RELATIVE NAVIGATION DETERMINATION IN THE CAPTURE OF NON-COOPERATIVE TARGETS

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ABSTRACT

The active removal of space debris has great interest nowadays because of recent events of space collisions in LEO and unexpected object re-entry. There have been some test flights, e.g. ETS-VII [1] and Orbital Express [2], for on-orbit satellite servicing and autonomous rendezvous and docking, with the advantage of being cooperative targets, which gives aid for attitude and position determination by the chaser.

In case of space debris, no cooperative information is given and the chaser satellite must extract accurate information about the behaviour of the tumbling debris. For this, specific sensors will be used during each phase of the rendezvous approach in order to ensure a secure and safe mission during the complete process. The purpose of this paper is to describe the use of possible sensors for autonomous rendezvous to space debris, i.e. non-cooperative targets.

1 AUTONOMOUS RENDEZVOUS

The on-orbit space debris removal is one of the proposed solutions for the reduction of the population of space junk in orbit. The utilization of a chaser satellite will be planned, which will encounter the target debris based on autonomous manoeuvres and specific sensors used in each phase of the rendezvous process.

For far range rendezvous phase, the chaser satellite would be located in a position farther than 5 km from the target. In the close range phase the chaser satellite would be from the target between 5 km and 5 m. For the final approach, the chaser would be within the last 5 m to the target, being the last phase of the rendezvous. The locations of the boundaries between the different phases are not definitive, and they could change based on the sensor system and its performance, as well as the approach strategies chosen for the mission. In the Fig. 1 it is shown a schematic from the three different phases of the rendezvous process.

2 FAR RANGE SENSORS

Despite the position of the target in the orbit is known by surveillance systems and is catalogued, there always exists a percentage of errors in the real location. Therefore, it is needed to have accuracy in the debris location in order to avoid sudden collisions and/or waste of power and fuel resources from the chaser. Hence, for the long distances in this phase the use of microwave radar and optical sensors suits for the purpose of the mission.

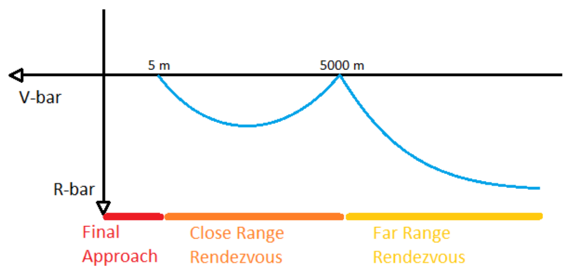

Figure 1. Autonomous Rendezvous Phases

2.1 Microwave Radar

Radio-frequency (RF) sensors have been used for space rendezvous missions in order to measure the distance between the chaser and the target, and also for measure the direction of the target object with respect to the chaser spacecraft [3]. Because of the high range achievement and operability under any illumination conditions, the RADAR (Radio Detection And Ranging) is very useful for the first target localization.

Different types of radars are used for detecting targets and measure the range between the radar and the object. For instance the Kurs system was used by the Russian Soyuz and Progress spacecraft for rendezvous with the Mir space station and then the ISS [3]. In this case there was cooperative communication between the spacecraft and the station. Otherwise, a Ku-band radar on the Space Shuttle was executed for passive target rendezvous, i.e. no collaboration from the satellite [4,5].

Based on the requirements of the mission, a system that will be capable to measure range, velocity and position angle of the target under interest will be chosen. For accomplish those requirements, the selection of certain characteristics will allow the achievement of the mission requests. Firstly, the use of a continuous wave (CW) allows to the system good velocity measurement due to the use of Doppler-frequency. In addition to this, other

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advantage is the lower required peak power for operation in comparison with pulse radar [6].

However, this kind of radar carries the disadvantage of not being able to measure range due to the absence of gaps in the transmitted and received signals, i.e. continuous. Hence, it is required to shift the frequency using a linear ramp in the frequency domain [7]. The difference between the reflected frequency and the transmitted frequency determines the target range. This radar system works under a Frequency-Modulated Continuous-Wave (FMCW).

In addition, the use of high frequencies allows having accurate measurements because they provide wider bandwidth, i.e. better range accuracy and range resolution, as well as narrower antennas with better angle measurement and angle resolution [6]. For instance, an operation frequency of around 100 GHz gives a velocity resolution of about 0.01 m/s. [3]. The corresponding band of the electromagnetic spectrum is the W-band, which range is established for transmission frequencies between 75 and 110 GHz [6]. Therefore it is more appropriate to classify the RF sensor as Millimetre-wave (MMW) radar because of the used frequency, i.e. wavelength.

2.2 Infrared Optical Sensor

The MMW radar is a good sensor for first identification of the target, but a visual representation of the space debris target is required, in order to know at first hand the current conditions and the attitude of the body with respect to the chaser satellite, when the distance between them both is enough for visual detection.

An on-orbit infrared sensor validation was performed on the Shuttle mission STS-131, where an infrared camera could detect the International Space Station (ISS) at a distance of 43.4 km [8,9]. Of course, the high range achievement depends on the size of the ISS and heat threshold configured for the sensor. In case of space target debris, both aspects must be recognized in order to have a good identification of the target. Furthermore, the infrared detection could also confirm the range [10] and bearing information obtained from the radar, and the current condition of the space debris before capture procedure could also be seen.

Otherwise, the sensor can suffer of external disturbances related to light sources in its field of view (FOV), e.g. reflections of sunlight from target or the sun itself [3].

2.3 Visible Wavelength Optical Sensor

The use of infrared sensors could be more complex because they could need a cooling system for operation. In this case it would be useful to have a charge-couple device (CCD) or complementary metal oxide semiconductor (CMOS) camera, which uses the range of visible wavelengths, i.e. among 400 and 800 nm.

This camera system is very simple and does not require big power requirements. It was demonstrated in on-orbit mission that the detection of the target was possible for an approach between 30 km and 3 km using a monochrome CCD camera [11,12]. Due to the fact that the target has only a size of few of pixels in the sensor at those distances, it was only possible to provide the line-of-sight (LOS) to the target. Based on a dynamic filter of the relative orbit including a set of pre-planned manoeuvres, the range and LOS information could be determined with sufficient accuracy.

The major drawback from this system is the dependency from illumination conditions, i.e. only when the sun illuminates the target. Also, like the infrared sensor, it has to cope with wrong measurements when there is the sun in FOV.

3 CLOSE RANGE SENSORS

After locating the space debris target, and following its trajectory, it is feasible to have another mean for best accuracy in terms of range, angle and their respective variations through time. At the close range rendezvous phase the precision of the measurements increases with the reduction of the range. For having such advantages, the employment of a laser range sensor will be analysed.

3.1 Laser Range Sensor

The acronym LIDAR, which means Light Detection and Ranging, was used for first time in 1953 [13], and its operation principle is similar to radar systems. The difference between them both is the operating frequency of each one. Sometimes it is used the term LADAR, which means Laser Detection and Ranging, comparable to the radar acronym. Hence, the backscattered light is used for measurement and further analysis of position and attitude of the space debris target.

The LIDAR system can be catalogued in similar way as the radar systems, e.g. the transmitted waveform or the type of measurement. But the most usual classification for the LIDAR is based on whether the system illuminates part of the target by scanning the area with a narrow laser beam, or illuminates at once most of the target [14].

Based on the latter, the LIDAR has the capability of producing 3D image of a target or scene, based on the mission requirements. Here, the system can determine the range between the sensor and the target, calculated by the time-of-flight (TOF) of the reflected light at the debris, which was generated by the laser.

First of all, the laser beam detection system scans the target by rows and columns until the whole object has been "observed", generating a 3D image from a photodetector, which collects the light reflected [14].

But the system must include a complex opto-mechanical array, i.e. gimbals and mirrors, and it requires more power for operation, generating high volume and mass to the system. On the other hand, the full illumination of the target can be performed with the use of a single laser shot with a large diverged beam. The purpose is to generate a kind of "flash" comparable to the light bulbs used in conventional cameras, not only capturing most of the target in the sensor FOV in a single shot, but also measuring the intensity of the reflected illumination and the time of flight of the laser pulse.

The use of the laser flash is of great advantage in the case the target debris has a tumbling behaviour, so the laser system has to be fast enough in order to obtain a representation of the debris attitude in a very short time frame [14]. It is easier and more reliable to have one laser flash shot instead a single narrow laser beams scanning the scene. On the opposite side, a disadvantage is the high power requirements for the laser due to illuminate a full scene instead of a narrow point. Fig. 2 and Fig. 3 show the laser emission from the narrow laser beam scanning and the flash LIDAR systems, as well as the point of view from the sensors respectively.

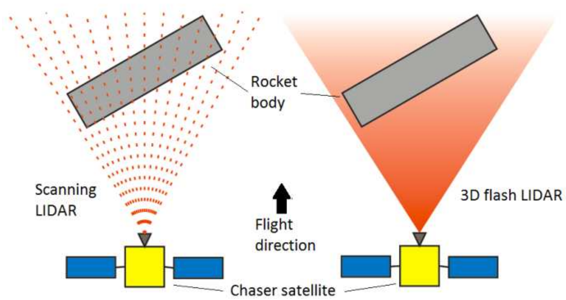

Figure 2 Illumination of two-type LIDAR

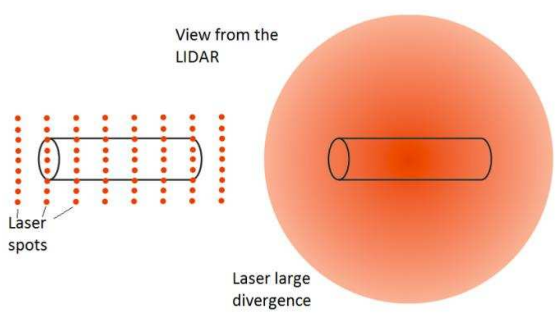

Figure 3 LIDAR point of view

Finally, both scanning and 3D flash LIDAR have great advantage with respect to other optical sensors, because the laser provides the illumination of the target, and they have lower sensitivity for other lighting sources, e.g. the sun, because the optics of the system can be adjusted to the laser wavelength [7]. In the case of having a wired 3D computer-assisted design (CAD) model of the target previous to the mission, it would be possible to match the target in the recorded images with the model and have a more accurate calculation of the space debris attitude frame to frame.

4 FINAL APPROACH SENSORS

The closest and, hence, dangerous phase is when the chaser satellite is near to capture the debris. Here it is really important to have fast enough object detection system, and trying to use minimum power resources for this task.

4.1 Photonic Mixer Device

This sensor is commonly called PMD, and it has the same operation principle of TOF. The sensor illuminates the whole scene like the 3D flash LIDAR, but using infrared light emission diodes (IR LED) instead of laser.

The advantages of this sensor are the lower mass and lower power requirements, making of it a very good candidate for the final rendezvous phase, obtaining a non-ambiguous range of around 7 m [15]. Also the frame rate of a PMD sensor could be greater than those from the LIDAR, and this increment in images obtained per second can enhance the safety of the operation. For instance, if the target is rotating around one of its axes, and this rotation rate is faster than the sensor frame rate, this changing state could appear as a blur in the image, i.e. bad imaging of the object, and consequent bad attitude calculation.

Even though the PMD sensor operation on-orbit and respective performance in space environment have not been yet assessed, it is considered to be used in this research project due to its great potential.

4.2 Monocular and/or Stereoscopic Camera

It has been previously described the operation of an optical sensor in section 2.3. Here, at the final phase of the rendezvous, these kinds of sensors could be useful with a proper illumination system, which allows the image recording when the lighting conditions are not good enough. When the range between both chaser and target is so close enough, the possibility of having light blockage from any of them, even both at the same time, could be high.

Monocular cameras have presented some advances in the possibility in extracting attitude information with good results using hardware-in-the-loop simulations [16], although the image is in 2D and no depth information is obtained. Otherwise, the stereoscopic camera simulates the binocular human vision, and therefore the sensor has the capability of obtaining images in 3D from the object under observation. The matching of the object points in the stereo system will allow calculating the depth distance of the object in the image [17], providing high accuracy for attitude calculation. It could also be used the wired CAD models overlapped on the images in order to increase the accuracy of attitude calculation of the space debris target.

5 SPECIAL CASE: GNSS REFLECTED SIGNALS

The Global Navigation Satellite Systems (GNSS) are a solution for geo-spatial positioning on the Earth. With many applications, the most substantial is the spacecraft orbit determination. In the case of autonomous rendezvous, the GNSS can be uses for the absolute position determination of the chaser satellite and for relative position determination in the case of cooperative targets as the ISS. But it is also well known that the GNSS signals can experience blockage and multipath in close regions of large structures [18]. The reflected signals from the Global Positioning System (GPS, which is the GNSS from the United States of America) were also confirmed in an on-orbit experiment carried by the Shuttle mission STS-125, in which servicing for the Hubble Space Telescope (HST) was performed [19].

The proposed idea is to use the GPS signals emitted from the constellation and reflected onto the space debris target, which the chaser is going for. From this point of view, the arrangement of this configuration is similar to a bi-static radar, where the receiver is a passive sensor in the chaser satellite and the GPS satellite acts as the transmitter. The sensor is configured to detect only the reflected signals from the target. This is possible because the GPS signals change their polarization after reflection. At the same time one direct signal could be coming from the same GPS satellite to the GPS receivers at the chaser. Estimating the time delay between these both signals, it is possible to calculate the range between the target and the chaser.

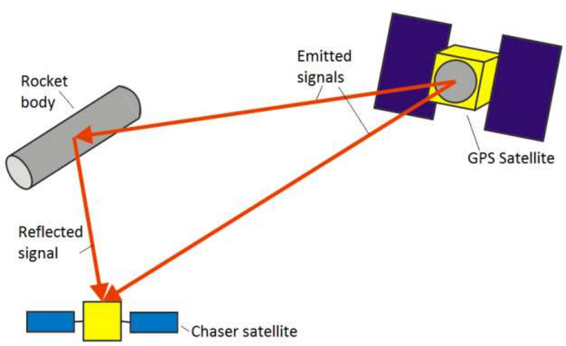

Figure 4 Operation principle for estimating range using reflected GPS signals

Otherwise, this possible measurement system it is not enough reliable to work as the best solution for a relative guidance sensor [19]. The main reason for this is the power of the reflected signals, which can suddenly drop because of the visibility of the signals, i.e. the GPS geometry configuration changes with time. In addition to this, the available range measurement depends on the size of the target debris. Hence, when the debris is bigger, it has more probabilities for having reflected signals on it.

On the other hand, the evaluation for other GNSS reflected signals is based on information availability, e.g. power of transmission, among others. Due to the fact that the operation frequency from the four systems is operated in the same bandwidth, i.e. L-Band, the results may depend more on satellite constellations than on signal characteristics.

6 CONCLUSIONS

This paper has included a summary of the possible sensor solution for an autonomous rendezvous in order to capture a desired space debris target. Defined the 3 phases for rendezvous manoeuvre, the solution for each segment has been explained. For far range rendezvous, the use of MMW radar could accomplish the proposed task for first object detection, because of the high level of accuracy for estimating range and attitude, with low power consumption. Furthermore, the use of an IR and visual wavelength optical sensors will allow the first visual inspection of the target when the conditions will be optimum, i.e. range and no reflections in FOV. For the close range rendezvous, the use of a 3D flash LIDAR will provide the first 3D representation of the target, offering the range and attitude at the same time, although the high power requirements. The final approach could be supported by a PMD sensor with less power requirements, less volume and fast data acquisition, although it is not approved for space operation. Besides, the use of stereoscopic camera will give good results without big power resources. An additional technique will be evaluated for range detection as complement for the other systems, based on reflection of GPS signals. The evaluation of the sensors will be performed in order to select those which fit better for the active space debris removal mission. The respective guidance algorithms will be implemented in future simulations.

7 ACKNOWLEDGEMENTS

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