→ DISCOVERY

Deep Active Tracking: an AI-based system for an active tracking of Earth features from OPS-SAT

Executive Summary

Early technology development

OSIP OPS-SAT EXPERIMENTS CAMPAIGN

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Activity summary:

A proof of concept of an attitude control system based on Artificial Intelligence, as an alternative of current state-of-the-art systems based on model approaches, has been developed and tested in a simulator and in the EM of the OPS-SAT. The system relies on Computer Vision and Deep Reinforcement Learning algorithms to command the OPS-SAT reaction wheels in order to actively modify its attitude, so that the on-board optical camera keeps framed and focused on a target without the aid of any other instrument, such as the star tracker, the ADCS or the GPS receiver.

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ACRONYMS

ADCS: Attitude Determination and Control System

AI: Artificial Intelligence

CV: Computer Vision

DAT: Deep Active Tracking

DKE: Dynamic and Kinematic Environment

DQN: Deep Q-Network

EM: Engineering Model

FM: Flight Model

FPS: Frames Per Second

FOV: Field of View

SEPP: Satellite Experimental Processing Platform

TRL: Technology Readiness Level

1. INTRODUCTION TO THE DAT-SYSTEM

The ability for a spacecraft to process data onboard and to make autonomous decisions becomes near critical as high-performance spacecraft motion planning autonomy is essential to the space activities, from deep space exploration to Earth observation. AI exhibits long-term planning and situational awareness that may outperform traditional control methods when dealing with complex dynamical environments.

Computer Vision, **Deep Neural Networks** and **Reinforcement Learning** approaches are promising tools to develop active tracking systems that can leverage their relatively low computational requirements when deployed in edge devices, avoiding data transfer and ensuring autonomous spacecraft attitude control. The OPS-SAT platform provide a unique platform for experimentation in this field.

Guided by this vision, Adática has developed **the proof of concept of an attitude control system based on Artificial Intelligence for a spacecraft**, as an alternative of current state-of-the-art systems based on model-based approaches. The system is named as **Deep Active Tracking system** (DAT system). The development targeted the OPS-SAT as the platform for the deployment of the system demonstrator as well as the testbench for evaluating its performance.

The mission entrusted to the DAT system within the OPS-SAT is to command its reaction wheels in order to actively control and modify the attitude of the prove, so that its optical camera keeps framed and focused on an Earth feature observable from its orbit and previously detected by the system itself without the aid of any other instrument installed in the OSP-SAT, such as the star tracker, the ADCS or the GPS receiver

Islands were selected as target for the DAT system demonstrator. Yet, the inherent capacity of AI algorithms within the DAT system to generalize allows it to be trained to carry out an active tracking of any other natural or man-made feature observable in orbit.

Two AI-based algorithms are placed at the core of the DAT system. A **computer vision** algorithm that processes the information from images taken by the HD optical camera of the OPS-SAT in order to detect the presence of a target (in this case, islands) and to output its location. And a **smart agent** that, after having received the location of the target from the first algorithm, decides which sequence of actions are the optimal to place and keep the target centered on the images taken by the OPS-SAT camera.

The inability to train the smart agent of the DAT system in the real space environment in which the OSP-SAT operates forces the use of a simulated environment, the so-called Dynamic and Kinematic Environment (DKE), for that task. The DKE simulates both the OPS-SAT dynamic/kinematics and the optics of its optical camera in order to capture the whole physics of the problem involved with a certain degree of accuracy. The creation of this DKE was also part of the development.

2. ACHIVEMENTS

Computer Vision algorithm

A functional object detection algorithm based on YOLO neural network architecture was developed for detecting the presence of islands, providing their boundaries in the form of bounding boxes from which the location of the target is obtained.

The performance of the model was tested against an evaluation set of images and their corresponding ground truth annotations. The trained model is highly accurate with the evaluation set obtaining a mean average precision (mAP) of 0.7136. Figure 7 shows samples of unlabeled images from the OPS-SAT dataset passed through the trained detector model. In red the predicted bounding boxes (with average detection confidence of 68.50%).

Smart Agent based on Deep Reinforcement Learning algorithm

A functional smart agent model, based on DQN algorithm and trained with Deep Reinforcement Learning, has been developed and trained in an ad hoc simulated environment (DKE) of the OPS-SAT physics. The trained smart agent is capable of outputting the relevant sequence of actions to maintain a stable active tracking of a target by keeping the target centered in the camera frame.

Dynamic and Kinematic Environment (DKE)

An ad hoc simulated environment, the so-called Dynamic and Kinematic Environment (DKE), was developed to train the smart agent of the DAT system on ground.

The DKE is a model-based algorithm that simulates both the OPS-SAT dynamic/kinematics and the optics of its optical camera in order to capture the whole physics of the problem involved with a certain degree of accuracy. Note that the DKE is not a perfect representation of the real physical environment, but only a suitable representation of the physics involved, accurate enough for the purpose of training the smart agent in its duty on ground.

The DKE can propagate dynamics of OPS-SAT as a result of the interaction with its reaction wheels. Then, it is able to convert the change of OPS-SAT attitude into a change of the target position within the focal plane of the camera. The DKE was coded to fit within the Gym format from OpenAI in order to ease the interaction with the smart agent during training in a standard way within deep reinforcement learning community.

Smart Agent testing in the DKE

The smart agent has shown to be capable of outputting the relevant sequence of actions to maintain a stable active tracking of a target and to keep it centered in the FOV when tested in the DKE simulator.

In particular, the smart agent takes less than 18 seconds on average to get a steady tracking of the target after its detection, whatever the initial attitude of the prove is, and it is able to maintain the active tracking until the target is out of sight. Moreover, the agent consistently keeps the target centroid centered within a square of ca. 200x200 pixels relative to the original image resolution.

Furthermore, the smart agent has shown a good performance when facing scenarios in the DKE simulator different to those in which it was trained. In particular, the behavior of the smart agent is resilient to variations of the angle of vision of the optical camera (+/- 5º); to variations of the mass and inertial distribution of the OPS-SAT (+/-5%); to variations of the actual torque supplied by the reaction wheels (+/-5% regarding its theoretical values); to misunderstanding or skipping the commands sent to the reaction wheels (up to 10% occurrence probability); or to skipping a state vector coming from the CV detector (up to 10% occurrence). However, the agent's behavior is quite sensitive to the variation in the integration time between two commands to the reaction wheels, that is, the control frequency or the time between two consecutive commands to the reaction wheels: the longer the time, the lower the capacity of the agent to keep a stable tracking of the target or even track the target at all.

Deployment in the OPS-SAT SEPP

All the building blocks of the DAT system were properly deployed in the OPS-SAT SEPP as binary programs compiled to run on the SEPP operating system. The management of all those programs is carried out by means of a script written in plain Python, that runs directly in the SEPP. This code was tested to run successfully in the EM of the OPS-SAT.

Experiments in the EM

The DAT system has been subjected to a series of test in the Engineering Model (EM) of the OPS-SAT. The purpose of them was to verify the proper operation of every building block of the DAT system, prior to the final deployment to the Flight Model (FM). The tests on the EM included:

- **T. 1:** Assessing the proper functioning of the *ad hoc* binary programs for the image pre-processing, object detection and attitude control steps.
- **T. 2:** Testing of the proper link between the computer vision algorithm and the on-board HD camera, the correct functioning of the image acquisition process, and ensure the experiment runs through the object detection pipeline.
- **T. 3:** Testing of the proper link between the smart agent and the on-board reaction wheels, the correct functioning of the reaction wheels commanding, and ensure the experiment runs through the whole attitude control pipeline.
- **T. 4:** Assessing the proper running of the whole experiment in ground conditions

Several insights were captured from these tests, including the confirmation of a successful deployment and running of the DAT system on the EM. Both the acquisition and processing of the images are identified as the bottleneck in terms of computational time. The time for an image acquisition and its availability to the system varies from 4.5 to 6 seconds. This time adds up to the image processing (ca. 5 seconds) and later object detection inference (ca. 5 seconds) required to obtain data for subsequent attitude control prediction.

Experiments in the FM

A set of in-orbit experiments was proposed for assessing the performance of the DAT system in standard and singular conditions (with disturbances). The latter judges the generalization capability of the agent to well operate when facing non-trained-before or unexpected situations. A petition for a first test was formulated but not accomplished yet. Therefore, conclusions about the performance of the DAT system are formulated based on results from tests in the DKE Simulator, from on-ground tests and from what is expected from in-orbit tests.

3. CHALLENGES FACED DURING DEVELOPMENT AND DEPLOYMENT

The development team of the DAT system has had to tackle with a number of unexpected technical challenges throughout the development of the DAT system and its deployment into the OPS-SAT SEPP. Despite they cannot be considered as showstoppers, they did directly impact on the performance of the system, its development, the deployment process and, ultimately, the objectives completion as per what was initially defined.

- **Challenge 1**. Faced with the unfeasibility of installing the required Python libraries on the OPS-SAT SEPP, some of the system building blocks needed to be re-defined, re-coded and compiled into self-standing binary programs using C/C++ programming language at an advanced stage of development. This had a huge impact on the original definition of the system, the initial requirements, the deployment strategy as well as the schedule and work resources needed to execute the modifications. It also led to an intense and time-consuming debugging process on the EM with the necessary support of the OPS-SAT team.

- **Challenge 2**. Despite the on-board camera capability to acquire images at high FPS, the DAT system needs the images are available in the SEPP and the latter processes them at a high rate to be able to provide the smart agent with the position, velocity, and acceleration of the target. However, the time the camera and the SEPP take to do it is not short enough. This fact strongly constrains the control frequency of the DAT system, that is, the time between consecutive attitude control actions. As a result, the DAT system is not able to achieve an accurate and stable tracking of a moving target as defined in its requirements and shown when running in the DKE simulator.
- **Challenge 3**. The image dataset taken from OPS-SAT is very limited in terms of image number and target presence. Alternative data sources and image processing were considered to adjust the training dataset to be close enough to the expected images taken from the OPS-SAT. Images taken from Sentinel-2 were sued for training the CV algorithm. This fact might impact the performance of the detection algorithm in terms of target detection accuracy resulting in a potential lower rate of positive detections and/or low accuracy.

4. CONCLUSIONS

The use of AI and trained neural networks changes the traditional paradigm for system and software development. Instead of foreseeing the design and explicit coding of the software from a set of functional requirements to obtain an intended behavior, now this intended behavior can be directly captured from data, from which the behavioral model is derived through a training phase. The benefit of this approach encompasses the ability to understand long-term dependencies, deal with complex dynamic environments as well as uncertainty and exhibit long-term planning and situational awareness that potentially might outperform traditional methods.

At the end of the project, it has been proved the feasibility of the DAT system to work within a simulated local environment, this is: the capability of the system to actively track Earth features by means of the application of state-of-the-art AI-based technologies, such as deep learning, deep reinforcement learning and computer vision; and taking advantage of RGB images and taking attitude control actions within the simulated dynamics/kinematics of the OPS-SAT.

The deployment of the system to the platform proved to be challenging. Incompatibilities of software requirements with the platform (challenge 1) led to a series of changes that made the system rely on additional languages, instead of following the initial approach of developing the system with a single framework, i.e., Python and relevant external libraries. The deployment of the system required not only an intense debugging process with the support of the OPS-SAT team, but also impacted on the development time due to the needed re-definition of the system.

Despite all functionalities of the system were successfully tested with on-ground conditions, the deployment and testing of the system on the Engineering Model required more time than what was initially expected. Upon the project closure, only planned tests for on-ground conditions were carried out. However, the analysis of test results from DKE simulator and EM provides insights to predict what the performance of the DAT system would be when deployed in the FM.

The window of opportunity for detection of a target and reaction before it exits the FOV is relatively sort (evaluated in some 15 seconds in nadir position). This fact will make difficult for the DAT system when finally deployed in the FM to ensure a stable tracking since the computational time required by the **on-board camera** for image acquisition and making it available, and the **SEPP** for processing of the image, inference for detection and eventual tracking is substantially higher than initially expected. The DAT system needs to handle images acquired by the on-board camera, as well as deal with image processing and inference, which is a heavy operation for the SEPP. EM testing has evidenced how much the processor of the on-board camera and the SEPP are constraining the DAT system capabilities. Considering a more powerful computer, equipped with GPU and additional working memory, is a key element to be able to grasp the full potential that the DAT system has already shown in the simulator.

As a conclusion, the DAT system has shown evidence of its potential to carry out an active tracking of targets in a simulation environment according to the requirements defined at the beginning of the development in terms of accuracy, tracking time and stability. Moreover, the deployment of the system on the EM has been accomplished and therefore, it is found that the DAT system has reached a TRL4 after the deployment and testing in the EM of the OPS-SAT. However, the EM is just the previous step before deployment on the FM, which has not been conducted so far and therefore, preventing the in-orbit experiment campaign from taking place.

5. WAY FORWARD

The good performance of the DAT system on the simulator is a solid starting point to consider AI as an enabler to challenge the performance of state-of-the-art attitude control systems based on model-based approaches. However, the system needs to be run, and potentially validated, in real conditions to mature its TRL. Therefore, the next logical step at the end of this development phase is to find the way to carry out the in-orbit campaign of tests that could not happened to date on board the OPS-SAT FM. This could draw comprehensive conclusions on the performance of the DAT system regarding what is expected after having run it in the simulator.

Moreover, since the OPS-SAT SEPP is not found as the optimal platform for the DAT system, as long as it prevents the system from reaching its full potential, it would be interesting to define which other computer platform would not limit its performance. For instance, running the DAT system on a computer with AI acceleration modules and additional working memory would allow it to process images and make demanding calculations fast enough to, at least, accomplish with the requirements settled for the system in terms of accuracy, tracking time and stability, and proved in the DKE simulator.

Once defined, a demonstrator of the DAT system deployed in that computer platform would be the next step in the development, so that software and hardware can be tested together in relevant conditions. In the best-case scenario, they could be though as COTS module ready to be installed in other satellites to provide them with tracking and observation performances at a low cost and with the potential to serve different missions, leveraging the generalization ability of the AI algorithms in the core of the system.