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POLIMI OPTICAL SENSOR FOR SPACE SURVEILLANCE AND TRACKING

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Near-Earth space has become progressively more crowded in active satellites, inactive spacecraft and space debris. Consequently, an international effort is currently being devoted to enhancing the available networks of sensors for space objects monitoring. Within this framework, the Department of Aerospace Science and Technology of Politecnico di Milano (Milano, Italy), in collaboration with the Italian Space Agency, is setting up a new optical sensor. The sensor will be located in the Centre for Space Geodesy of ASI in Matera (Italy) and will be fully robotic and remotely operated. Featuring an optical tube with f-number equal to f/2.2 the instrument is able to collect an high number of photon on the detector plane. This feature reduces the required exposure time and allows capturing fainter and faster objects. Furthermore, the tube is installed on an equatorial fork mount equipped with stepper motors and absolute encoders, to assure accurate control response, reaching the slewing speed of 4 deg/s. The features and high slewing speed of the mount allows tracking fast object with a pointing accuracy up to 0.1 arcsec^2. The features of the sensor system can be exploited to perform classical GEO survey, to perform precise orbit determination of GEO objects, as well as LEO and MEO observations. The aim of the sensor is twofold. First of all, it will contribute to space objects monitoring by observing objects selected from available catalogues and performing orbit determination refinement. In addition, it will be used as testbed for the development of new observation and operation strategies, with the ultimate goal of promoting autonomy in observation planning and optical telescopes operation.

Keywords:Remote Control, Optical Sensor, Space Debris, Space Surveillance and Tracking

1. Introduction

Since the first launch of a space object almost 70 years ago, the space environment has seen a constant increase of the population of orbiting bodies. By analyzing the evolution of the space environment reported by Rossi [1], the last reports of European Space Agency (ESA) Space Situational Awareness (SSA) program and the U.S. Air Force Space Command [2, 3], it is possible to observe the increasing amount of Resident Space Objects (RSOs).

However, of more than 20 000 RSOs tracked by the Space Surveillance Network (SSN), only the 4%[2] are active payloads or satellites. Moreover, particles with size larger than 1 cm are nearly 750 000[3].

The proliferation of space debris threaten to harm the space activity with consequences that can be catastrophic, such as in orbit fragmentation, collision or uncontrolled re-entry. For this reason the space environment needs to be continuously monitored and tracking man-made objects becomes a priority needed to reduce the risk of collisions with active satellites and to provide support to authorities in case for uncontrolled atmospheric re-entries.

Comparing the Low Earth Orbit (LEO) region with the Medium Earth Orbit (MEO) and Geosynchronous Earth orbit (GEO), the first appears more crowded than the other two. This leads to the reasonable assumption that the LEO region presents higher risk. LEO objects can be tracked with accurate measurements using radar sensors. The power constraint of radar sensors is linked with the objects distance from the sensor and for this reason surveying up to the GEO region is particularly difficult. On the other hand, MEO and GEO objects can be observed by means of optical sensors.

Under this context, Politecnico di Milano in collaboration with the Italian Space Agency is coordinating the development of the PoliMi Space Surveillance and tracking Telescope (POSST) system. POSST is an optical telescope that will be installed at the Centre for Space Geodesy of Agenzia Spaziale Italiana (ASI) in Matera (Italy) and is equipped with a remote control system which allows both executing autonomously work schedules and monitoring the system status.

The objectives of the POSST system are similar to other observatories: initial orbit determination of unknown objects, orbital parameters update of known objects, detection and cataloguing of new objects. Furthermore, Politecnico di Milano and other academic collaborators, using the POSST system could carry out researches in various field: building an academic catalogue of RSOs, development and testing of algorithms for data association and object correlation, customization of the image acquisition process and astrometric reduction, development of control procedure for the tracking of LEO objects as well as improvements of general optical instruments technologies with the aim of studying the space debris population.

The present work describes the architecture of the POSST system. Section 2 describes the components of the system focusing on the features of the optical tube coupled with the fork mount and on the monochrome cooled CMOS detector. The implementation of the software for the remote operation of the system is described in Section 3 with particular emphasis on the client-server architecture adopted. Section 4 describes the strategies used to acquire images and to track objects in LEO while in the last section some remarks are provided about the current and future work are reported.

2. POSST Hardware Architecture Design

This section describes the hardware of the designed sensor system, highlighting the main features that drove the selection of the main components. The hardware part of the sensor system is connected to the end user through the software which will be described in details in the following section. A block diagram of the connection between the hardware system and the end user is shown in Figure 3.

The designed optical sensor system is equipped with a Celestron optical tube that is realized following a modified reflective Schmidt-Cassegrain scheme. Celestron improved the optical tube design tailoring it to astrophotography. The outcome is the Rowe Ackermann-Schmidt Astrograph model, which is described in details in Section 2.1. The optical tube is coupled with a monochrome cooled 4/3" CMOS detector and installed on an equatorial fork mount MOFOD MkII model of Gemini Telescope Design. The optical tube is equipped with a mechanical focuser that can be used to move the primary mirror that is responsible of focusing the light flux on the focal plane where the camera detector is placed. The mechanical focuser is not suitable for a completely remote control of the sensor system. Therefore, the upgrade to a fully controlled automatic focuser is planned.

All the active devices are connected to a common control unit which is realized with a rugged low-power computer. The control unit is realized using open source solutions and it is based on a Linux operative system. It exploits the INDI framework for the connection with both the devices and the main Operation Control Center, that is the main interface with the end user.

2.1 *Rowe Ackermann-Schmidt Astrograph Optical Tube*

The Rowe Ackermann-Schmidt Astrograph (RASA) optical tube is characterized by a focal length of 620mm and an aperture of 279mm, providing an f-number equal to f/2.2. The RASA configuration consists of a Schmidt correcting plate at the entry side of the light, a primary spherical mirror and four-element corrector lens before the camera sensor plane which is placed at the focus of the primary mirror. For this reason the camera is positioned ahead of the tube, in the position where the secondary mirror of a classical Schmidt-Cassegrain would be. A representation of this configuration is shown in Figure 1.

The correction plate and the four-element lens drive and correct the light path in order to create a planar image on the focal plane without significant aberrations. This optical system exhibits a mild vignetting represented by a loss light which is 23% at 21.65 mm from the center of the sensor. This parameter is important for the selection of the dimension of the detector.

Figure 1: A scheme of the RASA assembly and the light path. Courtesy of Celestron, LLC[4].

2.2 *Monochrome Cooled CMOS detector Camera*

The selection of the camera was driven by the need of detecting faint objects travelling very fast, therefore a high sensitivity is required. In order to exploit the available light spectrum to increase the sensitivity of the camera, a monochrome detector has been selected. Moreover, the detector should be able to reduce as much as possible the noise. For this reason the dimension of the detector should be maximized. Considering the vignetting features and the front side sizing constraint of the RASA, the ZWO ASI1600-MM has been identified as the best compromise. The camera is equipped with a cooled 4/3" CMOS detector, with a diagonal of 21.9 mm and a resolution of 16 megapixels. The diagonal dimension means that at the corner of the sensor (10.9 mm out of axis) the light loss value for vignetting is less than 5%. Coupling the camera with the RASA, a field of view of 98×74 arcmin^2 is obtained.

2.3 *Equatorial Fork Mount*

The optical tube is mounted on an equatorial fork mount. The small inertia of this configuration (as no counterweight are necessary) increases the achievable slewing speed and reduces pointing perturbations. Those features are perfect for pointing and tracking fast objects. As no meridian flip is needed, the problem of possible collisions with the pier are completely avoided, which simplifies the motion planning when tracking fast objects.

The fork mount is equipped with stepper motors and absolute encoders that grants high precision in angular positioning and excellent response to stop and start commands. The mount has a maximum slewing speed of 4 deg/s, with positioning resolution of 0.1 arcsec^2. Furthermore, the transmission of motion is realized by friction wheel. This guarantees high positioning precision and avoid oscillations during tracking operations.

2.4 *Ancillary Devices*

The sensor system requires ancillary devices for its protection and operation. In particular a dome and meteorological station will be required in the final deployment.

Figure 2: The System preliminary test in Milan.

The dome considered exploits an all sky configuration. This is required to reduce the moving parts of the system and increase the reliability during tracking of fast objects. The dome allows operating the telescope also when in close position to simplify the procedure needed for the preparation of the actual observation. When the dome is in open position, the optical sensor is able to acquire images down to horizon. Therefore, the resulting masking angle of the sensor depends only on orographic and illumination constraints.

One typical drawback of all sky configuration, is the extended time required to open and close entirely the dome. In particular, in order to safely operate the sensor system remotely a meteorological station is required to carefully plan the opening and closing of the dome. As the deployment of the sensor system will be at the Centre for Space Geodesy of ASI in Matera (Italy), data about the weather will be provided by the weather station already available.

The sensor system under development and integration at Politecnico di milano is shown in Figure 2.

3. **POSST Software Architecture Design**

The software architecture is a crucial part of the system. The main idea in designing the control software is that the architecture should be extremely flexible and scalable to possibly adapt to a wide range of sensors, devices and observatories. In this way, the control software can be exploited in subsequent generations of the sensor system.

In order to fulfill these requirements and the ones deriving from the remote control needs, it has been decided to base the architecture on a client-server scheme. Moreover, to improve flexibility, the control software should be capable of decoupling the low-level hardware control from the high-level operation scheduling. Furthermore, the choice should privilege protocols with extensive scripting capability that allows highly customizable automation procedure. According to the previous considerations, the selected framework is based on the open source Instrument-Neutral Distributed Interface (INDI) protocol (http://indilib.org).

At this point it is important to select the basic programming language that should be used to develop the control software which make use of the INDI protocol. One possible solution is the adoption of the more common C++ language, extensively used for this kind of applications and supported by the INDI framework. However, in order to simplify and speed-up the software design, it has been decided to use the high-level dynamic language Python (http://python.org). This language is very flexible, it has a huge repository of existing libraries among which a great number are for scientific applications. The python language is used to create the client-side of the control software that communicates with the server-side that is entirely provided by the INDI framework. In this way, the python code can be used as a wrapper between the high-level control software and the low-level server which is directly connected to the hardware.

3.1 *System Architecture*

The POSST system is composed of three main blocks. The first one is the Observatory, that is the lower level of the system and corresponds to the actual hardware as described in Section 2. The access to the devices is not allowed directly to the end user, the devices are interfaced with an embedded processor board that runs a tailored version of the Linux OS. The control of the devices is implemented using the INDI protocol and exposing them to the network (server-side).

The embedded processor is not exposed directly to the user network but is connected to the second element of the system, the operation control center, through a local network. The operation control center exploits three processes to govern the telescope functionalities. One process monitors and checks all changes of the system state reporting the tasks status and problems. A second process generates the tasks for tracking and survey according with the cataloguing and users requirements. One last process elaborates the generated task scheduled for the observations and sends the command to the observatory.

The operation control center can be eccessed both locally and remotely by the users. The local access is employed by the operator directly from the operation control room that is located at the same site of the telescope, while the remote access uses a client interface realized in common browser to connect to the control room. Therefore, the telescope can be controlled remotely by any computer on the network using the web application interface which is also based on the INDI protocol. This architecture allows remote access to the telescope for direct control independently on the OS used.

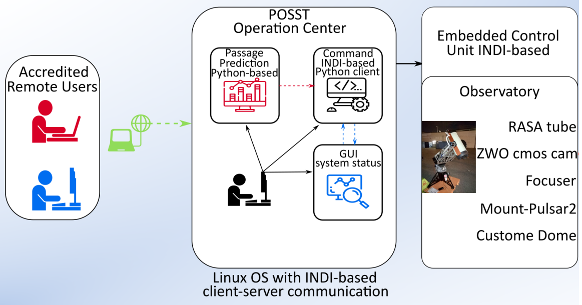

Figure 3: The POSST Diagram block.

3.2 *Manager and Controller of the Devices: INDI (server)*

The INDI [5] protocol is the key of the system that allows the communication between the observatory devices and the clients. The protocol allows asynchronous query and response, reducing synchronization issues in the remote operations. However, when sending the command no acknowledgement is received from the devices, so no error could be received for inappropriate or illegal command. As said above, this simple configuration prevents the possibility of deadlock conditions, but a procedure to monitor the state of the command execution is needed.

The observatory devices are not in direct contact with the client but they communicate using an intermediate INDI server installed on the embedded control unit. With the basic configuration the server receives the commands from the client and transmits them to the devices unaltered and do the same the other way around for the data produced by the devices.

Every block of the system is equipped with the INDI protocol in order to be able to interpret the communication to and from the devices. The embedded processor of the observatory is the high level server directly connected to the devices. The other working blocks of the control center are also INDI-based but they communicate with the server using a client based on Python inter-link as it will be discussed in the following section.

3.3 *Front-end Operation Control and Task request (Client)*

The front-end for the user and operator is gathered at the operation control center and is divided into three main process-blocks. This arrangement minimizes the interference between the different procedures.

The Passage Prediction block is a Python-based software, the functionalities are explained later in the next section, and is exposed to the network by means of a JavaScript-based GUI. The predictor module enables the operators to select the targets from the embedded catalogue or select their own targets to compute the passage prediction. The widget of the GUI easily allows to define the temporal windows of the passage and modify any default constraint for the observation session. This configuration should give the possibility to use the module with any other sensor outside the system or to adapt the system to additional sensors and devices. Indeed, the module has the possibility to chose or to store new observatory stations with the purpose to use two sensors at the same time to observe the same object. Currently, once all the constraints and configuration are selected the outputs are the split passages over the sky of the observatory.

The monitoring of the system is demanded to the GUI monitoring block. This block can not send commands to the server but is linked to it as it receives information from the devices and provides to the operator useful parameters of the system. The monitoring is meaningful for remote operation or before executing tasks or the requests by the command block.

The main component of the operation control center is the *Command* block that is responsible of executing the tasks scheduled from the operator.

The front-end operation control is the only module of the operation center that can send and receive information from the INDI-server and so from the devices. The front-end operation control client is Python-based and a different module is created for each device. Each device module has specific methods implemented to carry out all the possible tasks requested by the operator. This strategy allows the user to access the device only through the Python wrapper and the Python-client, thus enhancing reliability and robustness of the system.

In conclusion all the operation control center components are based on Python and the INDI protocol allowing automatic execution of schedules and acquisition of the data.

4. **Observation Strategies Design**

The aims of the developed system are survey and tracking of space objects complying with user requests or for catalogue maintenance. The complete automation of the system will provide also service for collision prediction and re-entry monitoring. The software to predict the passage of the Earth orbiting objects is currently the cornerstone of the automation system of POSST and for the survey and tracking strategies.

4.1 *Space Object Passage Prediction application: 'SOPass'*

The observation strategies are strongly dependent on the different kinds of sensors. In case of POSST the main issue is the identification of the pointing direction necessary to catch the passage of a space object. The SOPass is able to manage a user list of objects and a selected time observation window providing the pointing for the mount of the sensor. The pointing of the objects can be retrieved within different coordinate reference system but the standard one is in term of Right Ascension and Declination. Moreover, the software manage the constraints for the Moon separation angle, the magnitude estimation, sun position and will improve the relative position with the deep-sky objects (i.e the Milky Way and shining galaxy cluster).

4.2 *Tracking Strategies*

The tracking strategies are implemented to obtain one or more passage acquisition of the objects per night, chasing it while crossing the sky. The strategy purpose is collecting information on the tracked objects to fulfil two main aims: increasing the catalogue population and improving the orbit of increasing the objects that are already catalogued.

The current strategy developed by the team exploits the SOPass software to predict a split passage of the objects with an optimized time span according with the selected time observation windows. Each discrete state of the passage should be used to point the telescope nevertheless, by fitting the discrete states, it is possible to track the object along its passage using few repositioning. This procedure is simpler with the GEO objects. However, considering the characteristics of the system (the high slew speed of the mount) it is possible to propose and test the same procedure for the LEO objects. Furthermore, especially for the faster objects, the acquisition of the tracklets at the border of the Field of View (FOV) can be avoided by selecting a suitable sequence of pointing angles. This reducing the light loss due to vignetting. In addition, the mount is capable of employing a custom tracking rate, thus the objects can be tracked as fixed points into the FOV with the background moving stars.

5. Conclusions

The POSST is a testbed developed by the team of Politecnico di Milano in collaboration with the Italian Space Agency to perform orbit determination refinement for catalogued objects and initial orbit determination for unknown objects. The system is currently being tested. First examples of acquisition are shown in Figure 4 and Figure 5.

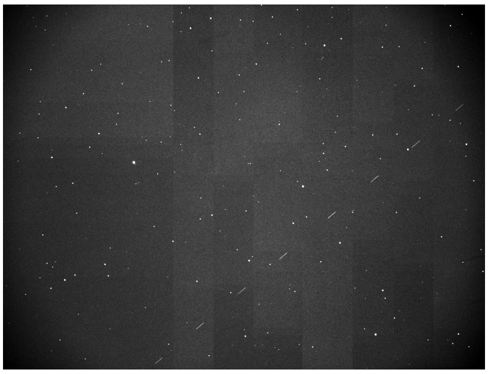

Figure 4: Acquisition superimposed of 2018-03-22 21:24:26 of GALILEO-5 NORAD 40128 with exposure time of 3s per capture.

The system will be endowed with the ability to automatically process the images, and to perform astrometry and orbit determination.

Figure 5: Acquisition of an unidentified LEO object and 4 GEO ones with exposure time of 10s.

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