AI and space security: collision risk assessment

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Abstract

The space environment has experienced drastic changes in the last years and the scenario for the next decade is expected to evolve notoriously. Mega-constellations with thousands of satellites, commercial small satellites, and low thrust propulsion spacecraft will not be the exception but the norm. Current safety strategies and collision avoidance procedures will no longer be capable to deal with the increase of information and alerts this new environment will imply. In this context, Artificial Intelligence is presented as the alternative approach for space security, due to its ability to deal with a great amount of information, support decision-making and automatizing.

Introduction

These days, the space environment is under a radical transformation that affects technologies, use of the space, mission concepts and operations. Electrical propulsion, once proved its reliability and capabilities, has started to be used during the last decade on commercial and scientific satellites, both in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO), and its use is expected to grow. Late 1990's technology improvements have resulted in miniaturization of space components that eventually have allowed satellites to reduce its size. Since 2003, when the first CubeSat was launched, the use of such small satellites by universities or for commercial usage has continuously increased and analyzes on future space environment evolution suggest this growth will maintain in the next decade. Along with this increase on small satellites, a higher rate of launches per year and new countries and private actors entering the scene are also expected. Among these new actors, maybe one of the most relevant, due to its impact on the orbit environment will be swarms and constellation mission. Along with small satellites, mega-constellations will represent the most profound change in the LEO regime during the next decade. Several of these constellations, each of them compounded by thousands of satellites, are planned and some of them have already started the deployment stage. It is expected that in the next years, the number of satellites in orbit multiply by several times. Bearing in mind that the current number is slightly below 2,000, it will push the figures to tens of thousands of operational satellites in orbit at the same time (Hugh et al. 2017).

On top of this, the most common element in Earth orbits is, however, space debris objects. Space debris refers to all man-made objects in space apart of operational satellites as well as micrometeoroids captured by the Earth's gravity. It includes upper stage rocket bodies, inoperative satellites remaining in orbit, objects left by missions and fragment from old satellites due to fragmentation or collision. From the beginning of the Space Era in 1958, the number of space debris objects has kept growing to reach the current state where there are in orbit more than 34,000 objects bigger than 10cm, more than 900,000 between 1cm and 10cm and millions of them even smaller (ESA Report 2019). These numbers are also expected to increase in the following years, not only linked to the increase in space traffic, but also due to improvements in the current tracking techniques. New infrastructures are expected to start their operation in the next decade allowing the detection of smaller objects, which have not been possible to track until now. While this increase in the cataloged objects does not mean an increase in the actual number of objects since they are already in orbit, it will boost the number of conjunction alerts experienced by satellite operators (Haimerl and Fonder 2015).

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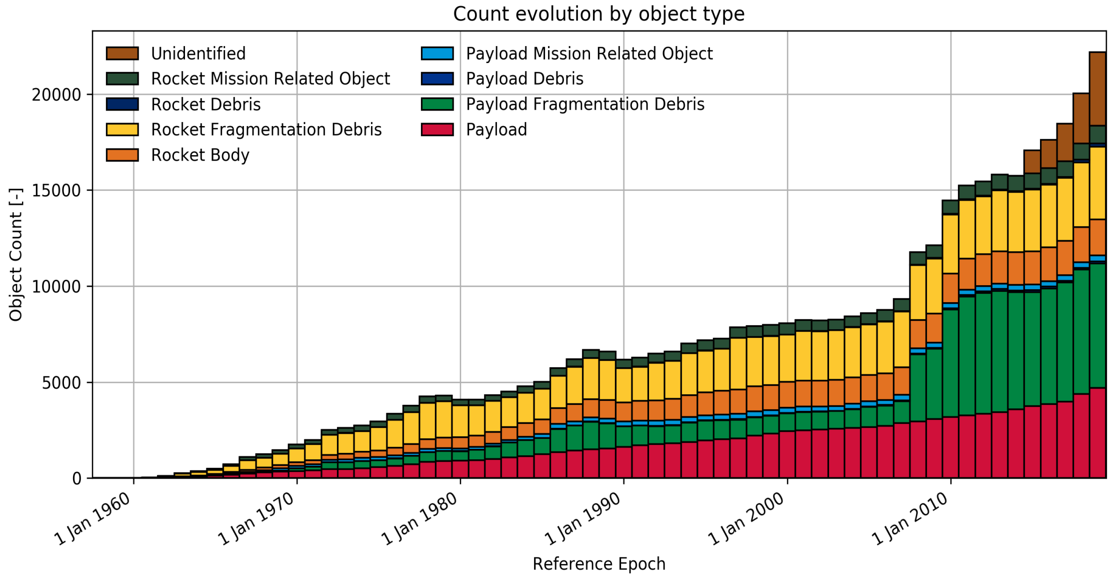

Figure 1: Evolution of number of object in orbit by type. (Credits by ESA) PERMISSIONS

What does it mean for safe operation of satellites? First of all, the collision between operational satellites between them or operational satellites and pieces of space debris will become a more tangible threat. So far, there has been only one accidental collision event involving an operational satellite, the Iridium-33/Cosmos-2251 collision in February 2009, which occurred when the number of space objects was small compared with the expected future figures and while a conjunction alert system was already operational. An event of this characteristics is likely to happened again, especially regarding the increasing space population. In the second place, the operation of those new satellites, both small satellites with reduced propulsion capabilities or mega-constellations operating in already congested regions, will bring an increment on the work load and dedicated time for operators to manage the possible conflicts. Not only during their operational life, but also during deployment and disposal, when these thousands of satellites will cross other populated regions below their operational altitude. In addition to this, new satellites are likely to be equipped with low thrust engines that on the one hand are more efficient but on the other required more time for executing maneuvers. Longer maneuvers time means more time for planning a collision avoidance maneuver (CAM) and longer periods crossing populated regions during deployment, disposal and routine maneuvers. In this context, it is worth to mention the CAM the ESA's satellite Aeolus was forced to implement to avoid one of the StarLink constellation satellites. It was the first implemented by any ESA's satellites for avoiding a mega-constellation satellite and and gaps on the communications between operator and the lack of protocols were notorious. It has occurred even when the constellation is not completely deployed, highlighting the impact of future New Space's satellites and the precariousness of the system at critical stages when agreeing a common avoidance strategy between operators. On the third place, the increase on cataloged objects, operational satellites, and the potential new space debris objects will translate in an unmanageable number of conjunction alerts received by operators. The occurrence of these alerts does not necessarily mean the collision is going to happen, but they are high resource-consuming for operators, since a detailed risk conjunction assessment is required. With current levels of space traffic, ESA's Space Debris Office has to deal with hundreds of conjunction alerts per week only affecting the near 20 satellites they operate. Among these alerts, just a small percentage are actionable alerts (alerts which required a more detailed analysis or the collection or better quality data), and just one among 5-10 of these actionable alerts required an avoidance maneuver (Merz et al. 2017). The expected boost of alerts during the next years, even if they not required any actions, can collapse the current system, taking into account the work load and time it requires and the coordination it implies. If besides, the Probability of Collision, the metric used for evaluating events as high-risk or low-risk conjunctions, presents important limitations (note that the aforementioned Iridium-33/Cosmos-2251 collision event presented a Probability of Collision not classified as high risk by several operators), the system leads to a catastrophic result unless major renovations are implemented (Peterson et al. 2018).

Among those renovations, automation is a major one. A shift from a system where each satellite is operated by several agents to a system where only one operator can manage several satellites is desirable. However, such a situation is not possible with the current system structure, especially considering the expected traffic growth. It is at this point where Artificial Intelligence (AI) plays a crucial role. AI techniques can operate faster than current models and take decision considering a wider set of parameters than human operators and have the capacity to perform better when the available data increases, which is the scenario expected for the next years in space. If a certain set of reliable data is provided, AI systems are able to learn directly from them and predict accurate results without the need for any physical model. In a scenario where more and more data will be available and when time is a critical resource, using the surrogate model these techniques provide can be the key for the automation of the Space Traffic Management system required. While only a few examples of AI applied to Space Traffic Management can be found, they have been successfully used for predicting events, classification and decision support in other engineering fields, including space and air traffic management. This allows thinking that AI systems are a promising trend in the next years.

The rest of the Chapter deepens on the application of AI in space engineering in general, and in Space Traffic Management in particular. First, a summarize of the current situation of the Space Traffic Management (STM) and Space Situational Awareness (SSA) systems is presented, highlighting the critical situation for the future regarding the expected increase in space traffic. An overview of studies about AI in the field of traffic management, collision avoidance, and space engineering is then presented, followed by a survey of the main works on the application of AI on the STM system. Finally, some challenges to be addressed for a good implementation of AI techniques are stated.

AI and space security: collision risk assessment.

Space safety system

A fundamental concept in space security is Space Traffic Management (STM), which is defined as "the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space and returns from outer space to Earth free from physical or radio-frequency interference" by the IAA (International Academy of Astronautics) in the Cosmic Study on Space Traffic Management. This concept includes a wide field where different knowledge areas play a role on space security and safety. On one hand, there are the rules, standards, and recommendations related to the satellite operations, maneuvers, conflict resolution and collision avoidance. This group also includes the protocols to be implemented if a conjunction between two operational satellites is reported as well as the good practices on sharing satellite's operations information. On the other hand, are the technical aspects whose aim is the implementation of the previous protocols and good practices for the safe operation of the satellites, including tracking of space objects, conjunctions detection and risk assessment as well as action for the mitigation of the risk of collision.

Another concept related to space security is Space Situational Awareness (SSA) that involves the actions, techniques, and technologies for the tracking, orbit determination and calculation of ephemerides of the space objects. Both SSA and STM are closed related since the STM system needs the knowledge provided by SSA about the state of the satellites to provide conjunction alerts, perform the correct CAM if needed... Combined, these two systems create a more complex one that involves information of thousands of space objects, requires the coordination of different operators, satellite owners, and teams, and provides alerts and actions to be taken whose consequences have to be managed in a short interval of time.

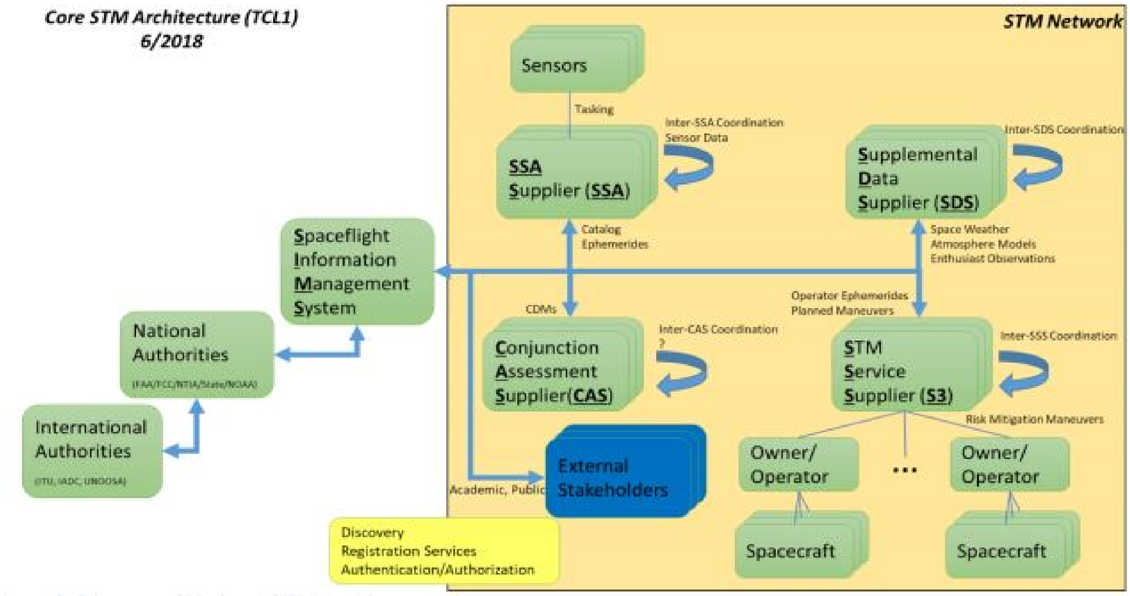

Figure 2: Proposed STM architecture inspired in NASA UTM system. (Credits by NASA) PERMISSIONS

Continuous monitoring of all the trackable space objects around the Earth, both operational and non-operational satellites, is carried out by SSA services providers. The main actor is the US's USSTRACOM, although commercial companies and other states are getting more relevance in the last years. When a potential encounter between one operational satellite and a piece of space debris or another operational satellite is detected when propagating the observable states, a Conjunction Data Message (CDM) is created and send to the operators in charge on the involved satellites. Since information collected by the SSA system (USSTRACOM) presents low quality, especially for space debris objects, the observable state and the propagated one are affected by uncertainty. A more dedicated following can be carried out to reduce this uncertainty. With all the available CDMs associated with a single event, a conjunction risk assessment is executed by the operators' CARA (Conjunction Assessment Risk Analysis) team to determine if the event represents a true threat for the satellite and the space security or not. In the case of a high probability of collision associated with the event, a complex process starts. The first step, if the event involves two operational satellites, is agree a common strategy, relying on manual communication between operators that delay the process. The common procedure (the two satellites moves, the biggest one moves, the one with propulsion system moves...) is then analyzed with the payload team, flight dynamics team, and ground stations to come up with a possible collision avoidance maneuver strategy. This step requires a lot of coordination, time and workload as it is critical for the success of collision avoidance. Secondly, the proposed strategy is then evaluated to ensure the risk of the current event is reduced and no future possible collision arise: with the same object (secondary collisions) or with other bodies (tertiary collisions). Finally, once the maneuver is approved, the event is closely monitored and one or two days before the Time of Closest Approach (TCA), as long as the risk remains high, the CAM is performed. After the CAM is executed, the state of the satellite should be monitor again to check the maneuver has been correctly performed.

It can be seen how many critical points the performance of a single CAM associated with only one event presents. In the first place, the tight interval of time the whole process requires since information of conjunction is provided just a few days in advance. Since CDMs are available for the last 7 days before TCA, this is the time window operators have. However, the actual time interval is shorter since first CDM present high uncertainty and better quality data are usually required. In the second place, the computationally expensive and time consuming some of these step are, something that is added to the tight time window where the process is carry out. If better quality data are demanded for the conjunction risk assessment, sensors require time for providing accurate orbit determination information. Not only that, but also accurate orbit propagation is time-consuming, and it is an operation that has to be implemented in several stages: using actual orbits for obtaining the risk of collision, for evaluating different CAM proposals or for assessing future collisions once the CAM is implemented. It is not just a time issue. Besides, coordination effort is a key aspect of the process. Flight control, flight dynamics, ground station teams restrictions and mission requirements have to be considered when evaluating the possible collision avoiding strategies. The coordination tasks would be even more critical if the potential collision involves two operational satellites when teams of both missions have to agree a common strategy, a problem that worsens due to the lack of protocols and specific regulations (Peterson 2018).

On top of that, STM is not just responsible for performing CAM, but also it has to manage all the conjunction alerts received before the collision risk assessment process stipulates the event represents high probability of collision or not. All those alerts that do not need a conjunction risk assessment and those that after the assessment do not require a CAM are considered as false negatives. They do not give any information about real collisions but increase the operators' workload. There is a greater number of not actionable alerts than actual high-risk events, which means that an important part of the resources is spent on events that are not relevant for space safety. Contrary to these false alarms (false positives) there is the possibility of false negatives to occur. False negatives are those high-risk events that are misclassified, which can lead to collision or risky events not noticed by operators in advance. As mentioned before, the collision between Iridium-33 and Cosmos-2251 was a situation like this (Peterson et al. 2018). The root of these events resides, partially, in the bad quality of initial position data, especially for the space debris objects, what makes the acquisition of better quality information essential, bringing more information to the system to be managed.

Note that the situation presented shows the current state of the system, where the traffic of space objects has not experienced the growth of the next years. The implementation of a CAM explained above involves only a pair of space objects and however involves multi-disciplinary teams to coordinate a lot of information in a very constrained interval of time. False alerts and false positives mentioned in the previous paragraphs currently happen. The boost of launches programmed for the next decade leads to the scalability of the system, the final issue STM and the space safety system will face scalability. The space traffic increase will make operators struggle in managing all this information and sub-optimal decisions are likely, with their effect on space security. If currently, hundreds of alerts are triggered, the future space environment will push this number to limits that the system may not cope with. Since more resources should be put on filter false alarms, the assessment of collision risk and mitigation strategies will suffer from this increase of alerts. Besides, future operators' systems would not be based on a team taking care of one or a few satellites, but smaller teams will have to control the whole constellation with several satellites each. Such a situation is not currently possible if a greater level of automatizing is implemented and the use of a decision support system is implemented to replace most of the operators' tasks (Nag et al. 2018).

Figure 3: Planned mega-constellation for the next decade. (Credits by SpaceNews) PERMISSIONS

SSA, a fundamental part of the system, also introduces critical points to the process. It is responsible for obtaining position information about all the objects orbiting the Earth, satellites, rocket bodies or pieces of debris, as well as the ephemerides of those bodies. As can be expected due to a large number of objects orbiting the Earth, the amount of information the system has to deal with is already enormous, not counting for the expected growth of space traffic of the next years. Furthermore, the next years will witness the start of the Space Fence system, the new SSA system developed by the US for improving the monitoring of space objects. The expected increase in sensitivity will allow the track of smaller objects, invisible at the moment, including bodies in the range of 1 to 10cm, making it possible to include up to 200,000 orbiting objects in the catalogs. It means that information related to space objects position and ephemerides will increase even more at a rate much bigger than the numbers of launches since most of the new objects that will enter in the catalogs are already in orbit. A last contributor to the data SSA system has to deal with are the commercial providers, that independently to the traditional sources, carry out track campaigns, whose information has to be merged with those of the US catalogs (Crosier 2017).

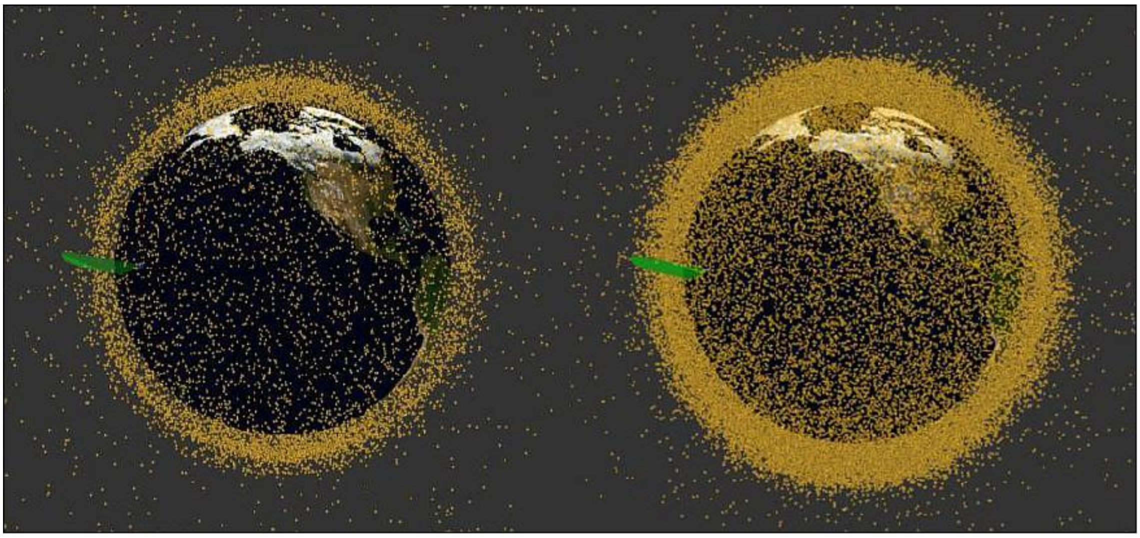

Figure 4: Current LEO catalogue versus expected catalogue when Space Fence is operative. (Credits by USAF, Lockheed Martin) PERMISSIONS

The New Space environment presents similarities with Air Traffic Management (ATM) and Unmanned Air Traffic Management (UTM) systems, where the increased on traffic population have forced them to adapt themselves to the new circumstances. ATM system is a good settle system which has coordinated an increasing air traffic population for several years. A key aspect of this system is the clear distribution of responsibilities, a good set of protocols and common practises, and the effectiveness to control several objects under only one control center, which has facilitated the automation of activities previously carried out by human operators. However, as in STM, the population growth, especially in certain regions, has forced actors involved on the system to develop a more automatic system (Kochenderfer et al. 2011). UTM system is another example where automation has been implemented to handle the rapid traffic increase and the necessity of a quick decision-making process. Some studies show the efficiency of implementing automation on the UTM and the possibility to adapt the proposed system structure to the STM (Murakami et al. 2019). Furthermore, Decision Support Systems (DSS) based on AI has started to be implemented on unmanned aerial vehicles (UAVs) control systems not for automatizing, but for supporting operators on the decision-making stage. These proposed systems use AI, fuzzy logic and other related techniques for rapidly taking into account a wide set of parameters and compute a ranking of the best options to implement under a conflict, automatizing tasks previously done by operators and speeding up the whole process. Operators can then select the appropriate actions based on the ranked list of alternatives based on certain criteria, reevaluating alternatives under new criteria or recomputing the list if more information is available. While STM presents its particularities respect UTM or ATM, it is clear that when traffic management systems have experienced the congestion of the environment, they have tended to the automation of the system, usually relying on AI techniques.

The successful examples of applying AI on other engineering fields, including space and traffic management have boosted the interest on applying these techniques on the STM system for automatizing tasks, speeding up the process, or supporting operators on taking optimal decision in an environment that is overcoming the capacity of human operators since more and more data and variables have to be considered. Among the actors interested on implementing AI for STM ESA and NASA can be named, both with programs to study the availability and applicability of AI methods onto real missions and scenarios (Benjamin Bastida et al. 2019), (Mashiku et al. 2018). ESA has identified three main aspects to be addressed by AI for facing the population increment on the orbital environment: reducing operators' workload (automation), lowering the decision-taking time on risk conjunction assessment and collision avoidance planning, and scaling down the number of false alerts.

Artificial Intelligence in engineering

Artificial Intelligence is referred to as the ability of computers for learning from data, reasoning, acquire knowledge, react to the environment and corrected themselves to imitate human intelligence or behavior without being specifically programmed to do it. It is a wide knowledge area including Machine Learning, Natural Language Representation, Computer Vision, Data Mining among many others (Russell and Norvig 2009). It has been studied for some decades, but only during the last years, when the computer advances and the possibility to access and manage big datasets, it has been possible its implementation into real applications in a broad range of disciplines, including engineering.

Among some of the applications of AI in engineering, one interesting field related to space security is traffic management and collision avoidance. An important trend in recent years is the application of AI on autonomous cars. Image recognition, intelligent decision systems, and autonomous collision avoidance are issues presented in this field and addressed by AI. However, the applicability of those techniques to a completely different environment as it is space it is not a straightforward task and it is currently under research. The development of robotics has also brought some improvements in autonomous collision avoidance algorithms. Regarding the increasing autonomous of satellites, bringing them closer to the general idea of what a robot is, some attempts of extrapolating those algorithms to the space environment have been analyzed and it is an interesting research area where promising results are expected on the next years.

The See Traffic Management (SeTM) system presents also some examples of the application of artificial intelligence on collision avoidance. While space and maritime environment presents notorious differences, there is also some similarities, like an initial sparse and wide space which has experimented an increase on traffic density, having led to the necessity of implementing autonomy on the traffic management system, or regions where this density is reaching current system limits, like ports on the see environment and the LEO region in space. In this sense, it is interesting the work presented in Statheros et al. (2008) for applying an intelligence system for ships collision avoidance, combining physical models with AI methods.

In the field of traffic management, there are also examples of using AI in the Aircraft Traffic (ATM) system and Unmanned Aircraft Traffic Management (UTM) systems. Autonomy whereas the vehicles and or the operators activities, is spread on these systems, although not necessarily by using AI. Nevertheless, the increase in air traffic and the irruption of commercial UAVs interacting with the convectional aerial traffic have forced the system to implement AI techniques for supporting the operators on the management of the system. (Kochenderfer et al. 2011), (Julian and Lopez 2018) and (Ramirez Atencia 2017).

The space sector is getting interested in AI too, having incorporated techniques and methods in different areas. Natural language processing (Berquand et al. 2018), knowledge representation, automated reasoning, computer vision (Jasiobedski et al. 2001), trajectory optimization and navigation (Izzo et al. 2018), satellite autonomy (Anderson et al. 2019) or robotics are some of the fields in space engineering where AI have made interesting contributions.

Artificial Intelligence in space security

Seems clear there is a well-established field of research and application of AI in different fields of engineering, including dealing with conflict, managing traffic and supporting decision-making. Based on the studies presented in the previous section, it is reasonable that AI and Machine Learning (ML) methods can be applied also in STM. As mentioned previously, space agencies and other actors involved on space security have started to implement lines of investigation on this direction and it is worth to explain in more detail the three main issues stated by ESA AI is expected to solve (Benjamin Bastida et al. 2019):

- Reducing the tasks operators currently carry out by implementing automation. Future increase in space traffic will translate in growth on the time and effort operators will spend just dealing with alerts, classifying events, performing detail conjunction risk assessment, planning and executing maneuvers, collecting better data or managing end-of-life strategies. Currently, some of these activities present a certain degree of automation, while others require several dedicated hours. Investing in the automation of most of these activities will allow operators to focus on the decision-making stage, on the nominal operation of satellites or handling more satellites simultaneously. Another important area where automatizing can liberate much of the operator's time is on the coordination between teams and other operators in the event of a conflict, switching for the current manual procedures for a much more automatic one, with clear protocols and standardized steps.

- Lowering decision-taking time. Automation of operators' tasks will allow them to spend more time and effort on the critical steps of decision-taking in collision risk assessment, collision avoidance maneuvers or disposal strategies evaluations. However, the expected rise in space population will imply the number of satellites to be controlled and the amount of information to be considered will exceed human operators' capacities. AI-based systems for supporting on the decision-making stages, like DSS agents, will be able to handle all this information and propose alternatives strategies to operators in much less time than current approaches taking into account a wider range of variables. Besides, surrogate models provided by AI techniques for skipping computational expensive propagator or dynamical models, or the uses of databases with predefined maneuvers examples to automatically find the optimal one are other AI-based options for reducing time in the future STM system.
- Reduce false alarms. Currently, the vast majority of conjunction alerts reported to operators correspond to events that not required any additional action (neither avoidance maneuvers nor a more detailed evaluation). While triggering alerts, this kind of events do not imply true collision scenarios, but consumes time and resources unnecessarily. In the next decade, when smaller objects can be tracked and more satellites will be in orbit, the number of such events will boost and more resources would be needed only to filter the actual collision encounters or high-risk events from all the non actionable cases. Correctly selecting events without missing the high-risk ones (false negatives) nor wasting resources on false alerts (false negatives) will be as essential as challenging for future STM, regarding current databases are dominated by those less interesting low-risk events.

While AI has been used in other areas of space engineering, its application on Space Traffic Management and Space Situational Awareness is much more limited. However, it is possible to find some pioneer works on this subject. While scarce, they cover different aspects of the STM and SSA system, addressing some of the previous aspects highlighted by ESA as priorities.

Some of those works are focus on improving orbit determination by the implementation of ML. In Peng and Bai (2018a), Support Vector Machine is used for reducing the positional error of satellites after orbit determination and orbit propagation processes. In Peng and Bai (2018b), they continued with this line of research, switching from SVM to Artificial Neural Networks (ANN). What they proposed in those works is the use ML for improving orbital determination parting from the idea that classical models keep unused certain embedded information from historical data. Using both SVM and ANN, they tested the models for predicting a satellite's position and velocity error caused by measurement and dynamic propagation model limitations. Using the historical information of a certain resident space object (RSO) during a interval of time, they expected to find the relation between them and the aforementioned error in three circumstances: for the same RSO in the same interval of time of the historical data, but at epochs not including in the training set, for the same RSO but for times after those included on the historical data, and for near RSOs, both in the same interval as the training data and posterior epochs. They demonstrated by different numerical experiments the possibility of using ML for reducing orbit determination error and thus, improving orbit position knowledge. The benefits of this method for the SSA system are clear. While SSA is responsible to keep track of all the thousands of RSOs orbiting the Earth, the accuracy of observations and models is restricted due to the great number of objects and limited knowledge of environment when building the models. Being able to correct the errors associated with them, especially deviated from imperfect modeling of the dynamics (drag, solar activity...) and limitations of the observation sensors will automatically provide a better position for detecting conjunctions and evaluating their risk. Nevertheless, the same authors are aware of some of the limitations affecting this approach as reported on another paper (Peng and Bai 2017). Lack of real data for propagating, time window limitations on the predictions and restricted generalization to other objects different than the ones used for training are some of them.

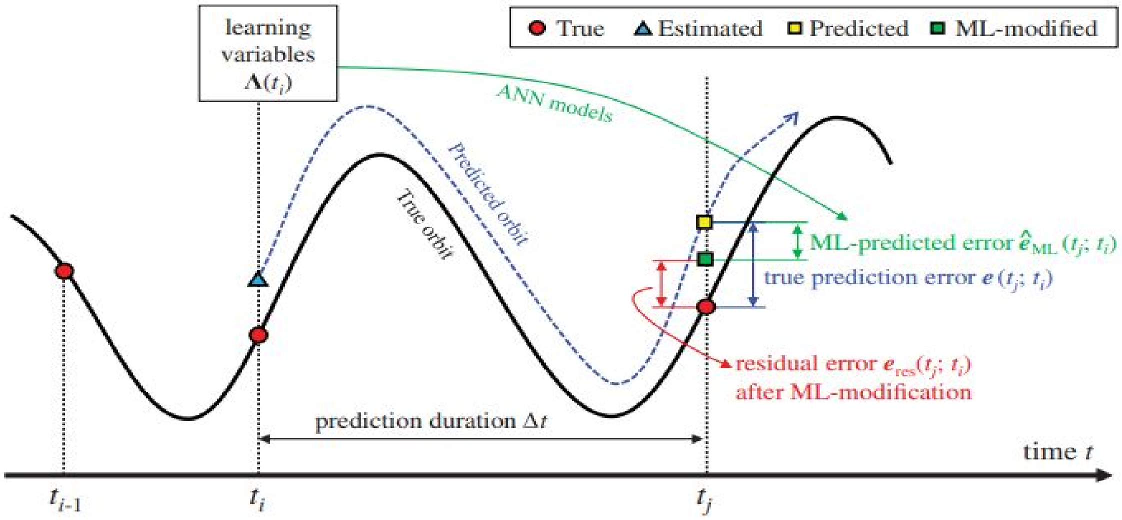

Figure 5: Reducing orbit determination and propagation error using AI. Peng and Bai (2018b) (Credits by ARC) PERMISSIONS

The previous approach correct orbit determination and propagating errors, but it is still limited to the fact that propagation of the orbit of each of the object of interest is needed, which implies a time consuming step if several bodies are considered. Sanchez et al. (2019) proposes an ML-based system for predicting collision encounters by using a set of ANNs for predicting the equinoctial parameters of a satellite during an interval of time, by providing exclusively the initial Keplerian parameters. By comparing the predicted orbits of a couple of objects, the equinoctial parameters obtained during the whole interval of time are good enough for estimating potential conjunctions by calculating the impact parameter (B-parameter) between the two bodies. In the end, the proposed method it is not anything else but an orbit propagator, substituting the dynamic models by a surrogate model based on data. Some interesting aspects explain the importance of this approach and summarize some of the general advantages of ML methods. First of all, this method provides a surrogate model of the underlying problem (the two bodies perturbed movement) that does not rely on any dynamic model nor use any integration method (nor analytical nor numerical). Since no integration is involved in the propagation, it performs faster. We are moving towards an environment where thousands of pieces can be a threat to the operational satellites and where operators will be responsible not only one but several of them, even constellations. Moreover, the tracking system will struggle on providing good positional data from every piece of space debris at any time. Possessing a fast and accurate model able to compute the propagate orbit of these thousands of satellites becomes crucial for the future of STM. The second advantage this approach presents is the model relies on the data used for training. As in Peng and Bai (2018a) and Peng and Bai (2018b), dynamic model errors are avoided since ML does not use any physical model, but build one based on the available data. In this way, by using the historical real position data, the uncertainties associated with drag, solar radiation pressure and any other physical effect difficult to model simply do not influence the final result. As can be seen on the results proposed in Sanchez et al. (2019), the error is not dependent on the closeness to the initial epoch, as it usually happens on dynamic based orbit propagators, since a independent set of six ANN has been trained for each epoch based on the real orbital parameters of the training RSOs. This work is presented as a first step towards the use of ML in STM and, therefore, also presents some limitations: data used for training (assumed as real position) comes from a virtual database obtained by using a high fidelity propagator and the conjunction events prediction is made assuming the Keplerian propagation of one of the satellites involved on the conjunction. However, despite these limitations and being a relatively simple ANN model, it can provide accurate results for equinoctial parameters and detection of conjunction event of RSOs different from those used for training. In addition, it performs quickly compared to orbital propagators when several object´s orbits are propagated. Although it provides preliminaries results, it sets a promising path for using ML in orbit determination and orbit propagation.

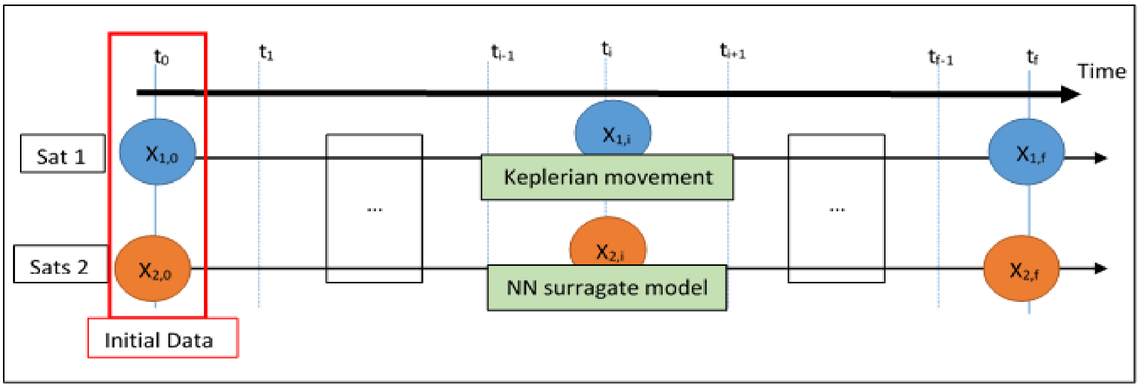

Figure 6: ANN for orbit propagation and conjunction event prediction. Sanchez et al. (2019) PERMISSIONS

Other approaches have been followed for applying AI in STM. In Sanchez et al. (2020), ML algorithms have been tested for classifying conjunction events based on a new approach for evaluating the risk assessment. The new approach pretends to overcome some limitation of the current most used risk metric, Probability of Collision, by using the Belief and Plausibility concepts coming from Evidence Theory, accounting thus for epistemic uncertainty on collision risk assessment. This approach takes the conjunction geometry between the two objects involved in a conjunction and includes the uncertainty from the point of view of the Evidence Theory. Assuming one or more sets of statistical distributions, each parameter defining those distribution is provided as an interval or intervals where the true value can be included, according to the different sources, i.e. sensors or experts. Each of this intervals are associated a basic probability assignment accounting for the reliability of each source, which allows taking into account not aleatory and epistemic uncertainty independently. The classification criteria proposed for conjunction events is then based on time, Belief and Plausibility thresholds. Some ML methods, like Artificial Neural Networks, Random Forests, and K-Nearest Neighbours have been tested for creating two different intelligent classification systems, one using as inputs values of Belief and Plausibility as well as time, the other considering time and geometry, allowing skipping the time consuming step of computing the Belief and Plausibility curves. Each of the classes are related with an actions that would be suggest to operators in the decision-making process. The results proposed in this work the potential used of ML for decision-making support. Another intelligent decision support system is presented in Vasile et al. (2017). The idea of the proposed method is supporting operators in the planning and implementation of collision avoidance maneuvers when needed. An interesting contribution of this work is the creation and exploitation of a database of possible predefined maneuvers to be implemented in a conjunction event scenario. A virtual satellite position dataset was created to obtain conjunction events and later, computing the optimal maneuvers, which were stored in a new database. The new orbits generating after the CAM were also storage in the initial database and analyzed for detecting future encounters and thus, obtaining a wider range of CAMs for feeding the ML algorithms. The availability of a database with these characteristics, with a broad variety of possible maneuvers, provides fundamental information to an intelligent decision system for providing alternative proposals based on certain criteria. The criteria selected on this worked considered the risk of not executing the collision compared with the risk associated with future possible collisions. The ideas presented on those works lay the foundations for future intelligent DSS for supporting operators. Other criteria can be implemented on the AI-based DSS to elaborate more sophisticated ranked lists of proposals to the operator like confident on the sources, the inherent risk of executing a maneuver, the cost of the maneuver versus the cost of the satellite itself, restriction due to mission requirement or fuel usage limits. Sophisticated DSS system accounting for several variables and proposing alternatives in relative short interval if time has already proposed in other fields of traffic management (Ramirez Atencia 2017).

There is another aspect of the satellites' mission crucial for space security: the disposal and re-entry stages. The end of life of a satellite affects space security in several aspects. First of all, it is essential for decrease the rate of space objects in orbit, since it is the easiest way of removing bodies from space, second, during the decay stage satellites have to cross highly populated regions, something that will become more critical when mega-constellations are completely disposed of. Finally, it is an extremely uncertain stage since atmosphere drag start to be the dominant effect and density models are imprecise, solar activity is still not well modeled and knowledge on the behavior of satellites during re-entry is hard to predict. Minisci et al. (2017) presented a study for uncertainty propagation during the last stages of a GOCE mission. Besides the uncertainty quantification and characterization study, the use of High Dimensional Model Representation (HDMR) methods and the creating of large databases have set the path for the future use of AI on re-entry time windows prediction. In the same work, meta-models based on AI were preliminary studied for mapping initial stated and model uncertainties to re-entry time windows. Initial results suggest that it is possible to estimate the re-entry window by this method and without any propagation. Further analysis is being carried out for a better implementation of this idea and results suggest the potentiality of this approach.

Some other works and studies relating AI with space security, STM and SSA have been carried out recently. Furfaro et al. (2019) used a Recurrent Neural Network (RNN) and Convolution Neural Networks (CNN) for classifying and characterizing RSOs based on their curve of light for STM. In Mashiku et al. (2019), supervised and unsupervised ML algorithms and Fuzzy Logic have been implemented for predicting close approaches by using not only the classical probability of collision but other parameters as well. Finally, Shabarekh et al. (2016) uses a ML approach for predicting where and when may maneuver will be executed in the future to improve SSA capabilities.

Challenges for the future

AI is a promising approach for being implemented in STM to face the challenges of the new space environment expected for the next years. Space agencies, operators and commercial agents have shown interest in these techniques to ensure the future of space satellites, and there are already ongoing researches for addressing the issues. However, being a new approach meaning it has to face several challenges before we can talk about a space safety system based on AI.

As can be seen from current and past studies, a common problem is the lack of appropriate datasets for training the models. AI techniques are based on the availability of enough information to fit the models, extract information or capture the patrons relating data. However, actual information from real satellites is not always available in the desired format or with the required quality. Indeed, orbiting satellites are periodically tracked, allowing accessing to a great amount of historical data, however, some of these objects are not tracked with good enough quality to allow AI techniques to extract reliable information or more accurate results than traditional methods. On the other hand, some information is not available at all, like maneuvers implemented by satellites, or the information is not enough to allow the AI models extracting patterns. Therefore, current AI techniques relay on simulated databases, that have the advantages of creating a broad casuistic. However, an important challenge for the coming years regarding the implementation of AI is the creating of databases with information coming from real scenarios: real CDMs, information about implemented collision avoidance maneuvers, uncertainties associated with measurements and state propagation...

Artificial Intelligence involves a wide set of branches. So far, space security have just scratch the surface on the application of those techniques in STM. Most of the methods implemented and studied are centered on the Machine Learning branch, more specifically on supervised learning. However, there is a wide range of possibilities in AI where STM can take techniques from. Intelligent Problem Solving, including Evolutionary Computing and Constraint Satisfaction Programming, can be an interesting branch for DSS development along with Fuzzy logic, Automating Reasoning or Knowledge Representation. Computer vision and image recognition are also open areas where STM can benefit from, besides Data Mining. The implementation of AI in STM is still a new research area, but the potential for solving some of the problems already identify is huge. The advantage is that AI is a more tested technology in other fields, including engineering. As has been seen, traffic management has already benefited from AI, and Space Engineering has already been used AI techniques for some years. STM system has now the possibility of taking that experienced and apply for its issues.

There is still another challenge to face, as it is the implementation of these kinds of techniques onto real applications. The work carried out so far is focused on proving the capability of these techniques to improve the STM system and ensure space security in the oncoming scenario. However, there is still a long way for being able to implement those techniques on real missions or in the actual system. More research has to be done for really understating the relation between training AI models and the physical laws ruling the data, more detailed studies for optimizing techniques should be performed as well as adapting the system for gradually incorporated the proven methods. It is now a perfect time for testing new approaches since the space environment is changing and new techniques are not advisable but mandatory for the sustainability of the system, but at the same time, it is critical to implement reliable methods in order not to collapse the system. This leads to the last and main challenge the implementation of AI in STM has to face: the lack of standards on STM. Several AI-based approaches can be suggested, but as long as there are no protocols of actuation and standardized actions in conflict situations, the problem of a congested space will still be there. AI techniques as a way for supporting operators and moving to an automated scenario will work as long as a set of common rules and practices are shared by the different agents using the space.

Conclusions

New Space will bring great challenges to space security in the next decades. The implementation of new technologies, new concepts of satellites and new kinds of missions, like low-thrust engines, small satellites or mega-constellations, will push the limits of the space system to its limits. On top of all of this, the problem of space debris, which is going to become worse with the increase in space traffic, will make it completely necessary to carry out drastic changes on the system in order not to collapse it.

Although these changes can come from different approaches, there is a consensus on the space community that automation of the Space Traffic Management and Space Situational Awareness systems is one of them. To achieve the required level of automation, AI techniques arise as the most promising tool due to a series of factors. Their ability to deal with huge amount of data, and not only that but also learning from them and improving performances when more information is available, the advances on computer systems that allow its implementation both in the ground segment and in-orbit computers, the wide range of fields of application and task they can be applied to or the possibility to speed up the process where they are used and the capacity for automation and decision-making support are just some of their advantages.

While used in other engineering fields, like traffic management or computer vision among many others, the application in space engineering started near in the past, focused on image recognition, autonomous navigation, satellite autonomy, orbit trajectories or robotics. However, it is only in recent years where space security has started to implement AI techniques, where only a few promising studies have been carried out. However, the trend followed by agencies and space actors points in an increasing relevance of AI for STM since it may be the only tool able to handle all the information the congestion environment expected for the next decade will generate.

Three main issues are expected to be addressed with the implementation of AI on space security, space traffic management, and collision avoidance: automation of certain task to reduce operators man workload, minimize time between decision (conjunction risk assessment or collision avoidance planning and implementation) and reduce the number of false alerts in relation of potential high-risk conjunction events.

However, as a starting technique on the field, there are still some challenges to be overcome. A common limitation already faced is the lack of proper database based on real scenarios. AI techniques are based on the availability of representative data. The creation of appropriate databases with information coming from real satellites, events, and scenarios, or at least, a database of virtual scenarios closely similar to real situations is vital for obtaining the better performance of these techniques. AI is a wide area with several fields. At this moment, only some of them have been preliminary studied, mainly focused on the Machine Learning area. Studying different approaches and performing analyses to determine to determine the best AI branch to solve each problem related to space security is highly recommendable to obtain the maximum benefits from AI. Finally, lack of protocols and standardized practiced is a drag for obtaining the best performances of some of these methods. A promising area on AI is the development of intelligent agents or intelligent decision support systems. However, these methods required a series of clear rules to provide the appropriate advice to operators. Agreeing on common rules and practices for all space actors is essential for the proper implementation of AI in space security.

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