Visual Inspection System for Autonomous Robotic On-Orbit Satellite Servicing

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ABSTRACT

Nowadays, within the space robotics, there is a substantial interest in achieving on-orbit satellite servicing operations autonomously. On-orbit servicing (OOS) requires ability to rendezvous and dock by an unmanned spacecraft minimizing human intervention. This paper is presented like a step in this course. In RoboticsLab, we have developed the RISANAR testbed to simulate scenarios of autonomous relative navigation between satellites using computer vision. The scenario to simulate consists on the recognition and the inspection of a satellite (target) using another autonomous satellite (chaser), which approaches the target and verifies its actual state. The methodology adopts a vision system that combines object recognition, pose estimation and tracking of an uncooperative satellite. The obtained information is used for the guidance and control of the chaser relative navigation. A visual servoing technique that controls and guides the test-bed manipulator based on a camera image fulfills this dynamic task.

INTRODUCTION

There are several cases where satellites have failed to function properly in orbit. Satellite system redundancy is no longer sufficient to ensure reliability due to cost constraints. Due to this fact, some authors consider that the true commercial utilisation of space relies on two principal capabilities: advances in inexpensive re-usable transportation to reduce launch costs, and the development of remote complex manipulation for on-orbit activities [1]. Therefore, one solution is to use freeflying robotic spacecrafts which are a natural evolution from EVA (Extra Vehicular Activity). In EVA, the astronaut acts directly as manual worker for small activities while a telemanipulator operates for heavier duties. Robotic OOS would free the astronaut from repetitive tasks and fully utilise astronauts for more appropriate tasks requiring human flexibility and ingenuity. OOS tasks consist in the refuelling, repairing and orbit recovery. The technology developments should reduce the exposure of astronauts to risks using robotic systems and unmanned autonomous spacecrafts. To reach this objective a spacecraft with autonomous system of relative navigation, grasping and docking is very useful. These systems will depend on developing technologies such as vision systems that are able to detect, identify and estimate the pose of objects in some unknown space scene. A robotic chaser is expected to turn into the workhorse for such space activities in the future [1]. Thus, it is necessary to develop an autonomous system that allows performing these manoeuvres in an efficient and cheap form and in a short time. Such capability has considerable immediate commercial application upon until now sub-exploited markets.

The project RISANAR [2] has been developed at RoboticsLab of the University Carlos III of Madrid, and it presents as its main characteristics a vision system with the capacity to provide a flexible and adaptable service, by means of...
libraries of geometric 3D modelling of the satellite indicated by the user. This allows changing, at any given time, the features to locate in the images, since it is based on an iterative method based on geometric projections which allows establishing analytical restrictions. An experimental testbed was designed and built for simulation of space scenarios according to the scheme shown in Fig 1. The autonomous navigation developed in this project employs a visual servoing like technique to perform the relative navigation tests that simulate a satellite servicing system. The implementation is based on a vision system which processes monocular images, to estimate pose and motion of the satellite during the approach operations. Once the pose is estimated, the chaser trajectory is generated to feedback the robot control system (in the simulation testbed) whereas the vision system tracks the satellite movement during the subsequent flights until achieving the final approach point.

The paper is organized as follows: Section II summarizes the vision based OOS mission. A general description of the RISANAR assumptions, scope and requirements are described in section III. Section IV presents the satellite vision system. Section V reports on the results of experiments, and the paper is concluded with a brief discussion in section VI.

II. BACKGROUND

Several space projects have used the International Space Station as a focus for their robotics and automation research particularly concerning OOS repair and assembly. The USA and Canada have concentrated their robotics research effort for the ISS on their Mobile Servicing System (MSS) designed by the Canadian Space Agency. The initial approaches to space vision applications were focused on image analysis taken from satellites to perform image processing, structures and natural phenomenon detection, sensorial fusion or 3D modelling. About these ideas some works has been done to perform simulation tests of spatial operations by means of vision based control systems for docking tasks [3]. Generally, these systems are based on the matching between a pattern and an image of an object with landmarks. MD Robotics has presented a stereo vision system to determine the pose of a known object. This system has a straightforward general architecture to perform the approach automatically [4]. The difference with the geometric object model is minimized, using iterative algorithms that assure the convergence for some possible alignment (not necessarily the correct one). This implies the necessity to initialize suitably the pose estimation algorithm.

ROTEX (Robot Technology Experiment) of the DLR was one of more extensive space robotic experiments in Europe. One of the tasks performed successfully was an ORU (Orbital Replacement Unit) exchange type operation as well as grasping a free floating object [5]. Artificial intelligence techniques was used for the solution of pose calculation without landmarks, the vision system is trained off-line, where it is taught different CAD views of the object [6]. The used methodology does not represent the correspondence restrictions analytically; and the neuronal network training implies an operation of a considerable time off-line.

In support of their space robotics programme, Japan’s NASDA (National Space Development Agency) designed and constructed the Experimental Test Satellite, ETS-VII, to test a space manipulator teleoperated from the ground to demonstrate automated rendezvous and docking tasks on a small satellite. ETS-VII consisted of two satellites (chaser and target) where a computer vision system was used to close the feedback control loop as a teleoperated system [7].

More recently, the ideas of autonomous navigation, inspection, rendezvous and docking are leaving the laboratories and reaching the stage of real demonstration. In this line, the US Air Force Research Laboratory (AFRL) is building and demonstrating a new class of low-cost satellites weighing less than 100 kilograms. These new satellites are being flown under the Experimental Spacecraft System (XSS) Microsatellite Demonstration Project. The satellites are intended to demonstrate unmanned operations of inspection; rendezvous and docking; repositioning; and techniques for close in proximity manoeuvring around on orbit targets [8]. In addition, NASA’s Demonstration of Autonomous Rendezvous Technology project (DART) was launched on 2005. DART was designed to perform autonomous rendezvous with the MUBLCOM satellite [9]. Unfortunately, DART collided with the MUBLCOM.

![Fig. 2. Servicing mission reference.](image-url)
III. SYSTEM DESIGN CONSIDERATIONS

Ideally, the autonomous chaser vehicle is a service satellite that would be situated on a range of orbits covering a Low Earth Orbit (LEO) -around 320 km above the Earth surface-; or covering an important interval of GEO that is over 35,000 km. Therefore, the operations can consider several steps to reach the target satellite, which should be performed using minimum energy consumption.

Reference Mission Scenario

In order to consider these circumstances, it is important to generate the adequate trajectories to fulfil both these conditions and the space dynamics laws. It is necessary to perform approach strategies for each step. For this reason a typical reference mission scenario has been designed (as illustrated in Fig 2):

Phase 1. Approach to the inspection zone: The chaser vehicle is injected in an orbit of a different altitude of that of the target satellite.
Phase 2. Identification of the relative position and orientation: The chaser performs an initial approximation of the target behaviour.
Phase 3. Inspection: The inspection process consists of a series of flights around the target vehicle taking into account its motion and the objective of the inspection.
Phase 4. Final approach: The chaser position should be in an optimal location to perform the final approach to the target. Another problem consists of performing a guidance that minimizes the risks of collision.

Visual Space Environment

The space environment may contain variable intense light and dark periods and shadowing. The absence of any atmosphere and lack of a rich background prevents scattering of light, generating large contrasts of intensity which are characteristic of this environment. Most spacecraft are white providing high reflectivity which can cause flaring on camera images [10]. Then, it is possible that image data are lost because the camera dynamic range is exceeded. In addition, the satellites may be covered with reflective materials or thermal blankets to protect from the space environment. Such surfaces may produce shadows and reflects when illuminated directly by the Sun or on-board lights. These can produce difficult problems for the vision systems.

Space Simulation Platform

To develop reliable algorithms intended for satellite pose estimation and vision based relative navigation it is necessary to perform the validation of the results. Since it is not feasible for us to use real spatial systems to do so, it has been decided that an experimental laboratory testbed is adequate and acceptable for use in this case. Therefore, the developed
testbed consists of an industrial robot and a support platform, which also houses a support and drive mechanism for a scale satellite model, to simulate the different satellite geometries under space dynamics laws. In addition, the robot has attached to its end-effector a camera as part of a complete computer vision system. The system implements the algorithms corresponding to recognition and relative navigation used in the visual feedback. The developed testbed includes the following elements (see Fig. 3):

The main element is a robot manipulator capable of simulating 6 DOF motion of a satellite on-orbit. In the current application, the robot manipulator simulates the chaser satellite and it has attached to its end-effector a camera. To achieve a realistic relative simulation movement, although simplified scenarios, the laws of orbital mechanics, flight mechanics and the space environment have been taken in consideration and reflected in the robot motion.

A scaled re-configurable model of a satellite SPACEBUS 3000B is attached to a support platform designed specially for this purpose. Different representative rotational states can be simulated for a target satellite. This constitutes another main moving element of the testbed.

A system that simulates the illumination conditions for different experiments. The system has to be capable generating punctual illumination, Sun like light, and uniform illumination conditions such as the Sun light reflected from the atmosphere.

A computer vision system for the recognition of the geometry, position and movement of the mock-up of the target. This system is composed by a CCD camera in addition to the related equipments of image acquisition and processing. The camera has a certain vertical and horizontal mobility by means of a platform with movement pan/tilt.

A software module to produce the orbital simulation and scale it to the experimental setup was developed and implemented. The trajectories are applied to the robot and the satellite model and generated the synchronized motion.

Two electronic boards have been designed and developed to establish the adequate physical connection between the testbed and the computer in charge of its control to perform the signal conditioning and the necessary hand-shaking. These boards play a role of a bridge between all the wiring going to and coming from the control computer and sensors and actuators in the testbed.

IV. SATELLITE VISION SYSTEM

The testbed vision system integrates algorithms for the recognition of the movement of a satellite model in "uncontrolled" mode. These algorithms scan the search space to detect the presence of the satellite and recognize the type of the satellite model under consideration and its different parts. This development implies that the following issues have to be dealt with: a) a library with geometric models of satellites as well as a simple interface for the possible
incorporation of future models; b) implementation of geometric recognition algorithms for articulated models in real
time; and c) to determine the type of satellite failures suffered and that produces its malfunctioning.
The first step in the process of target detection, recognition and tracking is to extract the feature points from image. An
algorithm developed based on Hough's Transform is employed to obtain this data [11]. Thus, it is possible to estimate
the corners of polyhedral objects, and therefore the necessary main features to use in the algorithm of 3D pose
estimation. The process consists of using a series of general routines of image processing. Subsequently, Fig. 4 shows
the process to calculating the feature points using an application based on the Hough Transform algorithm.
Next, the recognition and the pose estimation stage is executed using the extracted point features. This process is based
on a proposed approach in [12], which estimates the pose of the object without landmarks and once implemented is
relatively easy to adapt it to different objects by means library exchanges. From our point of view, this is a key
commercial capability that can be exploited by the vision system. The system could be adapted to customer needs
without using a long training time, reducing the workload involved in setting identifiers in the target satellites.

3D object pose estimation

The autonomous vision system needs to perform a process that allows the 3D object recognition from 2D shapes and the
estimation of the object spatial orientation. The 3D information lost can be compensated using image formation
properties by means of perspective projection. A very useful methodology based on these considerations is the location
of 3D objects from an image by means of the interpretation of the image lines as projections of the object model [13].
An analytical way to solve the problem is to use perspective projection [14]. It is important to note that the pose and
correspondence problems are strongly connected, and solving one of them requires solving the other before. In this line,
a simultaneous solution of pose and correspondence problems was developed using geometric projection [15]. This
technique has been implemented and the obtained results are very effective in our consideration.

Projective Geometry Approach

This algorithm uses an approximate perspective projection called weak perspective. Summarizing, the method consists in
assuming that the depths \( Z_i \) of the different points of the given object are not very different from each other and therefore they could be located at a reference depth \( Z_0 \). To calculate the coordinates of the image points \( (x, y) \) a reference point \( (X_0, Y_0, Z_0) \) is taken, and a scale factor \( s \) is defined according to (1):

\[
s = \frac{f}{Z_0}
\]

The projected coordinates of the image points \( (x_i', y_i') \) are obtained using linear algebra and a first order approximation as defined in (2) and (3):

\[
x_i' = x_0 + s(X_i - X_0)
\]

\[
y_i' = y_0 + s(Y_i - Y_0)
\]

It is possible to calculate the pose by means of a simple iterative process. Although to determine the correspondence
between the points in the image with those of the object a matching matrix is used to indicate an explicit assignment
between two groups of points. In the first iterations, it results difficult to satisfy matrix correspondence. However, using
statistical techniques such as the deterministic annealing the convexity of the energy function is forced to avoid local
minima. This allows the formulation of the points matching in a parameters assigning problem. This is the key factor of
the SoftPOSIT algorithm; the pose estimation and correspondence problem are combined by means of the minimization
of a no-linear objective function [15].
A graphical demonstration of converge process of the 3D pose estimation algorithm is shown in Fig. 5. In short, it is
possible to note a general satisfactory behaviour of the 3D object recognition and pose estimation. The method obtains
very good precision of the rotation and translation values when it converges. It proved to be very robust to noise and to
point values slightly displaced in the image. However, it can not deal with situation of high symmetry of the objects,
which results in orientation errors. The convergence time depends on the initial pose (starting guess). The closer the
starting pose to the real pose the faster the algorithm converges.
On the other hand, a new method based on Genetic Algorithms (GA) has been developed and tested to prove efficient
for 3D pose estimation [16]. The algorithm is capable of dealing with multiple models simultaneously and identifying
objects after suffering partial alterations. To test its performance in a real time process, the algorithm is being integrated on the experimental platform.

V. EXPERIMENTAL RESULTS

In order to assess the effectiveness of the proposed approach, a number of experiments have been performed. This section reports the results obtained for a subset of the images used during the testing of the 3D pose estimation algorithm.

A set of experiments was aimed at probing the pose estimation algorithm on static objects. Thus, the algorithm performance was evaluated comparing results from simulated data with the data obtained using the vision system developed for the test-bed. The algorithm was run until convergence, and the average total orientation and position errors are computed with randomly generated rotation angles and translations in the camera plane where performed at a distance w.r.t. camera fixed unknown by the algorithm.

Table 1 summarizes the results of the experiment. The error represents the 3D distance between the estimated position and the correct one and the orientation error is the average of the three orientation errors. The table shows that the implemented algorithm have reasonable performance as far as precision is concerned. It is worth noting that the precision of the SoftPOSIT can be improved as desired by imposing stricter tolerances, however at higher running time.

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Position Errors (Average)</th>
<th>Orientation Errors(º)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tx</td>
<td>Ty</td>
</tr>
<tr>
<td>Simulation</td>
<td>0,17</td>
<td>0,06</td>
</tr>
<tr>
<td>Testbed</td>
<td>0,06</td>
<td>0,22</td>
</tr>
</tbody>
</table>

As from the 3D model features with a given position and orientation, the values of image features matrix are calculated theoretically by the evaluation of algorithm performance. The errors of position and orientation computed from the theoretical values are considered. The orientation error is determined such as the angle in degrees required to align the coordinates of the object system in the theoretical orientation. The relative position error is defined as the norm of difference of calculated and theoretical translations, divided by the norm of theoretical translation.

A second set of experiments consists of determining the vision system performance based on the relationship between the object size and the distance relative to the camera. It is possible to observe the distance effect over position errors and speed of convergence in the table 2.
Table 2. Vision System Performance (Distance effect)

<table>
<thead>
<tr>
<th>Distance/Size</th>
<th>Simulation Nº Iterations</th>
<th>Position Errors (Average)</th>
<th>Testbed Nº Iterations</th>
<th>Position Errors (Average)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tx</td>
<td>Ty</td>
<td>Tz</td>
<td>Tx</td>
</tr>
<tr>
<td>1</td>
<td>173</td>
<td>0.10</td>
<td>0.06</td>
<td>0.09</td>
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<tr>
<td>1.5</td>
<td>173</td>
<td>0.10</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>174</td>
<td>0.33</td>
<td>0.18</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Table 2 shows that the convergence speed is not as fast as expected. This occurs despite of the rapidity introduced by geometric pose estimation iterations. The constraints that assignment matrix establishes affect the convergence speed. This result implies that it is important to study improvements about the matrix computation by each step. It is though that it is feasible to utilise the current vision system in spatial applications, such as in OOS missions mentioned in this paper, where the relative navigation between two spacecrafts is accomplished. However, it is important to take into account the use of alternative strategies to mix them with the proposals in this paper. For example, in far distance recognition a simplified model of the target could be used to accelerate early-stage computation. The feature points of the satellite panels can be confused with the noise of the image, generating unsatisfactory results or causing the no convergence of the algorithms. On the other hand, the rigid body of the satellite is not only more reliable for determining the pose geometrically but also avoids the long distance problems caused the panel image. Moreover, it is logical to expect that in relative short distances, the object find itself so close to the retinal plane that the perspective approximations may lose its validity. Because of this situation, in the approach stages it is necessary to use any strategy that is activated in close proximity.

CONCLUSION

This paper presents the system concept, design, algorithmic details, and some preliminary results of a proposed system treating relative autonomous navigation between satellites based on computer vision feedback. The work is aimed at developing vision and navigation algorithms to implement in future real systems. The results and tests provide a positive feedback concerning the functioning of the testbed and the feasibility of the proposed ideas.

There exist other solution approaches to satellite pose determination and tracking. But, it is thought that the approach presented here offers a number of benefits over the other alternatives. The system depends only upon a single standard camera which is currently available. This kind of sensors will likely prove to be more reliable and less expensive than other sensors. The system also does not require any landmarks to be placed on the satellites, which can be expensive. Further, there currently exist a great number of satellites in orbit which do not have suitable identifiers. Another benefit over the use of landmarks is that severe space lighting conditions can reduce the visibility of these identifiers, whereas obtaining more clear images of the shape of satellite body.

The developed experimental platform provides a useful tool to experiment with visual control technique and is expected to aid in providing useful results for industrial applications as well. On the other hand a more exhaustive study of the pose estimation algorithms has been performed to evaluate the possible improvements on precision and speed, by combining and switching between different approaches, according to the operation in hand. In particular the mentioned GA is fast, but less precise than the one based on projective geometry. The GA approach can be used as a starting point to provide the initial guess for the projective geometry algorithm.

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REFERENCES


