# Low-cost Approach of Ground-based GNC experiments of distributed space systems

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2025 IEEE 12th International Workshop on Metrology for AeroSpace (MetroAeroSpace) | 979-8-3315-0152-5/25/$31.00 ©2025 IEEE | DOI: 10.1109/MetroAeroSpace64938.2025.11114591

***Abstract*—Robotics facilities have a long history in the development of space equipment, since they allow to perform tests on systems like guidance, navigation and control, visual-based navigation and docking mechanisms. Those facilities are based on two manipulators, one representing the a target satellite, the other the chaser satellite which perform a relative motion with respect to the first. This approach has been used in the past to perform tests on docking operations, visual-base navigation system to populate databases. Delft University of Technology recently developed its own robotics facility for GNC and multi-satellite systems applications. It hosts two robots on a moving base, which work in synergy to extend the operational space. They operate in a dark environment, where there are lights to simulate the sun disturbance and a beamer that projects the Earth to have a representative background. The purpose of this paper is to describe the laboratory, along with the control architecture of the robots and provide some tests executed to assess the accuracy of them in tracking a given trajectory.**

## I. Introduction

In missions like In-Orbit Servicing, In-Orbit Assembly or Active Debris Removal, inspection, manipulation and rendezvous and docking tasks are required. Such tasks involves several sensors, actuators and algorithms. Therefore, having a method to reproduce the relative orbital motion and attitude change between the space vehicles is of key importance to test relative control and navigation systems at different scales. For these reasons, the development of robotics-based facilities proceed hand in hand with the complexity of the missions. The famous EPOS facility of the DLR [1][2], which employs two industrial KUKA robots (one fixed and the other mounted on a rail) to reproduce the relative orbital dynamics of two satellite mock-ups. The two robots are equipped with a force and torque sensor on the tip in order to update the pose of the mock-ups when the two mock-ups touch each other during the docking phase.

A similar approach is used by Stanford University [3], where two manipulators (one fixed and the other mounted on a rail) are used to collect images of a satellite in order to populate a database to train machine learning algorithms also with light and albedo disturbances. The collection of images is required to train neural networks for relative navigation with respect to celestial bodies or artificial satellites [4][5]. The training of neural networks, requires a well-defined image database of the target, meaning that, each image has to be taken in a known position, and robotic facilities offer this advantage.

Manipulators also offer the possibility to test guidance, navigation and control algorithms in a closed-loop mode. In this application, a computer computes the orbit propagation, which is translated into the Cartesian position and attitude of the robots. The orbit and attitude are updated if external forces (like the mating forces during docking phase) are executed to the satellites mock-up, The orbit and attitude are also changed as the effects of the control actions of the GNC algorithm [6].

In addition, to the above example, robotic manipulators can be used to test navigation algorithms for rendezvous and docking operations. Here, the motion is imposed by the arm, while the algorithm estimates the relative state and sends to the robot the desired position to reach and mate the counter part of a docking system [7][8][9][10].

Despite the control actions are imposed by the movement of the robots, so they are not representative for those of real on-board hardware (e.g., thrusters and reaction wheels), robotics-based facilities have advantages of allowing a full six degree-of-freedom pose, which is not ensured by other facilities like low-friction planes. In addition, robotics facilities requires less maintenance and the set-up is faster with respect to low-friction planes.

At the Delft University of Technology, a GNC Robotics Lab has been established within the Department of Space Engineering. The GNC Robotics Lab has the objectives to reproduce relative orbital motion and attitude variation between space vehicles or other objects. The Lab uses two manipulators, both mounted on an omnidirectional vehicle with Mecanum Wheels, in order to extend the operational space of the robots with respect to the reported examples. This brings big advantages as both the robots can emulate the motion of space vehicles (or target), and evaluation tests on GNC algorithms will be more reliable. On the other hand, the approach of having two moving robots poses several challenges on the control side of the robots, since the tracking accuracy must be ensured for both the robots. This will be done by using a motion capture system that surrounded the working area of the GNC Robotics Lab, whose purpose is to act both as a ground truth to compare data with and to close the control loop of the robots ensuring the tracking of a given trajectory.

To further improve the reality of the experiments, the working area of the robots is kept completely dark, with just spot light which represents the presence of the sun and a screen to project Earth images.

The paper is organized as follows: Sec. II provides a detailed description of the Lab and its devices; Sec. III shows the evaluation of the tracking accuracy of the robot exploiting an experiment of an inspection manoeuvre of a target satellite; finally, conclusion and future works are provided in Sec. V.

## II. Laboratory description

The GNC Robotics Lab has the aim to execute experiments on relative navigation and multi-satellite systems, such as Io-Orbit Servicing, In-Orbit Assembly or active debris removal. The relative navigation includes both the navigation between satellites and between a satellite and an asteroid, where this one is produced with additive manufacturing technique based on real data [11].

The Lab is divided into two areas: the monitoring area and the Dark Room. The second is the main focus of the Lab, since the environment is kept as dark as possible to mimic the space environment; while the first hosts the computers to communicate with the inside of the Dark Room in order to launch and supervise the experiments.

### A. Overview

The Dark Room (shown in Fig. 1) has a total area of approximately $8\,\mathrm{m}\times 3\,\mathrm{m}$ and hosts: (i) two robots systems; (ii) a spot light; (iii) a motion tracking system; and (iv) a screen to project Earth images. The robots (Fig. 1 above) have the purpose of hosting satellite mock-ups and moving them through trajectories reproducing a relative orbit motion (see Sec. III for a more detailed description). The spot light has a spectrum which is similar to that of the Sun, allowing to simulate light of the Sun. The motion tracking system, yields the ground truth in order to have a constant reference frame for the motions. The screen allows to project images of Earth (or other celestial bodies) for navigation or disturbances purposes (Fig. 1 above).

Thanks to the flexibility of the Lab, a large variety of experiments is possible. The most commons regard sensors characterization, image collection and verification of GNC algorithms. In the case of image collection or sensor characterization, one robot, caring the camera or the sensor, performs either inspection or rendezvous trajectories with respect to the other robot which moves the target mimicking an attitude motion. In the case of GNC, instead, the satellite mock-up takes pictures of the target and elaborates them in order to estimate the relative pose, and apply control actions that make the robot to move through the target.

The two robots have their own computers, which are connected to a wireless network to exchange data between them and with the monitoring area. In this way, the experiments can be set in three different ways:

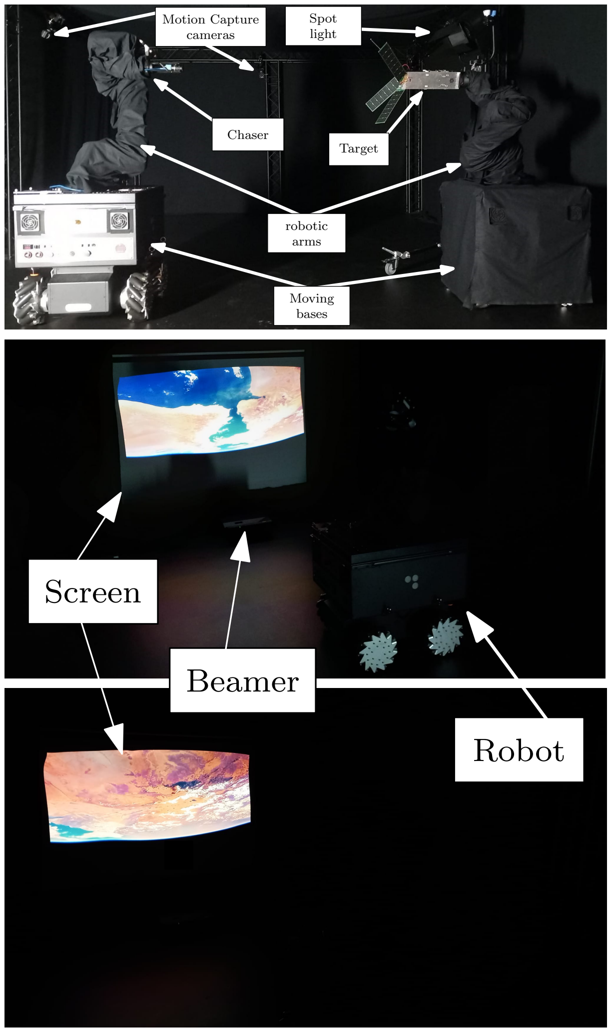


Fig. 1. Overview of the Dark Room with the two robots (above) and the projection screen with an Earth image (below). The image below was taken in two different light conditions to demonstrate how items are arranged and to appreciate the darkness of the room.

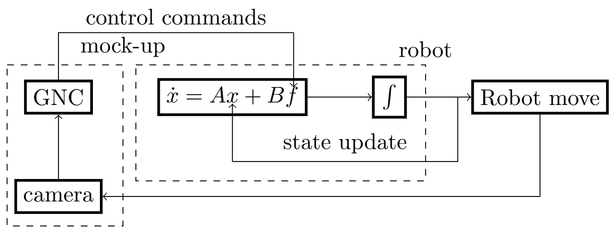


Fig. 2. The logical diagram to execute a rendezvous experiment in the GNC Robotics Lab. The scheme also reports which device executes what.

- *Characterization.* Space applications require a lot of different sensors, especially for rendezvous and docking tasks. Most of the time, these sensors are a miniaturization of existing ones, therefore characterize them is a milestone for their development. In this context, the robots will act as positioning systems to evaluate the capabilities of the sensors.

- *Inspection*. The two robots will execute a motion by reading a loaded file, which reports the position of the end-effector of each robot. The robot translates the position of the end-effector into the variable to move the robot. The main purpose of this experiment will be to collect images to populate a database, with the purpose of training image-base navigation algorithms.
- *Rendezvous*. The robot of the chaser will be equipped with a satellite mock-up with the needed sensors to measure the relative pose of the target and a computer to estimate the relative state and provide command actions To improve the reality, the GNC algorithm will be executed by a computer which has similar performances of a satellite on-board computer. The control commands will be sent to the robot computer (with a wired communication system) which elaborates them and executes the motion accordingly to the orbit and attitude dynamics (the logic scheme of this approach is shown in Fig. 2).

### *B. Robots description*

The two robots are equal, each of them is made of a moving base equipped with a six degrees of freedom manipulator. The base has the purpose to extend the operational space of the manipulator, since it is able to move along $x$ and $y$ thanks to its omnidirectional mecanum wheels.

Into the computer of the base, a ROS (Robot Operating System) environment is installed to manage and monitor all the devices, including the manipulator and other sensors (such as cameras, and force and torques sensors). This architecture allows also the execution of other algorithms like those that compute the inverse kinematics for the arm and move the base when the arm is out of its operating space, or update the orbit and the attitude dynamic.

The arm (Universal Robots UR16e) is the most accurate positioning system, while the base (Robotnik) has poor accuracy, due to its minimum allowed motion (approximately $5\,\mathrm{mm}$ linear and $1\,\mathrm{deg}$ angular). Therefore, the system of base and arm is not controlled as a single entity, instead a logic is used to move the base only when required. Following the scheme in Fig. 3, the base is moved when the arm cannot reach the desired position or when the required position is out of the joint bounds. By using this logic, instead of considering the whole system, the base is moved only when required, avoiding to move the base too much, reducing its positioning errors. In addition, thanks to the motion capture system, the positioning errors of the base are measured and added to the motion of the arm in order to ensure the track of the trajectory.

### *C. Trajectory generation*

Rendezvous and docking tests require that the satellites mock-ups track the imposed trajectory with high precision. In addition, during the mating and docking phases, the trajectory should be updated accordingly to the loads exchanged during the contacts between the docking interfaces. These loads are measured by a 6 degrees of freedom force and torque sensor,

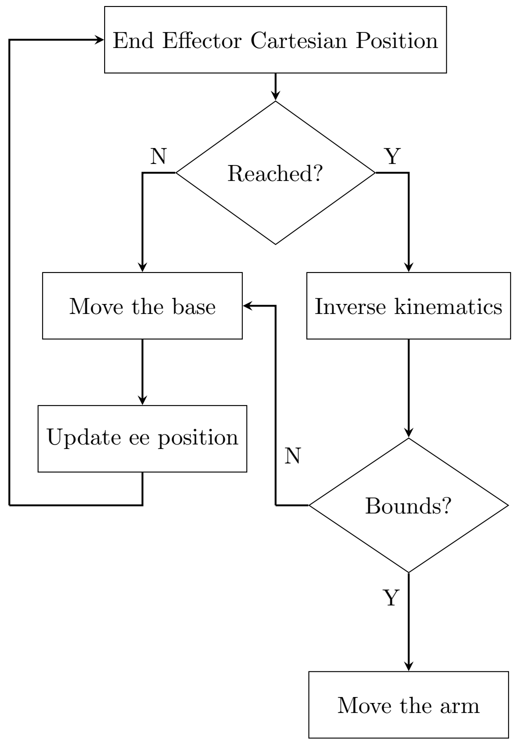


Fig. 3. The logic scheme describing how the robot choose between the motion of the base and that of the arm.

which is placed at the hypothetical barycentre of the satellites (therefore, it is not important where the actions are located).

These tasks are managed by the trajectory tracking and control algorithms of the robots. Referring to the scheme of Fig. 4, the logic of the control is as follows:

- The force and torque sensor provides the measurements of the contact forces;
- Forces are used in the relative orbit propagator to update the trajectories of chaser and target;
- Torques are used to update the attitude of chaser and target.
- At the same time, external sensors (such as a motion capture system) are used to track the actual trajectory of the mock-ups.
- The actual trajectory is compared with the desired one and the errors are compensated.

The whole process requires a time in the order of tens $\mathrm{ms}$ to be completed. However, especially for docking, the velocities are very slow (in the order of $\mathrm{cm/s}$ [12]), therefore, the time it takes the robot to move is at least one order of magnitude higher than the motion of a satellite during docking. This means that the delays in the motion of the robots do no affect the validity of the tests.

## III. Inspection experiment

The first experiment performed in the GNC Robotics Lab is an inspection manoeuvrer of a target satellite (a $3\,\mathrm{U}$ CubeSat). The experiment has the double purpose to (i) collect images to populate a data base in order to train vision-based navigation

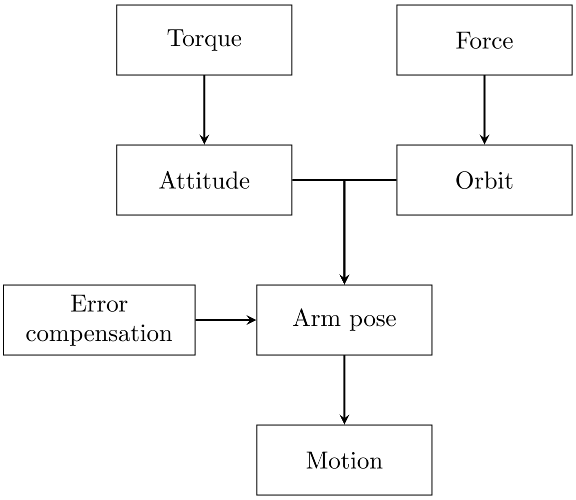


Fig. 4. Logic scheme of the trajectory control and update for chaser and target mock-ups.

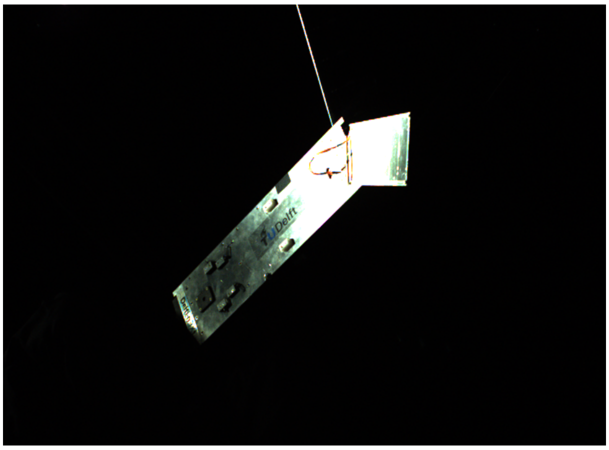

Fig. 5. Example image acquired during the inspection experiment.

algorithms, and (ii) assess the tracking accuracy of the robot of a given trajectory.

An example image acquired during the inspection experiment is shown in Fig. 5.

The relative orbit considered for the experiment is a circular orbit (with respect to the target) with a radius of $2\,\mathrm{m}$, while the target had an attitude motion of $0.1\,\mathrm{deg/sec}$ around the roll axis. Considering a Low Earth Orbit with a period of approximately $90\,\mathrm{min}$, a navigation algorithm working at a frequency of $10\,\mathrm{Hz}$, the chaser has to take a picture every $0.06\,\mathrm{deg}$. However, for space reasons, only half trajectory has been executed, therefore the number of images is 2700, which coincides with the number of waypoints of the arm carrying the camera. In addition, the time between each image is lower than the orbital case to save time. This approach does not effect the validity of the experiment, since the purpose of the experiment is to take the image in the right relative position, no matter the time of motion.

In this first application for the GNC Robotics Lab, a numerical simulation was used to defined first the relative orbit and then divide it into the waypoints for the arm. The simulation also provides the waypoints of the base, which moved when the arm is not able to reach the desired position of the camera, resulting in a total of twelve waypoints for the base. A top view of the experimental setup is shown in Fig. 6.

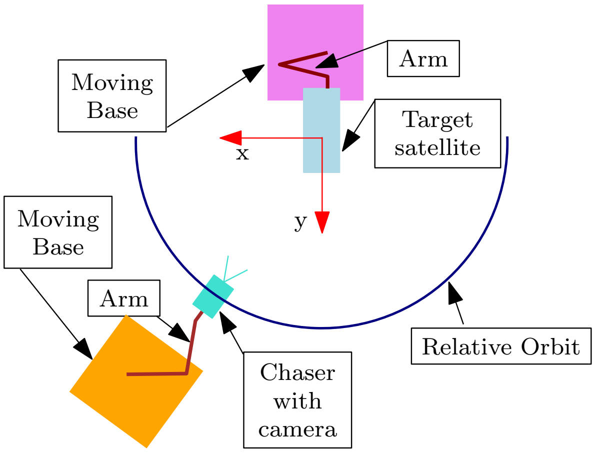


Fig. 6. Top view of the arrangement of the robots during the inspection manoeuvrer. In the image, T refers to the target satellite and C to the Chaser.

## IV. Trajectory Tracking Analysis

The inspection experiment had also the purpose of collecting information about the ability of the robotic system to track a trajectory. For this reason, an open-loop approach was used to evaluate the tracking capabilities of the chaser robot in tracking several semi circular trajectory with radius in the rang $1.6\,\mathrm{m}$ and $2.0\,\mathrm{m}$. The following analysis is for the larger radius, but the same holds for all the others.

The trajectory was recorded by the motion capture system. The comparison between the desired and actual trajectories is illustrated in Fig. 7 (above). From the comparison, the low accuracy is evident. The error between the desired and the actual trajectories reaches its maximum value of approximately $0.6\,\mathrm{m}$ the end of the trajectory (see Fig. 7, below). This is due to the low accuracy of the base, which does not move to the desired location, leading to a cumulative error of approximately $0.6\,\mathrm{m}$ (as illustrated in Fig. 8), meaning that the base has a positioning error of approximately $50\,\mathrm{mm}$ for each movement.

The algorithm used to translate the positions of the end-effector it the robot variables works as follow (refer also to Fig. 3):

1) An initial configuration between the base and the arm is imposed.
2) Verify if the relative distance between the end-effector and the base is less than a threshold ($1\,\mathrm{m}$ in this case, to avoid over overextending the arm).
3) If the distance is larger than the threshold, the base is moved to reach the initial configuration between the base and the arm.

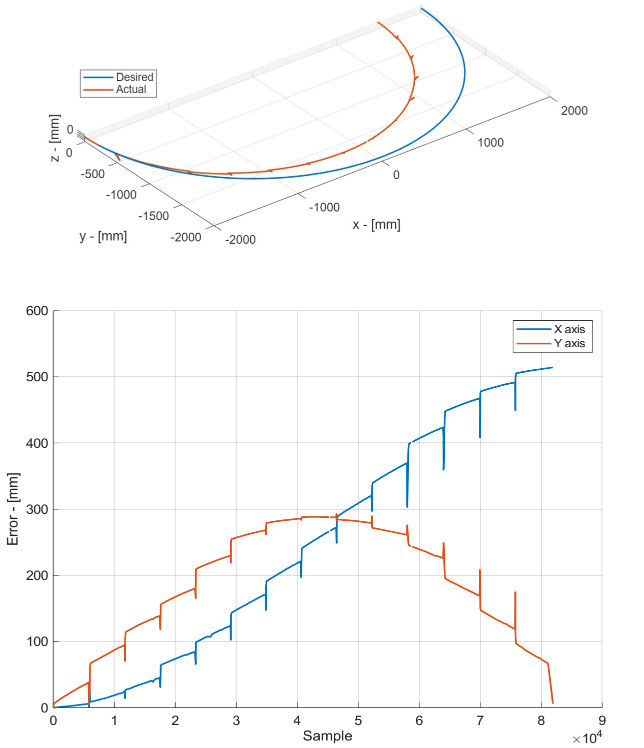


Fig. 7. The comparison of the desired and the actual trajectories (above) and the evolution of the tracking error during the manoeuvrer (below).

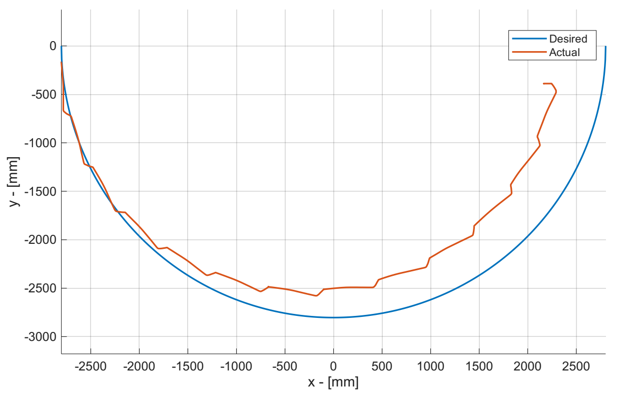


Fig. 8. The trajectory of the base compared with its ideal one. Each segment represents one base motion.

4) If the distance is less than the threshold, the inverse algorithm solves the inverse kinematics of the arm.

This procedure is applied for all the positions of the end-effector, resulting in a division of the trajectory into equal pieces (twelve, in this case). At the end of each piece of trajectory, the arm rapidly returns to its initial position, creating the peaks on the recorded trajectory of Fig. 7. These peaks are visible only in the motion capture data, since images are not taken during motions.

The reasons of the low accuracy of the base are multiple and difficult to solve. The first is the low accuracy of the wheels, as they perform only movements larger than $5\,\mathrm{mm}$ and $5\,\mathrm{deg}$ and it is not possible to perform linear and angular motions at the same time. This con not be solved since the base is an industrial product and acting on it will compromise its integrity. The second is related to the high friction that generates between the floor (covered with rubber) and the wheels when the base perform a lateral motion or a rotation. The latter reason requires a completely new floor to be solved. The first, instead can be solved by using a smart way to control the robot that reduce its movements and avoid rotations. This is possible since the arm has a large working area and can rotate more than $360\,\mathrm{deg}$ around its firs joint. In addition, the arm will be used for high accuracy tasks and to compensate the errors of the base.

To compensate the errors of the base a close loop control can be employed. In this architecture, the motions capture system can be used to send the actual position to the robot computer, which compare it with the desired position. The difference between the two positions are the errors that the arm has to compensate (as shown in Fig. 9). This approach is an ongoing improvement of the GNC Robotics Lab, which will increase the ability of the robots to track a trajectory, and then improve the whole Lab for future testing campaigns. Since the end-effector of the arm is controlled point-to-point, this is not a real control, since the errors will be compensated with the next way point, therefore, the delay caused by the wireless communication will not affect the performance of the system. In addition, such manoeuvrers are executed with a speed in the order of $\mathrm{cm/s}$, and a delay of some $\mathrm{ms}$ does not affect the validity of the test. To further improve the system, the model of the wheels [13] can be used.

This control method ensures a very accurate trajectory tracking in terms of position and attitude. However, in real life, satellites experience several errors that are added via software as modification of the waypoints. In this way, also the real tracking errors are under control and can be tuned based on the experiment.

## V. Conclusions and Future Works

In this paper, the GNC Robotics Lab of TU Delft has been described. The purposes of the Lab include (i) characterization tests of sensors for proximity operation or attitude; (ii) the creation of dataset of satellites or asteroids images to test algorithms for relative navigation with respect to satellites or celestial bodies; and (iii) test of GNC algorithms for rendezvous and docking or space robotics for Io-Orbit Servicing or Active debris Removal. To satisfy the purposes, the Lab hosts two manipulators mounted on moving bases in order to extend their operational workspace.

An evaluation of the trajectory tracking error of the robots has been done, since the ability of keeping the error as low as possible is of crucial importance for emulating the orbital motion of two vehicles. The results of the evaluation are very poor, since the tracking error of the moving base is very high,

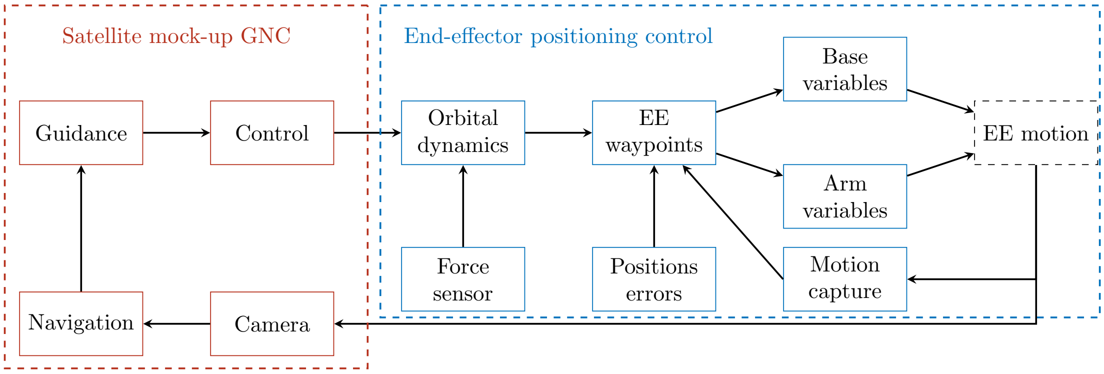


Fig. 9. Logic scheme of the errors recovery to ensure the tracking of the imposed trajectory.

leading to a cumulative error of more than $0.2\,\mathrm{m}$ at the end of a circular trajectory.

Future works will include the improvement of the tracking abilities of the robots with a close-loop approach; the use of GNSS emulator to use absolute navigation during rendezvous and docking tests; the development of two satellites mock-ups with their computers and sensors to perform docking experiments; and the generation of a database of real images taken during different approaches and relative orbits to train image-based navigation.

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