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EXECUTIVE SUMMARY OF THE THESIS

STRATEGIC: telescope movement prediction and control software for unknown orbiting object tracking

LAUREA MAGISTRALE IN SPACE ENGINEERING - INGEGNERIA SPAZIALE

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1. Introduction

Over the last years, the launch of satellites has drastically increased due to a wider use of those for commercial purposes. For this reason, orbit overpopulation and space pollution are becoming serious issues for the new generations, resulting in an increasing number of collisions and discarded objects that generate orbital debris around the Earth. As a direct result, each year active satellites need to dodge out of their way an increasing number of objects [3]. Clearly, it is of vital importance to take action before collisions occur in order to avoid fragmentation or explosions of operative spacecrafts. For this reason, Space Surveillance and Tracking systems (SST) are constantly developed by all the mayor space agencies over the world. Generally, SST systems retrieve data from observing debris via radars and optical telescopes both ground-based and space-based. Those are processed to update a catalogue containing information about all the observed objects, i.e. orbit parameters and dimension. With a complete catalogue, SST systems can provide collision avoidance alerts. In order to obtain and maintain this kind of catalogue, it is necessary to grant access to as many observable objects as possible. Space-based optical sensors are significantly more effective than ground-based ones, but, in spite of their limitations, any ground telescope could potentially contribute to space debris observation and orbit determination. The most widely used for already catalogued debris monitoring are optical telescopes, which detect space objects using the visible spectrum, gathering photons coming from the orbiting object on CCD or CMOS cameras. This thesis work proposes a new, possible approach for unknown orbit debris tracking from a ground based optical telescope operating in staring mode, using AI for real-time detection and INDI server as telescope controller. The software is called “STRATEGIC”: Space debris TRacking Algorithm for TElescope Guidance and Instantaneous Control, based on the blocks represented in Fig. 1.

2. Fundamentals

The main goal of STRATEGIC is to keep on tracking the angular position of an unknown object pass in the sky. To accomplish this mission with a real telescope, a simulation has been carried out with a virtual telescope, shooting synthetic night sky images in .FITS format. The telescope routines such as movements and image

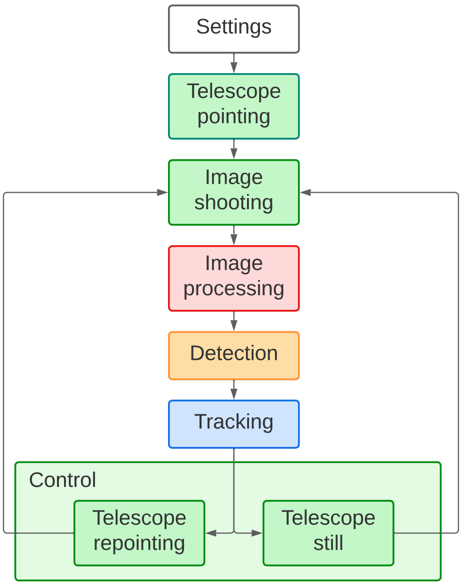


Figure 1: STRATEGIC main workflow.

shooting are controlled by INDI server, which stands for "Instrument Neutral Distributed Interface". It is a software able to control astronomical equipment acting as a bridge between software clients and hardware devices. The virtual telescope shoots a synthetic image of the sky, where celestial objects are artificially represented with white dots. INDI server relies on KSTARS catalogue, including all planets and stars but no artificial satellites. Usually, a real object captured by a CCD or CMOS camera leaves a streak on the photo, although, since KSTARS catalogue [5] does not include them, this process needs to be simulated. The trail is printed directly on the synthetic image by means of an algorithm called Tracklet Image Generator (TIG)[2]. The code relies on a file called "SCOOP" where a set of known object passages are listed in Azimuth-Elevation coordinates to identify the exact placement of the tracklet inside the image. The image is also converted to ".PNG" 8-bit, a more suitable format for the subsequent detection step. Whenever STRATEGIC software will be applied to a real telescope, the TIG processing block is going to be removed, since a real shoot already includes the object tracklet. At the end of this process, the resulting image resembles the one in Fig. 2.

Figure 2: TIG tracklet printing.

At this point, STRATEGIC moves the image to the detector's folder, where an AI, by means of a Convolutional Neural Network called YOLO (You Only Look Once)[4], identifies the position of the tracklet inside the image, drawing a Bounding Box around the target, as in Fig. 3, together with a set of text outputs used for tracking and control.

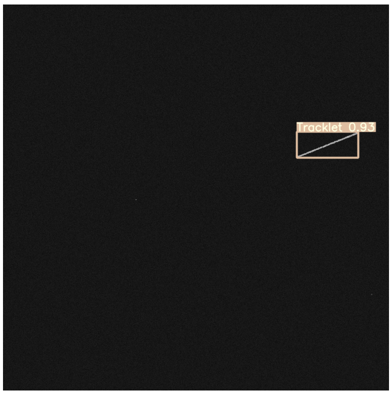


Figure 3: YOLO Bounding Box.

3. STRATEGIC: Tracking and Control Software

STRATEGIC is a modular software based on blocks with specific tasks. The main tools employed are the algorithms listed in Fig. 4, that cooperate to track an unknown object for its whole visible passage and will be explained in the chapter hereafter. The figure also shows to which task each block is referred to ease the reader understanding of the overall pipeline.

3.1. STRATEGIC

As it is possible to notice in Fig. 1, STRATEGIC is divided into 6 main blocks: SETTINGS, IMAGE PROCESSING, DETECTION, TRACKING, PREDICTION and CONTROL. The control part takes the prediction block output re-

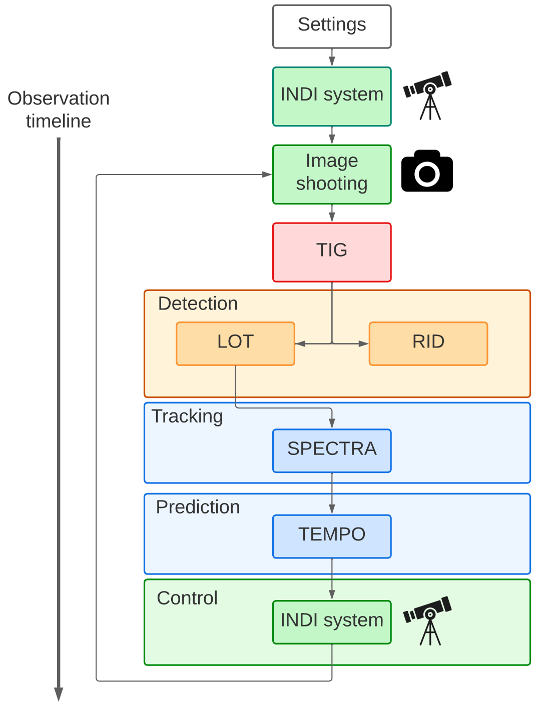


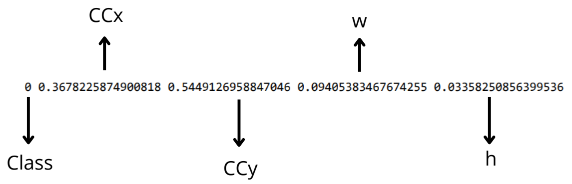
Figure 4: STRATEGIC modular composition.

garding the telescope coordinates and decides if before the next iteration the camera frame needs to move or not. In the latter case, INDI system commands update the new telescope coordinates and activate the mount, starting a new iteration. At the beginning of STRATEGIC settings, INDI server is launched.
After the first pointing, a photo is shot and TIG prints the tracklet. Once the image is moved to the detection folder, LOT analyzes it.

3.2. LOT

LOT stands for Linear Orbit Tracker[1]. It allows to detect if a satellite or an orbiting debris is passing in front of the CCD camera, analyzing the photo taken and searching for a tracklet in it. If many pictures are shot and a tracklet is found in two or more consecutive images, LOT is able to examine the possible trajectory of a streak and understand if the object in the latter image is the same as the one in the former, thanks to a geometrical analysis on the tracklet slope. Indeed, LOT is able to retrieve three different kind of useful outputs in non-dimensional, cartesian coordinates:

1. the first one is a text file containing the centroid coordinates ("$CC_{x,y}$") of the bounding box (see Fig. 3) detected by YOLO together with its width (w) and height (h), as the example given in Fig. 5.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0 0.3678225874900818 0.5449126958847046 0.09405383467674255 0.03358250856399536
```

Figure 5: LOT first text file.

2. the second text file contains the computed two possible slopes and intercepts each tracklet can assume inside the bounding box;
3. the third file is generated **only** if LOT determines that the last two tracklets belong to the same object and it contains the coordinates of the last two centroids detected.

LOT has no references to the real position of the image in the sky, neither to its shooting time. This is a great limit for LOT and the main reason of object tracking failure if no corrections are applied to its outputs. Moreover, LOT is a fast but inaccurate detection algorithm and it is not able at all to detect if more than a single tracklet is present inside the image. For this reason, another detection neural network has been involved in STRATEGIC software.

3.3. RID

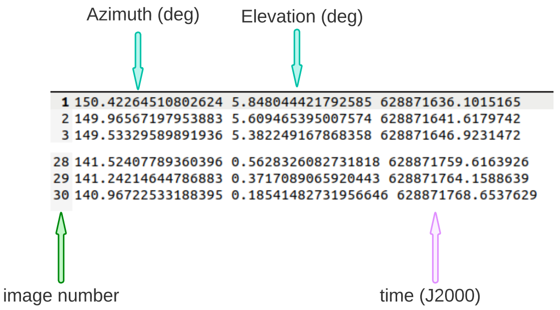
The Real Image Detector[1] could be considered the "earlier version" of LOT: it does not correlate consecutive images, but it applies on them a slower, more effective detection. As a comparison, LOT requires about 0.2s-0.4s to execute a detection on a image, while RID can take from 0.6s-0.8s up to 2.4s. The connection between RID to LOT has been carried out not only for detecting multiple tracklets, but also because LOT fails about 1 over 30 analyzed synthetic images. Indeed, it may fail repeatedly with real photos, more affected by background noise and clouds disturbances. The process required the two neural networks to work in parallel since they operate with different net weights and models. For this reason, a new code launching RID starts running in parallel to the main. Whenever LOT fails its detection, the image is sent to RID's folder, where another detection is applied. LOT waits 1s for RID to retrieve the same text file as in Fig. 5. If the detector is faster than 1s, the file is placed in the same folder LOT would have located it and the code proceeds as a nominal case, otherwise the detection fails and an off-nominal case raises up. This allows to avoid the user to trade off between the detection of faster objects thanks to LOT and the chance of recognizing more than a single tracklet inside an image. Moreover, it decreases the amount of off-nominal cases, reducing the possibility of losing the object tracking.

3.4. SPECTRA

STRATEGIC's SPace dEbris TRAcker (SPECTRA) is able to provide all the absolute coordinates an observed object assumes during its passage and raises an alert if the detectors did not produce any output. SPECTRA takes as input:

1. the time instant of the shooting, computed as the mean time between the intial and final moment of exposure, namely when the object should pass through the centroid of the tracklet;
2. LOT's text file containing the cartesian coordinates of the tracklet centroid;
3. the telescope pointing coordinates.

The function converts the relative, non-dimensional cartesian coordinates in absolute celestial Azimuth-Elevation ones, and at each iteration it updates a text file with the object location both in space and in time, keeping track of the debris passage in the sky and creating a discrete set of data for a future orbit determination algorithm. At the end of the operation, the obtained file is similar to the one in Fig. 6.



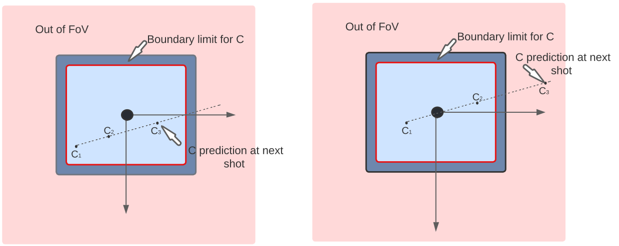
```
 1 150.42264510802624 5.848044421792585 628871636.1015165
 2 149.96567197953883 5.609465395007574 628871641.6179742
 3 149.53329589891936 5.382249167868358 628871646.9231472

28 141.52407789360396 0.5628326082731818 628871759.6163926
29 141.24214644786883 0.3717089065920443 628871764.1588639
30 140.96722533188395 0.18541482731956646 628871768.6537629
```

Figure 6: SPECTRA text file.

3.5. TEMPO

The TElescope Movement Prediction and Oversight algorithm predicts when and where the telescope needs to move to keep an orbiting object inside the camera field of view. TEMPO is connected in the main code of STRATEGIC after SPECTRA since it is not able to understand when LOT fails the detection. Indeed, TEMPO needs the information of the last telescope movement and if a detection has been missed by LOT and RID to recognize an off-nominal case and fix LOT's data misinterpretations. TEMPO takes as input LOT's text file containing the position of the last two centroids and links those coordinates with their corresponding time instants. This way, TEMPO is able to estimate a linear velocity along x and y of the object movement, and it predicts if after a shooting time the next centroid is going to exit the camera FOV (Field of View) or not, as shown in Fig. 7. If so, a telescope re-pointing is necessary; thus, the next centroid position is estimated considering the telescope movement and the next iteration processing time. The relative distance between the actual telescope position and the future one is computed and converted into absolute celestial coordinates.



(a) Telescope must shoot another picture. (b) Telescope must be retarget.

Figure 7: Graphical representation of future centroid's estimation.

LOT is not aware of different telescope frames, neither of previous failures. This causes two possible misinterpretations of the centroids coordinates: in the former case, they are associated to the same absolute position even though the telescope has moved meanwhile. Instead, in case of a previous failure, the two centroids are not consecutives anymore, thus they would be associated to the wrong time instant. TEMPO, thanks to SPECTRA alert and by knowing all the telescope movements, understands if one of those events happened and acts consequently, solving the possible criticality.

3.6. STRATEGIC loop

STRATEGIC as of today is a “While True” loop, that has to be stopped manually. New ways of sky scanning could be implemented to improve the telescope pointing while searching for a new object to chase.

4. Results

STRATEGIC has been tested with a set of satellite passages, each one with different trajectories, to prove its consistency. The results were obtained in the following way:

1. An object is chosen within the SCOOP file dataset;
2. initial observation moment and initial coordinates are set to simulate the first picture in which a random object is found;
3. after the first shot STRATEGIC automatically follows the object.

As an example, one of the tracked objects is reported in Table 1.

Exposure time	1.5s
FoV	2°
Object number	1
Observation date	06 DEC 2019
Initial observation time	02:49:50
Available final time instant	02:52:41
First Right Ascension pointing	16.430380°
First Declination pointing	6.629000°
Last Right Ascension pointing	31.411010 °
Last Declination pointing	0.056500 °

Table 1: Object data.

STRATEGIC was able to shoot 69 images with a streak inside the camera FoV before TIG ended the available data on SCOOP. A representation of the object trajectory is shown in Fig. 8.

4.1. Off-nominal cases

In this case, the trajectory has an extremely low slope and 62 images were obtained over the observation time. Initial parameters are summarized in Table 2. LOT could not detect four tracklets; RID required more than 1s in three of those cases. Therefore, Fig. 9 shows the three empty rows of SPECTRA file. None of them caused a criticality in the observation, which arrived at the end of TIG limit either way.

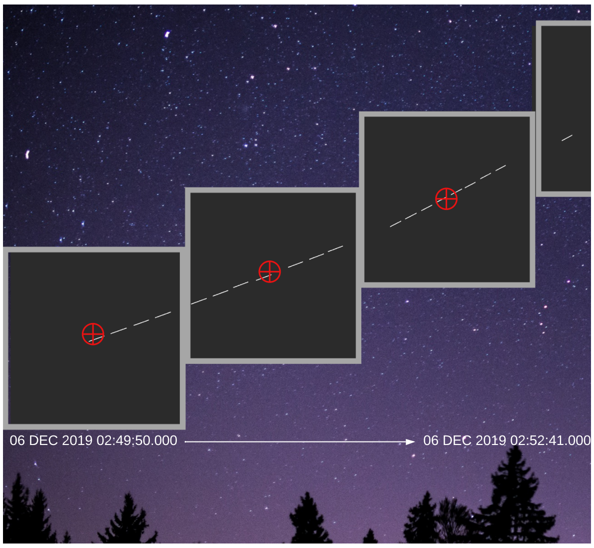
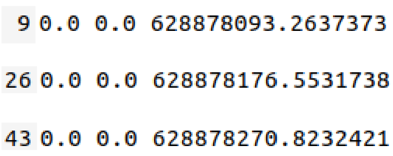


Figure 8: Object trajectory in the sky.

Exposure time	4s
FoV	2°
Object number	2
Observation date	06 DEC 2019
Initial observation time	04:19:27
Available final time instant	04:25:15
First Right Ascension pointing	207.309070°
First Declination pointing	6.007530°
Last Right Ascension pointing	173.534590°
Last Declination pointing	0.044540°

Table 2: Second object data



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9 0.0 0.0 628878093.2637373

26 0.0 0.0 628878176.5531738

43 0.0 0.0 628878270.8232421
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Figure 9: Object 2 SPECTRA off-nominal results.

Tracklet 9 is indicated in Fig. 10 with a white arrow. TEMPO spent an higher amount of time than the other iterations to predict the next position, thus the successive trail is more distant than the others. Results are represented in Fig. 10.

Figure 10: Object 2 passage representation in the sky.

5. Conclusions

STRATEGIC is a fast, innovative, modular software able to provide data on a completely unknown object and predict its movement with linear assumptions. Its innovation comes from the employment of Artificial Intelligence for real-time images detection, a new field which is recently exponentially growing and enhancing its performances. Moreover, STRATEGIC is able to take advantage of the properties of more than a single Neural Network all in once and this is a great innovation it brings to previous works, together with the possibility, for the first time, to actually track an object in the sky and retrieve concrete information about its passage. Further implementations could optimize also the timing performance of the software, still at its prototype phase. Furthermore, STRATEGIC results still need to be tested on real images, with a real telescope.

References

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