Proceedings of the 15th IAA Symposium on Small Satellites for Earth System Observation

Introduction

Small Satellites for Earth System Observation are nowadays a key part of the critical space infrastructure and of the highest societal relevance. In addition, they are an important facilitator for the UN Sustainable Development Goals. These missions can be conducted efficiently, provide increased opportunities for access to space and help to realize new capabilities and services. The design of such satellites, its bus and payload systems, cover a wide span: ranging from optimized off-the-shelf systems, with little or no requirements for new technologies, to innovative and tailored high-tech systems. Thus, new classes of advanced small satellites can be created – including autonomously operated satellites or employing onboard machine learning algorithms for increased agility or downlink efficiency, which render missions more efficient or open new areas of applications for science, industry, governments or the public. In addition, multi-satellite systems, such as constellations and formations, offer exciting opportunities for a new economy in space, when utilising small satellites. We are building this year's edition on the success of past IAA Symposia, where authors from more than 35 countries, representing space agencies, industries, research institutes and academia, confirmed in their oral presentations and poster sessions that these missions can be conducted efficiently and offer opportunities for new applications and technological innovation. The venue, the Ludwig-Erhard-Haus, provides an inspiring environment, excellently suited to let us explore the latest developments in the field. We have an incredible line-up of speakers, who will share their expertise and insights. We encourage students to present their work. IAA is pleased to serve as the principal sponsor of this symposium because its objectives complement and re-enforce the purpose of the Academy.

It is a pleasure for the German Space Agency at DLR to be the host of this symposium. The Agency undertakes statutory tasks in the space sector on behalf of the German Federal Government and implements the space strategy of the Federal Government, develops and manages the national space programme and represents the interests of the Federal Republic of Germany in space-related international bodies in accordance with the tasks assigned to it. The Agency advises the Federal Government and develop initiatives and strategic approaches for space policy. With its missions and projects, the Agency strengthens Germany's scientific excellence and expands the technological expertise and global competitiveness of German industry. Promoting the commercialisation of space technologies, the innovation potential of German SMEs and technology transfer are essential tasks of the industrial policy mandate. Space technologies and applications are intended to benefit people on Earth and improve the quality of life in Germany, Europe and the rest of the world. The Agency's space missions make a significant contribution to solving global and societal challenges. Examples include providing information on climate change and climate protection, the further development of digitalisation and communications technologies, and contributions to national security.

The Technical University of Berlin is pleased to be the co-host of the 15th edition of the symposium. The Chair of Space Systems has already brought into space 31 satellites for Earth observation, satellite communication, and technology demonstration, which were designed, built, and operated by students. Another three small satellites, currently in development, along with two mission studies extending beyond Earth orbit, underline TU Berlin's position at the forefront of academic research and innovation.

It is a great pleasure for us, the chairpersons of this symposium, to have welcomed the international community to the 15th IAA Symposium on Small Satellites for Earth System Observation (SSEO). The Symposium took place from May 4th – 8th, 2025 in Berlin and we are now excited to present to you the proceedings of this year's symposium.

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Contents

Optimal manoeuvring of small Earth Observation platforms for frequent re-targeting

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Abstract: The study of this paper involves establishing an optimal retargeting manoeuvre for an agile Earth Observation satellite and investigating the criteria to perform the manoeuvre. Reaction wheels in a 4-wheel pyramid structure are considered as torque actuators. An optimal manoeuvre is calculated for the shortest distance to a target orientation, and an attitude tracking method is employed to perform the manoeuvre. The results are validated through a numerical simulation.

Key words: Attitude Control, Earth Observation, Reaction wheel, Agile Satellite, Optimal Manoeuvre.

1. INTRODUCTION

The present times in satellite Earth Observation (EO) is undergoing a significant evolution, driven by the rising demand for high-resolution, near real-time information. However, the established framework of large EO spacecraft exhibits limitations in addressing this expanding need, burdened by increased operational costs and limited periodicity of the same ground coverage [1,2]. Consequently, very few large EO satellites are in active operation and to increase their number is not a cost-effective approach. Data secured by these large platforms encompass wide time periods for the same area coverage resulting in low temporal resolutions. In this context, the advent of small satellites represents a fundamental transformation in operation, cost-effectiveness, and periodicity of EO data acquisition. Enabled by advancements in micro-electronics and economical launch alternatives, these platforms enable access to lower cost space-based EO. Configurations of small satellites offer near-continuous coverage, facilitating the observation of dynamic events with higher temporal resolution.

The understanding of agile EO operations, defined by frequent re-targeting and on-demand coverage, is reliant on sophisticated attitude control mechanisms. Operating within demanding resource constraints, small satellites offer innovative solutions balancing performance and efficiency. Unlike, large EO platform, the acquisition sensors on board the space platform have constraints on the degrees of freedom allowed to its movement. Mechanical motors can be installed to offer some limited movement of the sensor with respect to the space platform. However, this approach makes the spacecraft system sophisticated, bulkier and costlier. Since one of the objectives is to facilitate cost-effective EO solutions, innovation and research is focused towards the movement of the entire space platform instead of the on-board sensor. Therefore, precise and rapid attitude maneuvers are critical for high-fidelity image acquisition and pointing stability.

The maneuver for frequent re-targeting of small satellites for multi-object observation is studied to plan the most optimal path which the satellite attitude must follow during the repointing phase. The initial stages of this research begins with establishing a framework and a tool to simulate and study an optimal manoeuvre for precise attitude control on a small EO satellite.

2. RETARGETING MANOEUVRE

2.1 Reference Frames

Spacecraft attitude is a satellite's orientation in three dimensional space whose representation and control is predicated upon the precise definition and application of appropriate reference frames. The body frame, with the origin lying at the satellites centre of mass is rigidly affixed to the spacecraft, serves as the primary coordinate system for articulating the satellite's spatial orientation and the integration of sensor and actuator systems. The careful selection of reference frames is paramount for achieving mission-critical objectives, with the Earth-Centered Inertial (ECI) frame serving as a foundational inertial reference. The orbital frame, is essential for the articulation of Earth-relative pointing requirements. For a circular orbit, this frame is established with its x-axis aligned with the satellite's velocity vector, the z-axis is aligned with the local nadir direction, and the y-axis completes the right-handed orthogonal system in Figure 1.

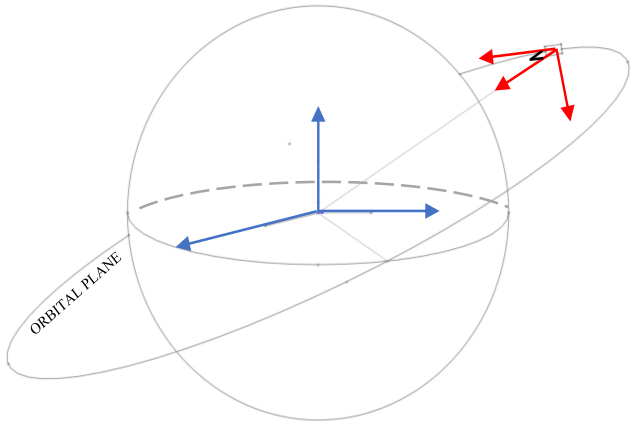

Figure 1. Sketch of the orbital and ECI frames.

2.2 Commanded Frame

The commanded frame defines the desired attitude of the satellite, facilitating precise control of its orientation. This time varying frame specifies the manoeuvre that the satellite's body frame must attain at each time instant, particularly during attitude retargeting maneuvers. The attitude control system utilizes the differential between the actual body frame orientation and the commanded frame orientation to compute and apply control torques, thereby ensuring tracking of the desired orientation. To facilitate a clear analytical framework, this study assumes a circular orbital trajectory and an initial condition wherein the satellite's body frame is coincident with the orbital frame.

The commanded frame at initial time instant aligns with the orbital frame. As time progresses, the commanded frame performs a rotation about an axis that is defined based on the target attitude. Moreover, the angular velocity of the orbit is to be considered since the orbital frame is also moving with respect to the ECI frame. To define a quaternion from the commanded frame to the ECI frame (**Q_{CI}**), one must establish an intermediary quaternion for orbital with respect to ECI (**Q_{OI}**) and another one is the commanded with respect to the orbital (**Q_{CO}**). To establish these quaternions, the orbit of the EO platform must be known. For this research a hypothetical circular orbit set at an altitude of roughly 820 km is assumed. Having set the orbit parameters and establishing the mean motion of the satellite in its orbit, it is now possible to define the quaternions Q_{OI}, Q_{CO} and Q_{CI} and the relation between them given by Equation (1) as a quaternion product [10].

$$Q_{CI} = Q_{CO} \otimes Q_{OI} \tag{1}$$

2.3 Time Optimal Path-Planning

To achieve the desired attitude for the EO platform, the knowledge of the target must be established. The target area can be defined and identified by the geographical latitude and longitude. With the prerequisites set, the target attitude is calculated and fixed in terms of 3-2-1 Euler angles with respect to the orbital frame. The optimal manoeuvre as discussed by Yang et al [4], which introduces a time optimal path plan for EO platforms has put focus on two main aspects: selection of the manoeuvre with the shortest angular displacement for the satellite to achieve the desired attitude, selection of the angular velocity to minimize the time taken for the manoeuvre.

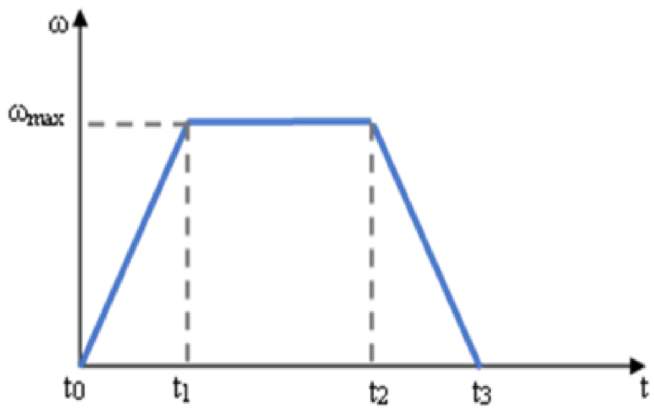

Figure 2. EO platform angular velocity change over time for optimal path of the shortest distance during repointing.

The attitude manoeuvre is a rotation about the eigen axis of the target attitude with respect to the orbital frame [4]. To achieve the desired manoeuvre, the platform reaches the maximum angular velocity of the commanded frame with respect to the orbital frame as quick as possible considering that the initial and the final angular velocity is zero. On a plot of time vs angular velocity in Figure 2, the path that the spacecraft must take is followed by a uniform acceleration, constant velocity and uniform deceleration phase. Taking the time of start of the manoeuvre at t_0, the planned manoeuvre starts from zero angular velocity and with uniform angular acceleration at a maximum value that is generated from the torque actuators to reach the maximum allowable angular velocity at time t_1. This limit on angular velocity is set to a maximum, ω_{max}, by considering several factors including, scan rate of EO sensors, calibration and sensitivity of attitude sensors, structural integrity of platform, etc. From t_1 to t_2, the platform will rotate with uniform angular velocity which will be equal to the maximum allowable angular velocity. From t_2 to t_3, the platform is given a uniform deceleration equal and opposite to the acceleration to bring the angular velocity to zero or to desired values. The times t_1 and t_2 are selected so that, the satellite achieves a rotation about the eigen axis equal to the eigen angle Φ.

3. SPACE PLATFORM

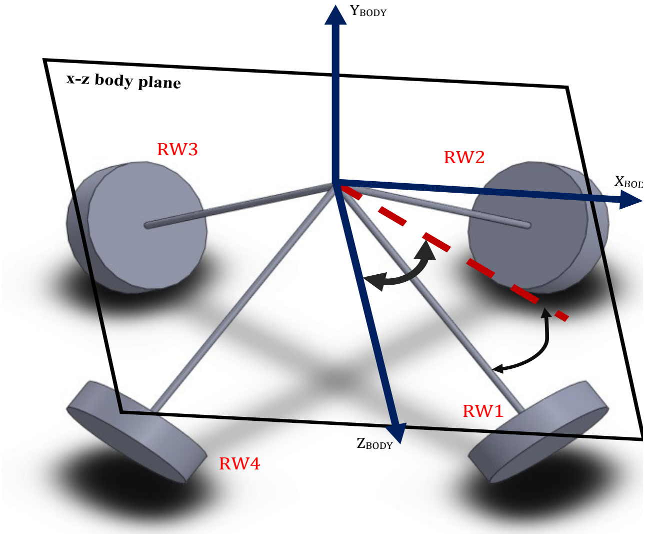

Figure 3. The 4-reaction wheel setup used for this study.

The selection of actuators and sensors plays a pivotal role in the attitude control mechanism's adaptability. Reaction wheels, recognized for their precision, are frequently employed, but require periodic desaturation. Different configurations of reaction wheels were considered [5]. In this study, the 4-reaction wheel setup is used. This setup begins first, by arranging the axis of the 4 reaction wheels along the positive and negative axes of the 'x' body frame and 'z' body frame. rotation by an angle (γ = 45°) of the 'y' body brings the reaction wheel assembly to an intermediate configuration. Following which the axis of each reaction wheel is skewed away from the 'x-z' plane, towards the negative 'y' axis by an angle η = 35.26°. his rotation is measured on the planes that are perpendicular to the 'x-z' plane and parallel to each axis of the 4 reaction wheels and is illustrated clearly in Figure 3. The angle γ = 45° is chosen in such a way that the torque contribution along the 'x' and 'z' axes are provided by the cumulative of all 4 reaction wheels instead of just 2 in each of the 'x' and 'z' directions. he angle η = 35.26° is selected so that the maximum torque values (τ_{x_max}, τ_{y_max} and τ_{z_max}) acting on the platform are all equal. With this setup of the reaction wheels, the angular momentum generated by the actuator system is used to drive the suitable control torque required for the attitude manoeuvre. The attitude dynamics of the satellite is given by Equation (2)

$$\mathbf{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \mathbf{I}\boldsymbol{\omega} = -\sum_{i=1}^{4} \dot{h}_i \mathbf{p_i} - \boldsymbol{\omega} \times \left(\sum_{i=1}^{4} h_i \mathbf{p_i}\right) + \mathbf{T_e} \quad \textbf{(2)}$$

where **I** is the satellite inertia matrix. In this study, **I** is a diagonal matrix whose elements are equal to 14.05 kg/m^2, 14.65 kg/m^2 and 12.86 kg/m^2. Symbol $\boldsymbol{\omega}$ denotes the column matrix of the angular velocity of the platform in body coordinates. The reaction wheel setup that is employed for this study gives the orientation of the axes of all the reaction wheels with respect to the platform body axes, which is represented by a3x4 matrix **P** which is calculated in Equation (3) using the values of γ = 45° and η = 35.26°. The 4 column matrices extracted from **P** give the orientation of the spin axis of each reaction wheel in body coordinates from Figure 3 denoted by $\mathbf{p_i}$. The scalar part of Equation (2), h_i is the magnitude of the angular momentum contributed by each reaction wheel relative to platform. Effect of environmental torques is represented by $\mathbf{T_e}$ and is set at zero for this initial study. In further developments of this research, the dynamic effects of different environmental torques can be considered for detailed study. Equation (4) shows the control torque generated by the four reaction wheels.

$$\mathbf{P} = \begin{bmatrix} cos\eta\ sin\gamma & cos\eta\ cos\gamma & -cos\eta\ sin\gamma & -cos\eta\ cos\gamma \\ -sin\eta & -sin\eta & -sin\eta & -sin\eta \\ cos\eta\ cos\gamma & -cos\eta\ sin\gamma & -cos\eta\ cos\gamma & cos\eta\ sin\gamma \end{bmatrix} \quad \textbf{(3)}$$

$$\mathbf{T_c} = -\sum_{i=1}^{4} \dot{h}_i \mathbf{p_i} - \boldsymbol{\omega} \times \left(\sum_{i=1}^{4} h_i \mathbf{p_i}\right) \quad \textbf{(4)}$$

4. ATTITUDE TRACKING

It is important for the EO space platform to correctly track the commanded frame during the active attitude manoeuvring. In ideal cases, the body frame of the platform and the commanded frame should be perfectly aligned at every time instant during the active manoeuvre. In real word scenarios, several factors must be considered and the error build up from the various sections lags the body frame behind the commanded frame. To set a parameter for the attitude tracking of the satellite, the target attitude is set from the knowledge of the observation target on the earth surface. From the theory of time optimal path planning presented in section 2.3, a commanded frame is established that translates the attitude of the EO platform from the initial attitude that is aligned with the orbital frame to the target attitude. The commanded frame is necessary as it is used to establish the ideal control torque, which is the commanded torque ($\mathbf{T_{CMD}}$) that the satellite actuators must generate and is calculated using a proportional-derivative control law [6, 7] in Equation (5).

$$\mathbf{T_{CMD}} = \mathbf{I}\,(k_d\boldsymbol{\omega_e} + 2k_p\mathbf{Q_{CB\_v}} + \dot{\boldsymbol{\omega}}_{\mathbf{CI}}) + \mathbf{T_g} \quad \textbf{(5)}$$

$$\boldsymbol{\omega_e} = \boldsymbol{\omega_{CI}} - \boldsymbol{\omega} \quad \textbf{(6)}$$

The angular rate error matrix ($\boldsymbol{\omega_e}$) is found with Equation (6). The commanded frame is defined with a quaternion ($\mathbf{Q_{CI}}$) from inertial reference system. The quaternion of commanded frame with respect to the body frame ($\mathbf{Q_{CB}}$) at each time instant is calculated by computing the readings and inputs from the attitude sensors and establishing the quaternion of the body frame with respect to the inertial frame ($\mathbf{Q_{BI}}$) in equation (7).

$$\mathbf{Q_{CB}} = \mathbf{Q_{BI}}^{-1} \otimes \mathbf{Q_{CI}} \quad \textbf{(7)}$$

The vector portion $\mathbf{Q_{CB}}$ is separated to obtain $\mathbf{Q_{CB\_v}}$, which is then used in Equation (5). $\mathbf{T_g}$ is the gyroscopic feedforward torque which is found using Equation (8).

$$\mathbf{T_g} = \boldsymbol{\omega_{CI}} \times (\mathbf{I}\boldsymbol{\omega}) \quad \textbf{(8)}$$

During preliminary investigative studies, the proportional gain k_p and the derivative gain k_d are set at a fixed value of 1 in Equation (5). Different values will have to be investigated to find an optimal value or range of values for k_p and k_d in planned future developments of this study.

The $\mathbf{T_{CMD}}$ is not the one that the actuators will generate but $\mathbf{T_C}$ which is obtained by the knowledge of $\dot{\mathbf{h}}$, which is unknown. For computation, a new variable $\mathbf{g}$ is introduced defined with Equation (9). It is computed using a modified version of Equation (4) which is Equation (10).

$$\mathbf{g} = \sum_{i=1}^{4} h_i \mathbf{p_i} \quad \textbf{(9)}$$

$$\mathbf{T_{CMD}} = -\dot{\mathbf{g}} - \boldsymbol{\omega} \times \mathbf{g} \quad \textbf{(10)}$$

To find the correct values of $\dot{\mathbf{h}}$ for each individual reaction wheel from Equation (9), which is a system of homogeneous equations, a pseudo inverse is applied on $\mathbf{p_i}$. The resultant $\dot{\mathbf{h}}$ is directed to their respective reaction wheels.

5. SIMULATION AND DISCUSSION

5.1 Simulation pre-requisites

In the development and research for finding an optimal manoeuvre for agile EO satellites, a tool has been coded using Matlab and Simulink to demonstrate the proposed optimal path for rapid repointing of single and multi-observation targets. The program reads a series of inputs from the operator which is then used to create a simulation of the proposed manoeuvre. The simulation step lists out important figures and readings which frame block generates the commanded frame that defines the path from nominal or the initial state to the target attitude. The orbit of the satellite is propagated in this block using the orbital parameters extracted using Two-Line Elements (TLE) data of the satellite. In the simulation, a realistic TLE is considered, which corresponds to the TLE of satellite PROBA-V (NORAD ID: 39159) [8] measured on 01-01-2025 [9]. The target attitude is defined through the following 3-2-1 Euler sequence of ϕ = -15°, θ = 18°, ψ = 6° with respect to the orbital frame. The quaternion rotations between the ECI, orbital and the

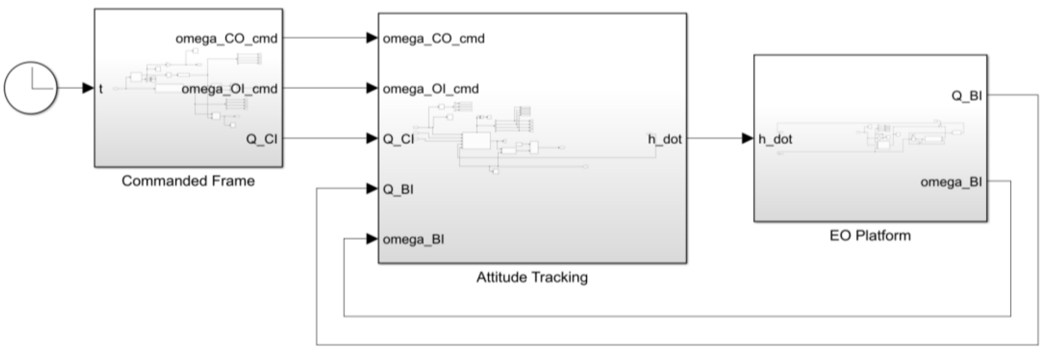

Figure 4. Simulation Block diagram in Matlab/Simulink.

commanded frames are established and forwarded to the next block, the Attitude Tracking block. The Attitude Tracking is a system of equations that generates the $\mathbf{T_{CMD}}$, from which $\dot{h}$ is calculated and forwarded to the next block, the EO platform. This is where the necessary $\dot{h}$ is applied to the reaction wheels to generate the torques necessary for changing the platforms attitude to point at the target.

5.2 Discussion

The first plot in Figure 5, showcases the development of the angular velocity of the commanded frame with respect to the orbital frame along each of the coordinates in the commanded reference frame. Similarity Figure 2 shows the time-optimal path following the sequence of uniform acceleration, constant angular velocity, and uniform deceleration. In this simulation, the $\omega_{max} = 8$ deg/s which is taken as reference [4], $\dot{\omega}_{max} = 2.3$ deg/s^2 is computed using the values of inertia matrix **I** and of matrix **P**.

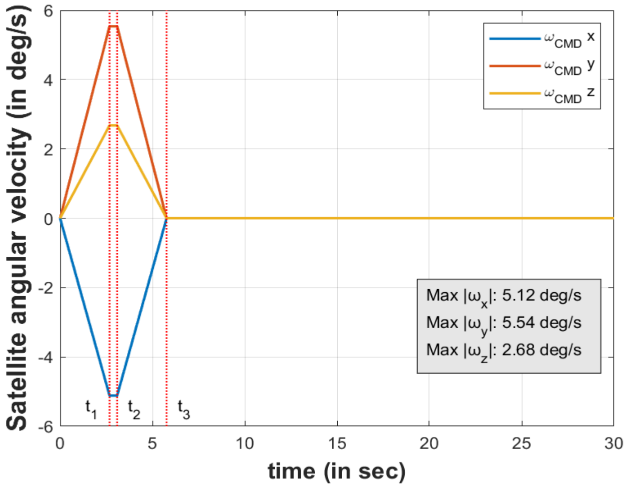

Figure 5. Path plan of the commanded attitude.

The second plot in Figure 6 demonstrates the change in the quaternion rotation from commanded to body frame of the satellite as it performs the repointing manoeuvre. Because the body frame lags behind the commanded frame, the vector part of the quaternion from commanded to body frame has a non-zero opening value which starts to converge to zero after about 9 s. Concurrently, the scalar part also converges to one after the manoeuvre ends, respecting the unitary law of quaternions.

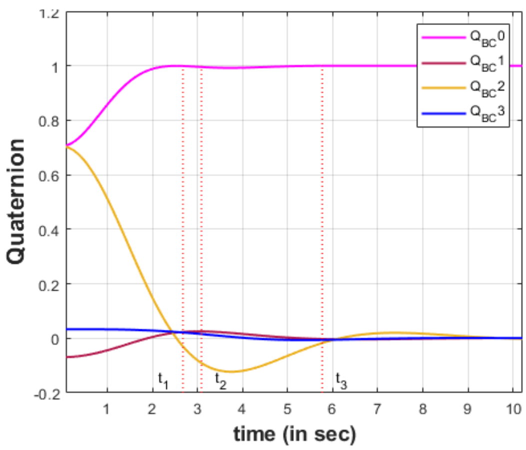

Figure 6. Quaternion rotation from commanded to body frame during repointing manoeuvre.

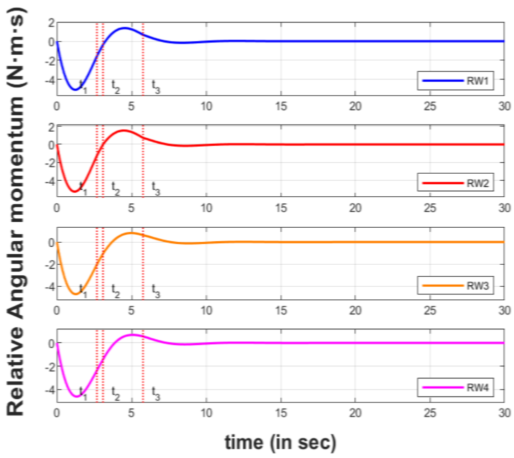

Figure 7. Relative angular momentum of each reaction wheel.

The third set of plots in Figure 7 shows the time behavior of the relative angular momentum of each reaction wheel, h_i, numbered as shown in Figure 3. For the defined target attitude each reaction wheel rotates at its own functioning relative angular momentum contributing a fraction of the total angular overall momentum of the platform.

6. CONCLUSION

The preliminary foundation of the research in designing the optimal path for a rapid-repointing manoeuvre of an agile satellite is established. The ideal case of circular orbits with absence of environmental torques and non-consideration of the saturation of the reaction wheels has displayed interesting time behaviors of the rapid repointing of the attitude for small and large angle manoeuvre. Research is going to continue further on this topic starting with the introduction of reaction wheel saturation and moving forward addressing each issue to make the model suitable for real word applications in Earth observation or other fields. In further development of this tool, it will also be made possible to have the possibility to rely the target on the surface defined by local latitude and longitude and have the tool compute the relevant eigen axis and angle.

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