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PREDICTING THE POSITION UNCERTAINTY AT THE TIME OF CLOSEST APPROACH WITH DIFFUSION MODELS

Abstract

The risk of collision between resident space objects has significantly increased in recent years. As a result, spacecraft collision avoidance procedures have become an essential part of satellite operations. To ensure safe and effective space activities, satellite owners and operators rely on constantly updated estimates of encounters. These estimates include the uncertainty associated with the position of each object at the expected time of the closest approach (TCA). These estimates are crucial in planning risk mitigation measures, such as collision avoidance manoeuvres. As the TCA approaches, the accuracy of these estimates improves, as both objects' orbit determination and propagation procedures are made for increasingly shorter time intervals. However, this improvement comes at the cost of taking place close to the critical decision moment. This means that safe avoidance manoeuvres might not be possible or could incur significant costs. Therefore, knowing the evolution of this variable in advance can be crucial for operators. This work proposes a machine learning model based on diffusion models to forecast the position uncertainty of objects involved in a close encounter, particularly for the secondary object (usually debris), which tends to be more unpredictable. Diffusion models are a class of state-of-the-art deep learning probabilistic generative models based on non-equilibrium thermodynamics. They capture multiscale effects by creating a succession of simplified views of a sequence, modelled as a Markov chain. Such a Markov chain can be reversible, and in this mode the model develops complex and realistic predictions from noisy and partial information. Such properties are well-suited to predicting the position uncertainty of space objects at the TCA. We compare the performance of our model with other state-of-the-art solutions and a naïve baseline approach, showing that the proposed solution has the potential to significantly improve the safety and effectiveness of spacecraft operations.