POLITECNICO DI MILANO
School of Industrial and Information Engineering
Department of Aerospace Science and Technology

Executive Summary Of The Thesis

Multispectral Vision-Based Relative Navigation To Enhance Space Proximity Operations

Master Of Science In Space Engineering

Author: Massimiliano Bussolino
Advisor: Prof. Michèle Lavagna
Co-advisors: Gaia Letizia Civardi, Margherita Piccinin
Academic year: 2021/2022

1 Introduction

With the ever-increasing number of uncooperative artificial objects in orbital regions such as LEO and GEO and the risk associated with their presence, the necessity for mitigation strategies such as Active Debris Removal (ADR) has become even more urgent in recent years. Because of the fast dynamics when performing close proximity operations about an uncooperative target, ADR missions face very challenging conditions for the GNC subsystem. To avoid undesired collisions, it is paramount to estimate onboard the relative position and attitude with respect to the target.

Dealing with inherently non-cooperative targets, ADR missions shall be equipped with vision-based sensors able to provide a high-frequency relative pose estimation to avoid undesired collisions with the target. In this context, monocular cameras in the visible spectrum represent a very mass and power-effective solution [5], although presenting important operational limitations. Their strong dependency on the illumination conditions of the target limits their range of applications in case of low illumination conditions or eclipse. A promising solution to enhance the reliability of monocular cameras is to use collaboratively two sensors working in the visible and thermal spectrum [6]. Thermal sensors measure the thermal radiance of the target, which is influenced by the illumination coming from the Sun, but it is not subject to shadowing or reflections. However, the overall quality of thermal sensors is lower because the produced images are subject to a higher blur and a lower resolution.

In the thesis, a novel visual navigation filter is proposed to perform relative navigation about a known uncooperative target using only a visible and a thermal camera. The algorithm exploits the features detected on the images and a wireframe model of the target to perform model-based estimation. The multispectral data are fused at feature level with a tightly-coupled approach, using a Multiplicative Extended Kalman Filter for sensor fusion and pose refinement.

The thesis aims at providing a deeper understanding of the contribution of multispectral imaging to the relative navigation problem. Specifically, it investigates how sensor fusion expands the range of applicability of monocular visible navigation by combining data from multiple spectra to improve robustness in challenging environments. Moreover, the effectiveness of thermal navigation as a standalone solution is presented, studying the possibility of substituting the visible counterpart when its output is compromised.

2 Visual navigation filter

The visual navigation filter proposed in the thesis work consists of a Multiplicative Extended Kalman Filter (MEKF), which estimates the target's relative position, velocity, attitude, and angular rates with respect to the chaser spacecraft. The innovative aspect of the filter is given by its measurement model, which takes the point features extracted from the images as measurements and the projection of the target model landmarks on the image plane as pseudo-measurements. The point features are extracted from the visible and thermal images by a dedicated image processing routine, which performs pre-processing and tracks the key points along the sequence of images.

To reduce the effect of sensor modelling errors and of the variation of the spectra performances in different illumination conditions, the measurement noise covariance matrix is estimated online with a residual-based method. The present section presents the most relevant aspects of the proposed navigation pipeline.

2.1 Filter's dynamical model

The filter estimates the target's relative translational and rotational motion of the target about the chaser. In particular, the filter states are comprised of the position and velocity of the target in the chaser LVLH frame, a three-element attitude error, and the angular velocities of the target body frame expressed in the chaser body frame.

For the relative translational motion, the Clohessy–Wiltshire (CW) model of motion [2] was selected for the filter's dynamic. The selection of such a simplified model is justified by the short measurements update intervals of proximity operations and by the quasi-circular orbit of space debris in LEO orbits. The CW equations of relative motion are described in Equation (1).

$$\begin{aligned} \ddot{x} - 2n\dot{y} - 3n^2 x &= 0 \\ \ddot{y} + 2n\dot{x} &= 0 \\ \ddot{z} + n^2 z &= 0 \end{aligned} \tag{1}$$

x, y, and z are the components of the target position in the chaser LVLH frame, while n is the chaser mean motion. The State Transition Matrix (STM) of the model of motion computed analytically.

Since the angular accelerations of the target can not be determined in an uncooperative scenario, the model used for attitude dynamics assumes constant small relative angular velocities, as proposed in [7]. The three-element attitude error (a_p) propagated by the filter is expressed in Modified Rodriguez Parameters (MRP). The differential equations for attitude propagation are reported in Equation (2).

$$\begin{aligned} a_p &= -\frac{1}{2}[\boldsymbol{\omega}\times]\mathbf{a}_p + \boldsymbol{\omega} \\ \dot{\boldsymbol{\omega}} &= \mathbf{0} \end{aligned} \tag{2}$$

In this case, the STM can not be computed analytically and requires numerical computation.

2.2 Measurement model

The measurements used by the filter to correct the pose estimate are the key points of the target extracted from the visible and thermal images. Therefore, to compute the pseudo-measurements of the states, it is necessary to project the 3D model landmarks of the target onto the image plane, expressing this transformation as a function of the relative position and attitude of the

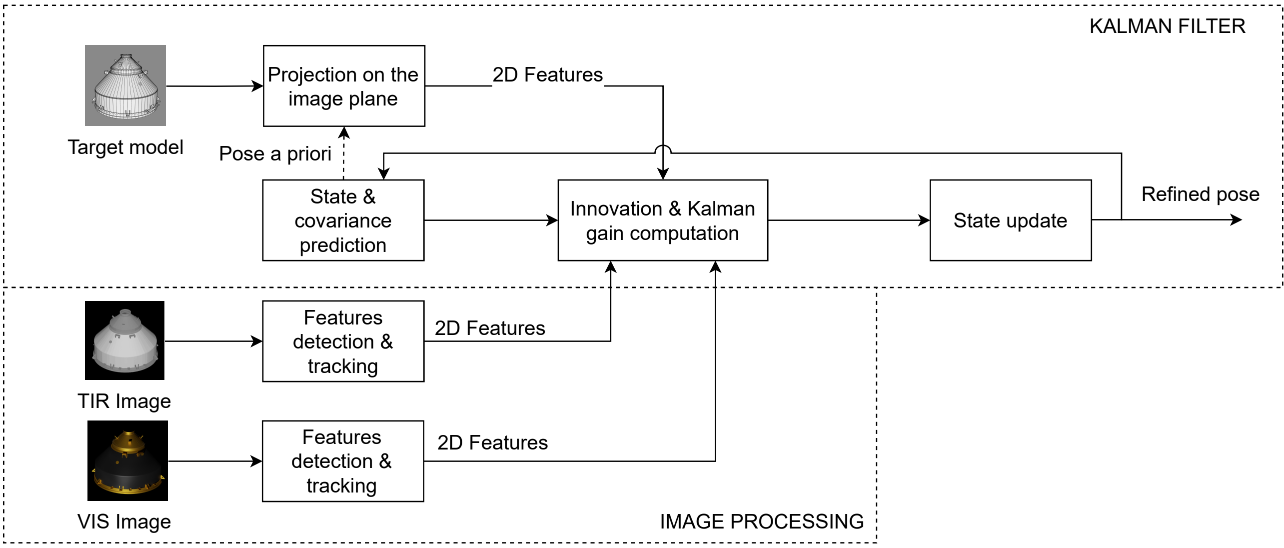

Figure 1: Visual navigation chain block diagram

target with respect to the chaser.
This results in the measurement function to be defined as the concatenation of a geometrical transformation of the landmark position expressed in the target body frame to the camera reference frame, its projection on the image plane according to the pinhole camera model, and finally, the transformation from homogeneous to Cartesian coordinates.
As the resulting measurement function is nonlinear, the Jacobian is computed analytically. Since the relative velocity and angular rates do not provide any information about the features' position at a given time, they do not appear in the measurement function and are null in the Jacobian matrix.

2.3 Image Processing

The scope of the image processing pipeline is to provide the image features location and their relation to the wire-frame model points. The position of the features on the image acquired at time t_k is the output of the Lucas Kanade tracker [4], using the obtained results at time t_{k-1} as the initial condition. As the features are tracked along different images, the information about their correlation with the model landmarks is maintained, avoiding the need for a matching process at each filter step. To remove spurious associations or errors that happened in the tracking step, a RANSAC [3] routine is added to remove eventual outliers.
The issue related to the feature tracking process is that the number of features decreases over time, requiring a re-initialization step when they drop under a defined threshold. The re-initialization step consists of detecting new key points in the image, then matching them with the model landmarks using a RANSAC-based approach developed within the context of the thesis.
The Image Processing pipeline is identical for the visible and thermal images, except for applying an histogram equalization routine to enhance the contrast in thermal images.

2.4 Measurement noise covariance adaptation

To reduce the effect of sensor modeling errors and to account for the change in performance of VIS and TIR cameras in different environmental conditions, a residual-based adaptive estimation of the measurement noise covariance matrix $\mathbf{R}$ proposed in [1] is implemented. The relation used to compute the estimate of the measurement noise covariance matrix at each step is reported in Equation (3):

$$\hat{\mathbf{R}}_k = \alpha \mathbf{R}_{k-1} + (1-\alpha)(\boldsymbol{\varepsilon}_k \boldsymbol{\varepsilon}_k^T + \mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_k^T) \quad (3)$$

where $\boldsymbol{\varepsilon}_k$ is the residual, $\mathbf{H}_k$ is the Jacobian of the measurement function at t_k, and P_k^- is the states covariance matrix prior to the correction step. α is a forgetting factor to limit fluctuation in the estimation due to noise in the residual.

3 Synthetic images

The proposed visual navigation pipeline is tested on synthetic images of the European space debris VESPA. The rendering tool used to generate the images was not developed within the thesis work; instead, it is used the one developed in [6] adapted for space debris applications. Both the visible and thermal rendering is based on the Blender software. For the TIR images, the rendering tool works under the assumption of a uniform temperature field of the target, making the target's appearance depending only on its overall temperature, the emissivity of the different surfaces, and the view factor. An example of a thermal and a visible image of VESPA is reported in Figure 2.

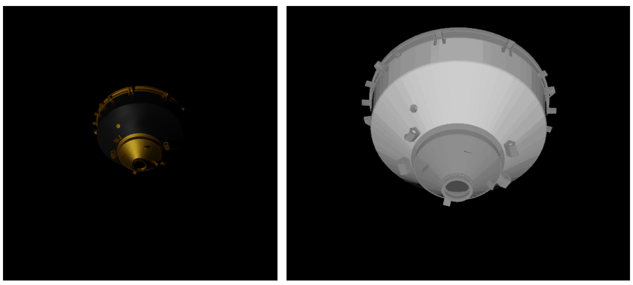

Figure 2: Example of a synthetic visible and thermal image

From Figure 2 it can noted that the target presents an axial symmetry because of its conic shape, which represent a critical condition for 6 degrees of freedom relative navigation.
The validation framework used to test the navigation filter presents a solid basis, although there is an overall lack of realism in the images due to the very simplified thermal model and the lack of noise in the images.

4 Results

The visual navigation pipeline proposed has been tested in different conditions to critically assess its advantages and limitations. The most relevant results are presented hereafter.

4.1 Good illumination conditions

The filter is initially validated in a situation where the visible and thermal sensors provide vivid images of the target. In this situation, the filter is tested both by fusing the multispectral information and using the two sensors independently.
In this case, it is observed that the multispectral application successfully estimates the relative pose along the simulation. It is uncovered that fusing the information from the visible and thermal cameras provides better performances than for the cameras to work independently. In Figure 3, the true and estimated trajectory of the chaser in the target body frame is reported, showing how the estimated path is bounded on the reference trajectory used to generate the synthetic images.

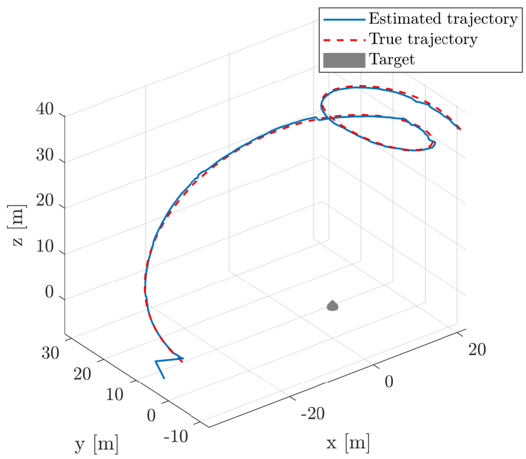

Figure 3: Ground truth and estimated trajectory in the target body frame

4.2 Low illumination conditions

To evaluate the pipeline's robustness to harsh illumination conditions, the visual navigation pipeline is tested on images rendered with an elevated chaser-target-Sun angle. In this condition, the navigation chain cannot produce meaningful results. In particular, the partial visibility of VESPA in visible images degrades the performances of the Image Processing pipeline, thus compromising the overall pose estimation process. The possibility of using the thermal images only in low illumination conditions is considered to tackle this issue. TIR-only navigation is investigated in a sunlit (hot) and an eclipse (cold) case of the target, with the latter presenting a degraded image as VESPA's temperature is assumed close to the lower bound of the sensor's temperature range.
It is assessed that the TIR-only application of the navigation filter provides more stable results than the multispectral one in low illumination conditions. However, a drift of the attitude error is observed in both the hot and cold cases. The source of the error is identified in the combination of the lower performance of the IP associated with the thermal images and the symmetry of the target, which requires robust tracking of specific elements such as bolts and flanges. This result is highlighted in Figure 4, where the Euler angles between the true and estimated target body frame for the eclipse case are reported using the rotation sequence Z (θ), Y (ϕ), X (ψ).

The obtained results for the sunlit and eclipse case indicate that the proposed navigation filter can not provide reliable standalone pose estimation based on the thermal spectrum only. However, being the instability associated with the symmetry of the target, it is possible that with a more distinguishable target shape, thermal navigation might indeed provide robust performances.

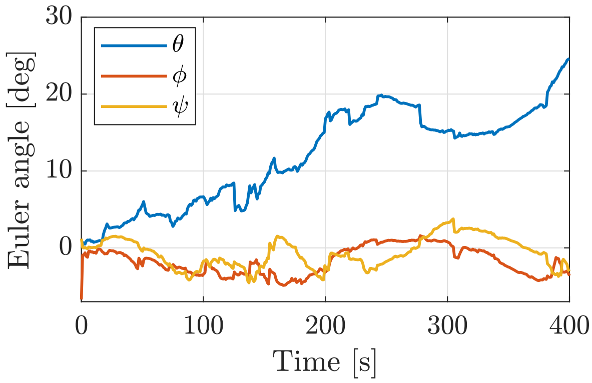

Figure 4: Euler angles between the true and estimated target body frame

5 Conclusion

This thesis presents a study on relative navigation around a known uncooperative target using multispectral imaging sensors. A novel visual navigation pipeline has been developed to exploit images acquired by both a visible and a thermal monocular camera, either by fusing the information or using a single spectrum. The proposed navigation solution has been critically tested on synthetic images of the VESPA debris to evaluate its performance and limitations.
From the obtained results, it is assessed that multispectral data fusion does not directly increase the applicability of monocular navigation for visible cameras. Instead, its contribution is limited to enhancing the accuracy of pose estimation. In cases where the target is not fully visible, it proved more convenient to discard the visible image entirely and use only the output from the thermal sensor. Although TIR-only navigation is not yet mature enough to provide consistently accurate tracking of the chaser-target relative position and attitude, the obtained results are promising and suggest that further research in this area could yield significant improvements.
The validity of the current analysis is limited by the realism of the testing framework. For further investigation of the work it is suggested an improvement of the validation method adding noise

to the images and using a more refined thermal model for the target.

References

[1] Shahrokh Akhlaghi, Ning Zhou, and Zhenyu Huang. "Adaptive adjustment of noise covariance in Kalman filter for dynamic state estimation". In: *2017 IEEE power & energy society general meeting*. IEEE. 2017, pp. 1–5.

[2] WH Clohessy and RS Wiltshire. "Terminal guidance system for satellite rendezvous". In: *Journal of the Aerospace Sciences* 27.9 (1960), pp. 653–658.

[3] Martin A Fischler and Robert C Bolles. "Random sample consensus: a paradigm for model fitting with applications to image analysis and automated cartography". In: *Communications of the ACM* 24.6 (1981), pp. 381–395.

[4] Bruce D Lucas and Takeo Kanade. "An iterative image registration technique with an application to stereo vision". In: *IJCAI'81: 7th international joint conference on Artificial intelligence*. Vol. 2. 1981, pp. 674–679.

[5] Vincenzo Pesce et al. "Autonomous relative navigation around uncooperative spacecraft based on a single camera". In: *Aerospace Science and Technology* 84 (2019), pp. 1070–1080.

[6] Margherita Piccinin. "Spacecraft relative navigation with electro-optical sensors around uncooperative targets". PhD thesis. 2023.

[7] Sumant Sharma and Simone D'Amico. "Reduced-dynamics pose estimation for non-cooperative spacecraft rendezvous using monocular vision". In: *38th AAS Guidance and Control Conference, Breckenridge, Colorado*. Vol. 2. 2017.