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Virtual Reality for Simulating Autonomous Deep-Space Navigation and Mining

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1. Introduction

In accordance with the space exploration goals declared by the National Aeronautics and Space Administration (NASA) in 2010 and 2013, the investigation of the deeper solar system becomes a central objective for upcoming space missions. Within this scheme, technologies and capabilities are developed that enable manned missions beyond low-Earth orbit - to lunar orbit, lunar surface, or even Mars and beyond. Particularly interesting targets are asteroids. They can serve as test beds for hardware and technology demonstration, which is needed prior to those aspired long-term missions. Asteroids can frequently be reached with smaller energy demands than those required for a mission to Moon or Mars. Furthermore, they are assumed to contain significant amounts of water and valuable metallic volatiles, which could serve as in-situ supplies for life support systems or spacecraft maintenance. Despite these technical facts, asteroids are also very interesting targets from a scientific point of view: They are remainders of the early formation phase of the solar system and are hold responsible for bringing life to Earth [DFJ90]. As the trend in future space exploration tends to focus on objects in deep space, the importance of autonomy increases on-board of spacecraft. With augmenting signal travel time due to great distances to Earth, it is difficult or even impossible to be able to react from ground on unexpected events for which time is a crucial factor. Up to this date, spacecraft in orbit follow specific timeline procedures during time-critical mission phases or pre-designed protocols in case unknown failures occur. The most common reaction on faults is the safe mode, during which the spacecraft shuts down every on-board module except the vital systems and awaits further (recovery) instructions from Earth ground stations. Hence, the demand for closed loop decision-making processes that are independent of the tele-commanding from ground. This includes not only the handling of errors but also navigation, guidance, and attitude/orbit control tasks. Therefore, the focus of this project is to make the spacecraft independent from the ground station as much as possible. This shall be achieved by autonomous navigation and autonomous decision making, so that it can determine optimal trajectories during flight and potential target asteroids autonomously for mining. The autonomy of the spacecraft is based on cognitive and biology-inspired algorithms. Assessment of these algorithms is necessary before they are applied in real scenarios. Therefore, algorithms have to be tested in a virtual environment with different virtual scenarios. This virtual environment should simulate motion of planets and asteroids, gravity, solar pressure, sensors of spacecraft, features of the asteroid, collision detection between asteroid and spacecraft for landing, etc. in real-time. In order to interact with this virtual environment, different 3D interaction metaphors have to be defined so that the user can change physical parameters, visualize different data, create different mission scenarios, change the spacecraft parameters, and even create new asteroid clusters and shapes (generated via 3D procedural modelling), which is necessary as the spacecraft might encounter new unknown asteroids.

2. Progress

2.1. Wait-free data exchange framework

A critical part of virtual reality systems and game engines is the generation, management and distribution of all relevant world states. In modern interactive graphic software systems, in our case virtual reality simulator for autonomous deep space navigation and mining, many independent software components need to communicate and exchange data. Standard approaches suffer the n^2 problem because the number of interfaces grows quadratically with the number of component functionalities. Such many-to-many architectures quickly become unmaintainable, not to mention latencies of standard concurrency control mechanisms. We have developed a novel method to manage concurrent multithreaded access to shared data in virtual environments. Our highly efficient low-latency and lightweight architecture is based on a new wait-free hash map using key-value pairs. This allows us to reduce the traditional many-to-many problem to a simple many-to-one approach as shown in Figure 1. This wait-free hash map, the so-called key-value pool, represents the complete shared world state of an VR system. The shared world state can be accessed and modified completely wait-free. Consequently, no software component has to acquire a lock or have to wait until a lock has been released. The many-to-one approach minimizes the overall synchronisation overhead while preserving a consistent shared world state for all software components. These software components can have arbitrary purpose such as spacecraft subsystems, autonomous decision making or scene graph operations. Therefore, it is well-suited to fulfil the real-time constraints of the above mentioned space mission as all software components run in parallel with a minimum of synchronisation overhead. We are currently investigating on further applications for this many-to-one approach. We believe that this approach can be applied to any other VR system architecture scenario, which focusses on massively parallel software components. Such architecture scenarios can incorporate collaborative virtual environments or other simulators such as autonomous underwater navigation. We compared the performance of our new approach to two different existing methods. The first competitor was a standard blocking hash map. We used the well-known boost library that uses shared mutexes and allows multiple readers and a single writer accessing the complete hash map. Additionally, we adopted a lock-free hash-map of the original hazard-pointer algorithm that supports wait-free reading and lock-free writing from [Mic04]. Figure 2 shows a comparison of the performance. You can see that our key-value database outperforms both competitors for reading as well as writing operations.

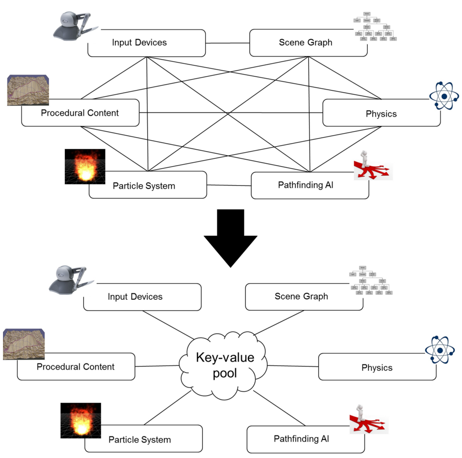

Figure 1: *Figure 1: Conversion from many-to-many dataflow to many-to-one dataflow [LWZ14]*

2.2. Procedural modelling of asteroids

To this day, our knowledge about asteroids is restricted to the outcome of planetary research on meteorites, spectrometry and the few satellite encounters with individual objects. Therefore, 3D models of the main belt asteroids are not available. Additionally, generating asteroids with different features on-the-fly is desirable. We developed a preliminary procedural asteroid modelling for deep space cruise-flight mission phases. In these phases, low-detail asteroid models can be used as input to spacecraft instruments for interplanetary cruise. Our preliminary algorithm focusses on speed and a geometry structure which supports easy level-of-detail implementations as the overall scene size is enormous.

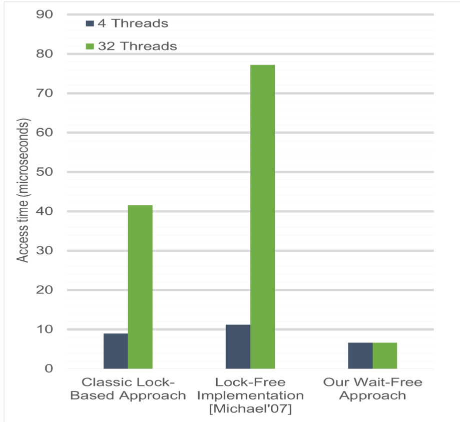

Figure 2: *Figure 2: Timings of our approach compared to other state of the art approaches for writing operations [LWZ14].*

2.3. Immersion and 3D interaction metaphors

Immersive virtual environments provide a more intuitive and natural interaction compared with conventional rendering of virtual environment. Therefore, we decided to stereo render our virtual environment on zSpace device (see Figure 3) in order to provide this immersion and also seeing objects in 3D is a natural and more intuitive way to understand spatial relationships. We also need to define and test new 3D interaction metaphors.

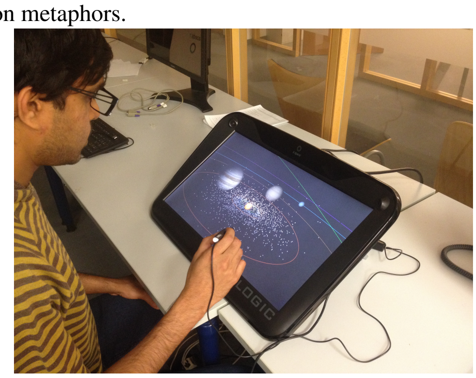

Figure 3: *Figure 3: Our Solar System Demo on zSpace device.*

3. Acknowledgements

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