Methods to operate and evaluate the performance of a cold-gas CubeSat propulsion system on a magnetically stabilised satellite

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Abstract—Propulsion systems allow satellites to perform many functionalities in space, such as orbital station keeping, reentry control, attitude control, orbital transferring, rendezvous operation, and even more thrilling, interplanetary travel. Indeed, propulsion systems in satellites have fostered a new favorable era of space exploration and application, therefore, detailed processes to operate propulsion systems need to be developed so that space missions, carrying this valuable system, are completed successfully. The aim of this study is to describe the most relevant operating procedures for the cold gas propulsion system NanoProp 3U, developed by GomSpace, on-board the 3U CubeSat MIST satellite developed by KTH. Procedures, such as power levels, telemetry considerations, propellant mass determination, Fault Detection Isolation and Recovery analysis, and decommissioning plan allow proper operation of NanoProp according to the mission requirements determined for MIST mission. Moreover, this study describes detailed mission experiments to be performed with NanoProp with the objective of assessing the performance delivered by the propulsion system itself, and other on-board subsystems which are required for monitoring and controlling the spacecraft according to the effects generated by the propulsion system. The planning and operation of a propulsion system should be outlined on-ground, during the mission design, so a clear understanding of the characteristics and limitations of the system are highlighted towards the development of a secure and solid space mission.

Index Terms—propulsion system, CubeSat, performance, operating procedure, mission experiment.

List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Semi-major axis</td>
</tr>
<tr>
<td>a₀</td>
<td>Initial semi-major axis</td>
</tr>
<tr>
<td>a_f</td>
<td>Final semi-major axis</td>
</tr>
<tr>
<td>a_cc</td>
<td>Acceleration</td>
</tr>
<tr>
<td>A</td>
<td>Cross-sectional area</td>
</tr>
<tr>
<td>B</td>
<td>Magnetic field</td>
</tr>
<tr>
<td>B</td>
<td>Derivative of magnetic field</td>
</tr>
<tr>
<td>c</td>
<td>BDOT gain</td>
</tr>
<tr>
<td>C_D</td>
<td>Drag coefficient</td>
</tr>
<tr>
<td>C_r</td>
<td>Reflectivity coefficient</td>
</tr>
<tr>
<td>d</td>
<td>Distance</td>
</tr>
<tr>
<td>e</td>
<td>Eccentricity</td>
</tr>
<tr>
<td>e₀</td>
<td>Initial eccentricity</td>
</tr>
<tr>
<td>e_f</td>
<td>Final eccentricity</td>
</tr>
<tr>
<td>f_sampling</td>
<td>Sampling frequency</td>
</tr>
<tr>
<td>F</td>
<td>Thrust</td>
</tr>
<tr>
<td>g₀</td>
<td>Gravitational acceleration (9.81 m/s²)</td>
</tr>
<tr>
<td>hₚ</td>
<td>Perigee altitude</td>
</tr>
<tr>
<td>h_a</td>
<td>Apogee altitude</td>
</tr>
<tr>
<td>i</td>
<td>Inclination</td>
</tr>
<tr>
<td>I</td>
<td>Moment of inertia</td>
</tr>
<tr>
<td>Iₜot</td>
<td>Total impulse</td>
</tr>
<tr>
<td>I_sp</td>
<td>Specific impulse</td>
</tr>
<tr>
<td>L</td>
<td>External torque</td>
</tr>
<tr>
<td>m</td>
<td>Mass of MIST satellite</td>
</tr>
<tr>
<td>m_d</td>
<td>Magnetic dipole</td>
</tr>
<tr>
<td>m₀</td>
<td>Initial mass</td>
</tr>
<tr>
<td>m_f</td>
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<tr>
<td>m_p</td>
<td>Mass of propellant</td>
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<tr>
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<td>Mass flow rate</td>
</tr>
<tr>
<td>M</td>
<td>Mean anomaly</td>
</tr>
<tr>
<td>n</td>
<td>Mean motion</td>
</tr>
<tr>
<td>R₀</td>
<td>Radius of Earth (6,378.15 km)</td>
</tr>
<tr>
<td>rₚ</td>
<td>Perigee radius</td>
</tr>
<tr>
<td>r_a</td>
<td>Apogee radius</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
</tr>
<tr>
<td>t_burn</td>
<td>Burn time</td>
</tr>
<tr>
<td>T₀</td>
<td>Initial temperature</td>
</tr>
<tr>
<td>T_f</td>
<td>Final temperature</td>
</tr>
</tbody>
</table>
\[ TP \] Orbital period
\[ \nu \] True anomaly
\[ v_e \] Effective exhaust velocity
\[ \beta \] Quaternion
\[ \Delta V \] Total velocity change
\[ \Delta V_{\text{max}} \] Maximum total velocity change
\[ \Delta a \] Semi-major axis change
\[ \Delta e \] Eccentricity change
\[ \Delta h \] Altitude change
\[ \Delta T_p \] Orbital period change
\[ \mu \] Standard gravitational parameter
\[ (398 \text{ 600.8 km/s}^2) \]
\[ \omega \] Angular velocity
\[ \omega_{\text{ARW}} \] Angle random walk noise
\[ \omega_{\text{bias}} \] Static error
\[ \omega_B \] Bias instability noise
\[ \omega_g \] Angular velocity from gyroscope
\[ \omega_p \] Argument of perigee
\[ \omega_{\text{RW}} \] Rate random walk noise
\[ \Omega \] Right ascension of the ascending node

I. INTRODUCTION

SINCE 1957, when the first artificial satellite, Sputnik I, was launched into orbit, space technology has been developed for different applications such as Earth observation, space exploration and science, communications, and more. However, it was not until the development of small, standardised, and affordable satellites in the late 1990s that the opportunity to provide hands-on experience in space technology and access to space to everyone became a reality.

These breakthrough satellites, called CubeSats, are 10 cm square-shaped satellites that are nowadays developed mainly for technology demonstration, scientific experiments, commercial interest, and most importantly, educational projects. In recent years, as a result of the miniaturisation and affordability of technologies, there has been an increasing trend in the number of CubeSats being deployed into orbit every year. Over the next 6 years, over 2 500 are scheduled to launch, [1].

Few of these CubeSats, however, contain a propulsion system limiting the functionalities they can provide to the end user. Without a propulsion system, CubeSats are orbiting in the same orbit they are deployed, increasing their likelihood of colliding with space debris and limiting their lifetimes due to being deployed at low altitudes. Therefore, a propulsion system allows CubeSats to manoeuvre their way into a desired orbit, or even just regulate their current orbit for a longer time. It also allows them to be deorbited to prevent them from contributing to the space debris problem.

A. Purpose and motivation

CubeSat propulsion will definitely drive in a new era of affordable space exploration. This will mean propulsion will become a standard component on the majority of CubeSats which clearly requires the development of structured operating procedures so the satellite can complete its mission objectives as planned.

Therefore, the purpose of the present study is to identify and characterise the operating procedures needed to run a cold gas CubeSat propulsion system, NanoProp 3U developed by GomSpace, on a magnetically stabilised CubeSat, KTH’s Miniature Student satellite (MIST). The study also aims to identify and describe the mission experiments that could be performed with this propulsion module with the objectives of evaluating the performance delivered by the system itself, and determining the capability of other subsystems such as the on-board Magnetoquer/Magnetometer board (iMTQ) of ISISpace or the new incorporated Inertial Measurement Unit board (IMU) to operate according to the outcomes induced by the propulsion system.

B. Scope of the study

The present study aimed at identifying and defining the operating procedures and mission experiments of NanoProp by considering the latest operating and design analyses of the MIST mission, and the required internal system operations of the propulsion module and the other interested subsystems.

Moreover, the overall approach of this study followed some of the space project and application standards developed by the European Cooperation for Space Standardisation initiative (ECSS), principally in the development of the Fault Detection Isolation and Recovery (FDIR) analysis and decommissioning plan:

- ECSS-Q-ST-30C - Dependability
- ECSS-Q-ST-30-02C - Failure modes, effects (and criticality) analysis (FMEA/FMECA)
- ECSS-U-AS-10C - Space Sustainability - Adoption Notice of ISO 24113: Space Systems - Space Debris Mitigation Requirements
- ESSB-HB-U-002 - ESA Space Debris Mitigation Compliance Verification Guidelines

This thesis does not, however, cover the identification and characterisation of system engineering general requirements of either NanoProp or MIST mission.

Proposed mission experiments and an analytical model of NanoProp operation were developed assuming the variation of thrust between thrusters as the main cause of thrust misalignment in NanoProp with a maximum difference of 10%. Moreover, the torques derived from thruster firings are the only ones influencing the spacecraft dynamics model, thus this study assumed an unperturbed environment for MIST. Additionally, the study was developed considering the application of iMTQ and IMU subsystems for monitoring and controlling the outcomes of NanoProp experiments instead of using the ADCS system on MIST.

Finally, thruster firing control was not included in this study mainly because NanoProp does not include throttle devices to regulate the thrust levels. Thrusters in principle only provide a particular thrust level based on thermal and pressure specifications as explained further on, leading to the need of a robust feedback firing control design which could be covered in a subsequent study.
C. Structure of the study

A more detailed account of the MIST mission and the fundamental internal system operations and specifications of NanoProp and all other subsystems are provided through Section II.

Section III of this study first describes the analytical model to evaluate the performance of NanoProp (thrust, thrust misalignment and $I_{sp}$), followed by the description of a Matlab/Simulink model designed to study the behaviour of MIST and subsystems throughout a NanoProp operation. After that, the study assesses the feasibility to operate NanoProp either automatically or manually by analysing the latest thermal and ground station accessibility analyses developed for MIST mission as well as power budgets for particular operating scenarios. Finally, the study describes the fundamental operating procedures for NanoProp such as power levels, telemetry considerations, propellant mass determination procedure, FDIR analysis and decommissioning plan.

In Section IV, NanoProp mission experiments are summarised, including a description of the Standard Operating Procedure (SOP) for NanoProp and a dynamic simulation of the entire process expected to be observed when operating NanoProp.

II. BACKGROUND

In order to characterise the operation of NanoProp, it is important to know the requirements of the space mission where this propulsion system will be working on, and the essential internal operations and specifications of each subsystem used throughout the firing operation. Therefore, this section describes the most relevant features of the MIST mission as well as significant internal system operations and specifications of NanoProp, iMTQ, and IMU.

A. MIST

The MIST mission aims at demonstrating new scientific instruments and electronic technologies in space. MIST is a 3U CubeSat whose payload consists of six experiments for educational or industry purposes as illustrated in Fig. 1.

1) Reference orbits: In the MIST project, analyses are performed using two reference orbits to cover the possible range of orbits corresponding to the available launch opportunities, [2]. The reference orbits are described in Two-Line Element sets (TLE), Fig. 2 shows the TLE description of one of the MIST reference orbits.

The other reference orbit for MIST only differs by its longitude of the ascending node, thus the altitude range and period are the same for both reference orbits. The orbital elements for MIST are defined for 0000:00 UT on 21 June 2017, [2].

Table I outlines the orbital parameters determined by MIST reference orbits and other resultant parameters such as orbital period and perigee and apogee radii.

The orbital period was calculated by using (1) where $t$ is the quantity of time in a day.

$$T_p = \frac{t}{n}$$  \hspace{2cm} (1)

Using (2), the semi-major axis of MIST reference orbit was calculated where $\mu$ is the standard gravitational parameter, [3].

$$a = \left[ \mu \left( \frac{T_p}{2\pi} \right)^2 \right]^{1/3}$$  \hspace{2cm} (2)

Consequently, the perigee and apogee radii were calculated by using (3), and (4), [3].

$$r_p = a (1 - e)$$  \hspace{2cm} (3)

$$r_a = a (1 + e)$$  \hspace{2cm} (4)

2) Communication access opportunities: In order to have an overview of the communication access to MIST’s ground station, the reference orbits are modelled using the AGI’s Systems Tool Kit (STK). The model indicates the average orbital period is approximately 98 min during which 33 min are spent in eclipse and 65 min in sunlight, [2].

Considering that the ground station will be located at KTH, Stockholm, Sweden, a 98-min orbital period yields approximately to 15 revolutions around Earth per day, however, there are only a few good passes over KTH each lasting 10–12 min, [2].
### Table I
**Orbital Parameters for MIST Mission**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( i )</td>
<td>97.943°</td>
</tr>
<tr>
<td>( \Omega )</td>
<td>250.633°</td>
</tr>
<tr>
<td>( e )</td>
<td>0.001</td>
</tr>
<tr>
<td>( \omega_p )</td>
<td>0°</td>
</tr>
<tr>
<td>( M )</td>
<td>0°</td>
</tr>
<tr>
<td>( n )</td>
<td>14.75896 rev/day</td>
</tr>
<tr>
<td>( a )</td>
<td>7020.45 km</td>
</tr>
<tr>
<td>( T_p )</td>
<td>97.57 min</td>
</tr>
<tr>
<td>( r_p )</td>
<td>7 013.43 km</td>
</tr>
<tr>
<td>( r_a )</td>
<td>7 027.47 km</td>
</tr>
</tbody>
</table>

3) **Coordinate systems and flight attitude:** MIST uses two main coordinate systems. The body frame \((X,Y,Z)\) and the orbital frame \((U,V,W)\) which are related as shown in Fig. 3. The relation between coordinate systems is then expressed by using (5), [2].

\[
(U,V,W) \equiv (Z,-Y,X) \tag{5}
\]

![Fig. 3. Relation between spacecraft body frame and orbital frame.](image)

In the orbital frame, \( U \) is along the radius vector from the Earth’s centre to the satellite, \( V \) lies in the orbital plane and points in the direction of orbital motion, and \( W \) is perpendicular to the orbital and completes the coordinate system.

There are three reference attitudes for MIST which are shown in Fig. 4. The primary flight attitude of MIST in orbit will be a tower configuration, [2].

![Fig. 4. Different possible reference attitudes for MIST, [2].](image)

**B. NanoProp 3U**

NanoProp 3U is a cold gas propulsion module suitable for 3U CubeSats. A schematic of the NanoProp system is illustrated in Fig. 5. It contains one main electronic board which controls 4 open-loop thrusters, valves, heaters, and temperature and pressure sensors of the entire system, [4].

![Fig. 5. Schematic of NanoProp 3U system, [4].](image)

NanoProp also contains a tank where the propellant, butane, is stored. It has a total internal volume of 100.78 cm\(^3\), however, the maximum amount of propellant allowed in the tank is 50 g. Overfilling the tank leads to over-pressures and possible break-up of the system when the tank is heated, [5].

1) **Thermal and pressure considerations:** The propellant is stored at a two-phase condition where liquid and gas are at equilibrium. The pressure inside the tank corresponds to the vapour pressure of butane given at a particular tank temperature, thus the storage tank temperature sets the feed pressure for the rest of the system, [5]. As a result, attention to thermal and pressure influences are crucial for an appropriate operation of NanoProp.

For instance, there is a risk of propellant condensation in downstream parts such as manifolds, piping or thrusters if those parts are set at a colder temperature than the propellant. A positive temperature gradient, however, decreases the risk of propellant condensation. The strategy is to gradually expose the propellant to warm temperatures as it goes down from tank to thrusters; this can be easily achieved by keeping the storage tank at “spacecraft equilibrium” temperature, i.e. not heating the propellant in the tank so the propellant is at its lowest temperature there, then manifold heaters are switched on for about 2 min to set manifolds at a warmer temperature than the tank, and thrusters are finally heated to a temperature warmer than manifolds, [5].
However, since energy is consumed when propellant undergoes a phase transition from liquid to gas, a gradual reduction in temperature, and consequently in feed pressure, usually happens during a firing operation. Therefore, it is also advised to keep heating the propellant during firing, primarily when performing long burns (i.e., more than 5 min), thus it is advised to permanently use the manifold heaters when performing long manoeuvres; it was initially suggested to use the tank heater for this operation, as suggested in the User Manual, but this has been modified since the tank actually receives significant radiated heat from thruster and manifold heaters when they are operating, [5].

Finally, in order to attain efficient thruster performance, pressure and mass flow should be high enough for the propellant to reach supersonic speed at nozzle throats, thus a minimum operating pressure is characterised to fire NanoProp. For NanoProp 3U this minimum pressure means that one has to consider 0 °C as the minimum operating tank temperature, [5].

2) Thrust and specific impulse: Fig. 6 shows that the thrust produced by NanoProp is proportional to the feed pressure, and consequently proportional to the storage tank temperature as well.

On the other hand, the feed pressure does not affect the $I_{sp}$ of the system. Thrusters can, however, become more efficient by heating the propellant before it enters the nozzle, yet the variation in $I_{sp}$ is minimal since the change is proportional to the square root of absolute temperature, [5].

Finally, Table II outlines the most relevant characteristics and nominal operating features assuming a 3-kg MIST satellite and all four thrusters of NanoProp firing. These parameters were used as reference points further on in the development of experiments for NanoProp.

3) Thruster states: Thrusters in NanoProp have the following operating states, [5]:

- **Off**: The thruster is inactive and no telemetry is collected. The thruster has to be Enabled in order to start the thruster operation.
- **Enabled**: The thruster is still inactive, but telemetry is collected. The thruster can now be commanded to enter the Arming state.
- **Arming**: The thruster is heated to arming temperature whose nominal value is 40 °C. When this temperature is reached, the thruster automatically goes to the Ready state.
- **Firing**: When entering Firing state, valves are opened and propellant is expelled through the nozzle, producing thrust. When the firing is complete, the thruster comes back to the Arming state.

A thruster can fire in two different modes: the indefinite firing mode and the impulse firing mode. In the former, the thruster fires as long as it is required, thus one defines and controls the duration of the firing. In the latter, on the other hand, the firing is automatically finished when the total impulse counter of the thruster reaches a specified total impulse set point, [5].

4) General operating procedure: Following operating procedures are shown to provide a basic understanding of how the system should be operated, [5]:

- **Satellite commissioning, in-orbit checkout and initial use**
  1) Power on propulsion system
  2) Set tank heater duty cycle to maximum
  3) Measure the current consumption of the unit and check that it exceeds 100 mA
  4) If possible, leave heater on for a few minutes, enough to measure a temperature rise in the tank
  5) Turn off tank heater
  6) Set manifold heater duty cycle to maximum
  7) Measure the current consumption of the unit and check that it exceeds 150 mA
  8) Turn off manifold heater
  9) Enable manual valve control
  10) Open thruster valves A, B, C, and D for 30 s to ventilate trapped atmosphere between first and second barriers. Note: this can affect spacecraft attitude
  11) Close all thruster valves and disable manual control
  12) Arm all thrusters
  13) Wait and ensure that all thrusters reach a state where they are preheated and ready (preheating nominal temperature is 40 °C)
  14) Power off propulsion system

---

**TABLE II**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$</td>
<td>3 kg</td>
</tr>
<tr>
<td>$m_p$</td>
<td>50 g</td>
</tr>
<tr>
<td>$F$</td>
<td>4 mN</td>
</tr>
<tr>
<td>$I_{sp}$</td>
<td>50 s</td>
</tr>
<tr>
<td>$\Delta V_{\text{max}}$</td>
<td>8.2 m/s</td>
</tr>
<tr>
<td>$v_e$</td>
<td>490 m/s</td>
</tr>
<tr>
<td>$I_{\text{tot}}$</td>
<td>25 Ns</td>
</tr>
</tbody>
</table>
In-orbit manoeuvres, normal use scenario
1) Power on propulsion system
2) Enable all thrusters
3) If tank temperature is less than 0 °C, turn on tank heater and wait until temperature is above 0 °C.
4) Turn off tank heater
5) Set manifold heater duty cycle to maximum
6) Arm thrusters
7) Wait until thrusters are preheated and ready (preheating nominal temperature is 40 °C)
8) Fire thrusters. Note: If burn time is expected to be more than 5 min, enable manifold heaters whilst thrusting
9) Wait until desired impulse has been reached, stop firing and disarm thrusters
10) Power off propulsion system

The operating time of the normal use scenario clearly depends on the firing time, but also in the time spent for heating propellant in the tank and arming thrusters, thus initial estimation of the heating rates of tank and thruster heaters was based on the operating records of a former 3U CubeSat mission with similar orbital parameters to the MIST mission of a commercial customer of GomSpace:
- Heating rate in tank = 180 s/°C
- Heating rate in thruster = 0.5 s/°C

C. iMTQ

A magnetically stabilised satellite depends on magnetometers (MTM) and magnetorques (MTQ). MTM measures the Earth’s magnetic field, which is then fed to the MTQ to produce torques to stabilise the satellite with respect to the magnetic field of Earth. Since MIST incorporates the iMTQ subsystem for autonomous detumbling and magnetic attitude control, it is also proposed to use the iMTQ for NanoProp operations; the iMTQ capabilities will allow to detumble the satellite once the firing manoeuvre is complete.

The ISISpace’s iMTQ is a CubeSat magnetic control module including a 3-axis magnetometer, 3 magnetorquers and a microcontroller. This subsystem is intended as a detumbling module based on a BDOT controller with following features, [6]:
- Detumbling mode is performed at a fixed BDOT frequency of 1, 2, 4 or 8 Hz.
- Default BDOT algorithm gain is $10^4$ Am²/s/T
- Actuation level in all 3-axis. Nominal value is 0.2 Am² at 20 °C, 5 V
- Maximum actuation envelope error < 5%
- Magnetometer accuracy < 3 μT

An increase in BDOT frequency in principle does not improve the detumbling performance, but only allows the BDOT algorithm to deal with higher angular rates, since it uses a first-order finite difference of the magnetic field as a measure for the angular rate. However, there are some side effects since the MTM can only be sampled when the MTQ is not active, so increasing the frequency will also decrease the time that the dipole can be effected, and thus decrease the detumbling performance. As a result, according to ISISpace, a BDOT frequency of 8 Hz allows the BDOT controller to handle angular rates up to 100 º/s.

D. IMU board - MPU6050

According to the dependability approach described in the ECSS standards, it became clear to develop a FDIR strategy for NanoProp mainly to avoid excessive rates building up to levels that the detumble function of the iMTQ cannot handle.

An IMU device (MPU6050), particularly the embedded MEMS gyroscope, can be used to measure the generated angular rates whilst performing manoeuvres. Therefore, the reading from the gyroscope will allow monitoring of the motion performance of MIST for the FDIR strategy and performance assessment of NanoProp.

The suggested MPU6050 device is an integrated 6-axis motion tracking system that combines a 3-axis gyroscope, 3-axis accelerometer, and a Digital Motion Processor (DMP). The MPU6050 features three 16-bit analog-to-digital converters (ADCs) for digitising the gyroscope outputs and three more 16-bit ADCs for digitising the accelerometer outputs. [7].

The 3-axis MEMS gyroscope has the following features:
- Digital output X, Y, Z axis angular rate sensors with a user-programmable full-scale range of ±250, ±500, ±1 000, and ±2 000 °/s
- Sensitivity Scale Factor of 131, 65.5, 32.8, 16.4 LSB/(°/s) for each full-scale range
- Integrated 16-bit ADCs enable simultaneous sampling of gyros
- Enhanced bias and sensitivity temperature stability reduces the need for user calibration
- Improved low-frequency noise performance
- Digitally programmable low-pass filter

It is important to note that as the sensitivity of the gyroscope increases, the full-scale range decreases, however, for this study the gyroscope can be set at the minimum full-scale range so the sensitivity of the gyroscope is at its best. This was determined by considering that the maximum angular rate supported by the iMTQ is 100 °/s and the angular rates produced from firing NanoProp are foreseen at a much lower value than the minimum full-scale range handled by the MPU6050’s internal gyroscope.

Finally, the MPU6050 device includes an internal calibration configuration so there might be no need for external temperature sensors or filters to perform a calibration process before operating the gyroscope.

III. Method

A. NanoProp evaluation - analytical model

One of the main objectives of this study is to determine a feasible strategy to evaluate the performance of NanoProp. Clearly, firing NanoProp influences in the dynamics of the spacecraft so it is evident to first outline the Euler rotational equations of motion shown in (6), [8]:

$$\dot{\mathbf{I}} \dot{\omega} = -[\dot{\omega}] \mathbf{I} \omega + \mathbf{L}_c$$

(6)
where $\omega$ is the body angular velocity vector, $I$ is the inertia matrix, and $L_c$ is the torque vector taken about the body centre of mass.

By choosing a body-fixed coordinate system that is aligned with the principal body axes, the inertia matrix $[I]$ will be diagonal and (6) reduces to (7)–(9), [8]:

$$I_{11}\dot{\omega}_1 = -(I_{33} - I_{22}) \omega_2 \omega_3 + L_1$$  \hspace{1cm} (7)
$$I_{22}\dot{\omega}_2 = -(I_{11} - I_{33}) \omega_3 \omega_1 + L_2$$  \hspace{1cm} (8)
$$I_{33}\dot{\omega}_3 = -(I_{22} - I_{11}) \omega_1 \omega_2 + L_3$$  \hspace{1cm} (9)

where $I_1$, $I_2$, and $I_3$ are the principal moments of inertia of the spacecraft; $\omega_1$, $\omega_2$, and $\omega_3$ are the rotational velocities around the principal axes; and $L_1$, $L_2$, and $L_3$ are the external influences about the centre of mass of the spacecraft which in this study only refer to the torques produced by firing the thrusters.

For the purpose of this study, the rotational equations of motion need to be solved for the external torques as shown in (10)–(12). Therefore, the angular rate data, measured by the MEMS gyroscope, will allow to estimate the external torque (10)–(12). Therefore, the angular rate data, measured by the MEMS gyroscope, will allow to estimate the external torque outlook applied on the spacecraft. The computed torques will indeed provide an approximate outlook of the thrust performance of NanoProp by taking into account the distances of thrusters from centre of mass as described in (13).

$$L_1 = I_{11}\dot{\omega}_1 + (I_{33} - I_{22}) \omega_2 \omega_3$$  \hspace{1cm} (10)
$$L_2 = I_{22}\dot{\omega}_2 + (I_{11} - I_{33}) \omega_3 \omega_1$$  \hspace{1cm} (11)
$$L_3 = I_{33}\dot{\omega}_3 + (I_{22} - I_{11}) \omega_1 \omega_2$$  \hspace{1cm} (12)

$$L = F \times d$$  \hspace{1cm} (13)

The best approach to characterise the torques is by firing pairs of thrusters so that the produced torque is either wholly or partially applied about one single axis, assuming a nonexistent or small misalignment of thrusters as illustrated in Fig. 7. Therefore, the misalignments need to be also accounted for and these can be a significant unknown (i.e. thrust vector with respect to nozzle mean vector, and nozzle mean vector with respect to thruster bracket or mounting misalignment of bracket).

In this study, for a simple characterisation, the misalignment of thrusters is modelled in two different ways: variation in thrust magnitude or thrust deviation from nozzle mean vector. The former is considered the main cause expected to experience in NanoProp, shown in Fig. 8, whose maximum difference is defined in 10%. The latter, on the other hand, describes the thrust misalignment with respect to nozzle mean vector in one plane as shown in Fig. 9.

In case the resulting torque outcome shows a significant torque production in $Z$ axis, which is called the roll axis, then the misalignment is in principle described by the thrust deviation from nozzle mean vector scenario. On the other hand, the variation in thrust magnitude scenario will in a sense produce torques only about two axes, pitch and yaw.

Certainly, a better interpretation and characterisation of thrust and thrust misalignment of each thruster is attainable by setting thrusters to specific thrust levels so an expected torque outcome is actually screened beforehand. The inconsistencies in thrust, expected to be minimal in NanoProp, can therefore be determined by evaluating the resulting torque outcome from the Matlab/Simulink simulation developed for this study.

Once the thrust performance is figured out, the $I_{sp}$ can be rated from each manoeuvre by using (14), where $F$ is the total delivered thrust and $\dot{m}$ is the mass flow rate of the expended propellant which can be specified from dividing the propellant mass consumption over the manoeuvre time, [3]:

$$I_{sp} = \frac{F}{\dot{m} g_0}$$  \hspace{1cm} (14)

Moreover, if thrusters are firing in impulse firing mode, the $I_{sp}$ can be determined by using (15) since one previously defines the required total impulse $I_{tot}$ provided by each thruster, [3]:

$$I_{sp} = \frac{I_{tot}}{m_p g_0}$$  \hspace{1cm} (15)

The simplest approach to know the propellant mass consumed during the manoeuvre or the total impulse attained by the thrusters is by reading internal registers specified by the NanoProp system.
B. Matlab/Simulink simulation

A Matlab/Simulink simulation was developed to analyse the dynamic behaviour of MIST and performance of MPU6050 and iMTQ subsystems throughout a NanoProp operation, and to test the performance of the thrust determination analytical model.

1) Satellite model: The simulation first presents a kinematic and dynamic model of MIST. The evolution of the angular velocities over time is modelled by considering the Euler rotational equations of motion, (7)–(9); and the attitude evolution due to angular velocities is described by Euler parameters (quaternions), shown in (16)–(19), since they provide a redundant, nonsingular attitude description, [8]:

\begin{align}
\dot{\beta}_0 &= \frac{1}{2} (-\beta_1 \omega_1 - \beta_2 \omega_2 - \beta_3 \omega_3) \\
\dot{\beta}_1 &= \frac{1}{2} (-\beta_0 \omega_1 + \beta_2 \omega_3 - \beta_3 \omega_2) \\
\dot{\beta}_2 &= \frac{1}{2} (-\beta_0 \omega_2 - \beta_1 \omega_3 + \beta_3 \omega_1) \\
\dot{\beta}_3 &= \frac{1}{2} (-\beta_0 \omega_3 - \beta_1 \omega_2 + \beta_2 \omega_1)
\end{align}

The latest inertia tensor proposed for MIST satellite was included in the simulation which is shown in (20).

\[
[I] = \begin{bmatrix}
0.051 & 0 & 0 \\
0 & 0.037 & 0 \\
0 & 0 & 0.0205
\end{bmatrix} \text{kgm}^2
\]  

2) NanoProp model: A model for NanoProp was then implemented to generate external influences that will affect the dynamics and kinematics of MIST when firing the thrusters. The NanoProp model allows simulation of different firing configurations, including the misalignment scenarios previously explained. A visualisation of the propulsion system with labelled thrusters is shown in Fig. 10.

The locations of thrusters in NanoProp 3U are shown in Fig. 11. In this study, it was assumed that NanoProp is assembled such that thruster A and B are placed in the +X face of MIST, and thruster C and D in the +Y face of MIST. The centre point of NanoProp is assumed to be aligned with the principal body axes. Moreover, the Z-distance between the thrusters and the centre of mass was determined to be 15 cm, considering NanoProp is positioned in the +Z face of MIST as shown in Fig. 1.

3) MPU6050 model: The dynamics of MIST will in reality be measured by the MEMS gyroscope contained in the MPU6050 board, thus a discrete-time IMU model, developed by Matlab, [9], was implemented to understand in particular the operating characteristics and limitations of the gyroscope.

The main disadvantage of using a MEMS gyroscope is that it contains error sources that need to be taken into account in measurements: static bias and random noise. The former describes errors that are generated by predictable features such as temperature bias, nonalignment of sensor or constant offset bias.

The latter, on the other hand, includes different types: Angle Random Walk (ARW), Rate Random Walk (RRW), and bias instability ($B_i$). ARW is characterised by the white noise spectrum of the gyroscope output, it specifies how much the angular measurement tends to drift during a certain period. RRW causes a drift in the angular rate measurement that can be caused by mechanical stress and temperature drift, it tends to grow as the operating time increases. Finally the bias instability is characterised by the flicker noise in the
electronics. Using (21) the mathematical model of a gyroscope can be modelled, [10] [11]:

\[ \omega_g = \omega + \omega_{\text{bias}} + \omega_{\text{ARW}} + \omega_{\text{RRW}} + \omega_{\text{B}} \]

(21)

where \( \omega_g \) is the output of the gyroscope, \( \omega \) is the actual angular velocity, \( \omega_{\text{bias}} \) are the static errors, \( \omega_{\text{ARW}} \) is the white noise, \( \omega_{\text{RRW}} \) is the RRV noise, and \( \omega_{\text{B}} \) is the flicker noise of the gyroscope.

These errors affect the accuracy of the gyroscope, therefore, it is necessary to process the noise and minimize the influence of errors in the measurement by filtering the output from the gyroscope, therefore a discrete-time Kalman filter, designed by Matlab, [12], was implemented in the simulation, [13]. The modelling of the Kalman filter in the simulation was for functional purposes; according to the specifications of the MPU6050, there is no need to implement such filter since there is already an internal filtering process.

4) iMTQ model: Once the manoeuvre is complete, the satellite undergoes rotations in one or more of its axes which have to be reduced in order to orient the satellite to a given attitude afterwards. A BDOT control algorithm, handled by the iMTQ board, was implemented to analyse the detumbling performance of this system.

The BDOT control relies on the application of MTQs to generate torques opposed to the rotation rates of the satellite. The control law is described in (22), where \( B \) is the derivative of the magnetic field vector \( \mathbf{B} \), and \( \omega \) is the angular velocity vector of the satellite, [14]:

\[ \dot{B} = B \times \omega \]

(22)

The control law then creates a magnetic dipole \( m_d \) in the opposite direction to the change in the magnetic field, estimated with MTM data as shown in (23), where \( c \) is the BDOT gain of the controller, [14]:

\[ m_d = -c \dot{B} \]

(23)

5) General overview: In the simulation, the coordinate frames of thrusters and gyroscope board are initially considered to be aligned to the body-fixed coordinate system of MIST. However, one can adjust parameters such as the principal moments of inertia, position of thrusters, orientation of coordinate frames with respect to each other, etc., further on once MIST is finally assembled and tested, therefore, the Matlab/Simulink model offers a feasible simulation to understand how MIST and subsystems respond from a firing operation.

Finally, Fig. 12 shows a functional schematic of the simulation. The performance evaluation block is not included in the simulation since it is manually solved.

C. NanoProp operating mode

This subsection assess the feasibility of operating NanoProp in two different modes: manually or automatically. The former refers to operating NanoProp over the KTH ground station, and the latter refers to running NanoProp at a given time during the orbit. The main operating mode for NanoProp was determined by looking at the thermal and ground station accessibility analyses with respect to the internal system operations of NanoProp described in Section II NanoProp 3U. The analysis also includes the development of power budgets for specific operating modes.

1) Thermal analysis: The reference orbits shown in Table III are those used in Thermica simulations. They are adaptations of the original TLE set of MIST to suit the format of orbital elements in Thermica. They represent the most extreme seasonal scenarios based on a thermal standpoint: cold case (maximum distance to the Sun, 8 Feb 2018) and hot case (minimum distance to the Sun, 1 June 2018), [15].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>8 Feb 2018 00:00:00 UT</th>
<th>1 June 2018 00:00:00 UT</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (km)</td>
<td>7 018</td>
<td>7 018</td>
</tr>
<tr>
<td>e</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>i (°)</td>
<td>97.943</td>
<td>97.943</td>
</tr>
<tr>
<td>( \omega_p ) (°)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( v ) (°)</td>
<td>1.3</td>
<td>272.3</td>
</tr>
</tbody>
</table>

Results from Thermica simulations for both seasonal cases are illustrated in Fig. 13 and Fig. 14. In the thermal simulations, several sensors are placed in different parts of the system to evaluate the temperature gradient of the whole system during an orbital revolution, [15]. However, for further analysis, it was assumed that the temperature of the propellant in the tank is equal to the temperature gradient measured by sensor T-1031 Lower Tank.

![Fig. 13. Temperature gradient of NanoProp in Cold case, [15].](image-url)
Considering the temperature gradient of sensor T-1031 in the cold case, the minimum temperature of the propellant in the tank will be approximately \(-8\, ^\circ\text{C}\) happening at exit from eclipse. On the other hand, the maximum temperature is approximately \(5\, ^\circ\text{C}\).

**Fig. 14. Temperature gradient of NanoProp in Hot case, [15].**

In the hot case, from the T-1031 sensor thermal analysis, the minimum temperature of propellant in tank is \(4\, ^\circ\text{C}\) at exit from eclipse; the maximum temperature is approximately \(21\, ^\circ\text{C}\).

2) **Ground station analysis:** Since it is relevant to determine the possibility of operating NanoProp over the KTH ground station, computations of the ground station passes for the same chosen seasonal references were analysed.

Cold Case: Table IV includes all the ground station passes in a day for the cold case, starting at 00:00:00 UT on 8 February 2018. The illumination column describes whether the communication window happens in sunlight or eclipse. The duration describes an average duration of the window.

<table>
<thead>
<tr>
<th>Window start</th>
<th>Window end</th>
<th>Illumination</th>
<th>Duration [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:35</td>
<td>08:46</td>
<td>Sunlight</td>
<td>660</td>
</tr>
<tr>
<td>10:12</td>
<td>10:24</td>
<td>Sunlight</td>
<td>720</td>
</tr>
<tr>
<td>11:48</td>
<td>12:00</td>
<td>Sunlight</td>
<td>720</td>
</tr>
<tr>
<td>13:25</td>
<td>13:33</td>
<td>Sunlight</td>
<td>480</td>
</tr>
<tr>
<td>15:01</td>
<td>15:06</td>
<td>Sunlight</td>
<td>300</td>
</tr>
<tr>
<td>16:35</td>
<td>16:41</td>
<td>Sunlight</td>
<td>360</td>
</tr>
<tr>
<td>18:08</td>
<td>18:17</td>
<td>Eclipse</td>
<td>540</td>
</tr>
<tr>
<td>19:42</td>
<td>19:54</td>
<td>Eclipse</td>
<td>720</td>
</tr>
<tr>
<td>21:19</td>
<td>21:31</td>
<td>Eclipse</td>
<td>720</td>
</tr>
<tr>
<td>22:58</td>
<td>23:07</td>
<td>Eclipse</td>
<td>540</td>
</tr>
</tbody>
</table>

**TABLE IV**

**COMMUNICATION WINDOWS FOR COLD CASE**

As explained in Section II MIST, in the MIST reference orbits, there are only a few long passes lasting approximately 10 to 12 min so two of them were selected for examination over the temperature gradient of sensor T-1031 as illustrated in Fig. 15:

- Communication Window Option 1: 10:12 to 10:24
- Communication Window Option 2: 21:19 to 21:31

From Fig. 15, both communication window options are during or close to eclipse, marked as grey zone, so the tank temperature during the window opportunities will be below the minimum operating tank temperature of NanoProp, \(0\, ^\circ\text{C}\), unless the tank heater is used to heat up the propellant.

For option 1, the beginning of communication starts 360 s after exiting from eclipse. In case a manual operation of NanoProp over the ground station is required, then it is needed to heat the propellant from \(-8\, ^\circ\text{C}\) to \(0\, ^\circ\text{C}\) in 360 s at most. However, considering the heating rate of the tank heater, described in Section II NanoProp 3U, this heating process takes approximately 1 440 s, more than the time allowed.

On the other hand, for option 2, in case a manual operation over the ground station is required, the best option is to start heating the propellant before, when the tank is still in eclipse. However, heating propellant in tank during eclipse is not recommended due to internal power limitations of NanoProp.

Hot Case: Table V includes all the ground station passes in a day for the hot case, starting at 00:00:00 UT on 1 June 2018.

<table>
<thead>
<tr>
<th>Window start</th>
<th>Window end</th>
<th>Illumination</th>
<th>Duration [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>07:24</td>
<td>07:29</td>
<td>Sunlight</td>
<td>300</td>
</tr>
<tr>
<td>08:59</td>
<td>09:11</td>
<td>Sunlight</td>
<td>720</td>
</tr>
<tr>
<td>10:36</td>
<td>10:48</td>
<td>Sunlight</td>
<td>720</td>
</tr>
<tr>
<td>12:12</td>
<td>12:23</td>
<td>Sunlight</td>
<td>660</td>
</tr>
<tr>
<td>13:49</td>
<td>13:56</td>
<td>Sunlight</td>
<td>420</td>
</tr>
<tr>
<td>15:25</td>
<td>15:29</td>
<td>Sunlight</td>
<td>240</td>
</tr>
<tr>
<td>16:58</td>
<td>17:05</td>
<td>Sunlight</td>
<td>420</td>
</tr>
<tr>
<td>18:31</td>
<td>18:41</td>
<td>Sunlight</td>
<td>600</td>
</tr>
<tr>
<td>20:06</td>
<td>20:18</td>
<td>Sunlight</td>
<td>720</td>
</tr>
<tr>
<td>21:43</td>
<td>21:55</td>
<td>Sunlight</td>
<td>720</td>
</tr>
<tr>
<td>23:24</td>
<td>23:30</td>
<td>Sunlight</td>
<td>360</td>
</tr>
</tbody>
</table>

**TABLE V**

**COMMUNICATION WINDOWS FOR HOT CASE**

In this case only one ground pass was selected for examination over the temperature gradient of sensor T-1031 as illustrated in Fig. 16:

- Communication Window Option 1: 10:36 to 10:48

From Fig. 16, the tank temperature at the beginning of the communication window is approximately \(8\, ^\circ\text{C}\), so there is no need to use the tank heater since the propellant is already above the minimum temperature. As a result, a manual NanoProp operation over the ground station is possible in the hot case scenario.
3) Power budgets: Power budgets for each of the cold and hot options were defined to complete the feasibility analysis of NanoProp operating mode. Power levels for each of the operating modes of NanoProp are described in Section III Power Levels.

Table VI shows the power budget for the communication window option 1 in cold case, considering the firing of two thrusters for 10 s and heating propellant in tank from $-8 \degree C$ to $0 \degree C$ in 1 440 s.

On the other hand, Table VII describes the power budget for the communication window option 2, considering the firing of two thrusters for 10 s and heating propellant in tank from $-4 \degree C$ to $0 \degree C$ in 720 s.

In addition, Fig. 17 illustrates the distribution of power levels in a timeline for both cold scenarios where the tank heater needs to be used for heating propellant up to a particular temperature. The timeline is not to scale.

Finally, the power budget for the hot case scenario is shown in Table VIII. It considers two thrusters firing for 10 s without previously heating the propellant in the tank because the initial temperature of this operation is above $0 \degree C$.

The power level distribution of the hot case is illustrated in Fig. 18. The total operating time evidently decreases since the tank is completely neglected in this case. The timeline is not to scale.

4) Outcomes: Based on previous analyses, mainly from the cold seasonal cases, it was determined that it is not feasible to manually operate NanoProp over the ground station. This type of operation would require a high amount of power and thermal control since most of the communication windows occur at temperatures below $0 \degree C$ as well as time spans not being long enough to heat the propellant up to $0 \degree C$ before the beginning of the communication windows.

As a result, the viable solution is to automatically operate NanoProp when the tank temperature naturally reaches $0 \degree C$. This type of operation avoids using the tank heater, and requires minimum power consumption and less operating time. In the hot case scenario, however, experiments can be performed manually over the ground station or automatically at any other time, but it is preferable to keep automatic operations in both seasonal cases. Consequently, the tank heater will be only used to heat the propellant when a desirable thrust is requested, and manifold heaters will be used for propellant conditioning and long manoeuvres.

The automatic operating mode for NanoProp then adopts following general procedure:

- First communication window: Upload telecommands (TC) of experiment to perform
- Satellite reaches $0 \degree C$: The experiment will be run by the OBC, collecting data from experiment results, checking FDIR, activating iMTQ to detumble satellite once the experiment is complete, etc.
- Second communication window: Download telemetry (TM) from experiment and upload next experiment TC in case it is needed.

All experiments to be completed with NanoProp are described in Section IV Experiments and Decommissioning operations. A few of these experiments are suggested to be performed only during the hot case scenario because of their specific operating thermal requirements, however, all experiments can be performed automatically at any time in orbit.

A Standard Operating Procedure (SOP) flowchart, describing step-by-step the interaction of the OBC software with NanoProp, is also described in Section IV Standard operating procedure.

D. Power levels

NanoProp has local dissipations grouped as shown in Table IX. Manifold heaters are not operated independently so the mentioned power requirement considers both manifolds. On the other hand, the power levels of thrusters and valves are valid per thruster.

NanoProp has particular internal operating modes based on the thruster states described in Section II NanoProp 3U: Idle, Propellant conditioning, Firing preparation, and Firing so it is important to identify the most relevant characteristics and power requirements for each of these modes, [4] [5].

1) Idle mode: Only the main PCB is active for status control. Main PCB includes the power required to operate the main board and all four thruster boards as shown in Table X.
TABLE VI
POWER BUDGET FOR COLD CASE OPTION 1

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>200</td>
<td>0</td>
<td>2 Idle System power up</td>
</tr>
<tr>
<td>2</td>
<td>1320</td>
<td>200</td>
<td>1000</td>
<td>1584 Propellant Conditioning Heat propellant in tank and manifolds</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>200</td>
<td>2500</td>
<td>324 Propellant Conditioning Heat propellant in tank and manifolds</td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>200</td>
<td>5000</td>
<td>125 Firing Preparation Prepare two thrusters for firing</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>200</td>
<td>5660</td>
<td>59 Firing Fire two thrusters</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>100</td>
<td>0</td>
<td>0.5 Off System power down</td>
</tr>
<tr>
<td>Total</td>
<td>1490</td>
<td>1100</td>
<td>14160</td>
<td>2095</td>
</tr>
</tbody>
</table>

TABLE VII
POWER BUDGET FOR COLD CASE OPTION 2

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>200</td>
<td>0</td>
<td>2 Idle System power up</td>
</tr>
<tr>
<td>2</td>
<td>600</td>
<td>200</td>
<td>1000</td>
<td>720 Propellant Conditioning Heat propellant in tank and manifolds</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>200</td>
<td>2500</td>
<td>324 Propellant Conditioning Heat propellant in tank and manifolds</td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>200</td>
<td>5000</td>
<td>125 Firing Preparation Prepare two thrusters for firing</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>200</td>
<td>5660</td>
<td>59 Firing Fire two thrusters</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>100</td>
<td>0</td>
<td>0.5 Off System power down</td>
</tr>
<tr>
<td>Total</td>
<td>770</td>
<td>1100</td>
<td>14160</td>
<td>1230</td>
</tr>
</tbody>
</table>

TABLE VIII
POWER BUDGET FOR HOT CASE OPTION 1

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>200</td>
<td>0</td>
<td>2 Idle System power up</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
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<td>0 Propellant Conditioning Heat propellant in tank and manifolds</td>
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<td>3</td>
<td>120</td>
<td>200</td>
<td>1500</td>
<td>204 Propellant Conditioning Heat propellant in tank and manifolds</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>200</td>
<td>5000</td>
<td>83 Firing Preparation Prepare two thrusters for firing</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>200</td>
<td>5660</td>
<td>59 Firing Fire two thrusters</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>100</td>
<td>0</td>
<td>0.5 Off System power down</td>
</tr>
<tr>
<td>Total</td>
<td>165</td>
<td>900</td>
<td>12160</td>
<td>350</td>
</tr>
</tbody>
</table>

TABLE IX
POWER REQUIREMENTS OF MAIN COMPONENTS OF NANO PROP

<table>
<thead>
<tr>
<th>Group</th>
<th>Component</th>
<th>Power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Main PCB</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>Tank heater</td>
<td>1.5</td>
</tr>
<tr>
<td>3</td>
<td>Thruster heater</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Manifold heaters</td>
<td>0.33</td>
</tr>
</tbody>
</table>

TABLE X
POWER BUDGET IN IDLE MODE

<table>
<thead>
<tr>
<th>Unit</th>
<th>Power [mW]</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>5V bus</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Bat. bus</td>
<td>200</td>
<td>200</td>
</tr>
</tbody>
</table>

TABLE XI
POWER BUDGET IN PROPELLANT CONDITIONING MODE

<table>
<thead>
<tr>
<th>Unit</th>
<th>Power [mW]</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main PCB</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Tank Heater</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Manifold Heaters</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Total</td>
<td>200</td>
<td>2300</td>
</tr>
</tbody>
</table>

2) Propellant conditioning mode: This mode is used to raise the temperature (and feed pressure) of the propellant in the tank. Thrust level is defined by the tank temperature as shown in Fig. 6.

This mode is also used to raise the temperature of manifolds to avoid condensation of propellant. The manifold temperatures shall be between tank temperature and thruster temperature as explained in Section II NanoProp 3U.

It is recommended to use the tank heater only when:

- The tank temperature is below 0 °C (minimum operating temperature)
- A specific thrust level is desired

The heater in the tank is automatically turned off when the temperature reaches 40 °C to avoid overheating and over-pressure.

A general power budget is shown in Table XI.

3) Firing preparation mode: Thrusters can only fire when the arming state is achieved. The heater in the thruster could also be used to get a minor increment in $I_{sp}$. Table XII illustrates the power budget in firing preparation mode for one thruster.

4) Firing mode: Thrust is proportional to the tank temperature (and feed pressure) and the number of thrusters firing. Moreover, the manifold heaters are used to compensate for heat required to evaporate propellant, this mainly happens when performing long firing operations. Table XIII shows the power budget for firing one thruster.
TABLE XII
POWER BUDGET IN FIRING PREPARATION MODE

<table>
<thead>
<tr>
<th>Unit</th>
<th>5V bus</th>
<th>Bat. bus</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main PCB</td>
<td>200</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>Tank Heater</td>
<td>1000</td>
<td></td>
<td>1000</td>
</tr>
<tr>
<td>Manifold Heaters</td>
<td>1500</td>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>Thruster Heater</td>
<td></td>
<td></td>
<td>2500</td>
</tr>
<tr>
<td>Total</td>
<td>200</td>
<td>5000</td>
<td>5200</td>
</tr>
</tbody>
</table>

 Thruster heater power consumption depends on number of thrusters used for the operation

TABLE XIII
POWER BUDGET IN FIRING MODE

<table>
<thead>
<tr>
<th>Unit</th>
<th>5V bus</th>
<th>Bat. bus</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main PCB</td>
<td>200</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>Tank Heater</td>
<td>1000</td>
<td></td>
<td>1000</td>
</tr>
<tr>
<td>Manifold Heaters</td>
<td>1500</td>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>Thruster Heater</td>
<td></td>
<td></td>
<td>2500</td>
</tr>
<tr>
<td>Valves</td>
<td>330</td>
<td></td>
<td>330</td>
</tr>
<tr>
<td>Total</td>
<td>200</td>
<td>5330</td>
<td>5530</td>
</tr>
</tbody>
</table>

 Thruster heater and Valves power consumption depend on number of thrusters used for the operation

Finally, the MPU6050 board has different local dissipations at normal operating mode depending on the equipment activated for the operation as shown in Table XIV, [7]. Regardless of the condition set up for MPU6050, the power requirement for this system was omitted in the power budget analysis of each experiment since it is much smaller than the power levels required by NanoProp.

TABLE XIV
POWER REQUIREMENTS OF MPU6050

<table>
<thead>
<tr>
<th>Group</th>
<th>Conditions</th>
<th>Power [mW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gyroscope + Accelerometer + DMP</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>Gyroscope + Accelerometer</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>Gyroscope only</td>
<td>12.5</td>
</tr>
</tbody>
</table>

E. Telemetry considerations

Since the operation of NanoProp and monitoring of motion of MIST will be controlled by the OBC, the need to study the register maps of both NanoProp and MPU6050 became clear. Table XV shows a register map table of NanoProp, the last column is length in bytes (B) for both writing and reading, except for the READ_ALL register whose reading length is approximately 45 B, [5].

For this study, the relevant registers from MPU6050 are the gyroscope measurements. Each gyroscope measurement is a 16-bit 2’s complement value, [16].

During an operating day of NanoProp, the system may be fired several times, but monitoring phases between firing experiments are also needed to regularly check the status of the system. The data coming from both the monitoring and operating phases will be stored in an OBC’s non-volatile memory for later transmission to the ground.

TABLE XV
REGISTER MAP OF NANOPROP

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>READ_ALL</td>
<td>Reading returns all registers</td>
<td>1</td>
</tr>
<tr>
<td>STATREG</td>
<td>Module status/control</td>
<td>1</td>
</tr>
<tr>
<td>THRFIRE</td>
<td>Thruster fire</td>
<td>1</td>
</tr>
<tr>
<td>THRX_CTRL</td>
<td>Thruster X status/control</td>
<td>1</td>
</tr>
<tr>
<td>THRX_TEMP</td>
<td>Thruster X temperature</td>
<td>1</td>
</tr>
<tr>
<td>THRX_PRESSURE</td>
<td>Thruster X pressure</td>
<td>2</td>
</tr>
<tr>
<td>THRX_THRUST</td>
<td>Thruster X thrust</td>
<td>2</td>
</tr>
<tr>
<td>THR_X_TMP</td>
<td>Thruster X total impulse counter</td>
<td>2</td>
</tr>
<tr>
<td>THR_X_IMP_SET</td>
<td>Thruster X total impulse setpoint</td>
<td>2</td>
</tr>
<tr>
<td>TANK_TEMP</td>
<td>Tank N temperature</td>
<td>1</td>
</tr>
<tr>
<td>TANK_PROPUSED</td>
<td>Tank N used propellant estimate</td>
<td>2</td>
</tr>
<tr>
<td>TANK_HEATER</td>
<td>Tank N heater duty cycle</td>
<td>1</td>
</tr>
<tr>
<td>MANF_HEATER</td>
<td>Manifold heater duty cycle</td>
<td>1</td>
</tr>
<tr>
<td>TANK_PASSIVATION</td>
<td>Tank passivation</td>
<td>1</td>
</tr>
<tr>
<td>VALVE_CTRL</td>
<td>Solenoid valve status/control</td>
<td>1</td>
</tr>
<tr>
<td>ARM_TEMP</td>
<td>Arm/Firing temperature setpoint</td>
<td>1</td>
</tr>
<tr>
<td>FIRMWARE_REV</td>
<td>Firmware version number</td>
<td>2</td>
</tr>
</tbody>
</table>

Samples can be collected every 5–10 minutes during the monitoring phase. The monitoring phase would produce 9 B per reading as shown in Table XVI which gives a maximum of 2.6 kB or 1.3 kB per day as computed in (24), and (25).

\[
\begin{align*}
9 \text{ B} & \cdot \frac{1440 \text{ min}}{5 \text{ min}} \cdot \frac{1 \text{ day}}{1 \text{ orbit}} \approx 2.6 \text{ kB} \\
9 \text{ B} & \cdot \frac{1440 \text{ min}}{10 \text{ min}} \cdot \frac{1 \text{ day}}{1 \text{ orbit}} \approx 1.3 \text{ kB}
\end{align*}
\]

All these samples will be collected in packets which will be sent to the ground station at later opportunities. The approach is to have one packet per reading, so each monitoring packet will have 9 B of data. As a result, the 5-min sample collection would generate 288 packets per day, and the 10-min collection would generate 144 packets during a day.

Moreover, the orbital period of MIST reference orbit is approximately 98 min so the frequency with which these 9-B packets are generated per orbit is outlined in (26), and (27).

\[
\begin{align*}
1 \text{ packet} & \cdot \frac{98 \text{ min}}{5 \text{ min}} \cdot \frac{1 \text{ orbit}}{1 \text{ orbit}} \approx 20 \text{ packets/orbit} \\
1 \text{ packet} & \cdot \frac{98 \text{ min}}{10 \text{ min}} \cdot \frac{1 \text{ orbit}}{1 \text{ orbit}} \approx 10 \text{ packets/orbit}
\end{align*}
\]

On the other hand, based on GomSpace recommendations, the following relevant data should be read at a higher speed,
1 Hz, during the operating phase of an experiment (Idle, Propellant conditioning, Firing preparation, Firing, Off):

- Tank Temperature
- Tank Propellant Consumption
- Thruster Status
- Thruster Thrusts
- Thruster Temperatures
- Thruster Pressures
- Thruster Total Impulses
- Angular Rates

### Table XVII

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Size [B]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank Temperature</td>
<td>1</td>
</tr>
<tr>
<td>Tank Propellant Consumption</td>
<td>2</td>
</tr>
<tr>
<td>Thruster Status</td>
<td>1 · (4 thrusters)</td>
</tr>
<tr>
<td>Thruster Thrust</td>
<td>2 · (4 thrusters)</td>
</tr>
<tr>
<td>Thruster Temperature</td>
<td>1 · (4 thrusters)</td>
</tr>
<tr>
<td>Thruster Pressure</td>
<td>2 · (4 thrusters)</td>
</tr>
<tr>
<td>Thruster Total Impulse</td>
<td>2 · (4 thrusters)</td>
</tr>
<tr>
<td>Angular Rate</td>
<td>2 · (3 gyroscopes)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>41</strong></td>
</tr>
</tbody>
</table>

The telemetry budget for each experiment is described in Section IV Experiments and Decommissioning operations, but the following computation just shows a general budget analysis for the operating phase.

Every second, 41 B need to be sent as shown in Table XVII so considering the Cold Case Option 1 operating time as an example, it generates 61 kB as described in (28).

$$\left[ \frac{8 \text{B}_{\text{thrust}}}{1 \text{s}} \cdot (4 \text{ thrusters}) + \frac{3 \text{B}_{\text{tank}}}{1 \text{s}} + \frac{6 \text{B}_{\text{gyro}}}{1 \text{s}} \right] \cdot 1490 \text{ s} \approx 61 \text{ kB} \quad (28)$$

The approach is to have one packet per experiment, yet the content size of a packet sent to ground station is limited to a maximum of 214 B so the results from this experiment would be stored in approximately 286 packets.

According to GomSpace, it might be more feasible to use the READ_ALL register for collection of those relevant parameters during the operating phase since the representation of those parameters for a specific time slot is more accurate than the process of independently getting those values.

However, the size of data sent to OBC per interrogation would be 51 B as shown in Table XVIII.

### Table XVIII

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Size [B]</th>
</tr>
</thead>
<tbody>
<tr>
<td>All NanoProp</td>
<td>45</td>
</tr>
<tr>
<td>Angular Rate</td>
<td>2 · (3 gyroscopes)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>51</strong></td>
</tr>
</tbody>
</table>

Therefore, considering the same operating time as before, 76 kB of data are generated which lead to have approximately 356 packets as computed in (29).

$$\left[ \frac{45 \text{B}}{1 \text{s}} + \frac{6 \text{B}_{\text{gyro}}}{1 \text{s}} \right] \cdot 1490 \text{ s} \approx 76 \text{ kB} \quad (29)$$

Finally, the decision for data collection during the operating phase depends upon the characteristics of the OBC and general MIST mission design.

### F. FDIR Analysis

A FDIR process ensures the safety and availability of the spacecraft by avoiding irreversible loss of the nominal mission after the occurrence of a failure. Since the operation of NanoProp will be mostly automatic, it was clear the need of a FDIR function executed by the OBC.

Appendix A shows a FDIR analysis of NanoProp at spacecraft level in the occurrence of failures systematically identified by a Failure Mode and Effects Analysis (FMEA) described in Appendix B. The FDIR analysis is based on guidelines defined by ECSS-Q-ST-30C Space product assurance standard.

There are some important details to consider when the FDIR analysis is inspected:

1) Manifold heaters are not operated independently so the mentioned failures consider both manifolds. On the other hand, the failures for thrusters are valid per thruster.

2) Based on the heating rate estimates for tank and thruster heaters, described in Section II NanoProp 3U, heating variables were defined. $T_0$ is the initial temperature of the propellant which is measured by the tank temperature sensor. $T_f$ is the final desirable temperature of the propellant. Since the heating rates are just estimates, the actual rates and offsets will be determined by performing a specific experiment in space:

- $T_1 = 180 \, s + \text{TBD \, s}$
- $T_3 = 0.5 \, s + \text{TBD \, s}$
- $T_{1\text{MAX}} = \left[ \left| T_f - T_0 \right| \cdot 0.180 \, s \right] + \text{TBD \, s}$
- $T_{3\text{MAX}} = \left[ \left| T_f - T_0 \right| \cdot 0.5 \, s \right] + \text{TBD \, s}$

### G. Propellant mass determination

The wet mass of NanoProp clearly decreases as propellant is consumed so it is important to keep track of this consumption in order to have a better insight of the actual status and performance of the system. Even though it is difficult to measure the exact propellant mass at any phase during a space mission, a bookkeeping method was characterised to determine the propellant mass evolution during the MIST mission.

1) **Bookkeeping**: This method involves determination of propellant consumed during each manoeuvre by on-ground recording of all manoeuvre data, [17].

Bookkeeping usually takes into account the propellant mass flow rate generated by each thruster. The mass flow rate allows one to compute the propellant mass required for a manoeuvre by integrating it over the manoeuvre time. The remaining propellant mass is then computed by subtracting the mass consumed for that specific operation to the mass value determined before the operation, [18]. Additionally,
the bookkeeping method can be developed on the MIST mission by just continuously reading the internal propellant consumption register of NanoProp, mentioned in Table XV, each time a manoeuvre is performed.

On-ground bookkeeping is a feasible and practical way to determine the propellant mass of NanoProp during the MIST mission. As primary strategy, reading the internal register of NanoProp is proposed since there is no need for additional equipment, yet inaccuracies can build up over time, thus the mass flow rate practice, first requiring the computation of the performance of NanoProp, will be used as an alternative solution to support the readings given by NanoProp.

H. Decommissioning plan

In order to meet the objectives of the ESA Space Debris Mitigation (SDM) policy, MIST-NanoProp operations shall be designed according to the following requirements, [17]:

- Clearance of the LEO protected region
  No space system left in LEO for more than 25 years after the end of mission. It is necessary to design a space system able to clear (after the mission) the LEO Protected Region by performing deorbit operations or place the space system in an orbit where natural orbital decay allows re-entry within 25 years.

- Re-entry casualty risk mitigation
  It is necessary to ensure that the re-entry casualty risk does not exceed $10^{-4}$ for any re-entry event (controlled or uncontrolled re-entry).

- End of mission (EoM) passivation
  Removal of stored energy to prevent debris generation after end of mission. Necessary to implement measures for depleting the stored energy in the space system at end of mission.

As a result, Fig. 19 is the general flowchart that MIST should follow to comply with the ESA SDM Policy.

![Fig. 19. End Of Life deorbit strategies, [19].](image)

Firstly, the orbit propagation analysis, illustrated in Fig. 20, shows that the selected reference orbit of MIST, described in Section II MIST, has sufficiently low altitude to ensure re-entry in about 16.5 years according to the ESA DRAMA tool and the following spacecraft parameters: random tumbling cross-section area (seen as the average area), [20], spacecraft mass as well as the drag and the reflectivity coefficient which are summarised in Table XIX.

The re-entry casualty risk for MIST mission can be analysed from a spacecraft re-entry survival analysis, and also computed in the DRAMA tool. Fig. 22 shows a general survival analysis during an uncontrolled re-entry into the atmosphere for some components of MIST which are simulated as simple boxes made of default materials provided by the DRAMA library as illustrated in Fig. 21 and Table XX.

![Fig. 20. Orbit life time of MIST reference orbit.](image)

![Fig. 21. MIST model for re-entry survival analysis.](image)

![TABLE XIX](table)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>0.0615 m$^2$</td>
</tr>
<tr>
<td>$m$</td>
<td>3 kg</td>
</tr>
<tr>
<td>$C_D$</td>
<td>2.2</td>
</tr>
<tr>
<td>$C_r$</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Assuming the re-entry initiates as soon as the altitude is around 120 km, all components are burned up into the atmosphere, except for the top stack which actually simulates being NanoProp. However, DRAMA tool indicates the total casualty probability under the 1D projection for this simulation is $6.5 \times 10^{-6}$ which is lower than $10^{-4}$, thus an uncontrolled re-entry can be performed for MIST which leads to design a passivation plan for NanoProp.

Finally, the passivation plan for NanoProp needs to implement measures such as venting, depletion burns or depressurisation for depleting the stored energy in the propulsion tank at end of mission to avoid from further adding to the space debris generation problem, [17].
IV. RESULTS

A. Experiments

Once the features of each of the fundamental operating procedures for NanoProp were outlined, experiments that NanoProp will perform during the MIST mission were characterised. The experiments, effective from the commissioning stage to the decommissioning stage, aim to assess the performance of the propulsion system, but also to evaluate the function of other subsystems by performing attitude and orbital manoeuvres:

Commissioning stage
- System function verification
- Heating rate definition

Operating stage
- Performance assessment via Indefinite firing mode
- Performance assessment via Impulse firing mode
- Translation assessment
- Eccentricity change manoeuvre
- Altitude change manoeuvre

Decommissioning stage
- Venting
- Depletion/Disposal manoeuvre

1) System function verification: Objective: To ensure that the system is operational after launch and spacecraft detumbling.

Procedure: All equipment is tested. This experiment can be performed manually during ground contact or automatically by the OBC. The step-by-step description of this procedure is outlined in Table XXI.

The power budget and timeline of power levels are shown in Table XXII and Fig. 23.

This experiment would require the following information:
- Tank Temperature
- Tank Heater Current Consumption*
- Manifold Heater Current Consumption*
- Thruster Heater Current Consumption*
- Thruster Status
- Thruster Temperature
- Thruster Pressure
- Angular Rates

*It was assumed the size of these parameters is 1 B. Size of others are described in Section III Telemetry considerations.

Samples can be collected every 5 s. As computed in (35), 378 B are generated and will be stored in approximately 2 packets since the content size of a packet is limited to 214 B.

The size per interrogation of each step of the experiment is computed in (30)–(34).

\[
\begin{align*}
\text{Test}_{\text{Tank}} &= \frac{2 \text{ B}}{5 \text{ s}} \cdot 360 \text{ s} = 144 \text{ B} \quad (30) \\
\text{Test}_{\text{Manifolds}} &= \frac{1 \text{ B}}{5 \text{ s}} \cdot 30 \text{ s} = 6 \text{ B} \quad (31) \\
\text{Test}_{\text{Valves\&Gyro}} &= \frac{14 \text{ B}}{5 \text{ s}} \cdot 30 \text{ s} = 84 \text{ B} \quad (32) \\
\text{Test}_{\text{Enable}} &= \frac{12 \text{ B}}{5 \text{ s}} \cdot 30 \text{ s} = 72 \text{ B} \quad (33) \\
\text{Test}_{\text{Arm}} &= \frac{3 \text{ B}}{5 \text{ s}} \cdot 30 \text{ s} = 18 \text{ B} \quad (34) \\
[\text{Test}_{\text{Tank}} + \text{Test}_{\text{Manifolds}} + \text{Test}_{\text{Valves\&Gyro}} + \text{Test}_{\text{Enable}} + \text{Test}_{\text{Arm}} \cdot (4 \text{ thrusters})] &= 378 \text{ B} \quad (35)
\end{align*}
\]

2) Heating rate definition: Objective: To verify the proposed heating rate estimates and to determine the FDIR offsets for heating processes in tank and thruster.

Procedure: This experiment can be performed manually during ground contact or automatically by the OBC. The step-by-step description of this procedure is outlined in Table XXIII.

The power budget and timeline of power levels are shown in Table XXIV and Fig. 24.

![Power level timeline for Heating rate definition.](image)

The power budget and timeline of power levels are shown in Table XXIV and Fig. 24.

![Power level timeline for System function verification.](image)
**TABLE XXI**

**PROCEDURE FOR SYSTEM FUNCTION VERIFICATION**

<table>
<thead>
<tr>
<th>Step</th>
<th>Test</th>
<th>Verification method</th>
<th>Success criteria</th>
<th>Comments</th>
</tr>
</thead>
</table>
| 1    | Activate tank heater  
Duty cycle = 95%  
t = 360 s | Temperature sensor  
Heater current consumption | Tank temperature increase is observable  
Measured heater current consumption exceeds 100 mA | Turn off tank heater after test                                                                |
| 2    | Activate manifold heaters  
Duty cycle = 95%  
t = 30 s | Heater current consumption | Measured heater current consumption exceeds 150 mA | Turn off manifold heaters after test                                                             |
| 3    | Open the four second barrier valves  
Activate the gyro board  
t = 30 s | Pressure sensors  
Gyro board signals | Thruster pressures are observable  
Produced angular rates are observable | To open the valves, first enable manual valve control (TANK_PASSIVATION)  
It is advised to have a delay of minimum 10 ms between each valve opening to limit the peak power consumption  
Close valves and disable manual valve control after test  
This step can affect the S/C attitude, iMTQ is used for detumbling the S/C |
| 4    | “Enable” all thrusters  
t = 30 s | Temperature sensors  
Pressure sensors | Thruster temperatures and pressures are observable |                                                                                               |
| 5    | “Arm” thruster A  
t = 30 s | Temperature sensor  
Heater current consumption  
Thruster status | Thruster temperature increase is observable  
Measure heater current consumption exceeds 100 mA | Ensure that thruster A reaches “Ready” state                                                   |
| 6    | “Arm” thruster B  
t = 30 s | Temperature sensor  
Heater current consumption  
Thruster status | Thruster temperature increase is observable  
Measure heater current consumption exceeds 100 mA | Ensure that thruster B reaches “Ready” state                                                   |
| 7    | “Arm” thruster C  
t = 30 s | Temperature sensor  
Heater current consumption  
Thruster status | Thruster temperature increase is observable  
Measure heater current consumption exceeds 100 mA | Ensure that thruster C reaches “Ready” state                                                   |
| 8    | “Arm” thruster D  
t = 30 s | Temperature sensor  
Heater current consumption  
Thruster status | Thruster temperature increase is observable  
Measure heater current consumption exceeds 100 mA | Ensure that thruster D reaches “Ready” state                                                   |

The size per interrogation of each step of the experiment is computed in (36), and (37).

\[
\text{Test}_{\text{Tank}} = \frac{1}{5} \cdot 360 \text{ s} = 72 \text{ B} \quad (36)
\]

\[
\text{Test}_{\text{Arm}} = \frac{2}{5} \cdot 30 \text{ s} = 12 \text{ B} \quad (37)
\]

\[
[\text{Test}_{\text{Tank}} + \text{Test}_{\text{Arm}} \cdot (4 \text{ thrusters})] = 120 \text{ B} \quad (38)
\]

3) **Performance assessment via Indefinite firing mode:**

Objective: to assess the performance and misalignment of thrusters.

Procedure: After verification and heating rate definition of the system, some indefinite-firing-mode experiments are performed to determine the thrust, thrust misalignment and specific impulse of the propulsion system.

Based on the Section III NanoProp evaluation - analytical model, the strategy is to fire pairs of thrusters for 1 min and evaluate the gyro board response to determine the influence of thrusters in the spacecraft rotation. In each fire, the pair of thrusters is set at equal “arm” temperature to produce uniform thrust. The spacecraft should be stabilised using the iMTQ board after each manoeuvre experiment in order to evaluate the detumble controller of the iMTQ board.

Therefore, the strategy is to fire each thruster a couple of times to precisely differentiate the performance of the thruster in respect of the others; assuming a nonexistent or minimal misalignment of thrusters, this strategy is prepared in a way that the torque is applied about one axis as illustrated in Fig. 7 when Thrusters A & B are simultaneously firing.

The following firing configurations were determined based on Fig. 10:

1) Fire thruster A & B
2) Fire thruster A & C
### TABLE XXII
POWER BUDGET FOR SYSTEM FUNCTION VERIFICATION

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>2</td>
<td>5.5 · 10⁻⁴</td>
<td>System power up</td>
</tr>
<tr>
<td>2</td>
<td>360</td>
<td>432</td>
<td>0.12</td>
<td>Test tank</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>51</td>
<td>1.4 · 10⁻²</td>
<td>Test manifolds</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>46</td>
<td>1.3 · 10⁻²</td>
<td>Open valves and Test gyro board</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>6</td>
<td>1.7 · 10⁻³</td>
<td>“Enable” thrusters</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>81</td>
<td>2.3 · 10⁻²</td>
<td>“Arm” thruster A</td>
</tr>
<tr>
<td>7</td>
<td>30</td>
<td>81</td>
<td>2.3 · 10⁻²</td>
<td>“Arm” thruster B</td>
</tr>
<tr>
<td>8</td>
<td>30</td>
<td>81</td>
<td>2.3 · 10⁻²</td>
<td>“Arm” thruster C</td>
</tr>
<tr>
<td>9</td>
<td>30</td>
<td>81</td>
<td>2.3 · 10⁻²</td>
<td>“Arm” thruster D</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>0.5</td>
<td>1.4 · 10⁻¹</td>
<td>System power down</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.24</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE XXIII
PROCEDURE FOR HEATING RATE DEFINITION

<table>
<thead>
<tr>
<th>Step</th>
<th>Test</th>
<th>Verification method</th>
<th>Success criteria</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>Activate tank heater</td>
<td>Tank temperature increase is observable</td>
<td>Turn off tank heater after test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Duty cycle = 95% t = 360 s</td>
<td>Heating rate is determined from timer evaluation</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>“Arm” thruster A</td>
<td>Temperature sensor</td>
<td>Thruster temperature increase is observable</td>
<td>To “arm” the thruster A, first enable the thruster</td>
</tr>
<tr>
<td></td>
<td>t = 30 s</td>
<td>Thruster status</td>
<td>Heating rate is determined from timer evaluation</td>
<td>Ensure that thruster A reaches “Ready” state</td>
</tr>
<tr>
<td>3</td>
<td>“Arm” thruster B</td>
<td>Temperature sensor</td>
<td>Thruster temperature increase is observable</td>
<td>To “arm” the thruster B, first enable the thruster</td>
</tr>
<tr>
<td></td>
<td>t = 30 s</td>
<td>Thruster status</td>
<td>Heating rate is determined from timer evaluation</td>
<td>Ensure that thruster B reaches “Ready” state</td>
</tr>
<tr>
<td>4</td>
<td>“Arm” thruster C</td>
<td>Temperature sensor</td>
<td>Thruster temperature increase is observable</td>
<td>To “arm” the thruster C, first enable the thruster</td>
</tr>
<tr>
<td></td>
<td>t = 30 s</td>
<td>Thruster status</td>
<td>Heating rate is determined from timer evaluation</td>
<td>Ensure that thruster C reaches “Ready” state</td>
</tr>
<tr>
<td>5</td>
<td>“Arm” thruster D</td>
<td>Temperature sensor</td>
<td>Thruster temperature increase is observable</td>
<td>To “arm” the thruster D, first enable the thruster</td>
</tr>
<tr>
<td></td>
<td>t = 30 s</td>
<td>Thruster status</td>
<td>Heating rate is determined from timer evaluation</td>
<td>Ensure that thruster D reaches “Ready” state</td>
</tr>
</tbody>
</table>

3) Fire thruster C & D
4) Fire thruster B & D

Two more firing configurations can be tested to analyse the performance of thrusters through the production of zero rotations about axes, assuming nonexistent or minimal misalignment as well:
1) Fire thruster A & D
2) Fire thruster B & C

According to the outcomes of the Section III NanoProp operating mode, these experiments are performed automatically by the OBC when the tank temperature reaches the minimum operating temperature (0 °C) in both the cold and hot scenarios.

The power budget is shown in Table XXV, but the timeline of power levels is the same as the one described in Fig. 18 since the tank is not used in this experiment.

These experiments will follow the strategy described in Section III Telemetry considerations for an operating phase, thus 41 B need to be sent to the OBC every second, as shown in Table XVII.

Considering the operating time proposed for this kind of experiment, it generates 8.8 kB as described in (39). The content size of a packet is limited to 214 B so the results of each experiment will be stored in approximately 42 packets.

\[
\frac{8 \text{B}_\text{thruster}}{1 \text{s}} \cdot (4 \text{ thrusters}) + \frac{3 \text{B}_\text{tank}}{1 \text{s}} + \frac{6 \text{B}_\text{gyro}}{1 \text{s}} \approx 8.8 \text{ kB}
\]  \hspace{1cm} (39)

On the other hand, 11 kB are generated by each experiment, as computed in (40), in case the READ_ALL register is used for data collection as explained in Section III Telemetry considerations. For this alternative, the results of each experiment will be stored in approximately 52 packets.

\[
\frac{45 \text{B}}{1 \text{s}} + \frac{6 \text{B}_\text{gyro}}{1 \text{s}} \cdot 215 \text{ s} \approx 11 \text{ kB}
\]  \hspace{1cm} (40)

4) Performance assessment via Impulse firing mode: Objective: to assess the performance of thrusters and to verify the results from Performance assessment via Indefinite firing mode experiment.
Procedure: Impulse-firing-mode experiments are performed to primarily determine the specific impulse and the exhaust velocity of thrusters.

The tank temperature will always be set at the same temperature so pressure and thrust delivered by thrusters remain the same. This strategy allows the synchronisation of the firing stop of thrusters with the condition that total impulse setpoint and “arm” temperature of all thrusters are the same.

Fire pairs of thrusters and evaluate the gyro board response to determine the influence of thrusters in the spacecraft rotation. The spacecraft should be stabilised using the iMTQ board after each manoeuvre experiment in case the detumble controller of the iMTQ board. These experiments will follow the same 6 firing configurations described in the Performance assessment via Indefinite firing mode experiment.

The firing time in these experiments is defined by the selected tank temperature and total impulse setpoints. To get observable results, the tank temperature is set at 10 °C so the thrust delivered by each thruster is 1 mN, and the total impulse setpoint is set at 150 mNs in each thruster, thus a firing time of 2.5 min is expected.

Because of the nature of the MIST mission, these experiments are also performed automatically by the OBC in both cold and hot scenarios, but only when the tank temperature naturally reaches a minimum temperature of 5 °C to reduce propellant conditioning mode operating time.

The power budget is shown in Table XXVI, but the timeline of power levels is the same as the one described in Fig. 17 since the tank is used to heat the propellant so that thrusters attain a specific thrust level.

These experiments will follow the strategy described in Section III Telemetry considerations for an operating phase, thus considering the operating time proposed for this kind of experiment, each manoeuvre generates 44.5 kB as described in (41). The results of each experiment will be stored in approximately 208 packets.

\[
\left[ \frac{8 B_{\text{thruster}}}{1 \text{ s}} \cdot (4 \text{ thrusters}) + \frac{3 B_{\text{tank}}}{1 \text{ s}} + \frac{6 B_{\text{gyro}}}{1 \text{ s}} \right] \cdot 1085 \text{ s} \approx 44.5 \text{ kB}
\]  

On the other hand, 55.3 kB are generated by each experiment, as computed in (42), in case the READ_ALL register is used for data collection. The results of each experiment will be stored in approximately 259 packets.

\[
\left[ \frac{45 B_{\text{thruster}}}{1 \text{ s}} + \frac{6 B_{\text{gyro}}}{1 \text{ s}} \right] \cdot 1085 \text{ s} \approx 55.3 \text{ kB}
\]  

5) Translation assessment: Objective: to verify how balanced the satellite is when all four thrusters are firing.

Procedure: In the tower position, fire (-U direction) all four thrusters in impulse-firing-mode and evaluate the gyro board response to determine the influence of thrusters in the spacecraft rotation. The spacecraft should be stabilised using the iMTQ board after the manoeuvre experiment in case angular rates are produced.

The tank temperature will be set at a specific temperature so pressure and thrust delivered by thrusters are the same for all of them. This strategy allows to synchronise the firing stop of thrusters with the condition that total impulse setpoint and “arm” temperature of all thrusters are the same.

The firing time in this experiment is defined by the selected tank temperature and total impulse setpoints. To get observable results, the tank temperature is set at 10 °C so the thrust delivered by each thruster is 1 mN, and the total impulse
The propellant conditioning (heating propellant in tank) time depends on the initial temperature of the tank. Therefore, to reduce the heating time, it is assumed that this mode starts when the initial tank temperature is 5 °C, leading to 900 s for heating propellant in tank at most.

Because of the nature of the experiment, it is recommended that this experiment is only scheduled during the hot case scenario to reduce the influence of power and thermal limitations; the proposed starting temperature for propellant conditioning mode is now set at 8 °C. Considering only the hot scenario, the experiment can be performed either automatically by the OBC at any time or manually during a pass over the ground station.

Table XXVII shows the power budget for this experiment and Fig. 17 represents the power level timeline.

This experiment will follow the strategy described in Section III Telemetry considerations for an operating phase, thus considering the operating time proposed for this experiment, it generates 21.2 kB as described in (43). The results of this experiment will be stored in approximately 100 packets.

\[
\frac{8 \text{ B}_{\text{thruster}}}{1 \text{ s}} \cdot (4 \text{ thrusters}) + \frac{3 \text{ B}_{\text{tank}}}{1 \text{ s}} + \frac{6 \text{ B}_{\text{gyro}}}{1 \text{ s}} \cdot 515 \text{ s} \approx 21.2 \text{ kB} \tag{43}
\]

On the other hand, 26.3 kB are generated by this experiment, as computed in (44), in case the READ_ALL register is used for data collection. The data will be stored in approximately 123 packets.

\[
\left[\frac{45 \text{ B}}{1 \text{ s}} + \frac{6 \text{ B}_{\text{gyro}}}{1 \text{ s}}\right] \cdot 515 \text{ s} \approx 26.3 \text{ kB} \tag{44}
\]

In case the thrust difference is larger than 10%, this misalignment shall be compensated for for longer firing burns. This can be done by selecting different total impulse set points for each thruster so the firing time variations compensate the imbalance of the spacecraft during a four-thruster manoeuvre.

6) Eccentricity change manoeuvre: Objective: to evaluate the delivered \(\Delta V\) and to measure the change in orbit eccentricity.

Procedure: A \(\Delta V\) manoeuvre is performed in the radial direction (−U direction) to attain a minimum eccentricity change without altering the period of the orbit.
scenario to reduce the influence of power and thermal limitations. Considering only the hot scenario, the experiment can be performed either automatically by the OBC or manually during a pass over the ground station.

To produce 1 mN on each thruster, in automatic operation, the OBC will start the experiment when the tank naturally reaches 10 °C, so there is no need to use the tank heater.

On the other hand, in manual operation, the manoeuvre could start at the beginning of the communication window since the expected tank temperature at this point is close enough to 10 °C according to Section III NanoProp operating mode, so there is no need to use the tank heater.

The power budget for this experiment is shown in Table XXVIII. The power level timeline for this type of experiment is illustrated in Fig. 25.

This experiment will follow the strategy described in Section III Telemetry considerations for an operating phase, thus considering the operating time proposed for this experiment, 31 kB are generated as described in (48). The results of this experiment will be stored in approximately 145 packets.

\[
\left( \frac{8 \text{ B}_{\text{thruster}}}{1 \text{ s}} \cdot (4 \text{ thrusters}) + \frac{3 \text{ B}_{\text{tank}}}{1 \text{ s}} + \frac{6 \text{ B}_{\text{gyro}}}{1 \text{ s}} \right) \cdot 755 \text{ s} \approx 31 \text{ kB}
\]

(48)

On the other hand, in case the READ_ALL register is used for data collection, 38.5 kB are generated by this experiment as computed in (49). The results will be stored in approximately 180 packets.

\[
\left( \frac{45 \text{ B}}{1 \text{ s}} + \frac{6 \text{ B}_{\text{gyro}}}{1 \text{ s}} \right) \cdot 755 \text{ s} \approx 38.5 \text{ kB}
\]

(49)

Finally, considering that this manoeuvre is performed at tower position towards the Earth in −U direction (radial manoeuvre), the satellite will attain a small eccentricity change without altering the period of the orbit. Following both solutions described in Appendix C, the attained \( \Delta e \approx 0.000053−0.000159 \), considering the MIST reference orbit parameters of Table I.

7) Altitude change manoeuvre: Objective: to evaluate the delivered \( \Delta V \) and to measure the change in orbit period as well as semi-major axis and, consequently, the altitude.

Procedure: A \( \Delta V \) manoeuvre is performed along the velocity vector direction (+V) to attain a semi-major axis change consequently altering the period of the orbit.

The change after the manoeuvre experiment is monitored by the space track application in order to evaluate the performance of the system for determining orbital changes.

“Arm” temperature is set equal for all thrusters to produce uniform thrust. The spacecraft should be stabilised using the iMTQ board after the manoeuvre experiment in case angular rates are produced.

Considering that the burn is also made within the line-of-sight of the ground station, the operation would generate a total impulse of 2.4 Ns and \( \Delta V = 0.8 \text{ m/s} \), assuming the thrusters produce 1 mN of thrust each.

As a result, all four thrusters are fired in indefinite-firing-mode for 10 min along the velocity vector direction (+V), and the change in orbital period or semi-major axis is measured to evaluate the delivered \( \Delta V \).

Because of the nature of the experiment, it is recommended that this experiment is only scheduled during the hot case scenario to reduce the influence of power and thermal limitations. Considering only the hot scenario, the experiment can be performed either automatically by the OBC or manually during a pass over the ground station.

To produce 1 mN on each thruster, in automatic operation, the OBC will start the experiment when the tank naturally reaches 10 °C, so there is no need to use the tank heater.

On the other hand, in manual operation, the manoeuvre could start at the beginning of the communication window since the expected tank temperature at this point is close enough to 10 °C according to Section III NanoProp operating mode, so there is no need to use the tank heater, yet the
manifold heaters must be switched on during the entire long burn experiment to reduce the pressure and temperature drop as propellant is consumed.

Since this experiment has the same requirements as the Eccentricity change manoeuvre experiment, the power budget and timeline of this experiment are represented in Table XXVIII, and Fig. 25. Moreover, the telemetry budgets for this experiment are described in (48) or (49).

Finally, considering that this manoeuvre is performed in the arrow position along the velocity vector direction (+V), the satellite will attain a semi-major axis change consequently altering the period from the original orbit. Based on the solution described in Appendix C, the attained $\Delta a \approx 1.5$ km and $\Delta T_p \approx 0.031$ min, considering the MIST reference orbit parameters of Table I.

However, in order to perform this manoeuvre, the satellite needs to be orientated with the thrust vector along the orbital motion (+V axis) so it is important to verify whether the ADCS system can produce and control this attitude change from the nominal attitude of MIST (tower position) to arrow position. For instance, the ADCS system is able to position MIST in a nominal attitude of MIST (tower position) to arrow position. However, it might be slightly complex to keep the least inertia axis towards the orbital motion direction.

### B. Decommissioning operations

Based on the strategy described in Section III Decommissioning plan, the passivation plan for NanoProp propellant tank should implement one or more of the following operations for depleting the stored energy at end of mission:

- Venting
- Depletion manoeuvres(s)
- Depressurisation at least down to a level such that no bursts can occur due to over-pressure or temperature

According to Fig. 20, NanoProp can just perform the venting operation since MIST is initially within the 25-year natural decay limit so there is no need to do any disposal manoeuvre, but it is important to control the unpredictable attitude result from this operation and assure the stability of the satellite afterwards.

On the other hand, performing depletion manoeuvres allow the consumption of the remaining propellant and, consequently, depressurise the tank, but most importantly they could also reduce the time of natural decay for MIST by performing these manoeuvres opposite to the direction of motion.

In any case, it is considered that the remaining mass of propellant in the tank is about 70% of the initial propellant mass at End Of Life (EOL).

1) Venting: Objective: to remove stored energy to prevent debris generation after end of mission.

   Procedure: To open the valves, first enable the manual valve control placed in the tank passivation register.

   Open the two first barrier valves to thrusters A+B and C+D respectively, then open all four second barrier valves without heating the propellant in tank, manifolds or thrusters.

   Using (50) and (51), an approximate operating time for the venting operation was computed, [3]. Assuming that the remaining mass of propellant $m_p$ at EOL is approximately 35 g, it would take 2 min at most to expel the propellant out to space. It was also assumed that the venting exhaust velocity is 10 m/s and a nominal thrust of 1 mN per thruster.

   $\dot{m} = \frac{F}{v_e}$  \hspace{1cm} (50)

   $t = \frac{m_p}{\dot{m}}$  \hspace{1cm} (51)

   However, it is recommended to perform an extra 2-min venting operation in the following orbit since the efficiency to vent the last amount of propellant is poor due to the possible ice-cold state of propellant.

   Finally, evaluate the gyro board response to determine the influence of venting in the spacecraft rotation. The spacecraft should be stabilised using the iMTQ board after the venting operation is complete.

   This operation can be performed manually during ground contact or automatically by the OBC in both the cold and hot scenarios.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>200</td>
<td>0</td>
<td>2</td>
<td>Idle</td>
<td>System power up</td>
</tr>
<tr>
<td>2</td>
<td>120$^b$</td>
<td>200</td>
<td>1500</td>
<td>204</td>
<td>Propellant Conditioning</td>
<td>Heat propellant in manifolds</td>
</tr>
<tr>
<td>3</td>
<td>20$^b$</td>
<td>200</td>
<td>11500</td>
<td>234</td>
<td>Firing Preparation</td>
<td>Prepare four thrusters for firing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Continue heating propellant in manifolds</td>
</tr>
<tr>
<td>4</td>
<td>600</td>
<td>200</td>
<td>12820</td>
<td>7812</td>
<td>Firing</td>
<td>Fire four thrusters</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Continue heating propellant in manifolds</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>100</td>
<td>0</td>
<td>0.5</td>
<td>Off</td>
<td>System power down</td>
</tr>
<tr>
<td>Total</td>
<td>755</td>
<td>8253</td>
<td>2.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$a$ Since this experiment will be performed for more than 5 minutes, the heaters in the manifolds are switched on during the entire experiment to keep a stable pressure and temperature. It is assumed that tank temperature is around 10 °C, tank heater will be only used in case the 10 °C criterion is not met

$b$ The firing preparation time depends on the initial temperature of thrusters; however, it is assumed that the minimum initial temperature that thrusters expect is 0 °C, leading to 20 s for arming thrusters at most
The power budget and power level timeline are shown in Table XXIX and Fig. 26.

![Power level timeline for Venting operation.](image)

Fig. 26. Power level timeline for Venting operation.

Even though the venting operation does not require firing the propulsion system, it is recommended that this operation collects the following relevant data with samples collected at a frequency of 1 Hz. Therefore, every second, 31 B need to be sent to the OBC as shown in Table XXX.

- Tank Temperature
- Tank Propellant Consumption
- Thruster Thrust
- Thruster Temperature
- Thruster Pressure
- Tank Passivation
- Valve Control
- Angular Rates

Considering the operating time proposed for this operation, 4.2 kB are generated as described in (52). The results of the operation will be stored in approximately 20 packets.

\[
\left[ \frac{5 \text{B}_{\text{thruster}}}{1 \text{s}} + \frac{3 \text{B}_{\text{tank}}}{1 \text{s}} + \frac{6 \text{B}_{\text{gyro}}}{1 \text{s}} + \frac{2 \text{B}_{\text{venting}}}{1 \text{s}} \right] \times 135 \text{s} \approx 4.2 \text{kB} \tag{52}
\]

On the other hand, in case the READ_ALL register is used for data collection, 7 kB are generated by this operation as computed in (53). The results will be stored in approximately 33 packets.

\[
\left[ \frac{45 \text{B}}{1 \text{s}} + \frac{6 \text{B}_{\text{gyro}}}{1 \text{s}} \right] \times 135 \text{s} \approx 7 \text{kB} \tag{53}
\]

2) Depletion/Disposal manoeuvre: Objective: to remove stored energy to prevent debris generation after end of mission, and to place the spacecraft in an orbit where natural orbital decay allows re-entry in less than 25 years.

Procedure: A “braking” ΔV manoeuvre is performed along the velocity vector direction (−V) to attain a semi-major axis change placing the satellite in a lower orbit leading to a decrease in the natural lifetime of MIST.

The change after the manoeuvre operation is monitored by the space-track application in order to evaluate the performance of the system for determining orbital changes.

“Arm” temperature is set equal for all thrusters to produce uniform thrust. The spacecraft should be stabilised using the iMTQ board after the manoeuvre experiment in case angular rates are produced.

By using (45), it is determined that the maximum attainable ΔV provided by this manoeuvre is 5.6 m/s, considering the specific impulse is 50 s, 1 mN of thrust delivered per thruster, and 15 g of propellant already consumed in previous experiments which yields to \( m_0 = 2.985 \text{ kg} \).

Following the analytical method described in Appendix C, a 5.6 m/s manoeuvre will place MIST in a final orbit whose semi-major axis is about 7 012 km, taking into account an \( a_0 = 7 021.94 \text{ km} \) which was generated by the Altitude change manoeuvre experiment.

Using (54) and (55) a burn time for this operation is computed, [3]. Since NanoProp has low thrust performance, the strategy is to perform this manoeuvre continuously, resulting in a spiral-type trajectory whose total burn time is 70 min, assuming each thruster delivers 1 mN of thrust, that is not recommended to do since it requires extreme operating, power and thermal control.

\[
a_{cc} \approx \frac{\dot{F}}{m_0} \tag{54}
\]

\[
t_{\text{burn}} = \frac{\mu}{a_{cc}} \left( a_0^{-1/2} - a_f^{-1/2} \right) \tag{55}
\]

Alternatively, it is possible to subdivide the overall “braking” manoeuvre into several submanoeuvres performed within the line-of-sight of the ground station, then each ΔV submanoeuvre will be 0.8 m/s as described in the Eccentricity change manoeuvre experiment when all thrusters deliver 1 mN of thrust.

As a result, 7 submanoeuvres are performed. For each submanoeuvre all four thrusters are fired in indefinite-firing-mode for 10 minutes opposite to the velocity vector direction (−V), and the change in orbital period is measured to evaluate the delivered ΔV.

Because of the nature of these operations, it is recommended that these operations are only scheduled during the hot case scenario to reduce the influence of power and thermal limitations. Considering only the hot scenario, the operations can be performed either automatically by the OBC or manually during a pass over the ground station.

To produce 1 mN on each thruster, in automatic operation, the OBC will start the operations when the tank naturally reaches 10 °C, so there is no need to use the tank heater.

On the other hand, in manual operation, the submanoeuvres could start at the beginning of the communication window since the expected tank temperature at this point is close enough to 10 °C according to Section III NanoProp operating mode, so there is no need to use the tank heater, yet the manifold heaters must be switched on during the entire long burn experiment to reduce pressure and temperature drop as propellant is consumed.

Since these operations have the same requirements as the Eccentricity change manoeuvre experiment, the power budget and timeline are represented in Table XXVIII, and Fig. 25. Moreover, the telemetry budgets for these operations are described in (48) or (49).

After performing the complete depletion/disposal manoeuvre operation, the decay time of MIST would be reduced down to 15 years since the disposal orbit is 7 012 km. Fig. 27 shows the 15-year natural lifetime of MIST as a function of altitude computed in DRAMA tool by ESA and considering the spacecraft parameters described in Table XIX.
TABLE XXIX
POWER BUDGET FOR VENTING OPERATION

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>200</td>
<td>2</td>
<td>$5.5 \times 10^{-4}$</td>
<td>Idle</td>
<td>System power up</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
<td>200</td>
<td>1320</td>
<td>0.05</td>
<td>Open all valves</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>100</td>
<td>0</td>
<td>$1.4 \times 10^{-4}$</td>
<td>Off</td>
<td>System power down</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>135</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It is advised to have a delay of minimum 10 ms between each valve opening to limit the peak power consumption.

TABLE XXX
TELEMETRY BUDGET PER INTERROGATION IN VENTING OPERATION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Size [B]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank Temperature</td>
<td>1</td>
</tr>
<tr>
<td>Tank Propellant Consumption</td>
<td>2</td>
</tr>
<tr>
<td>Thruster Thrust</td>
<td>2 \cdot (4 thrusters)</td>
</tr>
<tr>
<td>Thruster Temperature</td>
<td>1 \cdot (4 thrusters)</td>
</tr>
<tr>
<td>Thruster Pressure</td>
<td>2 \cdot (4 thrusters)</td>
</tr>
<tr>
<td>Tank Passivation</td>
<td>1</td>
</tr>
<tr>
<td>Valve Control</td>
<td>1</td>
</tr>
<tr>
<td>Angular Rate</td>
<td>2 \cdot (3 gyroscopes)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>31</td>
</tr>
</tbody>
</table>

As a result, the depletion/disposal manoeuvre would decrease the natural decay time of MIST about 1.5 years, considering that the initial natural lifetime of MIST was 16.5 years as determined in Section III Decommissioning plan. Finally, in order to perform these operations, the satellite needs to be orientated with the thrust vector along the orbital motion so it is important to verify whether the ADCS system can produce and control an attitude change from the nominal attitude of MIST (tower position) to arrow position.

C. Standard operating procedure

A special operating mode to fire NanoProp is clearly needed, thus a SOP was designed as a flowchart to describe the interaction between the OBC and NanoProp.

Folder “NanoProp SOP”, placed in MIST Dropbox/M174-NanoProp, shows in detail the main SOP for one thruster according to the set of modes of NanoProp: Idle, Propellant Conditioning, Firing, Firing Preparation and Off. The aim of this flowchart is to provide a general understanding of how to operate NanoProp. The SOP needs to be shaped according to the operating requirements of the experiments described in Section IV Experiments and Decommissioning operations.

D. Simulation Example

In order to have a better understanding of how the operation of NanoProp influences the dynamic behaviour of MIST and how other subsystems operate according to the outcomes induced by NanoProp, a Matlab/Simulink simulation of the experiment Performance assessment via Indefinite firing mode was performed.

According to Section IV Experiments, the objective of this experiment is to assess the performance and misalignment of thrusters by firing pairs of thrusters, thus firing configuration (Fire thruster A & B) with variation in thrust magnitude misalignment was selected. Considering that the maximum foreseen misalignment between thrusters is 10%, Thruster A is set to fire at 0.9 mN and Thruster B at 1 mN for 1 min. Fig. 28 illustrates this scenario.

From Fig. 28, it is clear that the simulated misalignment between thrusters A and B will produce pitch and yaw rotations, the main torque will be applied around the Y axis and a small torque will be generated about the X axis, therefore, considering the distances illustrated in Fig. 11, the torques applied into the system are shown in Table XXXII.

Table XXXII summarises the most important parameters for MIST, NanoProp, MPU6050, and iMTQ models to run the experiment.

Fig. 29 shows the dynamic performance of MIST over the operating time. Since the main torque is applied about...
it is expected to see no torques about X and Z axes, but the simulation shows torque generations about X and Y axes indicating that there is a misalignment between thrusters as expected.

By evaluating these outcomes, it can first be determined that the misalignment between thrusters is minimum since the torque generated about Y axis is similar to the value expected for the zero misalignment scenario. Second, it can be concluded that the misalignment between thrusters is caused due to variation in thrust magnitude because there is no torque generated about Z axis, moreover, since the torque generated about the X axis is positive, it can be defined that Thruster A delivers less thrust with respect to Thruster B.

Then, the torque results from the model concentrate around the values defined in Table XXXI, therefore, the torque evaluation model is able to provide a detailed overview of the thruster performance of NanoProp.

On the other hand, Fig. 31 shows the kinematic performance of MIST over the operating time. The computation indicates the spacecraft rotates mainly about the Y axis as NanoProp is firing. Once the manoeuvre is complete, MIST will be rotated 180° with respect to the initial X and Z references axes.

Finally, once the experiment is complete, the iMTQ is activated to detumble the satellite from the final angular velocities produced by the manoeuvre. Fig. 32 shows the BDOT detumble operation of MIST.

Considering that the orbital period of MIST reference orbit is approximately 98 min, the iMTQ will take about 2.5 orbits to detumble MIST so it can be orientated to a given attitude afterwards.

### V. Discussion and Future Work

Based on this study, the NanoProp propulsion system is able to provide a wide range of manoeuvres for a 3U CubeSat, but the application of those in space will mainly depend on thermal, power, and telemetry budgets developed for a specific mission, and in this case, since MIST is still under development, the proposed mission experiments offer a strong initial understanding and guideline of the requirements and limitations considered for the operation of NanoProp according to the requirements of the MIST mission.

Clearly, the need for a special operating mode for the OBC software to run NanoProp is crucial to effectively perform the proposed mission experiments. Therefore, the developed operating procedures such as the telemetry and FDIR analysis of NanoProp, together with the developed SOP, provide a feasible strategy to design the interaction between the OBC and NanoProp. Moreover, proposed mission experiments, including their power and telemetry budgets, present the basis for developing more practical system engineering budgets for the MIST mission.

According to the results presented in this study and the latest engineering budgets developed for MIST mission, the operation of NanoProp can be performed as proposed in the study. Yet, there are some specific operating details that need a further examination such as the opportunity to operate NanoProp during a ground station pass, the attitude change to perform manoeuvres in the arrow position or the implementation and operation of the IMU board in the MIST satellite.

### TABLE XXXI

<table>
<thead>
<tr>
<th>Thruster</th>
<th>( L_x ) [Nm]</th>
<th>( L_y ) [Nm]</th>
<th>( L_Z ) [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>(-3.24 \times 10^{-9})</td>
<td>(3.06 \times 10^{-9})</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>(3.6 \times 10^{-5})</td>
<td>(3.4 \times 10^{-5})</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>(3.6 \times 10^{-9})</td>
<td>(6.46 \times 10^{-9})</td>
<td>0</td>
</tr>
</tbody>
</table>

### TABLE XXXII

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIST</td>
<td></td>
</tr>
<tr>
<td>( I_x )</td>
<td>0.051 kgm²</td>
</tr>
<tr>
<td>( I_y )</td>
<td>0.037 kgm²</td>
</tr>
<tr>
<td>( I_z )</td>
<td>0.0205 kgm²</td>
</tr>
<tr>
<td>( \omega_q )</td>
<td>(10^{-3}) rad/s</td>
</tr>
<tr>
<td>( \omega_y )</td>
<td>0 rad/s</td>
</tr>
<tr>
<td>( \omega_z )</td>
<td>0 rad/s</td>
</tr>
<tr>
<td>( \beta_0 )</td>
<td>1</td>
</tr>
<tr>
<td>( \beta_1 )</td>
<td>0</td>
</tr>
<tr>
<td>( \beta_2 )</td>
<td>0</td>
</tr>
<tr>
<td>( \beta_3 )</td>
<td>0</td>
</tr>
<tr>
<td>NanoProp</td>
<td></td>
</tr>
<tr>
<td>( F_A )</td>
<td>0.9 mN</td>
</tr>
<tr>
<td>( F_B )</td>
<td>1 mN</td>
</tr>
<tr>
<td>( F_C )</td>
<td>0 mN</td>
</tr>
<tr>
<td>( F_D )</td>
<td>0 mN</td>
</tr>
<tr>
<td>( t_{burn} )</td>
<td>1 min</td>
</tr>
<tr>
<td>( d_A )</td>
<td>([34 \ 36 \ 150]) mm</td>
</tr>
<tr>
<td>( d_B )</td>
<td>([-34 \ 36 \ 150]) mm</td>
</tr>
<tr>
<td>( d_C )</td>
<td>([-34 \ 36 \ 150]) mm</td>
</tr>
<tr>
<td>( d_D )</td>
<td>([-34 \ 36 \ 150]) mm</td>
</tr>
<tr>
<td>MPU6050-Gyro</td>
<td></td>
</tr>
<tr>
<td>( f_{sampling} )</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Full scale range</td>
<td>(\pm 250 \ 500 ) μg/s</td>
</tr>
<tr>
<td>Sensitivity scale factor</td>
<td>131 LSB/(°/s)</td>
</tr>
<tr>
<td>( \omega_{bias} )</td>
<td>0 °/s</td>
</tr>
<tr>
<td>( \omega_{ARW} )</td>
<td>0.005 (°/s)/√Hz</td>
</tr>
<tr>
<td>( \omega_{GRW} )</td>
<td>0 (°/s)/√Hz</td>
</tr>
<tr>
<td>( \omega_{BI} )</td>
<td>0 °/s</td>
</tr>
<tr>
<td>iMTQ</td>
<td></td>
</tr>
<tr>
<td>( f_{sampling} )</td>
<td>8 Hz</td>
</tr>
<tr>
<td>( c )</td>
<td>(10^4) Am²Is/T</td>
</tr>
<tr>
<td>( m_A )</td>
<td>0.2 Am²</td>
</tr>
<tr>
<td>Actuation error</td>
<td>5 %</td>
</tr>
<tr>
<td>Magnetometer accuracy</td>
<td>3 μT</td>
</tr>
</tbody>
</table>

As shown in Fig. 29, it is important to perform a calibration in gyroscope before the start of the experiment in order to reduce errors in measurements generated by static bias and random noise.

Once the angular velocities are measured and filtered by the gyroscope, the torques are computed on-ground. Fig. 30 shows the resulting torque outcome produced by the torque evaluation model.

Assuming a zero misalignment scenario for this experiment, it is expected to see no torques about X and Z axes, but \( L_y = 6.8 \times 10^{-5}\) Nm. Instead, the resulting torque outcome from

\[
\begin{align*}
\text{TABLE XXXII} & \quad \text{INITIAL PARAMETERS FOR SIMULATION} \\
\text{Parameter} & \quad \text{Value} \\
\text{MIST} & \quad \text{ } \\
I_x & \quad 0.051 \text{ kgm}^2 \\
I_y & \quad 0.037 \text{ kgm}^2 \\
I_z & \quad 0.0205 \text{ kgm}^2 \\
\omega_q & \quad 10^{-3} \text{ rad/s} \\
\omega_y & \quad 0 \text{ rad/s} \\
\omega_z & \quad 0 \text{ rad/s} \\
\beta_0 & \quad 1 \\
\beta_1 & \quad 0 \\
\beta_2 & \quad 0 \\
\beta_3 & \quad 0 \\
\text{NanoProp} & \quad \text{ } \\
F_A & \quad 0.9 \text{ mN} \\
F_B & \quad 1 \text{ mN} \\
F_C & \quad 0 \text{ mN} \\
F_D & \quad 0 \text{ mN} \\
t_{burn} & \quad 1 \text{ min} \\
d_A & \quad [34 \ 36 \ 150] \text{ mm} \\
d_B & \quad [-34 \ 36 \ 150] \text{ mm} \\
d_C & \quad [-34 \ 36 \ 150] \text{ mm} \\
d_D & \quad [-34 \ 36 \ 150] \text{ mm} \\
\text{MPU6050-Gyro} & \quad \text{ } \\
f_{sampling} & \quad 10 \text{ Hz} \\
\text{Full scale range} & \quad \pm 250 \ 500 \ 500 \ \mu\text{g/s} \\
\text{Sensitivity scale factor} & \quad 131 \text{ LSB/(°/s)} \\
\omega_{bias} & \quad 0 \degree /\text{s} \\
\omega_{ARW} & \quad 0.005 \ (°/\text{s})/\sqrt{\text{Hz}} \\
\omega_{GRW} & \quad 0 \ (°/\text{s})/\sqrt{\text{Hz}} \\
\omega_{BI} & \quad 0 \degree /\text{s} \\
\text{iMTQ} & \quad \text{ } \\
f_{sampling} & \quad 8 \text{ Hz} \\
c & \quad 10^4 \text{ Am²/s/T} \\
m_A & \quad 0.2 \text{ Am²} \\
\text{Actuation error} & \quad 5 \% \\
\text{Magnetometer accuracy} & \quad 3 \mu\text{T} \\
\end{align*}
\]
In case it is desired to run some of the allowed mission experiments of NanoProp over the ground station, a complete system engineering budget, including the requirements of the other experiments in operation, is needed to determine the feasibility of this strategy. Fortunately, the study points out that all proposed mission experiments of NanoProp can be automatically performed at any time during the orbit.

Moreover, the required attitude change for arrow manoeuvres depends on the feasibility of the ADCS system and general power requirements of MIST to perform and control this attitude change. This condition actually questions the possibility of performing the suggested depletion manoeuvre at EOL of the mission which yields to consider the venting strategy as the primary option for passivation plan for NanoProp.

On the other hand, functional testing is needed to verify the operating characteristics mentioned in this study for the IMU board. It is particularly important to inspect the filtering process included in the system so one can have a better outlook on the needs and limitations of the embedded gyroscope board to read the induced angular rates. Similarly, the implementation of a functional testing campaign for NanoProp may be useful to understand the performance and operating requirements of the system, and most importantly, to validate the results proposed in this study.

Finally, according to the mentioned simulation example, the Matlab/Simulink model offers a feasible practice to understand the dynamic and kinematic interaction between NanoProp and the satellite, but in order to have a more realistic outlook, the implementation of other external perturbations in the environment of the spacecraft such as solar pressure or atmospheric drag should be considered in the simulation. They can clearly alter the angular rates induced by firing NanoProp, although to a minor extent. Moreover, the option to develop a more sensible firing model for NanoProp can be significant for the simulation. For instance, a pulse of exhaust propellant is in general in the shape of a steep thrust peak at the instant of
firing followed by a tail after the instant of the firing stopping. This special behaviour and some minor delays after sending a firing or stop firing command can shape the thrust levels delivered by NanoProp.

VI. CONCLUSION

A propulsion system clearly improves the performance of the mission by adding more functionalities to the spacecraft such as attitude and orbital manoeuvres, station keeping control, decommissioning strategy or interplanetary travel. However, it is important to notice that the accessibility to these functionalities mainly depend on the type of propulsion system selected for the mission and the profile of the mission itself to be performed, therefore, the implementation of a propulsion system in a satellite definitely requires an exhaustive understanding of the performance and internal operating requirements of the system as well as definition of the objectives and operating characteristics of the space mission.

As a result, a feasibility study and mission plan for the propulsion system need to be developed at early stage of the mission design in order to develop a spacecraft qualified to complete its mission objectives as demanded. For that reason, the results of this study, effective from the commissioning stage to the decommissioning stage, aim to determine the procedures and experiments to operate and evaluate the performance of the NanoProp 3U propulsion system according to the mission profile of the MIST 3U CubeSat satellite.

Finally, the presented results in this study also indicate a continuous interaction of the propulsion system with other subsystems on-board the satellite. The conditions to operate a subsystem evidently impact the conditions to run others as well as the general affordability of the space mission, therefore constant evaluation of the thermal, telemetry and power budgets need to be performed so that all elements in the spacecraft work together towards the development of a complete and safe space mission.
ACKNOWLEDGMENTS

Foremost, I would like to express my special gratitude to my supervisors Sven Grahn and Johan Sundqvist whose expertise, consistent guidance, and endless advices helped me to bring this study into success.

Moreover, I would like to thank to the MIST project and all my fellow teammates for giving me the opportunity to be part of a unique group developing a satellite that will be flying in space very soon. For a year and a half, I have attained immense memories and experiences that certainly will inspire in my future and personal projects.

I would also like to thank to GomSpace and the entire staff for their sincere guidance and help for completing this study.

Special thanks to CONACYT for giving me the opportunity and financial support to develop my graduate studies abroad.

My deepest appreciation belongs to my family, especially my parents Alejo and Dulce and my sister Karla, for giving me unlimited support and encouragement to undertake this wonderful adventure. You have always been by my side despite the physical distance that sometimes separates us, but remember in a few years we will be talking about light years away.

REFERENCES

# APPENDIX A

## FAULT DETECTION ISOLATION AND RECOVERY ANALYSIS

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Mode</th>
<th>Observable</th>
<th>Condition</th>
<th>SW Action</th>
<th>SW Flag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Propellant Conditioning</td>
<td>No tank temperature TM sent to OSC</td>
<td>TANKN_TEMP not received</td>
<td>TANKN_TEMP_FAIL</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>Propellant Conditioning</td>
<td>No completion of tank heating process before the time limit TIMAX</td>
<td>TIMER_T &gt; TIMAX</td>
<td>TANKN_TEMP_DRIFT</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>Propellant Conditioning</td>
<td>No increase in the tank temperature T1 s after heating command is sent AND Current consumption in the Battery line below 100 mA</td>
<td>No increment in TANKN_TEMP T1 seconds after TANKN_HEATER is sent AND BAT_BUS_J &lt; 100 mA</td>
<td>Send TRX_CTRL (Arm configuration) when NANOPROP_TEMP &gt; 0°C</td>
<td>TANKN_HEATER_FAIL</td>
</tr>
<tr>
<td>Temperature</td>
<td>Propellant Conditioning</td>
<td>No completion of tank heating process before the time limit TIMAX AND Current consumption in the Battery line below 100 mA</td>
<td>TIMER_T &gt; TIMAX AND BAT_BUS_J &lt; 100 mA</td>
<td>TANKN_HEATER_FAIL</td>
<td></td>
</tr>
<tr>
<td>Current</td>
<td>Propellant Conditioning</td>
<td>Current consumption in the Battery line below 130 mA</td>
<td>BAT_BUS_J &lt; 130 mA</td>
<td>MANF_HEATER_FAIL</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>Firing Preparation</td>
<td>No thruster temperature TM sent to OSC</td>
<td>THRX_TEMP not received</td>
<td>THRX_TEMP_FAIL</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>Firing Preparation</td>
<td>No completion of thrust heating process before the time limit TIMAX</td>
<td>TIMER_TH &gt; TIMAX</td>
<td>THRX_TEMP_DRIFT</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>Firing Preparation</td>
<td>No increase in the thruster temperature T3 s after arm command is sent AND Current consumption in the Battery line below 100 mA</td>
<td>No increment in THRX_TEMP T3 seconds after THRX_CTRL (Arm configuration) is sent AND BAT_BUS_J &lt; 100 mA</td>
<td>Disconnect NanoProp</td>
<td>THRX_HEATER_FAIL</td>
</tr>
<tr>
<td>Temperature</td>
<td>Firing Preparation</td>
<td>No completion of thrust heating process before the time limit TIMAX AND Current consumption in the Battery line below 100 mA</td>
<td>TIMER_TH &gt; TIMAX AND BAT_BUS_J &lt; 100 mA</td>
<td>THRX_HEATER_DRIFT</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>Firing</td>
<td>Tank temperature drops below 0°C while firing</td>
<td>TANKN_TEMP &lt; 0°C while THRX_CTRL (Firing)</td>
<td>TANKN_FAIL</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>Firing</td>
<td>Thruster temperature drops below tank temperature while firing</td>
<td>THRX_TEMP &lt; TANKN_TEMP while THRX_CTRL (Firing)</td>
<td>THRX_FAIL</td>
<td></td>
</tr>
<tr>
<td>Angular Velocity</td>
<td>Firing</td>
<td>No angular velocity TM sent to OSC</td>
<td>WX OR WY OR WZ not received</td>
<td>GYRO_FAIL</td>
<td></td>
</tr>
<tr>
<td>Angular Velocity</td>
<td>Firing</td>
<td>Difference between the angular velocity TM sent to OSC and the angular velocity measured on simulation higher than [FBC] ends</td>
<td>WX − WX_SIM &gt; [FBC] ends OR WX_WY_SIM &gt; [FBC] ends OR WZ − WZ_SIM &gt; [FBC] ends</td>
<td>Perform gyroscope calibration</td>
<td>GYRO_CALIBRATION</td>
</tr>
<tr>
<td>Angular Velocity</td>
<td>Firing</td>
<td>Angular velocity sent to OSC higher than 1.75 m/s</td>
<td>WX OR WY OR WZ &gt; 1.75 m/s</td>
<td>Connect BTG-24 to tank</td>
<td>GYRO_LIMIT</td>
</tr>
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</table>
APPENDIX B
FAILURE MODE AND EFFECTS ANALYSIS

To increase the reliability of the MIST-NanoProp mission, it is important to first perform an FMEA analysis in order to systematically identify potential failures in products (functional and hardware) and processes and subsequently set an adequate FDIR policy. This FMEA analysis only considers those potential failures that might occur in following equipment during the operation of NanoProp. The effects of these failures are assessed at spacecraft level.

- Tank Temperature Sensor and Tank Heater
- Manifold Heaters
- Thruster Temperature Sensors and Thruster Heaters
- Gyroscope Board

<table>
<thead>
<tr>
<th>Failure Modes and Effects Analysis (FMEA)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product:</strong> MIST</td>
</tr>
<tr>
<td>Mont. number</td>
</tr>
</tbody>
</table>
| 1 | Temperature sensor | Monitor tank temperature | Open circuit | Intrinsic failure | Propellant Conditioning Mode | a. No TM sent to OBC  
    b. Mission degradation – Low reliable operations | 4 | No tank temperature Td sent to OBC | GIC enables firing preparation mode when average NanoProp temperature is above 0°C |
| 2 |  |  | Short circuit | Intrinsic failure | NanoProp mission | a. Excessive TM sent to OBC  
    b. Mission degradation – Low reliable operations | 4 | No completion of heating process before the time limit TIMAX | GIC enables firing preparation mode when average NanoProp temperature is above 0°C |
| 3 |  |  | Short circuit | Intrinsic failure | Propellant Conditioning Mode | a. No heating  
    b. Mission degradation – No operation at cold temperatures and long burns | 4 | No increase in the tank temperature Tt after heating command is sent  
    Current consumption in the Battery line below 100 mA | GIC enables firing preparation mode when average NanoProp temperature is above 0°C  
    The tank heater is automatically turned off if tank temperature exceeds 40°C  
    If burn time is expected to be more than 3 minutes, GIC commands activation of tank heater while firing |
| 4 |  |  | Increase of contact resistance | Intrinsic failure | NanoProp mission | a. Degradation of performance  
    b. Mission degradation – Low reliable operations | 4 | No completion of heating process before the time limit TIMAX  
    Current consumption in the Battery line below 100 mA | GIC enables firing preparation mode when average NanoProp temperature is above 0°C  
    GIC commands NanoProp disconnection |
| 5 | Filling system (Tank, Pumps, Valves) | Supply propellant to thrusters | Leak | Intrinsic failure | NanoProp mission | a. Risk of performance degradation of NanoProp  
    b. Mission degradation – Unsteady control of S/C | 4 | Tank temperature drops below 0°C while firing | GIC commands NanoProp disconnection |
<table>
<thead>
<tr>
<th>Ident. number</th>
<th>Item/ block</th>
<th>Function</th>
<th>Failure mode</th>
<th>Failure cause</th>
<th>Failure effects</th>
<th>Severity classification</th>
<th>Failure detection method/ Observable symptoms</th>
<th>Equipment: Manifolds</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Heaters</td>
<td>Raise manifold temperature</td>
<td>Intrinsic failure</td>
<td>Propellant Condensing Mode/ NanoProp mission</td>
<td>a. No heating Risk of performance degradation of NanoProp b. Mission degradation – No operation at cold temperatures</td>
<td>4</td>
<td>Current consumption in the Battery line below 150 mA</td>
<td>OBC enables firing preparation mode when average NanoProp temperature is above 0°C</td>
<td>OBC command activation of manifold heaters.</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>Increase of contact resistance</td>
<td>Intrinsic failure</td>
<td>NanoProp mission</td>
<td>a. Degrading heating Risk of performance degradation of NanoProp b. Mission degradation – Low reliable operation</td>
<td>4</td>
<td>Current consumption in the Battery line below 150 mA</td>
<td>OBC enables firing preparation mode when average NanoProp temperature is above 0°C</td>
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</table>
# Failure Modes and Effects Analysis (FMEA)

<table>
<thead>
<tr>
<th>Ident. number</th>
<th>Item/ block</th>
<th>Function</th>
<th>Failure mode</th>
<th>Failure cause</th>
<th>Operation/ Mission phase</th>
<th>Failure effect</th>
<th>Severity classification</th>
<th>Failure detection method/ Observable symptoms</th>
<th>Compensating Provisions at system level</th>
<th>Remarks</th>
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</thead>
<tbody>
<tr>
<td>8</td>
<td>Temperature sensor</td>
<td>Monitor thruster temperature</td>
<td>Open circuit</td>
<td>Insulative failure</td>
<td>Firing Preparation Mode/ NanoProp mission</td>
<td>a. No TM sent to OBC b. Mission degradation – Low reliable operation</td>
<td>4</td>
<td>No thruster temperature TM sent to OBC</td>
<td>OBC commands NanoProp disconnection</td>
<td>“Arming” state where the thruster is heated to arm temperature (nominal 40°C).</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td>Short circuit</td>
<td>Insulative failure</td>
<td>Firing Preparation Mode/ NanoProp mission</td>
<td>a. Exposure TM sent to OBC b. Mission degradation – Low reliable operation</td>
<td>4</td>
<td>No completion of heating process before the time limit TIMAX</td>
<td>OBC commands NanoProp disconnection</td>
<td></td>
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<tr>
<td>10</td>
<td>Heater</td>
<td>Raise thruster temperature</td>
<td>Short circuit</td>
<td>Insulative failure</td>
<td>Firing Preparation Mode/ NanoProp mission</td>
<td>a. No heating Risk of performance degradation of NanoProp Mission degradation – No operation at any temperature</td>
<td>4</td>
<td>No increase in the thruster temperature 75 s after command is sent</td>
<td>Current consumption in the Battery below 100 mA</td>
<td>OBC commands NanoProp disconnection</td>
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<tr>
<td>11</td>
<td></td>
<td>Increase of contact resistance</td>
<td>Open circuit</td>
<td>Insulative failure</td>
<td>NanoProp mission</td>
<td>a. Degradation Risk of performance degradation of NanoProp Mission degradation – Low reliable operation</td>
<td>4</td>
<td>No completion of heating process before the time limit TIMAX</td>
<td>Current consumption in the Battery line below 100 mA</td>
<td>OBC commands NanoProp disconnection</td>
</tr>
</tbody>
</table>
## Failure Modes and Effects Analysis (FMEA)

<table>
<thead>
<tr>
<th>Ident. number</th>
<th>Item/ block</th>
<th>Function</th>
<th>Failure mode</th>
<th>Failure cause</th>
<th>Operation/ Mission phase</th>
<th>Failure effects a, b</th>
<th>Local effects</th>
<th>End effects</th>
<th>Severity classification</th>
<th>Failure detection method/ Observable symptoms</th>
<th>Compensating/ Preventing actions at system level</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>13</td>
<td>3-axis Gyroscope</td>
<td>Monitor angular velocity of S/C</td>
<td>Drift mode is value</td>
<td>Intrinsic failure</td>
<td>Firing Mode/ NanoProp mission</td>
<td>a. Degradation in performance and degradation of NanoProp</td>
<td>Mission degradation – Unsteady control of S/C</td>
<td>None</td>
<td>4</td>
<td>No angular velocity TM sent to OBC</td>
<td>OBC commands NanoProp disconnection</td>
<td>OBC commands activation of 3-axis gyroscope board while firing to monitor rotation rate of S/C. Once firing is complete, OBC commands 3MTQ activation to deactivate S/C.</td>
</tr>
<tr>
<td>14</td>
<td>3-axis Gyroscope</td>
<td>Monitor angular velocity of S/C</td>
<td>Drift mode is value</td>
<td>Intrinsic failure</td>
<td>Firing Mode/ NanoProp mission</td>
<td>a. Degradation in performance and degradation of NanoProp</td>
<td>Mission degradation – Unsteady control of S/C</td>
<td>None</td>
<td>4</td>
<td>Difference between the angular velocity TM sent to OBC and the angular velocity measured on simulation higher than [3%] rad/s</td>
<td>OBC commands gyroscope calibration</td>
<td>OBC commands gyroscope calibration</td>
</tr>
<tr>
<td>15</td>
<td>3-axis Gyroscope</td>
<td>External rotation</td>
<td>External failure</td>
<td>External failure</td>
<td>None</td>
<td>Mission degradation – Unsteady control of S/C</td>
<td>None</td>
<td>4</td>
<td>Angular velocity sent to OBC higher than 1.75 rad/s</td>
<td>OBC commands 3MTQ deactivation</td>
<td>OBC commands 3MTQ deactivation</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX C

ORBITAL MANOEUVRE ANALYSIS

This appendix shows the analytical methods to calculate the orbital changes when performing two types of orbital manoeuvres: radial and along velocity vector.

Moreover, the appendix analyses the feasibility of the NovAtel OEM615 GPS receiver and the Space Track software tool to detect the orbital changes expected to see for the MIST mission.

A. Radial Manoeuvre

A radial ∆V manoeuvre will attain a small eccentricity change without altering the period from the original orbit, [21].

Considering the orbital parameters for MIST which are described in Table I and R₀ = 6 378.15 km, the altitudes of apogee and perigee are:

hₚ = 635.28 km  hₚ = 649.32 km

The two solutions below determine the eccentricity changes from a ∆V = 0.8 m/s manoeuvre to be performed for the MIST mission.

1) Solution 1:

\[ \Delta h = \frac{\Delta V T_p}{2\pi} = \frac{0.8 \text{ m/s} \cdot 5 854.07 \text{ s}}{2\pi} \approx 745.36 \text{ m} \]

\[ \Delta e_1 = \frac{\Delta h}{h_a + h_p + 2R_0} = 0.000053 \]

\[ e_f = \Delta e_1 + e_0 = 0.001053 \]

2) Solution 2: Using (56), it is also possible to compute the total velocity increment, for quasi-circular orbits, required to realize a net eccentricity change from an initial value e₀ to a final value e_f, [22].

\[ \Delta V = 2 \sqrt{\frac{\mu}{a}} \left| \arcsin(e_0) - \arcsin(e_f) \right| \] \hspace{1cm} (56)

\[ e_{f,1} = \sin \left( \arcsin(e_0) + \Delta V \frac{3}{2} \sqrt{\frac{\pi}{\mu}} \right) \]

\[ e_{f,2} = -\sin \left( \Delta V \frac{3}{2} \sqrt{\frac{\pi}{\mu}} - \arcsin(e_0) \right) \]

\[ e_{f,1} = 0.001159 \] or \[ e_{f,2} = 0.00084 \]

\[ | \Delta e_2 | = 0.000159 \]

The differences between ∆e solutions are in the magnitude 10⁻⁴, therefore, it is determined that both approaches are sufficiently correct. As a result, the ∆e from solution 2 (Δe₂ = 0.000159) can be considered the maximum possible ∆e attained by this manoeuvre.

Finally, both eccentricity changes are compared with the eccentricity evolution of the former ESTCube-1 CubeSat mission which was determined by the Space Track software as illustrated in Fig. 33. The ∆e₁ = 0.000053 is shown as a red arrow and ∆e₂ = 0.000159 is shown as a green arrow.

Both eccentricity changes are also compared with the eccentricity evolution determined by the OEM615 GPS receiver on-board the GOMX-4B CubeSat mission when performing an 8 cm/s manoeuvre as shown in Fig. 34. Data were provided by GomSpace. The ∆e of this manoeuvre is smaller than the minimum changes expected to see from a 0.8 m/s manoeuvre to be performed for the MIST mission.

B. Along velocity vector Manoeuvre

On the contrary, a ∆V manoeuvre parallel to the orbit velocity vector will produce a change in both period and semi-major axis, [21].

By using (57), the required velocity increment, for quasi-circular orbit, to obtain a change in semi-major axis is computed, [22] [23]:

\[ \Delta V = \sqrt{\frac{\mu}{a_0}} - \sqrt{\frac{\mu}{a_f}} \] \hspace{1cm} (57)
Considering one more time the orbital parameters of Table I and a $\Delta V = 0.8$ m/s manoeuvre to be performed for the MIST mission.

$$a_f = \frac{\mu}{\left(\sqrt{a_0} - \Delta V\right)^2}$$

Finally, this type of $\Delta V$ manoeuvre will also produce a change in the orbital period.

$$T_p = 2\pi\sqrt{\frac{a^3}{\mu}} = 5\,855.94\,s = 97.6\,min$$

$$\Delta T_p \approx 0.031\,min$$

As shown in Fig. 35, the green arrow represents the $\Delta T_p = 0.03\,min$ to see for the MIST mission which is compared with the period evolution of the ESTCube-1 mission determined by the Space Track software.

On the other hand, the $\Delta a \approx 1.5$ km is compared with the semi-major axis evolution of the GOMX-4B CubeSat when performing an 8 cm/s manoeuvre as shown in Fig. 36. Data was determined by the on-board OEM615 GPS as well. The semi-major axis change is smaller than the expected change to see from a 0.8 m/s manoeuvre to be performed for the MIST mission.

In conclusion, both the NovAtel OEM615 GPS receiver and the Space Track ground tracking software tool are able to detect the orbital changes produced from $\Delta V = 0.8$ m/s manoeuvres which are planned to be performed on MIST in the $\pm U$ direction (satellite at tower orientation) and in the $\pm V$ direction (satellite at arrow orientation).

However, the precision of the GPS is not necessarily the limiting factor in orbit determination. A strategy must be developed for sampling the GPS in multiple positions along the orbit to exceed the accuracy of a single point navigation solution.