THE INSPECTOR SAT MISSION, OPERATIONS AND TESTBED FOR RELATIVE MOTION SIMULATION

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Abstract: The InspectorSat mission is a concept designed to demonstrate complex and close-proximity autonomous manoeuvres around a passive, non-cooperative target, focused on the development of a visual inspection payload for the observation of a co-orbital solar sail. The mission will aim to demonstrate inspection manoeuvres using the visual inspection payload and a novel micro-chemical propulsion system based on microelectromechanical components. The manoeuvres are expected to be autonomously commanded by guidance, navigation and control algorithms that are currently theoretically proven but remain largely untested under laboratory conditions.

This paper presents a description of the InspectorSat mission and two experiments that will enable the testing and validation of the visual inspection payload and its capability for spacecraft control using a microthruster. The visual inspection payload concept and its integration with the microthruster are presented. A new frictionless air table facility built to simulate planar orbital motion is described. Finally a spheroid reconstruction algorithm is tested under laboratory conditions to provide relative position and pose estimates of a passive target.

The results indicate that for a small satellite platform the visual inspection payload and microthruster provide a suitable system for autonomous inspection. The spheroid reconstruction algorithm is demonstrated to provide accurate estimates of relative position and pose of a target object.

Keywords: Visual inspection, solar sail, spheroid reconstruction, frictionless air table

1 Introduction

Autonomous co-orbital motion and formation flying opens many opportunities for missions that are typically technologically limited, e.g. communication latencies, or operationally limited, e.g. human-in-the-loop delays. Such applications include on-orbit servicing, construction, rendezvous and docking, all of which require some level of inspection prior to interacting with a target object. Technologies that achieve operations
such as these have been demonstrated on several small satellite missions to date, including the PRISMA and CanX-2 missions. New methods enabling formation flying by means of GPS measurements alone were demonstrated on the CanX-2 nanosatellite and are also planned for the CanX-4/5 mission [1]. Whereas PRISMA utilised three Guidance, Navigation and Control (GNC) methods based on combinations of Global Positioning System (GPS), Radio Frequency (RF) and visual measurements [2].

While these methods have shown promising results, all of the above examples depend upon some level of cooperation from the target spacecraft. Furthermore, the continuous use of subsystems such as GPS is typically limited on nanosatellite platforms by constraints in the available power budget. Performing observations without the aid of GPS or other cooperative methods while in orbit requires a high performance and robust Attitude and Orbital Control System (AOCS), coupled with passive target detection sensors and a precise spacecraft actuation system. The purpose of the InspectorSat is to provide platform for such a system, in the form of a “Visual Inspection Payload” (VIP), thus providing the means for the direct and autonomous on-orbit observation of a target spacecraft for extended periods of time.

The InspectorSat mission aims to demonstrate this concept through the execution of complex and close-proximity autonomous manoeuvres around a passive, non-cooperative target using a nano- to micro- (small) satellite platform. Current work at the Surrey Space Centre (SSC) is focused on the development of an inspection mission of a solar sail using such a small satellite platform. As such, the mission will provide an important opportunity for the integration and application of new, theoretically proven but empirically untested algorithms. The purpose of the VIP will be to provide spacecraft guidance, navigation and control (GNC) based on the estimation of the relative motion of a passive, non-cooperative target.

To compliment the VIP, the InspectorSat spacecraft will also incorporate a micro-propulsion system, suitable for the agile actuation of a small satellite platform. Liquid and chemical propulsion provides an impulse bit (Ibit) and response times superior to mechanical attitude control systems at the expense of a finite fuel supply. The “chemical-µPRopulsion for an Efficient and accurate Control of Satellites for Space Exploration” (PRECISE) consortium is currently developing a micro-chemical propulsion system (µCPS) based on microelectromechanical system (MEMS) devices [3]. Such a system will allow the integration of a high-performance chemical thruster into small spacecraft platforms, such as the InspectorSat.

2 The InspectorSat mission concept

2.1 Mission summary

The InspectorSat mission statement reads as follows:

“To demonstrate efficient and accurate control of a satellite using a micro-chemical propulsion thruster and visual inspection payload, enabling the development and execution of formation flying manoeuvres around a target solar sail spacecraft for the
purposes of visual inspection and measurement of co-orbital relative motion.”

The InspectorSat mission will place a small inspector satellite into co-orbital motion with a solar sail target. The two spacecraft are under separate development and do not include any collaborative or active navigation techniques to enable the measurement of relative range or motion. Therefore, the InspectorSat will rely on its VIP to passively estimate relative position and pose of the target and autonomously predict the respective orbital motion. The effect of Solar Radiation Pressure (SRP) will require such measurements to be made continuously as part of the GNC loop and precise adjustments to the InspectorSat orbit and attitude to be made using the $\mu$CPS.

The target Solar Sail Spacecraft (SSSC), “Vympel”, is currently under development by the Russian aerospace company NPO Mashinostroyenia. The proposed micro-thruster is a novel MEMS-based system currently under development by the PRECISE project consortium. The $\mu$CPS will enable the InspectorSat to perform both attitude and orbital manoeuvres, including detumbling, observation of sail deployment and unfolding, rendezvous, orbit (re-)phasing and compensation for SRP. The VIP will provide the relative position and pose estimates with which the motion of the SSSC can be predicted and, subsequently, plan the manoeuvres necessary to meet the inspection objectives.

As such, the InspectorSat mission aims to provide a technical demonstration of the novel hardware by:

- Demonstrating the $\mu$CPS thruster capability for AOCS actuation
- Optically capturing the solar sail spacecraft for relative motion estimation

The aims will be accomplished by the following objectives, which will demonstrate the scientific and mission-specific applications provided by the $\mu$CPS and VIP. That is, to:

- Perform orbit maintenance, perturbation mitigation, formation flying and attitude control manoeuvres
- Visually capture the solar sail deployment and surface features, including billow, creasing and folding patterns
- Characterise SRP on the solar sail spacecraft by analysis of spacecraft relative motion estimates from the VIP and $\mu$CPS requirements to mitigate these effects

As a technology demonstration mission, the primary payloads of the InspectorSat will be the VIP and the $\mu$CPS.

2.2 The Visual Inspection Payload

The InspectorSat GNC system architecture includes inputs from systems normally distributed around a spacecraft system and centralised through the on-board computer
(OBC). Therefore, when implemented on the spacecraft, the VIP resides on a dedicated computing board and includes the functions relating to inspection manoeuvres, i.e. planning, control and frame transformation routines. Sensing of the target spacecraft motion is based on a monocular imaging sensor. The image frames are filtered to provide state parameters describing the relative motion of the target spacecraft. Real-time processing provided by an FPGA soft-processor allows relative motion estimates to be incorporated into the InspectorSat GNC loop, complementing the orbit and attitude sensory data provided by GPS, sun sensors, star cameras or magnetometers. This data is fused to provide control inputs to the navigation computer path planner which is responsible for firing the AOCS actuators.

Characterisation of perturbations to the solar sail orbit due to SRP and inspection of other sail features will be accomplished by management of the relative motion between the two spacecraft. Three such manoeuvres are considered for inspection of a co-orbital target [4]. Assuming the SSSC orbit is circular or nearly circular, a 2-1 safety ellipse trajectory relative to the SSSC will allow the InspectorSat to remain within a range defined by its orbit. The motion is illustrated in Fig. 1a and demonstrates how a complete relative orbit of the target spacecraft is achieved for every complete orbit of the Earth. The 2-1 ellipse is a stable, natural motion but will drift slowly relative to the target over the course of several orbits due to SRP and other perturbation effects. Such disturbances can be mitigated by the \( \mu \)CPS based on observations made by the VIP.

Observation of the target spacecraft can be achieved either by maintaining a fixed orientation of the InspectorSat in either the Earth-Centric Inertial (ECI) or Local-Vertical Local-Horizontal (LVLH) frames. In the former case the maximum range of observation is limited by the Field-of-View (FoV) of the inspection camera optics. The latter case represents the more typical nadir-pointing mode of satellite operation and allows for the use of narrow-FoV or telephoto optics. However, active control is required to maintain pointing toward a target.

Forced motion modes may also be used to manoeuvre the InspectorSat into a specific orientation relative to the target, e.g. to align the principal axis of the camera orthogonal to the sail surface. To achieve such manoeuvres, a “pogo” orbit can be used to maintain position above or below the target spacecraft with respect to the Earth. The pogo orbit

![Figure 1: Inspection manoeuvres](image)

(a) 2-1 safety ellipse  
(b) Pogo  
(c) V-bar
is artificial and not naturally stable. When compared to the 2-1 safety ellipse, co-orbital motion by this method would require a more intensive regime of periodic thrusting, however, it would allow longer linger times around a specific position relative to the target spacecraft. The relative motion of the inspection platform takes the distinctive “tear drop” form shown in Fig. 1b.

Finally, a “V-bar perch” configuration, as illustrated in Fig. 1c, would position the InspectorSat in an identical orbit to the SSSC in either a lagging or leading position along-track. Unlike the pogo orbit, the V-bar perch would require very little fuel to maintain its relative position - enough to compensate for SRP - but would require attitude manoeuvres by the SSSC in order to perform observation and inspection tasks. This simple co-orbital configuration does, however, provide a naturally fixed position relative to the SSSC in order to perform SRP drag characterisation measurements.

To accomplish such manoeuvres the VIP senses a target using a wide-angle, monoscopic optical imaging sensor. The sensor is a standard planar CMOS chip equipped with a novel sphere lens. Initial ground experiments have focused on the use of a conceptual imager comprised of a 1.3 megapixel sensor paired with a uniform refractive index lens, 8 mm in diameter, constructed from S-LAH79 glass, with a refractive index of 2.00. To mitigate the typical issue of interfacing such lenses to a commercial-off-the-shelf (COTS) planar sensor, a faceted Fibre-Optic Face Plate (FOFP) is used to mount the lens to the sensor [5]. The nature of the optics allows a wide field of view of 120 degrees, while the FOFP allows the total package volume and mass to remain low. The complete imager, shown in Fig. 2, is less than 2 cm in height and has a mass of approximately 46 grams. The compact nature of this hardware naturally aligns with the low mass, low volume design requirements for the InspectorSat platform.

Figure 2: Sphere lens camera comprised of sensor, FOFP and sphere lens (after Laycock and Handerek [5])

Images of the target spacecraft captured by the imager are used to estimate the relative position and pose using a spheroid reconstruction (SR) algorithm [6]. The SR method provides a reduced-order process for passively sensing a target spacecraft attitude and range relative to the imaging sensor. Instead of extracting specific external features, the target projection on the sensor image plane is bound by a minimum area ellipse. A minimum bounding spheroid representing the target object is defined using a graphical model of the target, as illustrated in Fig. 3a. The spheroid is then fit to the ellipse projection, shown in Fig. 3b, providing position and pose solutions. The reduced
complexity of the spheroid form relaxes the computational burden when compared to feature recognition routines.

Figure 3: A minimum bounding spheroid and its elliptical projection on a 2D plane (both Figures after Wokes [7])

Incorporating the spheroid reconstruction data into the GNC loop allows the relative motion of the target spacecraft to be estimated and, therefore, its motion on orbit to be predicted. However, the precise estimation of position and pose parameters is required for the safe execution of close proximity inspection manoeuvres, hence the requirement to validate the characteristic performance of the algorithm using real targets under laboratory conditions.

2.3 MEMS micro-chemical propulsion

The inclusion of the PRECISE \( \mu \)CPS with the InspectorSat provides an additional actuator to control the spacecraft motion. It both compliments more traditional attitude actuation systems, such as magnetorquers or reaction wheels, and provides a means for manipulation of the orbital motion. The \( \mu \)CPS will provide a low mass, low volume monopropellant propulsion system with a thrust performance suitable for orbital maintenance and attitude control of small spacecraft, nominally of up to 50 kg in mass. Such a chemical propellant thruster system is ideal for the InspectorSat application as it provides both the low-frequency high-\( \Delta v \) burns typical of orbital manoeuvres, such as rendezvous, formation flying, position holding and atmospheric drag compensation and, conversely, the high-frequency low-\( \Delta v \) burns typical of manoeuvres for SRP compensation, orbital maintenance and attitude control.

Historically, such manoeuvres have been performed by various macroscopic thruster technologies, including electrostatics and electromagnetics, arcjets, resistojets, monopropellants, liquid and solid chemical propellants and cold gas jets [8]. The relative performance of these technologies is shown in Fig. 4, illustrating how monopropellant thrusters fill a performance gap between cold gas and liquid/solid chemical thrusters. A monopropellant thruster, therefore, provides the mechanical simplicity of a cold gas system while allowing the utilisation of the propellant chemical energy through a catalytic breakdown mechanism.
The use of MEMS technology in a cold gas thruster was flown on the PRISMA mission as a demonstration experiment. Each module, shown in Fig. 5, incorporates four co-planar thrusters in a cross arrangement; each includes a nozzle, valve, filter and heater. In place of the counterparts found in typical monolithic thrusters, each mechanical element is substituted for an equivalent micron-scale MEMS part. The benefit of such technology is a significant reduction in mass and volume requirements – at the expense of the magnitude of the thrust – making MEMS technology an ideal solution for implementation on small spacecraft platforms. The PRECISE $\mu$CPS is a hydrazine monopropellant microthruster which incorporates further new technologies constructed using MEMS processes. Most notably, the $\mu$CPS will include a micron-scale catalyst bed, in addition to improved components to meet the thermal and pressure requirements a monopropellant thruster demands. A comprehensive discussion of the novel technologies employed by the PRECISE $\mu$CPS can be found in Reference [3].

Using the expected $\mu$CPS performance characteristics, summarised in Tab. 1, fuel requirements for orbit phasing after separation and drift during spacecraft commissioning were estimated by means of the SSC “BSAT” application, a high-precision orbital
propagator using a Bulirsch-Stoer integrator [10]. The estimates of the motion included perturbations due to specified solar conditions and NOAA NRLMSISE-00 atmospheric drag and solar radiation models. Solar average environment conditions were considered, where the solar flux at 10.7 cm (f107a) is 120 (electrons/cm²/s/sr) and geomagnetic kp-index is 14. At the targeted operational altitude of approximately 1500 km, the total drift over a seven day period was estimated assuming a series of launch vehicle separation conditions [11]. Both angular differences between the InspectorSat and SSSC of 0 to 180° in ten degree increments and Δv increments of 0.5 m/s from 0 to 5 m/s were considered.

<table>
<thead>
<tr>
<th>Table 1: μCPS performance characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum thrust (mN)</td>
</tr>
<tr>
<td>Specific impulse (s)</td>
</tr>
<tr>
<td>Operational mode</td>
</tr>
</tbody>
</table>

The results indicate that in the best case scenario, where the angular difference at separation is zero and Δv is equal, natural drift increases to an estimated range of 25.42 km. Conversely, under the worse case scenarios of a 180 degree angular separation or 5 m/s difference in separation Δv, the relative separations were estimated to approach approximately 3,500 km and 7,000 km, respectively. Rephasing estimates were made using the methodologies developed by Palmer and Sauter to determine the Δv rendezvous requirements [12, 13]. Under the best case scenario the integrated Δv over the course of 1, 5 or 11 orbits was estimated at 11.11, 0.21 and 0.15 m/s per orbit, respectively. Differential Δv and angular separations resulted in integrated Δv values one or more orders of magnitude greater, thus lying outside of the scope of the μCPS design. As such, the InspectorSat and SSSC will be launched and separation from the launch vehicle as a single unit. Detumbling and observation of the sail deployment will take place as an integrated structure, before separation and orbit rephasing.

3 Frictionless air cushion testbed

3.1 Testbed description

To aid in the development of formation flying and inspection hardware a frictionless motion testbed has been developed to simulate the motion of orbital spacecraft. The system is based on a granite surface table, shown in Fig. 6a, providing a smooth and level surface. RMS variation in the surface smoothness is under 20 microns and the table is level to approximately 20 microns per metre. The result is a surface upon which bespoke air cushion platforms can manoeuvre with almost no friction other than air resistance. This provides a base upon which reference satellites and prototype payloads can be constructed and tested in the laboratory.

Actuation is provided by eight integrated cold-gas thrusters and the nature of the testbed provides a microgravity-like environment, i.e. actuation will instigate a motion that will not be cancelled until a secondary force is applied. Motion of this nature is provided in three degrees of freedom, two translational and one rotational. The facility thus
Figure 6: The 2 m by 3 m granite table provides a smooth and level, frictionless surface to support the air cushion platforms

provides a natural environment for the simulation of in-plane orbital manoeuvres. Furthermore, the compact scale of the air cushion platforms allows such simulations to include co-orbital manoeuvres and motion. Motion capture provided by Microsoft Kinect sensors provide feedback that can be used for both simulation of natural motion or interpretation as a navigation aid, such as GPS.

3.2 Air cushion platforms

The air cushion platforms are self-contained devices, carrying their own air supply and actuation systems. Each platform is comprised of three porous “pucks”, ceramic discs capable of providing a uniform cushion of air across their entire surface area, a gas cylinder, storing compressed nitrogen gas at a pressure of 12.4 MPa, pressure regulation to provide the 0.41 MPa air supply required by the porous pucks, and flow regulation. Each platform supports a cold gas thruster system to provide actuation in each of the three degrees of motion and a wireless micro-controller to receive and execute actuation commands.

Two concepts have been tested in the implementation of the air cushion platforms. For longer-duration flights, the larger platform, shown on the left of Fig. 6b, provides a versatile base to support complete satellite simulators or payloads. The compressed nitrogen supply is capable of supporting the air cushion for approximately 20 minutes and loads of up to 60 kg. The smaller platform, shown on the right of Fig. 6b, aims to closely replicate the mass, volume and inertial properties of a 3-unit CubeSat. As such, it is only capable of supporting loads of up to approximately 24 kg and the maximum time-of-flight is limited to between 4 and 5 minutes.

Not shown in the Figure are the cold gas thrusters used to actuate the respective platforms. The system is comprised of eight solenoid electrovalves, aligned to allow acceleration and deceleration in the two translation directions of motion without the need to reorient the spacecraft. Rotational control is enabled by mounting the thrusters in
pairs, allowing the firing of diagonally opposite pairs to increase or decrease the angular rate or rotation of the platform. The thrusters are supplied by the same gas supply as the pucks and operate at an identical pressure, allowing each air jet to produce approximately 75 mN of thrust. While this is somewhat higher than the nominal thrust expected from the µCPS, the electro-valves can be operated in a pulsed mode of up to approximately 100 Hz to reduce the net thrust.

4 Position and pose estimation using spheroid reconstruction

4.1 Image capture and processing

The VIP differentiates itself from other imaging payloads by the passive estimation of relative position and pose of target objects of known dimensions located within the camera field of view. The position and pose estimation method utilises the spheroid reconstruction algorithm to determine the location and orientation of a spheroid in 3-dimensional space using a single, monoscopic image. The projection of the spheroid onto a 2-dimensional image plane forms an ellipse which can be parameterised in terms of the semi-axes, rotation and position on the image plane. With knowledge of the imager optical parameters the algorithm provides a complimentary pair of unique spheroid solutions, reconstructed in 3D space.

The SR algorithm has been analytically proven to provide only two spheroid solutions for any given ellipse [6], where synthetic images have demonstrated the method in practice with low error. However, synthetic images provide a “perfect” target that does not necessarily represent real-world contrast, lighting and resolution constraints inherent to physical camera systems that will potentially affect the algorithm accuracy. The laboratory implementation of the VIP, therefore, uses SR to estimate the relative position and pose of a target spheroid of known proportions, with images taken using the sphere lens camera in Fig. 2. Test target spheroids have been manufactured using a fast prototyping process, thus generalising the experiments to enable the analysis of the algorithm alone.

The initial stage after capture of an image is to identify pixels which represent the boundary of the spheroid in the frame, thus forming the projection of the ellipse. The edge detection method is a simple identification of a threshold value based on the average pixel intensity from the luminosity weighted conversion equation. After flattening the input image to a grey-scale intensity map, e.g. that shown in Fig. 7a, a threshold representing the boundary of the ellipse with the background is selected. The threshold is set at the sum of the mean and standard deviation values of all pixels in the image, with the assumption that every pixel intensity greater than this value represents an element of the spheroid region in the image. The output is a binary image such as that shown in Fig. 7b, with a single white space representing the spheroid area on the image plane.

In this example, edge coordinates are extracted from the transition points between black and white in the binary image. The centroid coordinates are estimated by aver-
aging the minimum and maximum and points. Using the centroid coordinates, $Y_c$ and $Z_c$, the range and angle to each edge point is calculated. Examination of these data for maximum and minimum range values provides estimates for the ellipse semi-major and semi-minor lengths, $a$ and $b$, and the associated angles provide the final ellipse parameter, the rotation, $\omega$. Figure 7c shows a plot of range-angle data for the image. The semi-major axis length is given by the maximum value (315.2 px), indicated by the red line and the semi-minor axis by the minimum value (92.0 px), located at the green line. In this example, it is clear there is no apparent ellipse rotation. Indeed, the rotation value at the maximum range is found at 1.54 radians, giving $\omega = 88.0^\circ$, and the minimum at 3.14 radians ($\omega = 0.0^\circ$). An ellipse is drawn using the parameter estimates, overlaid with the edge data, in Fig. 7a.

![Image of spheroid projection, binary image, range-angle data, and ellipse projection](image_url)

**Figure 7**: Processing of a spheroid image to estimate the projected ellipse parameters

### 4.2 Algorithm accuracy

Using the estimated ellipse parameters, the spheroid reconstruction algorithm outputs position and pose vectors, and respectively, for both possible solutions. The position vector, $q$, denotes the spheroid centroid point relative to the origin of the camera plane. The pose vector, $p$, points from the spheroid frame origin in the direction of the semi-major axis and is a function of the rotations in the spheroid body frame,
\begin{equation}
\begin{bmatrix}
q_1 \\
q_2 \\
q_3 \\
\end{bmatrix}, \quad 
\begin{bmatrix}
p_1 \\
p_2 \\
p_3 \\
\end{bmatrix} = 
\begin{bmatrix}
\cos \theta \cos \phi \\
-\sin \theta \cos \phi \\
\sin \phi \\
\end{bmatrix}
\end{equation}

The accuracy of the system can be estimated using the measured ellipse parameters and quantified against an equivalent ellipse determined by the spheroid target ground truth, i.e. the known values of the spheroid parameters and the measured position and pose. The spheroid shown in Fig. 7a has a semi-major axis $A = 10$ cm and semi-minor axis $B = 2.5$ cm. Its position and pose vectors are, therefore,

\begin{equation}
\begin{bmatrix}
q_1 \\
q_2 \\
q_3 \\
\end{bmatrix} = 
\begin{bmatrix}
22.0 \\
-0.5 \\
1.0 \\
\end{bmatrix}, \quad 
\begin{bmatrix}
p_1 \\
p_2 \\
p_3 \\
\end{bmatrix} = 
\begin{bmatrix}
0.0 \\
0.0 \\
1.0 \\
\end{bmatrix}
\end{equation}

Using the truth vectors a truth ellipse can be defined. Table 2 summarises the truth ellipse parameters, the estimates extracted from the image data and the pixel error.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ellipse estimate</th>
<th>Truth ellipse</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-major half-length (pixels)</td>
<td>323.6</td>
<td>323.6</td>
<td>0.0%</td>
</tr>
<tr>
<td>Semi-minor half-length (pixels)</td>
<td>88.4</td>
<td>88.4</td>
<td>0.0%</td>
</tr>
<tr>
<td>Centroid x (pixels)</td>
<td>608.5</td>
<td>604.1</td>
<td>0.7%</td>
</tr>
<tr>
<td>Centroid y (pixels)</td>
<td>490.5</td>
<td>494.1</td>
<td>0.7%</td>
</tr>
<tr>
<td>Rotation (degrees)</td>
<td>-2.6</td>
<td>0.0</td>
<td>-2.6</td>
</tr>
</tbody>
</table>

Any given ellipse can fit one of two spheroid reconstructions, the VIP will include a filtering routine to identify the correct solution by analysing the relative error between multiple frames. The two solutions from the example ellipse parameters in Tab. 2 are processed using the SR algorithm to the provide position and pose vectors shown in Tab. 3, summarising the position and pose estimates and error from those of the truth spheroid. The incorrect solution is clear in this example as the angular error in Solution 1 is almost $180^\circ$. The error in Solution 2 is not insignificant, however, and arises from limitations in the methods used to measure the target truth parameters.

<table>
<thead>
<tr>
<th>Spheroid solution</th>
<th>Solution 1</th>
<th>Solution 1</th>
<th>Ground truth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position ($q$)</td>
<td>22.0342</td>
<td>22.0459</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>-0.5983</td>
<td>-0.6152</td>
<td>-0.5</td>
</tr>
<tr>
<td></td>
<td>-0.9231</td>
<td>-0.5617</td>
<td>1.0</td>
</tr>
<tr>
<td>Positional error</td>
<td>0.1294</td>
<td>0.4555</td>
<td>–</td>
</tr>
<tr>
<td>Pose ($p$)</td>
<td>0.0103</td>
<td>0.0749</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>0.0454</td>
<td>-0.0477</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>-0.9989</td>
<td>0.9960</td>
<td>1.0</td>
</tr>
<tr>
<td>Angular error (degrees)</td>
<td>177.33</td>
<td>5.10</td>
<td>–</td>
</tr>
</tbody>
</table>
4.3 Computational burden

The initial development of the test environment was performed on a desktop PC, where processor speed was typically over 3.5 GHz across multiple cores and equipped with several gigabytes of RAM. However, the VIP will be built using an embedded system based on a Virtex-5 FPGA, offering a much lower processing speed of approximately 75 MHz on a single-core LEON-3 soft-processor and only 512 GB of shared RAM. To study the performance of this system, the position and pose estimation processing stages were compiled for execution on the SPARC architecture upon which the LEON processor family is based.

The position and pose estimation performance was measured in terms of the time of execution of the processing stages required on the flight platform. These include extraction of the spheroid edges from an intensity map and output of an array of edge pixel coordinates; estimation of the ellipse parameters fitting these edge data; computation of the spheroid reconstruction solutions matching the ellipse and camera parameters. Three sample images were selected to demonstrate the execution of the spheroid reconstruction process on the hardware testbed. The images were selected to demonstrate the change in performance as resolution is increased. As such, they include a low resolution synthetic image from [7], (Synthetic Image, 800 pixels wide by 600 pixels high, Fig. 8a), the higher resolution test image shown above (Test Image 1, 1280 by 1024 pixels, Fig. 8b) and a very high resolution image (Test Image 2, 2048 by 1536 pixels, Fig. 8c).

![Image series](image-series.png)

(a) Synthetic Image  
(b) Test Image 1  
(c) Test Image 2

Figure 8: Test image series used to study computational burden of the SR algorithm

Each stage of computation of the spheroid reconstruction was run three times and the execution times collected and averaged. The results from each stage are presented in Tab. 4 and illustrate a clear and expected trend of increased processing time in the initial stages, where pixel by pixel processing is currently required. Ellipse estimation uses edge coordinate data, a subset of the full image data. Therefore, the execution time is much lower than the initial stages and proportional to the image resolution. The final stage executes only the SR algorithm, using identical data sets regardless of the input image properties. The results indicate the greatest bottleneck in the execution time lies in the initial processing stages, a limitation which can be addressed by reconfiguring the FPGA to add further processing cores. Furthermore, the objective sought from using the SR algorithm was to use a reduced order model of a target to minimise computational burden in estimating a target position and pose. The observed execution time of the algorithm is significantly lower than the initial stages, at approximately
Table 4: Mean processing time in seconds to estimate the position and pose of a target object

<table>
<thead>
<tr>
<th>Processing stage</th>
<th>Synthetic Image</th>
<th>Test Image 1</th>
<th>Test Image 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge detection</td>
<td>32.03</td>
<td>93.04</td>
<td>225.35</td>
</tr>
<tr>
<td>Ellipse estimation</td>
<td>1.50</td>
<td>3.76</td>
<td>10.07</td>
</tr>
<tr>
<td>Spheroid reconstruction</td>
<td>0.10</td>
<td>0.10</td>
<td>0.11</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>33.64</strong></td>
<td><strong>96.90</strong></td>
<td><strong>235.53</strong></td>
</tr>
</tbody>
</table>

0.10 s, demonstrating the success in meeting this aim.

5 Conclusions

The InspectorSat mission aims to demonstrate the use of compact imaging and actuation hardware suitable for use on a small spacecraft, nominally of a mass between 5 and 50 kg. The VIP and PRECISE μCPS make a logical pairing to enable such a small spacecraft to perform a useful campaign of inspection manoeuvres. Limitations currently found in this approach are in the total \( \Delta v \) the \( \mu \)CPS can provide and, subsequently, the total on-time of the thruster. Examination of the natural drift characteristics between the two spacecraft after separation from the launch vehicle suggests that the relative angle and \( \Delta v \) must be matched to minimise the \( \Delta v \) cost of an extensive rendezvous manoeuvre. This leads to the conclusion that the spacecraft will launch and separate as a single unit, before orbit rephasing and inspection manoeuvres are performed. A frictionless testbed providing microgravity-like conditions in three degrees of freedom will allow such manoeuvres to be tested in the laboratory.

Commanding of the spacecraft manoeuvres will also rely on the visual inspection payload. This system will utilise a new relative motion estimation method, requiring the development of the respective algorithms from a conceptual stage through to demonstration under “real-world” conditions. Spheroid reconstruction is of particular importance to the InspectorSat mission as it allows the passive estimation of relative position and pose. Using nominal spheroid targets, of known size, position and pose parameters, and a sphere lens camera, the spheroid reconstruction algorithm has been demonstrated to provide accurate results with minimal computational effort under laboratory conditions. Sensing of a target is, therefore, reduced to a simple optical imaging sensor and a coordinating soft-processor.

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7 References


