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A MULTIMODAL LLM-BASED COGNITIVE AND DECISION ARCHITECTURE FOR NEXT-GENERATION SPACE SITUATIONAL AWARENESS SYSTEMS

Abstract

The exponential growth of global space activities has led to a sharp increase in space objects including space debris, operational and defunct satellites, etc. Concurrently, advancements in spacecraft control capabilities have made the problems of close proximity reconnaissance and interference from non-cooperative spacecraft increasingly prominent. These challenges have significantly increased the risk of collision in space, imposing strict requirements on data fusion processing systems for space situational awareness (SSA). Conventional rule-based expert systems have limitations in maintaining rule databases and analyzing multimodal sensing data in large-scale object scenarios. Meanwhile, traditional deep learning approaches suffer from insufficient authentic data for supervised learning of non-cooperative target behavioral patterns, resulting in suboptimal generalization in real-world applications. This paper proposes a framework for constructing a data fusion and decision-making intelligent agent based on a multimodal large language model (MLLM), enabling human-like analytical reasoning capabilities with few-shot learning, thereby establishing a new paradigm for SSA system design.

Central in the work is to architect an MLLM-based intelligent agent comprising three core components: tool modules, memory modules, and planning modules. The proposed method can endow the agent with the ability of target recognition, behavior recognition, intention inference, threat assessment, and decision execution. While MLLMs demonstrate human-like reasoning capabilities, their inherent architectural constraints in numerical precision tasks make computational accuracy inferior to traditional deterministic algorithms. To bridge this gap, we first built an algorithmic toolkit that includes several key precision computing modules, such as orbit determination, target identification, behavior recognition, collision probability computation, etc. Through function-calling methodology, the agent achieves precise computational capabilities for significant data. Secondly, we implement a retrieval augmented generation system integrating domain-specific knowledge bases and historical databases of spacecraft cataloging. This enables the model with long-term memory and updating capabilities for expertise and historical data. Finally, we construct a high-quality multimodal question-answering dataset by experts encompassing complete reasoning chains. And employ LoRA fine-tuning combined with Tree-of-Thought prompting to enhance task-specific reasoning performance. In the collision avoidance and close-range reconnaissance scenarios, the simulation experiments are carried out using authentic multimodal data composed of images, tracks and text. The results show that the intelligent agent constructed by the proposed method demonstrates expert-level decision-making ability and demonstrates important engineering applicability.