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Vision-based relative navigation system for autonomous proximity orbital operations

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Abstract. The paper presents the research project of the author, focused on developing, implementing and testing a vision based relative navigation system for spacecraft. A temporal organization of the project is presented, with tasks assigned to each year of the PhD programme, while at the same time two main technical stages, “final” and “far” rendezvous are introduced together with their scientific objectives. Being an experimental work, the envisioned implementation of the system on COTS computing platforms is introduced as well as the experiments planned to gather real imagery to validate the algorithms. Finally, possible fields of application of the project are discussed.

Introduction

Among several kind of fields, space is becoming one of the highest growing businesses in the world. With private companies paving the way, it is estimated that the number of satellites will increase of 2500 units every year for the next 10 years, with constellation making up the 83% of this number [1]. Indeed, several commercial services which were typically bounded to terrestrial infrastructure, are rapidly shifting to a space-based architecture (e.g. internet).

Due to relaying more and more on such space services, it becomes of the uttermost importance to ensure the continuity of operations of this plethora of objects operating on orbit.

Providing spacecraft with autonomous capabilities in terms of Guidance, Navigation and Control (GNC) has proven to bring many advantages [2]: the number of objects on orbit is increasing, hence their tracking for safety purposes is becoming difficult to perform if only ground structures are involved. By providing spacecraft with autonomous capabilities, the tracing load on the aforementioned structures can be relaxed while contextually ensuring the safety. Moreover, when distance between spacecraft is reduced, the latency of ground structures and human operator to close the GNC loop might be excessive and a collision could happen [3]. Developing and implementing autonomous capabilities could also pave the way to more complex space missions, either on close celestial bodies like the Moon and Mars, but also to implement On Orbit Servicing.

With this premises, the objective of the author’s research project can be outlined: developing, testing and implementing a vision-based autonomous navigation system to perform a rendezvous with an uncooperative unprepared satellite on Commercial Off the Shelf computing platforms. Differently from other past projects, the absence of a detailed 3D model of the targeted spacecraft will be assumed.

Project outline

The project is divided in several stages, according to the three years of the PhD program. The first year will be dedicated to perform an extensive literature review to understand the actual state-of-the-art on the matter and to start design the prototypical detection and pose estimation algorithm. At the moment, the project is in this phase. The second year is dedicated to consolidate the

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algorithm designed as well as to implement it on the target hardware/software platform, identified between the end of the first year and the beginning of the second. As it will be described in the following sections, real imagery gathered with sounding balloons will be utilized to validate the algorithm. Finally, during the last year the system will be integrated and an extensive campaign of hardware in the loop testing will be conducted to validate the results obtained. The last 5 months of the same year will be reserved for the writing of the final thesis.

Methodologies

Shifting to technical point of view, the project is divided in two parts: the first one involves developing a method to estimate the relative navigation parameters of a target (relative position and attitude) when the chaser is at a distance of less than 300 meters. This phase will be called "final rendezvous". The second stage instead is focused on estimate the same parameters but from a far higher distance, ideally of kilometres. This second phase will be called "far rendezvous". The difference between the two stages lies on the metrics that need to be estimated and the accuracy requested, hence the methods to be applied. Nevertheless, at the end of the project, the final system shall be capable of implementing both methodologies on a computing platform comparable to those already flying in the class of minisatellites.

The rendezvous distances are being adapted from International Rendezvous System Interoperability Standard [4].

Final rendezvous

Despite the name, this stage was chosen as the starting point for the project due to the relative larger availability of literature on the matter. The objective of this phase, as anticipated before, is to estimate the pose of a generic target using solely vision-based techniques at a distance comprised between 300 and 0 meters. By using the same standard cited before, the accuracy requirements are between 1° and 5° degrees for attitude and between 0.01 and 1 meter for range.

In the past few years, several methods to estimate the asset of an object have been investigated, either related to space or to automotive as well as to medical imaging, but objects in space presents several features that makes them difficult to analyse. On the matter, in [5] it is presented a review of the Kelvin Satellite Pose Estimation Challenge, aimed at pushing the state-of-the-art of the problem. From the results reported, two technical solutions seem applicable, if properly tuned, to our project: the separation between the localization phase and pose estimation phase of the target and the implementation of one or more Convolutional Neural Network (CNN).

Without going into the details of the CNN architectures implemented, both solutions outperformed the other methods in terms of accuracy. Nevertheless, adding another layer of computation (localizing the target and cropping consequently the frame) could increase the overall complexity of the systems. Paired with the hardware resources required for a highly performing CNN, implementing both solution on a relatively simple platform could become tough if proper measures are not taken. Such measures will be studied in the following stages of the PhD project. The aforementioned paper mentioned also another approach, detailed in [6], based on perceptual organization. Despite the method makes use of an a priori knowledge of the target, it could be a good candidate for our study due to lower computational costs if compared to CNN based approaches.

Far rendezvous

While the final part of the rendezvous process is being analysed and technical solutions explored, the initial part is not yet under intense examination for the reasons listed before. Nevertheless, considering the limits of using mostly passive sensors, some methods of identification and estimation could be adopted from the military world. In particular, an approach based on kinematic ranging [7] is deemed the best candidate for estimating the position of an object distant kilometres. This approach assumes the possibility to track the target and by performing a manoeuvre, thanks

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to a controlled variation of the angle between target and chaser, the position is triangulated with an acceptable accuracy. If observed carefully, the procedure proposed seems to imitate the estimations which can be obtained using stereo cameras.

Utilizing Stereo cameras is still considered but, due to the short distance achievable between the two sensors, it is not supposed to deliver significant results.

Implementation and planned experiments

Implementation on hardware platform

As anticipated in the introduction, the whole project aims at developing an autonomous navigation system to be implemented on a computing hardware comparable to those already flying. As a means of example, CubeSat is an appropriate candidate platform.

In simple terms, this means being able to perform the required estimation with limited computing power, if compared to that available while prototyping on a commercial laptop. The reasons to such design choice are multiple: the first one is that the power required by high performance computing platforms is not compatible with space applications, or at least not with those constrained by small solar panels and economic resources. Indeed, cost is another factor that must be taken into consideration: differently from the past, the space industry is moving to cheaper orbital platforms to widen the access to orbit and increase profits.

By implementing the system on simpler platform, within the price range of a generic Raspberry Pi 4 and/or a FPGA Intel Cyclone, hardware in the loop testing is possible, hence the validation of algorithms with greater fidelity. This requirement imposes to perform code optimization in order to deliver the desired performances within acceptable latency values. Hence the conversion of algorithms from high level programming (i.e. prototyped on Matlab) to an optimized language suitable for the real time operating system adopted (at this stage of the project is envisioned using Sel4 or ROS). Nevertheless, this could also be a chance to experiment with optimization techniques which could not be explored otherwise.

Planned experiments

Given the nature of the project, several campaigns of test are required to gather as much data as possible. Indeed, differences in performances were observed in [5] where vision systems were tasked to estimate the pose of an object both from synthetic and real images.

Considering the remote feasibility of conducting a “space test” campaign, sounding balloons were deemed proper candidates to simulate the imaging condition of open space. Indeed, these types of balloons reach an altitude of around 30-40 km, where air is mostly absent and at the same time lighting conditions are as harsh as those on higher orbits.

The flight test campaign is structured following a buildup approach with the first launch, estimated to be in mid-April, will be focused on validating the experimental set-up, schematized in figure 1. A note on the set-up is necessary: considering the difficulties on launching 2 independent balloons, being one the chaser and one the target, and acquire useful image data together with relative positions, it was decided to design a structure in which the target and the chaser are linked together. In particular, the action cameras (being the main sensor at this stage of the project) are integrated on the main structure just below the ballon and point to targets (basically cubes of predetermined dimensions) attached to a 1.5 meters beam. Targets have some freedom of movements and are provided with an asset recording device which will be used as source of truth for the pose estimation, which will be performed offline.

A similar test campaign is set to be happen at the end of May with the same set-up or with eventual modifications required after the first launch and starting from this, once the basic pose estimation algorithm is completed, a campaign with on-line pose estimation could be organized.

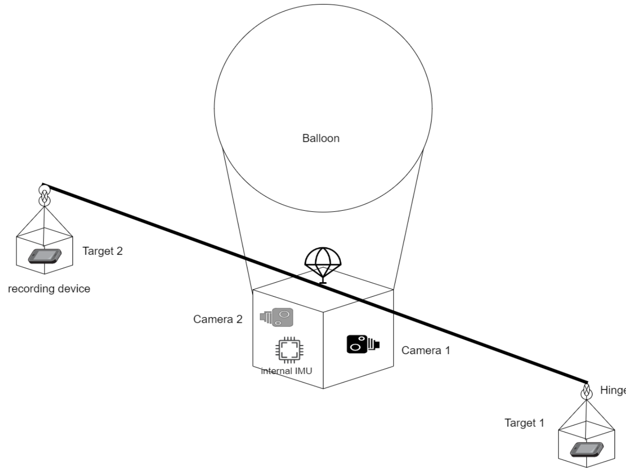

Figure 1 Sounding balloon set-up

Applications

Developing an autonomous vision-based navigation system can bring many advantages in different applications, the most obvious being On Orbit Servicing, active collision avoidance and automated rendezvous. On Orbit Servicing, enabled by automated rendezvous capabilities, could revolutionize the concept of orbital operations, both in terms of extending the useful life of precious spacecraft (similarly to what has been done with Hubble Space Telescope with the Shuttle program) but also when a controlled decommissioning of uncontrollable satellites is needed. Automating the approaching and the rendezvous phases becomes crucial when the aforementioned operations are performed away from Earth, where a human command is unpractical or at least not compatible with the latency required. On the side of long-distance operations, active collision avoidance systems could gain benefits from this project by scheduling more efficient manoeuvres thanks to a constant situation awareness of the surroundings of the interested spacecraft.

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