5 deg as shown in Figures 9 and 10, respectively [Nurulasikin1-4 *et al.*].

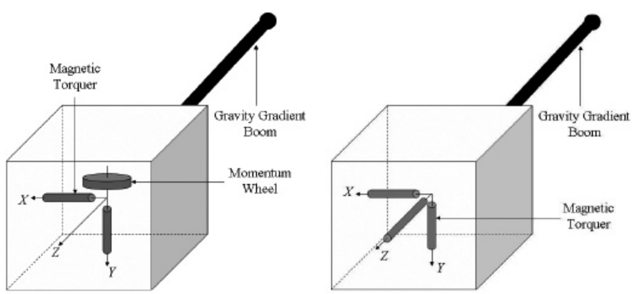


Figure 8 A Satellite with Two or Three Magnetic Torquers

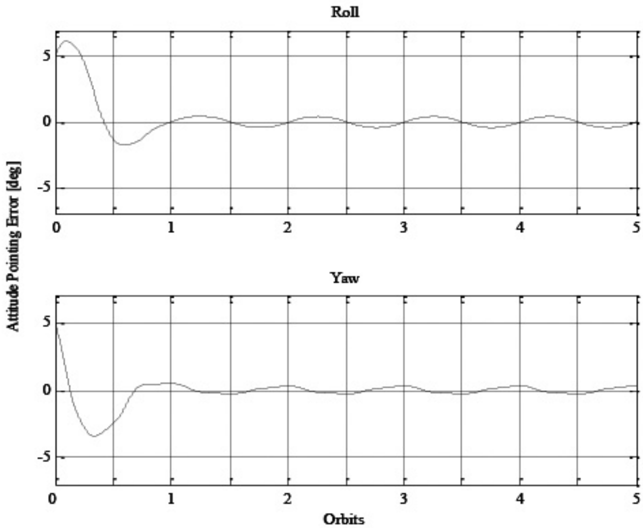


Figure 9 Satellite Attitude Control with Two Magnetic Torquers

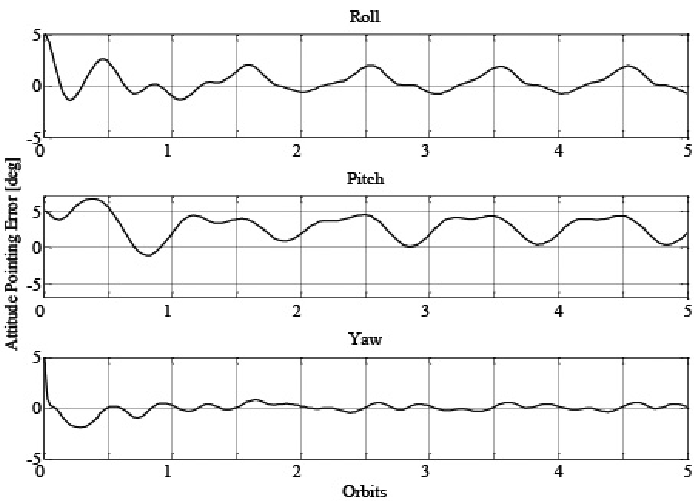


Figure 10 Satellite Attitude Control with Three Magnetic Torquers

iii. Satellite Attitude Determination with Magnetometers

The attitude determination based on the information derived from magnetometer measurements requires only the geomagnetic field data as an input (see Figure 11). The research work proposes three-axis magnetometers as they are reliable, usually inexpensive, and always able to provide information, which is not the case of Sun-sensors, star-trackers, or Earth-sensors. The attitude determination system state equation is nonlinear and justifies the fact that an extended Kalman filter (EKF) can be employed as follows

$$\frac{d}{dt}x(t) = f(x(t),t) + w(t) \tag{4}$$

where the vector *w(t)* is the process noise. The attitude determination algorithm was tested numerically and an attitude determination below 10 deg was achieved as shown in Figure 12 [Filipski1-3 *et al.*].

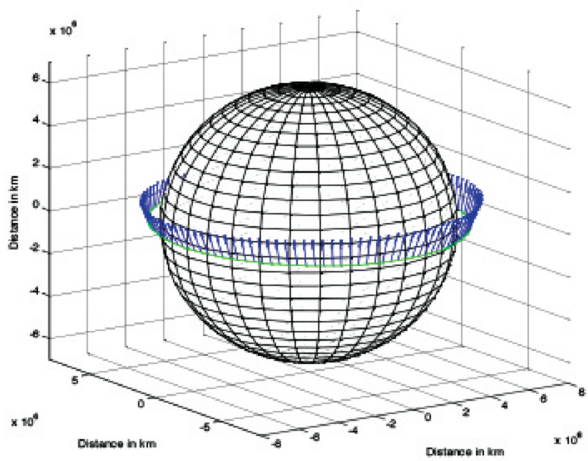


Figure 11 Earth's Magnetic Field Vectors

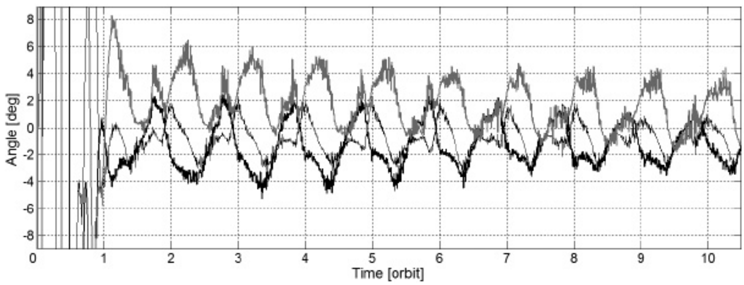


Figure 12 Roll, Pitch and Yaw Attitude Determination Performances

Innovative Spacecraft Synergetic System Researches

i. Combined Energy and Attitude Control System (CEACS)

A spinning flywheel possesses a great deal of rotational kinetic energy, but there are no provisions to use the energy in the electrical form on a spacecraft yet. Hence, having a motor/generator unit integrated onboard, the flywheels can be used not only for the attitude control but also for the energy storage of a spacecraft. A possible flywheel set-up is given in Figure 13. Therefore, a flywheel based energy storage unit as an alternative to conventional batteries for a spacecraft is reasonable [Renuganth1-5 *et al.*].

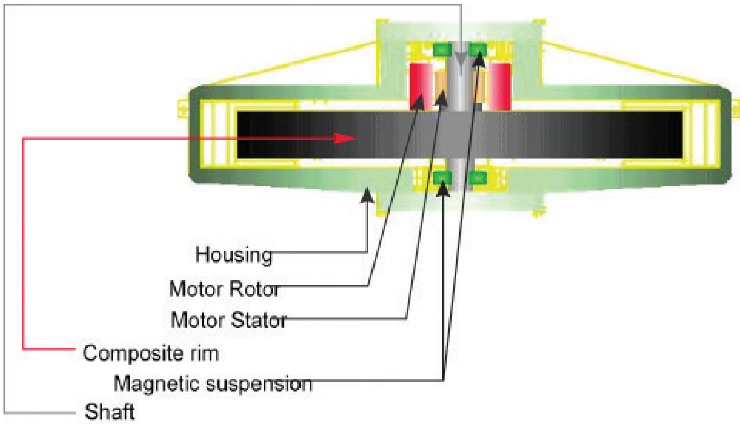


Figure 13 A CEACS Flywheel

Such a system consists of a double counter rotating flywheel assembly serving simultaneously for the satellite energy storage and attitude control. The CEACS attitude performance pertaining to the ideal and non-ideal test cases were investigated and discussed from the energy and attitude points of view. The CEACS performance shows its potential feasibility on the future spacecraft, particularly on small satellites [Renuganth6 *et al.*]. Three attitude control options were developed: proportional-derivative (PD) control, active force control (AFC), optimal control (H_∞/H_2 controls), and sliding mode control (SMC).

The PD attitude control option external orbit disturbance T_D rejection scheme is given by the transfer function

$$\frac{\theta_{sat}}{T_D} = \frac{1+\tau_w s}{K_P + K_D s + I_{sat}s^2 + \tau_w I_{sat} s^3} \tag{5}$$

where the proportional control gain K_p and the derivative control gain K_D can be computed. The achieved attitude pointing accuracies

θ_{sat} are well below 0.2 deg as shown in Figure 14 [Renuganth 7-8, Ibrahim *et al.*].

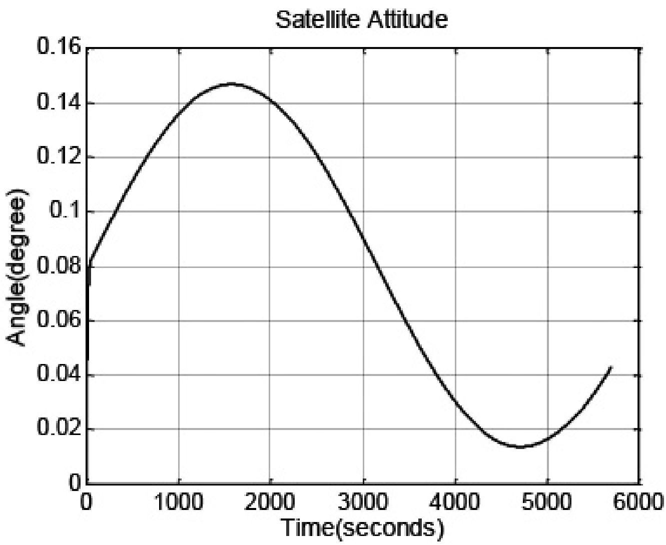


Figure 14 CEACS Attitude Control Performance (PD controller)

The PD controller can be further enhanced by incorporating the active force control (AFC). The AFC method is a technique that relies on the appropriate estimation of the inertial or mass parameters of the dynamic system and the measurements of the acceleration and force signals induced by the system if practical implementation is ever considered. Figure 15 shows that the PD-AFC option for CEACS has improved the pointing accuracies up to 0.01 deg [Renuganth9-10 *et al.*].

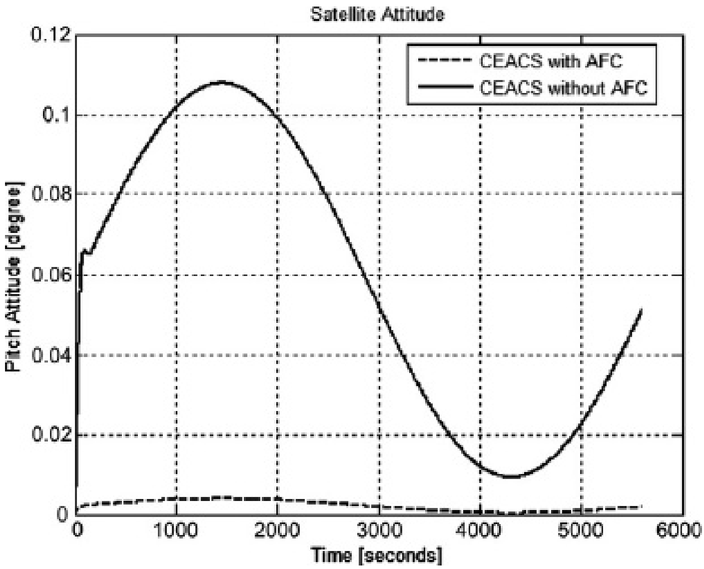


Figure 15 CEACS Attitude Control Performance (PD+AFC controller)

As for the optimal control options, the H_2 method was tested for CEACS under a collaborative effort with the Russian Academy of Sciences [Siang1 *et al.*]. The H_2 method works to minimize the following steady state cost function

$$J = \int_0^\infty \left(x^T(t) Q x(t) + u^T(t) R u(t) \right) dt \tag{6}$$

where J is the cost function, Q and R are positive semi-definite and positive definite weighting matrices, respectively. The H_2 controller improved the CEACS attitude pointing capabilities below 0.006 deg, see Figure 16.

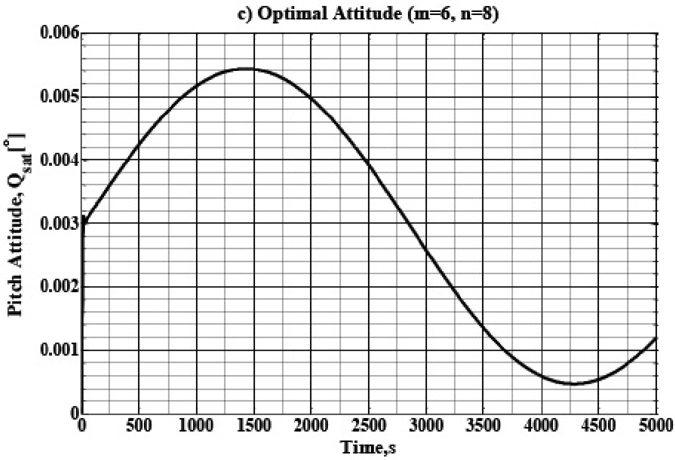


Figure 16 CEACS Attitude Control Performance (H_2 controller).

Further, the H_∞ method was tested as well for CEACS [Siang2 *et al.*]. This method is designed to control the plant by finding a controller *K* such that the ∞-norm of the closed-loop transfer function is

$$\|G_{zw}\|_\infty = \sup_t \frac{\|z(t)\|_2}{\|w(t)\|_2} \leq \gamma \tag{7}$$

where G_{zw} is the plant transfer function from *w* input to *z* output, *z* the system performance output, *w* the system input and γ the performance bound (is a small scalar value). Figure 17 shows a pointing accuracy around 0.043 deg. Another control option that is undertaken currrently for CEACS is the sliding mode control (SMC). This control technique also has shown a promising attitude pointing capability.

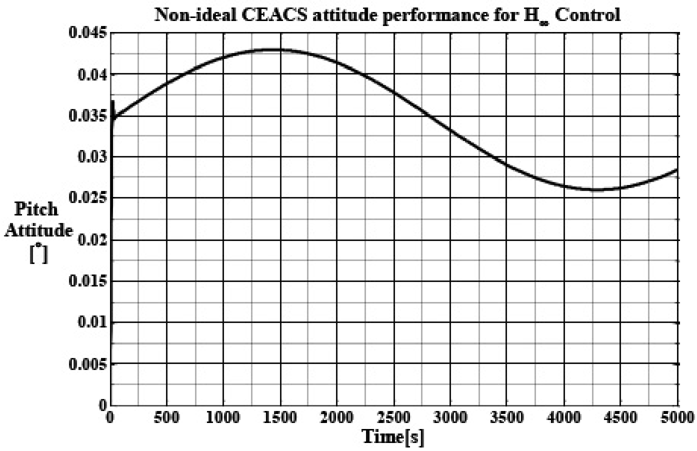


Figure 17 CEACS Attitude Control Performance (H_∞ controller)

ii. Combined Attitude and Thermal Control System (CATCS)

CATCS couples the thermal control system with the attitude control system by utilizing an electrical conductive fluid, which circulates in a closed loop to simultaneously serve as "heat conductor" and "momentum generator" as shown in Figure 18 [Renuganth11]. Therefore, CATCS could replace the existing heat pipes and reaction wheels. CATCS was tested for PD and PD-AFC attitude controllers, whereby the achieved pointing accuracy shown in Figure 19 is below 0.2 deg with respect to a heat transport of 500W [Khodari1-2 *et al.*]

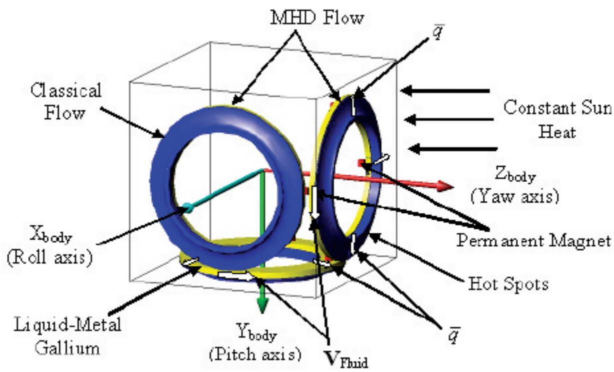


Figure 18 The CATCS Set-up

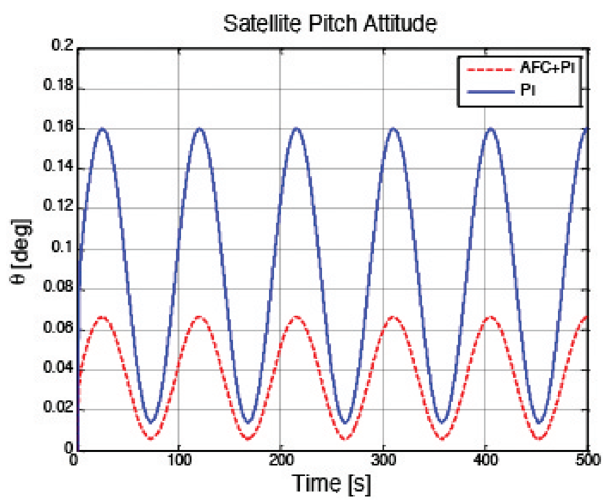


Figure 19 CATCS Attitude Control Performances (PD & PD+AFC controllers).

CATCS was further tested for H_2 and H_∞ attitude control methods. Their attitude control performances are depicted in Figures 20 and 21, respectively, whereby H_2 attitude control (0.025 deg) performs better than H_∞ attitude control (0.17 deg) [Khodari3 *et al.*].

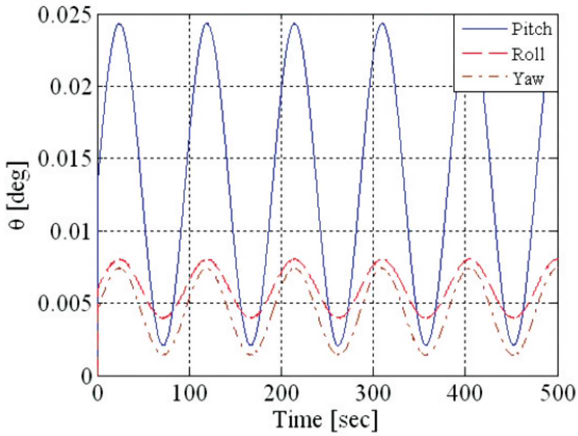


Figure 20 CATCS Attitude Control Performance (H_2 controller)

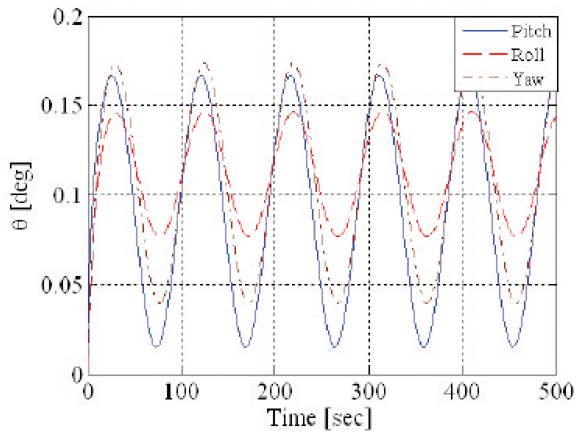


Figure 21 CATCS Attitude Control Performance (H_∞ controller)

iii. Combined Attitude and Sun Tracking System (CASTS)

The integrated attitude and solar tracking system is based on the existing solar array drive assembly (SADA), which includes a DC motor. CASTS is proposed to replace the standard attitude control reaction wheels while maintaining its sun tracking task (see Figure 22) (Renuganth12 *et al.*). This combined attitude and sun tracking system (CASTS) is based on a PD control architecture. The achievable attitude control performance is within 0.2 deg as shown in Figure 23.

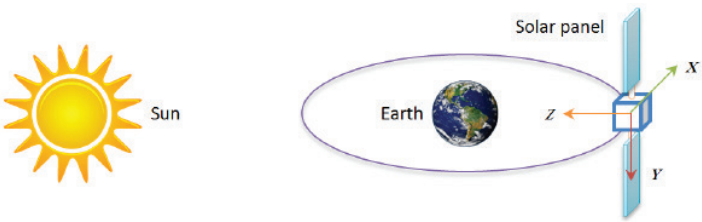


Figure 22 The Solar Array Drive Assembly (SADA) as an Attitude Actuator

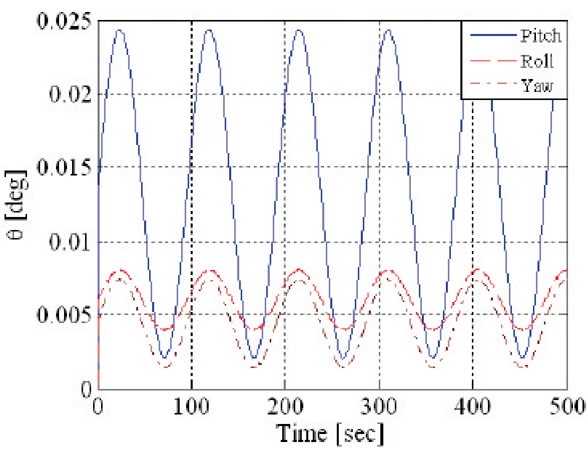


Figure 23 The CASTS Attitude Control Performance

Supporting Space System Researches

i. Tethered Formation Flying

Tethers are a reasonable option to conduct a deployment in space (see Figure 24). The investigation on the dynamic behaviour (e.g., failures) of different materials of a flexible tether under air-drag perturbation in Low-Earth-Orbit (LEO) is undertaken herein.

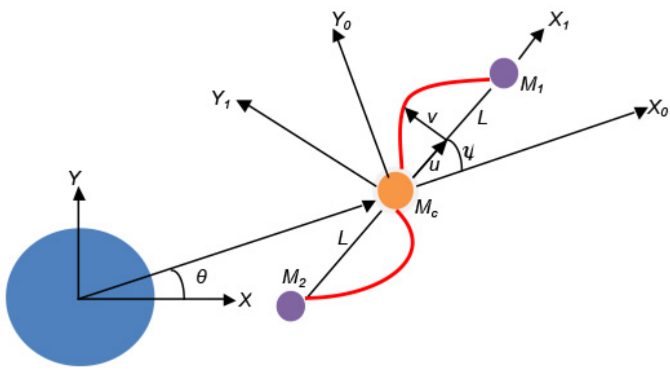
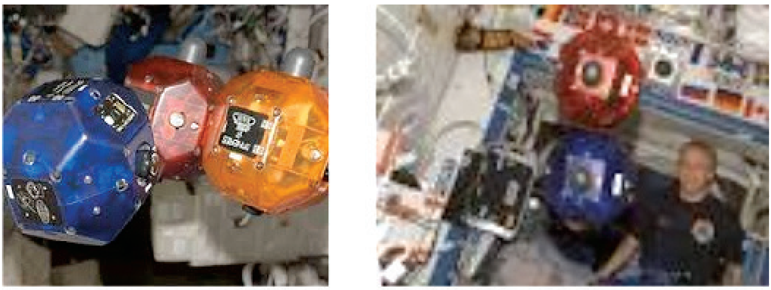


Figure 24 A Tethered System

Mathematical model based on a flexible continuous string type model together with the conservation of energies and utilizing the Lagrangian approach also has been developed [Hong *et al.*]. The analysis has shown that materials such as Kevlar-49 and Nylon are suitable depending on the specific tether design.

ii. Synchronized Position Hold Engage Reorient Experimental Satellites (SPHERES)

The Synchronized Position Hold Engage Reorient Experimental Satellites (SPHERES) involves a series of robotic experiments, in which satellites are controlled by astronauts aboard the International Space Station (ISS) as shown in Figure 25 [Stoll1-2 *et al.*]. The goal is to study the Human-machine interactions especially in a space environment. This joint study was conducted with the collaboration of the Massachusetts Institute of Technology (USA). The study has provided the insights of On-Orbit-Servicing (OOS) possibilities for future space missions.



(a) (b)

Figure 25 SPHERES in Micro Gravity Conditions

CONCLUSIONS

Spacecraft missions are becoming more challenging in recent years. Additionally, the requirements for space missions in terms of their performances are also gradually increasing. Therefore, the spacecraft has received attention for further optimisation. An approach would be to enhance the capabilities of each existing sub-system without altering the overall mass and volume budgets as in the same level today. Recent technology advances have triggered an appreciable enthusiasm towards off-the-shelf spacecraft subsystem concepts. There has been research on the idea of combining the conventional spacecraft subsystems. All the proposed novel hybrid spacecraft subsystems comply with the space mission requirements. Hence, the commissioning of these synergetic subsystems on the future spacecraft would benefit the missions, e.g., life duration, reliability and performance enhancements, mass and volume savings, etc. On the other hand, these novel spacecraft subsystems have paved the way for Universiti Putra Malaysia to lead the Malaysian impactful spacecraft research outputs. Malaysian indigenous space technologies would enable the sustainable growth of the space field and at the same time develop the strategic space technologies. In fact, these space research outputs have positioned Malaysia as the 44^{th} space member state in the Committee on Space Research (COSPAR), which was established by the International Council for Science (ISCU) in 1956 under the purview of the United Nations (UN). Finally, it is a hope that the spacecraft synergisms can be extended to incorporate the spacecraft platform and its payloads as well leading to solely **1-SYSTEM**!

Disclaimers: The views expressed in this inaugural lecture are professional views that are deeply thought to be informative; and therefore, the nature of the arguments is towards a general understanding only.

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BIOGRAPHY

Renuganth obtained his Diploma (Mech. Eng.) from Universiti Teknologi Malaysia in 1994, BEng. (Robotics) from Institut Teknologi Bandung (Indonesia) in 1997, MEng. (Space) from INSAE-Supaero (France) in 1998 and PhD (Space) from Dresden University of Technology (Germany) in 2003. He was selected (top 5) by the Malaysian Industry-Government Group for High Technology (MiGHT) in 1997 under the National Aerospace Development Program to spearhead the space study in France under the Malaysian Space Initiatives. Due to the exposure of different education systems, Renuganth acquired foreign language proficiencies as well especially in German, French and Indonesian. His professional academic career began as a tutor in the Department of Aerospace in 1997 and was appointed lecturer in 2003. He has taught several undergraduate core space subjects in Aerospace Engineering namely, Satellite Technology, Rocket Technology, Space Mechanics, Spacecraft Dynamics & Control and Programming. He has also taught postgraduate courses such as Space Systems, Space Trajectory, Advanced Design Technique and Group Business. He has supervised 19 undergraduate students in their final year projects as well as 14 MSc students (nine completed) and nine PhD students (four completed). He has also been appointed as internal/external examiner for postgraduate students from Universiti Putra Malaysia (UPM) and other universities.

Renuganth is the first PhD holder in Astronautics in Malaysia (2003). His research works are constantly needed for the country to embark on an international space research effort. With the support of the Malaysian government, he has established the best and an impressive Satellite Laboratory in the country. The laboratory is equipped with flight grade space hardware and a complete satellite platform, which serves for teaching and space research works. He has also been successful in securing space research grants sponsored by the Ministry of Science, Technology and Innovation Malaysia (MOSTI), Ministry of Higher Education (MOH) and Universiti Putra Malaysia (UPM) worth almost RM 2.5 million in total. Due to his active involvement in research, he has also been invited as the keynote speaker and forum panels for space scientific events. He has developed a strong research national network with institutions, such as the Malaysian Space Agency (ANGKASA), Academy Science Malaysia (ASM), Royal Malaysian Airforce (RMAF) and National Hydraulic Institute (NAHRIM) and other higher learning institutions such as Universiti Sains Malaysia (USM), Universiti Teknologi Malaysia (UTM) and International Islamic University Malaysia (IIUM).

He has now more than 65 journal papers, an International Book, three European Patents in Space, two Copyrights in Space, 50 Conference Proceedings, and four Edited Proceedings. His papers can be found in tier 1 space journals. Due to his space research contributions, he was invited to serve as an Associate Editor for *Advances in Space Research* (Scopus and ISI-Thomson), and as the Editorial Advisory Board Member for A*ircraft Engineering and Aerospace Technology* (Scopus and ISI-Thomson). At Universiti Putra Malaysia (UPM), he has been serving as an Associate Editor for the *Journal of Science and Technology*-Pertanika (Scopus). Also, he has been constantly serving as a reviewer for other reputed aerospace journals such as *Acta Astronautica, Journal of Guidance, Control, and Dynamics* (AIAA), etc.

Renuganth has been the Deputy Vice Chancellor (Industry and Community Relations), Universiti Putra Malaysia (UPM) since 2012 at the age of 39 up to the present. He was the Director of Industry Relations and Networks at the Office of the Deputy Vice Chancellor (Industry and Community Relations), Universiti Putra

Malaysia (UPM) and was the Head of Industry Relations at the same office in 2011. He has implemented the Green Mandate Project and various UPM and industry co-operations. He was previously the Head of Industry & Community Relations at the Faculty of Engineering, UPM from 2009-2011.

Renuganth has been responsible for establishing three international MoUs for almost 15 years of co-operation with University of Applied Sciences Aachen (FH Aachen –Germany). In fact, the UPM-FH Aachen student mobility program has been the only active bilateral undergraduate student exchange program in UPM for years. Renuganth has also involved in international space research activities with institutions such as the Russian Academy of Sciences (Non-Disclosure Agreement), German Space Center (DLR), University of Applied Sciences of Aachen (Germany), Massachusetts Institute of Technology (MIT-USA), Indian Institute of Technology (IIT Kanpur-India) and Nanjing Aeronautics and Astronautics University (NAAU-China).

In fact, he has been invited by NAAU-China to train their space scientists on Novel Approaches for Spacecraft Guidance and Control. He is also a panel member of international conferences organized by international institutions. In fact, his space research contributions have propelled Malaysia to be accepted as the 44th Space Nation in the Committee on Space Research (COSPAR) in 2011, which had been pending for almost two decades due to the lack of space research outputs in Malaysia. COSPAR was established by the International Council for Science (ISCU) in 1956 and provides its state members such as Malaysia new opportunities in space. Besides being a permanent Representative in COSPAR International, Renuganth is also currently serving as the President (COSPAR-Malaysia).

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I thank God that I have come to this stage of publishing my inaugural lecture. I am grateful to all my teachers who have taught me and to all my students as well for their interest and hard work. I also wish to place on record my sincere appreciation to the management of Universiti Putra Malaysia and the Faculty of Engineering for providing me with this opportunity. Special thanks go to my parents and my wife for their continuous interest in my work and career.

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