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Artificial vision assisted ground fine pointing system for experimental optical link for CubeSat communications

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Abstract. Considering the continuous increase of demands in satellite communications, it is imperative to determine systems with higher bandwidths. Furthermore, miniaturization trends coming from the development of nanosatellites as CubeSat's, constitute great restrictions to their design. Optical communications have the potential to lead with current data rates requirements. Nevertheless, the establishment of ground-LEO (Low Earth Orbit) optical links poses several challenges such as very strict and accurate tracking mechanisms, effects provoked due to the environmental conditions on the light beam as well as attenuation and Doppler effects. In this work, the precision of the tracking mechanisms is tackled by employing artificial vision as a proposal for a fine tracking system for an optical ground station to be able to locate a LEO CubeSat, so to proceed with data acquisition and tracking stages. The innovative and highly efficient algorithm herein developed for fine pointing is implemented in LabVIEW® as an example.

1. Introduction

Current demand for services offered by artificial satellites is continuously increasing, requiring higher bandwidths and power consumption. Recent research shows that the technological limit of conventional satellite communication devices is being reached [1]. There are three primary aspects to consider for the development of artificial satellites: Size, Weight, and Power (SWaP). These facts become critical when considering micro and nanosatellites. For instance, a size of 10x10x10cm, as well as 1.3 kg of mass restrictions, exist for 1U CubeSats. Thus, communication systems currently employed in CubeSat satellites involve a deployable monopole, as well as the patch antennas. They allow a better space configuration to optimize the size and power consumption [2,3], imposed by CubeSat norm [4].

Most CubeSats have not achieved more than few MBs at download, over the course of an orbit since its data rate is of about 9.6 kbps, and their sighting times are of about 5-10 minutes in Low Earth Orbit

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(LEO). According to [5], it has been possible to reach up to 3 Mbps by implementing amplitude shift keying systems (ASK). However, these data rates are insufficient for the increasing demands of the market. Among several alternatives [6], optical communications are a promising option due to their typically high data rates with respect to RF. It has been proved that optic-based data rates higher than 5 Gbps are achievable [7,8].

The Optical Wireless Communication or Free Space Optical Communication (FSO), inherits all the characteristics of optical communications. It consists of a tight beam providing higher gain and narrower beam pattern. These characteristics are very much suited for space missions where information transmission is also crucial. There is commendable advancement in optical components families which satisfy the criterion of small SWaP [9].

The use of optical based technology in a conventional CubeSat shall guarantee: more power efficiency, lightweight and more available space for a better components distribution; moreover, the communications features shall have much higher data rates and immunity to interference due to its line of sight nature. However, it must be considered that the use of this technology involves a set of problems such as: very high precision requirements, atmospheric effects on the light beam, attenuation of the signal, Doppler Effect, and scintillation [10-18].

Considering that an optical link requires a mandatory line of sight, the precision of the pointing system in the ground station must be at least of 0.25° to achieve a 50 Mbps consistent data transmission for a LEO-ground link [8]. In order to explore the feasibility of a ground to satellite optical link with respect to the attitude accuracy requirements, this work proposes a potential method to fine-locate a satellite orbiting in LEO; the method consists in the usage of artificial vision as a fine pointing mechanism.

2. Satellite Laser Communications

Optical technology has been used for communications since the last century; however, its implementation into satellite communications has only been tested since 2001 in different inter-satellite experiments, and in ground-satellite in further experiments in 2005 from several space agencies and research centres. Among the main missions concerning laser communications since the year 2001 are: GeoLITE, SILEX, LUCE, NFIRE, LLCDC, OPALS, and EDRS [19].

None of the satellites used for experimentation so far is a nanosatellite. However, the OCSD/AeroCube project is an undergoing experiment that uses three 1.5U CubeSats to demonstrate an efficient LEO to ground link. This mission has the purpose of testing the several experimental attitude sensors that can provide the sufficient stability to point these CubeSats towards their ground station to establish an uplink and downlink with high efficiency [20,21].

It is also important to note that optical communications are not as regulated as RF. For instance, the American National Standards Institute (ANSI) provides a metric for the maximum permitted exposure (MPE), which limits the power flux (W/cm^2) of the signal and depends on wavelength. Nevertheless, for laser communication downlinks, the transmitted power is spread out over a large area and does not approach the MPE limit [21].

The vast majority of laser-based communications systems use beacon tracking to locate the ground station or satellite. In this approach, the ground station sends up a wide beam at a predetermined wavelength towards the spacecraft and vice versa. Initial conditions for the spacecraft consist of orbital tracking knowledge. The mispointing induced by position error gets worse the closer the spacecraft is to the ground station. Pointing knowledge also induces error as the spacecraft relies on a combination of gyroscopes, magnetometers, accelerometers, sun sensors, Earth horizon sensors, or star trackers to determine its orientation with limited accuracy [19].

3. Optical ground-LEO simulation

Considering a LEO nanosatellite at 500 km, and an approximate orbital inclination varying between 90° and 45° with respect to Equator, simulations were made to acquire link times from the ground station with tracking capabilities towards the orbiting satellite. The proposed ground station is located, theoretically, in a latitude of 19.50187, longitude of -99.14071 and at an altitude of 2240 meters.

The orbital features are: orbital period of 94.6163 minutes, orbital altitude of 500 km, satellite speed of 456.76 km/min. The laser's operation for satellite communications is restricted to work in angles higher than 30° , according to the ITU. Table 1 shows the ground station-satellite link properties according to the inclination angle of the satellite.

Table 1. Ground station-Satellite link properties.

Links per day	Orbital Inclination	Maximum link time (min)
1	90°	2.891
1	80°	2.447
1	70°	3.452
2	60°	3.402, 2.329
2	50°	2.009, 3.602
1	45°	3.433

Figure 1 shows a successful link for a 70° orbital inclination simulation. Times shown in table 1 prove that the tracking system demands are very strict. For an optimal time of operation, the maximum time is 3.6 minutes in one day. The pointing, acquisition and tracking (PAT) of the satellite must be done instantly in order to exploit the time and achieve a high data transfer. By predicting the orbit, and implementing an artificial vision system for the fine tracking of the satellite, the established link can be achieved in less than 200 ms and without any time loss.

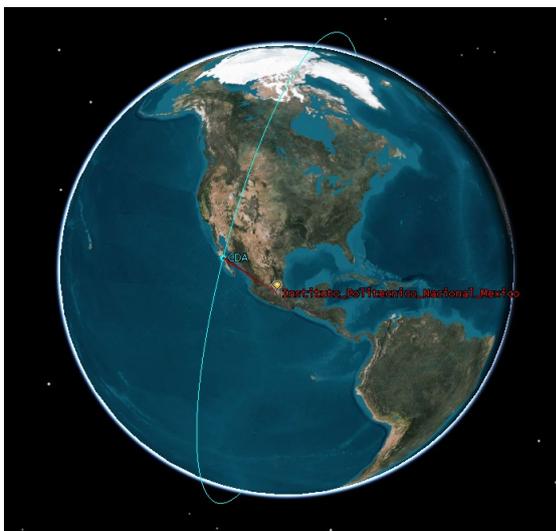


Figure 1. Simulation of a 70° orbital inclination established link.

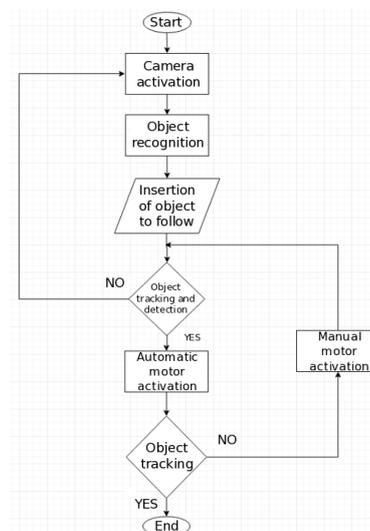


Figure 2. Artificial vision algorithm flux diagram.

4. Artificial vision implementation for fine tracking system

This PAT proposal consists in an artificial vision software that can identify and follow the satellite through its orbit. To accomplish this, it is necessary to extract spots from the image, to indicate which parts are the ones to follow and which are to be ignored. To achieve the blob extraction of a single image, some criteria must be considered, such as the colour of the object, shape or specific pattern.

The extraction of an image can be done by running through a scanned image twice. All operations are done in grey scale images where the value 1 represents the object to follow and 0 the rest of the image to ignore; the user determines the whitest spots to follow. The first analysis goes from the upper left corner to the bottom right corner and compares each pixel with its neighbours in the upper rows and to

its left. The second analysis is done backwards and compares with the inferior rows and pixels to the right. This way a binary image is created where the desired pixel to be followed is 1 and everything else is 0. Figure 2 shows the artificial vision and motor manipulation algorithm we propose to implement the PAT system.

Although this paper focuses on describing the artificial vision programming and motor manipulation, figure 3 shows the conceptual PAT system with artificial vision system embedded into an optical ground station based on a telescope and a camera to locate the satellite and the laser to establish communications.

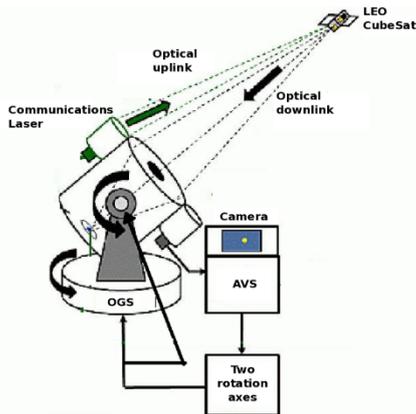


Figure 3. Main elements of the Optical Ground Station. OGS: Optical Ground Station; AVS: Artificial Vision System.

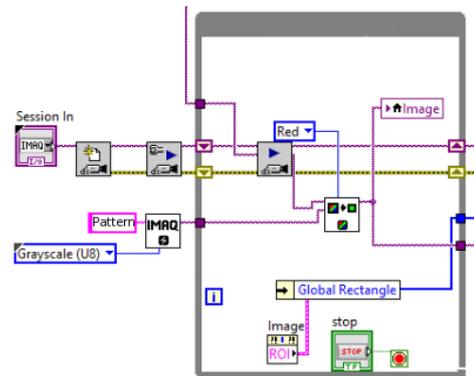


Figure 4. Initialization of camera and filter configuration for image processing.

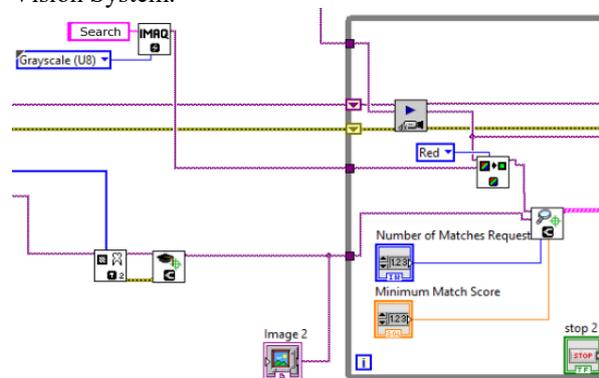


Figure 5. Geometric pattern programming block.

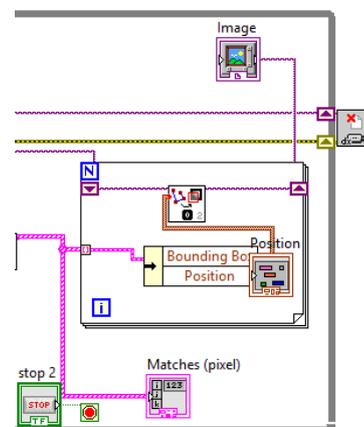


Figure 6. Tracked object visualization and closing of camera shutter.

The image acquisition process starts with the initialization of the camera, stepping through the image acquisition and reaching the closing of the lens shutter; this process must be done continuously, operating therefore into a while cycle. By using more programming blocks, it is possible to choose the instructions we want to locate inside a closed loop, thus alleviating the processing times of the system and assuring a better efficacy.

Due to the highly compatible list of components based on artificial vision developed by National Instruments technology, as a way to exemplify the implementation of the algorithm shown in figure 2, we used LabVIEW® because it is of widespread use. Figure 4 shows the programming blocks used to acquire the image and a filter to process the image to the desired ends. Firstly, the camera is initialized and configured, to proceed to the acquisition of the image to be tracked.

A colour of the desired object to track must be defined in order to proceed to the filter to process the image. This is to discriminate the background of the acquired picture and allows to develop a more efficient and precise system. To strengthen the system, one more stage was added to the image processing. This stage adds a block to imbue the system with the ability of learning a geometric pattern, i.e. now the system recognizes a predefined colour and shape. Figure 5 shows the block that learns the object shape.

Figure 6 shows the final stage of the artificial vision program which determines the position of the object by showing to the user its coordinates, the visualization of the desired object and the closing of the camera shutter.

5. Control and automation of PAT

The camera is redirected by using a coordinated movement of motors. We propose a motor manipulated by fuzzy control and its corresponding membership functions, which maintains the position of the camera. This considers a MIMO system due to the presence of multiple variables: the position interpreted by the camera according to the location of the tracked object, and signals sent to servo motors, which are the multiple outputs of the system. The programming blocks that describe this section are shown in figure 7.

The system works properly under certain conditions and close-range detection objects. Object detection is obtained in less than 100 ms and the tracking starts as soon as the object begins to move. However, specific environmental and lightening conditions must be maintained throughout the entire process.

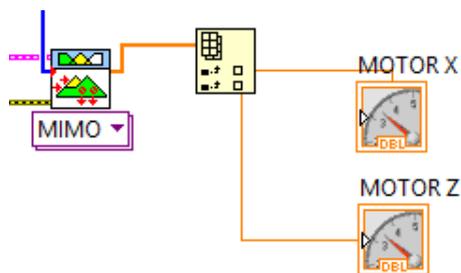


Figure 7. Servo motors position monitoring.

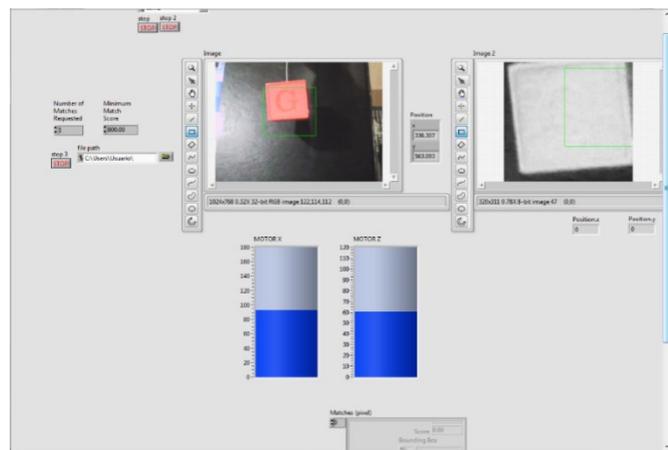


Figure 8. Motor correction according to tracked object location.

Figure 8 shows the motor correction working depending on the location of the tracked object. The system proves its detection algorithm works, which is automated for close distance objects.

6. Conclusions

In this work, an automated motor motion is achieved via artificial vision and fuzzy control, and the tracking of an object depending on its shape and colour is also described. The use of artificial vision is a promising technique to develop an entire PAT system for an OGS. However, artificial vision systems often have problems identifying objects due to the variation of lighting conditions, and this is the case; if the camera perceives too much light the program sometimes detects more than one object or the motors start malfunctioning. Nevertheless, it is well known that these issues may decrease if the camera quality is increased, and further research is required for the implementation of the OGS, because it is required to contemplate the whole pointing mechanism. Moreover, this PAT proposal can be improved by increasing the number of degrees of freedom of the mechanical system herein devised,

which currently stands at two degrees, or even by considering further degrees of freedom to reach the great precision required. Nonetheless, this is out of the scope of this work, which is currently in progress.

The pointing and tracking module is strict and continuous, considering 0.2 degrees of precision; therefore, a kinematics analysis is required according to the corresponding orbital mechanics, to predict the main orbits and times that the satellite shall be travelling on, so to gain accuracy by *a priori* orbital pointing knowledge. Also, the implementation of a beacon on the tracked object may help to increase the accuracy and reliability of this system.

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