Modular Vision-Based Navigation System for Autonomous Rendezvous and Docking in Geostationary Transfer Orbits

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Abstract Nowadays, the growing demand for autonomous in orbit servicing (IOS) missions, such as inspection, refueling, and docking, has made vision based autonomous navigation a critical element of Guidance, Navigation and Control (GNC) systems. In particular, rendezvous operations require robust solutions across a wide range of conditions, from the initial detection to the final docking phase.

This work presents a modular vision-based navigation system with a dual-mode architecture tailored for fully autonomous rendezvous and docking. Specifically, in the far range phase, a dynamic mode switching logic evaluates the alignment between the target geometric center and its center of mass. When alignment is detected, Line of Sight (LoS) only measurements are employed. Otherwise, a pixel based range estimation is added. This adaptive measurement strategy feeds an Extended Kalman Filter (EKF), ensuring robust relative state estimation across varying distances and visual conditions.

Within 15 meters, the system transitions to close range navigation using ArUco markers on the target docking face. Marker detections enable 6-DoF pose estimation via a Perspective-3-Point (P3P) algorithm, refined through the Unscented Quaternion Estimator (USQUE). Moreover, a camera switching mechanism ensures continuous marker visibility during final approach.

Validated within the GEORyder project, this system offers adaptive far range estimation, high precision close range tracking without external aids, and a scalable architecture for future IOS applications.

Introduction

The increasing demand for autonomous in orbit servicing (IOS) operations, which include inspection, refueling and docking, has made vision-based navigation crucial for spacecraft guidance, navigation and control (GNC) systems. Particularly challenging are the rendezvous operations, where the relative navigation must be robust over a wide range of conditions, from initial detection at long distances to precise alignment for docking. In this context, the development of a flexible, reliable navigation module capable of handling such dynamic transitions is both a technological necessity and an open research problem.

To address these challenges, this work presents a modular vision-based navigation system tailored to support fully autonomous rendezvous and docking maneuvers in space. The system integrates both narrow and wide field of view (FoV) cameras and is structured to support two operating modes, far range and close range navigation, defined by the relative distance between the chaser and the target spacecraft. This dual mode approach ensures both robustness and resilience during early detection and tracking, while delivering the precision required for the final approach and docking.

Far range navigation strategy

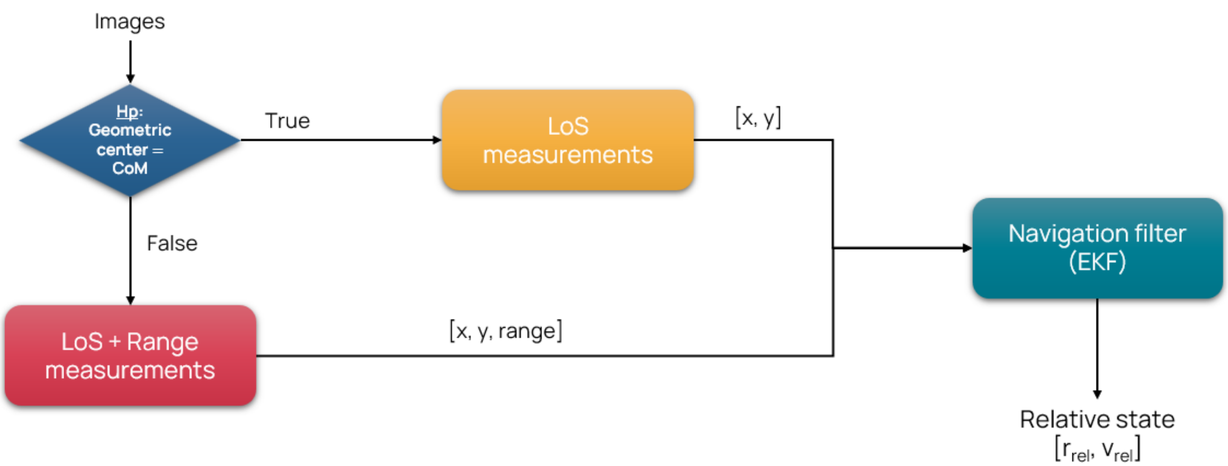

Figure 1: Far range navigation strategy

In the far range navigation phase, as demonstrated in Figure 1, the system primarily relies on Line-of-Sight (LoS) measurements extracted from the narrow angle monocular camera [1]. While this approach is effective under ideal conditions, LoS data can become unreliable due to factors such as target orientation, perspective distortion, or partial occlusion. Thus, a dynamic mode switching logic is introduced [2]. Specifically, this mechanism assesses if the target projected geometric center aligns with its image-based center of mass (CoM). When the target appears smaller than a pixel, suggesting a distant, symmetric, and undistorted projection, the two centers are considered to be aligned, therefore LoS measurements alone are deemed sufficient for accurate navigation. Conversely, if a misalignment is detected, the system transitions to a combined LoS + Range mode, incorporating a range estimate based on the apparent pixel size of the target in the image, enhancing observability and robustness.

The measurements will be then processed by an Extended Kalman Filter (EKF) designed to estimate the chaser relative position and velocity with respect to the target. At each time step, the EKF propagates the relative state through a nonlinear dynamics model, which accounts also for impulsive maneuvers via the Gates model [3], capturing uncertainties related to actuator resolution and pointing accuracy. During each update, the filter dynamically adapts: in LoS-only mode it uses centroid data, while in LoS + Range mode it integrates both centroid and estimated distance. This flexibility allows the system to maintain estimation quality across varying visual conditions and mission phases.

Close range navigation

As the chaser approaches within 15 meters of the target, the systems transitions to the close range navigation phase, where a fundamental shift in measurements strategy occurs. At this stage, the navigation module leverages a set of fiducial ArUco markers [4] mounted on the docking face of the target. This structured marker configuration enables full 6-degrees-of-freedom (6-DoF) pose estimation, critical for precise docking operations.

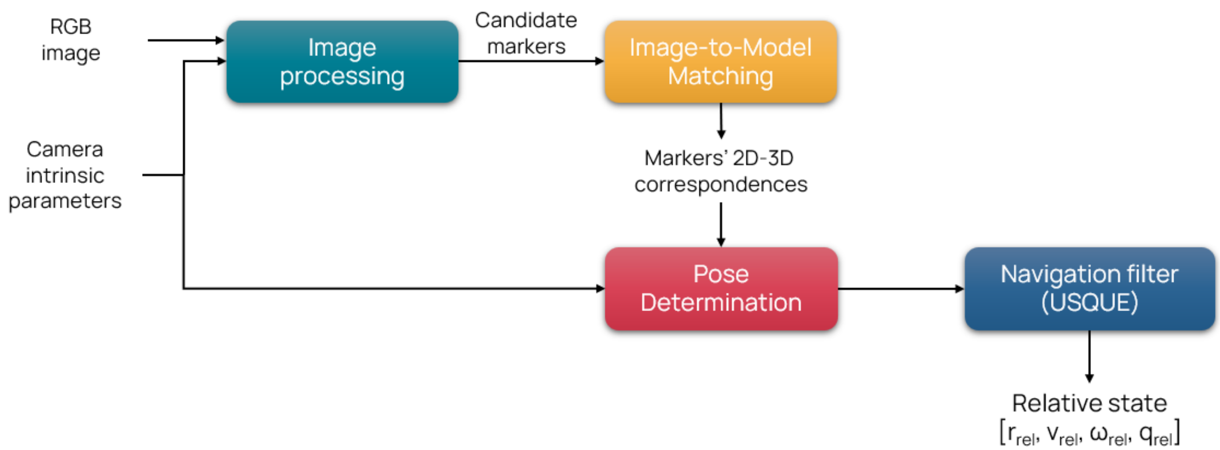

Figure 2: Close range navigation strategy

The pose estimation pipeline, illustrated in Figure 2, begins with real time image acquisition and processing to detect visible markers. Each detected marker provides 2D image coordinates and a unique ID, which are later matched to their known 3D positions on the target surface using a simplified geometric model. The 2D-3D correspondences are then fed into a Perspective-3-Point (P3P) algorithm to estimate the camera pose in terms of position and orientation relative to the target Local Vertical Local Horizontal (LVLH) frame.

The resulting pose estimates are finally passed to an Unscented Kalman Filter (UKF), chosen for the ability to handle the nonlinear nature of the 6-DoF relative dynamics without requiring explicit linearization. The UKF estimates the full relative state, including position, velocity, angular velocity, and attitude. However, standard UKF implementations struggle with maintaining the unit norm constraint of quaternions. Thus, to address this, the Unscented Quaternion Estimator (USQUE) [5] is preferred instead, which avoids direct quaternion estimation, but rather it estimates the orientation error using Modified Rodrigues Parameters (MRP). In particular, these represent small rotations safely in Euclidean space, allowing the filter to apply corrections properly and then reconstruct a valid quaternion, preserving the unit norm automatically and ensuring stability within the filter.

Another noteworthy feature of the system is the sensor switching mechanism. For distances beyond 2.5 meters, the narrow angle camera continues to support marker detection. However, as the chaser enters the terminal guidance zone, the system has the need to activate the wide angle camera to maintain visibility of all necessary markers, avoiding loss of tracking due to field-of-view limitations and guaranteeing continuity in pose estimation.

Conclusions

This architecture brings three main innovations to the field of spacecraft navigation. First, the dynamic switching mechanism in the far range EKF represents a novel and effective strategy to maintain estimation observability without overcomplicating the measurement model. Second, the transition to high fidelity marker-based pose estimation in close range ensures high accuracy, supporting autonomous docking operations without the need to rely on external aids. Finally, the combination of two specialized Kalman filters, an EKF for far range estimation and USQUE for 6-DoF close range estimation, yields a cohesive framework adaptable to a wide variety of IOS mission scenarios.

In summary, this work contributes to the current state of the art by providing a complete vision-based navigation pipeline for full range rendezvous, by introducing adaptive measurement strategies based on geometric reasoning, and by demonstrating a scalable implementation ready for operational deployment. The flexibility and modularity of the architecture make it well suited not only for servicing missions, but also for orbital debris removal, formation flying, and space logistics in the emerging commercial space ecosystem.

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