Streamlining Verification & Validation of GNC Subsystems using NeXosim: an Open-Source, Rust-Based Discrete Event Simulator

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***Abstract*—Over the past decades, the complexity of both commercial and scientific space missions has steadily increased. As new classes of space missions are undertaken, and their technical and programmatic objectives become increasingly ambitious, more advanced spacecraft architectures are developed to support them. In-Orbit Servicing (IOS) missions constitute a particularly relevant example of space endeavors that stimulate the development of novel spacecraft subsystem technologies. Those technologies include highly sophisticated Guidance, Navigation & Control (GNC) systems with growing levels of autonomy. Unfortunately, considering that on a typical spacecraft project, a substantial amount of time can be attributed to Verification & Validation (V&V) activities, advanced GNC systems are at elevated risk of not being thoroughly verified. As a result, increasingly complex GNC systems can suffer from verification gaps — differences between ground-based system behaviour observed during V&V activities, and the actual in-flight behaviour. The following paper describes how NeXosim — an open-source, Rust-based Discrete Event Simulation (DES) framework — can help address this issue in the context of preflight validation of future GNC systems. To illustrate this process, a demonstration case study featuring a Hardware-in-the-Loop (HIL) demonstration stand is introduced. This is followed by the discussion of how enabling Digital Twinning of GNC hardware by NeXosim can facilitate launching hardware-centric V&V activities, even before physical components are available for testing. Finally, to outline how NeXosim is leveraged in the context of upcoming IOS missions, its role in the development of the Infinite Orbits' Endurance and Orbit Guard 3 vehicles is briefly summarized.**

***Index Terms*—software, control systems, verification & validation, in-orbit servicing, simulation**

I. INTRODUCTION

With 206 commercial rocket launches in 2025 [1], it is clear that the rise of reusable space launch vehicles in the late 2010s has marked the beginning of significant growth in the space economy. Largely driven by the accelerating deployment of small and medium satellites in Low Earth Orbit (LEO) [2], growing space traffic and the increasing amount of space debris have motivated the industry to revisit its current modus operandi, in which satellites are treated as disposable commodities. As a result, the space industry is progressively shifting its focus towards a more sustainable space economy in which space vehicles can be supported and their operational lifetimes extended while in orbit.

The key technological enabler for the above paradigm shift is In-Orbit Servicing (IOS) operations, conducted by IOS vehicles. Formally, IOS refers to close-proximity activities conducted by a space vehicle which performs up-close inspection of, or results in intentional and beneficial changes to, another Resident Space Object (RSO) [3]. In practice, IOS vehicles can provide cooperative or non-cooperative targets with services such as non-contact support, orbit modification, maintenance, refueling, commodities replenishment, upgrades, repair, assembly, and debris mitigation.

However, while offering significant benefits, IOS missions present substantial technical challenges. IOS servicer vehicles, designed for safe rendezvous and close-proximity operations around RSO, require sophisticated Guidance, Navigation & Control (GNC) systems, which entail high levels of autonomy. This introduces a certain level of complexity into the GNC system. To ensure that the GNC system operates as intended, and that autonomy does not result in undesired emergent behaviour, the additional complexity must be properly addressed during the Verification & Validation (V&V) stage. As established by the inter-agency GNC V&V initiative [5], this necessitates novel V&V methods, tools and processes [6].

NeXosim is an open-source, Rust-based framework that supports this use case. It represents an established category of tools used to support V&V activities — Discrete Event Simulators (DES). DES, or system-level simulators, allow replicating complex state machines down to low-level interactions between avionics, spacecraft sensors, spacecraft actuators, and space environment [7]. This enables the simulation of GNC subsystem functional behaviour, allowing early verification and validation either exclusively in the virtual domain, or at the intersection of the virtual and physical domains. In the context of V&V of GNC subsystems, this provides multiple benefits, including early start of V&V activities, their parallelization, support for Hardware-in-the-Loop testing, and the consideration of multiple scenarios. The rest of this paper presents how NeXosim can streamline the V&V process of complex GNC systems, including highly autonomous systems that lie at the cornerstone of safe IOS missions.

II. In-Orbit Servicing Missions

The concept of IOS is not new. Among others, early demonstrations of autonomous rendezvous and proximity operations include NASA's Demonstration for Autonomous Rendezvous Technology (DART) mission (2006). Although DART was successfully placed in orbit, it was lost due to an anomaly, which was later attributed, among other factors, to shortcomings in the V&V activities of GNC systems [6]. More recently, the IOS concept has been demonstrated through missions such as Orbital Express by DARPA (2007); Mission Extension Vehicle-1 (MEV-1) by Northrop Grumman (2019); and ELSA-d by Astroscale (2021). Examples of planned IOS missions include the Endurance Mission and Orbit Guard missions by Infinite Orbits; the ELSA-M mission by Astroscale; the ClearSpace-1 mission by ClearSpace; and the RAVEN mission led by PIAP Space [2] [4] .

A. *In-Orbit Servicing Mission Phases*

Although each IOS mission is different, efforts are being made to unify the terminology associated with close-proximity spacecraft operations [6]. Figure 1 shows the core IOS mission phases, as defined by ESA [8]. The phases involved in the rendezvous include: phasing & transfer, far-range rendezvous, close-range-rendezvous, closing, and final approach.

As the servicer vehicle progresses through the mission phases and approaches the target vehicle, the relative dynamics between the spacecraft evolves, the availability of navigation information changes, and the operational risk increases. As a result, the level of autonomy required to safely complete maneuvers increases. The initial phases usually require a low level of autonomy, or no autonomy at all, with maneuvers executed as planned by the ground segment. Due to its criticality, the rendezvous (RV) is usually designed to be fully autonomous. This contributes to stability, precision, and responsiveness when operating close to RSO. In addition, GNC autonomy ensures that the speed of decision-making is not limited by communication constraints, the critical decisions can be made

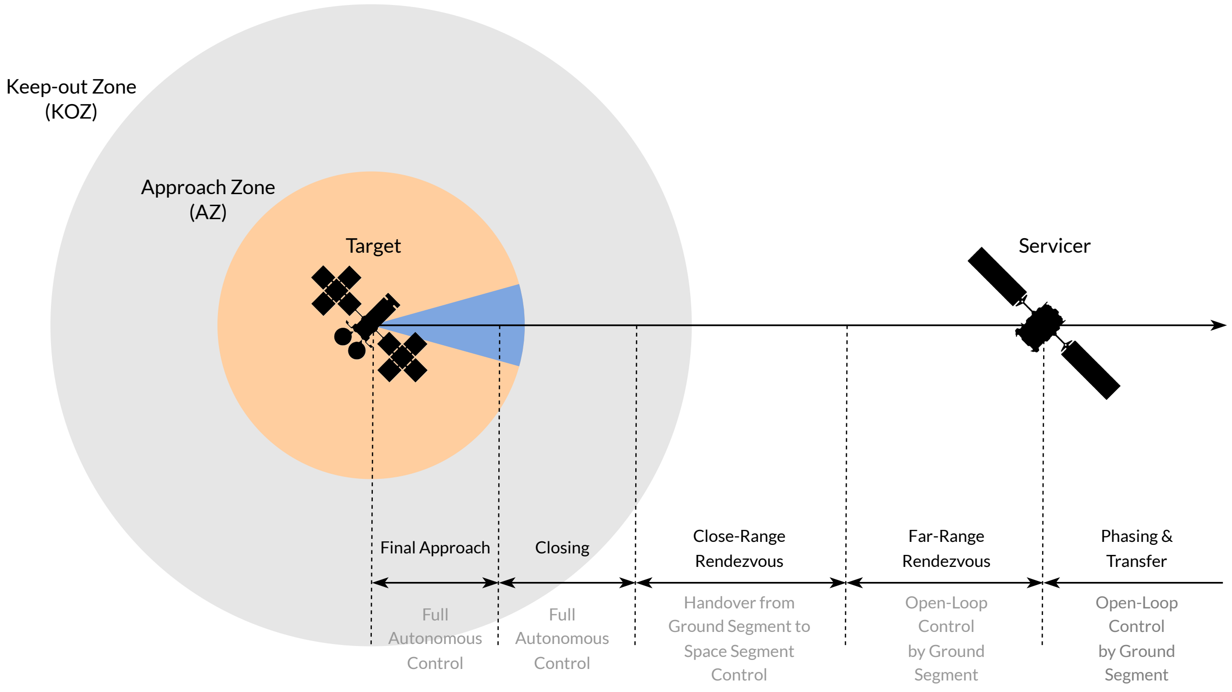

Fig. 1: Core rendezvous (RV) phases and zones of a typical In-Orbit-Servicing mission, as defined by ESA [8] .

using complete on-board data, and the risk associated with human-in-the-loop operations is eliminated [6]. It is important to note, that depending on the phase of the mission, and the level of autonomy involved, a different suite of sensors, as well as different algorithm might be used to control the spacecraft.

B. In-Orbit Servicing Mission GNC Architecture

To support a typical IOS mission profile, illustrated in Figure 1, the top-level GNC subsystem architecture must ensure a smooth transition between ground-based control and fully autonomous operation as the servicer vehicle approaches the target vehicle. As a result, the control hierarchy architecture for a typical IOS mission may resemble the setup shown in Figure 2 [9].

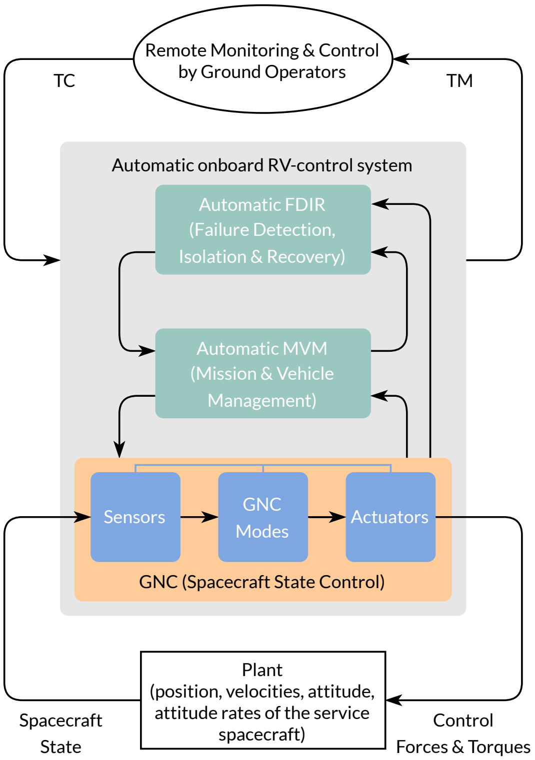

Fig. 2: Control hierarchy for a typical IOS mission, illustrating interactions between the GNC subsystem and higher-level control layers.

In this configuration, the GNC subsystem interfaces with higher-level control system layers. Those include: Ground Segment (GS), which supports human-in-the loop operations; Failure Detection, Isolation & Recovery (FDIR) layer, which enables detection and recovery from system and equipment failures; and Mission & Vehicle Management (MVM) layer, which is responsible for sequencing GNC modes & maneuvers, and scheduling of equipment for such modes. While GS controls the spacecraft through sending telecommands (TC) and receiving telemetry (TM), it does not take part in the fully autonomous operations, where the automatic onboard control system takes over.

The architecture presented in Figure 2 illustrates that a complex space mission, such as an IOS mission, requires not only an advanced GNC subsystem but also a GNC subsystem which is robust when interacting with higher-level control layers. Interfacing with FDIR and MVM, which are often themselves based on complex state-machines, may potentially result in undesired emergent behaviour. Consequently, thorough V&V of the GNC subsystem requires an extensive set of test scenarios.

III. VERIFICATION & VALIDATION

Traditionally, V&V of a GNC subsystem is conducted in distinct phases, including Model-in-the-Loop (MIL) tests, used to verify fundamental control algorithms (typically using MATLAB/Simulink models); Software-in-the-Loop (SIL) tests, used to verify the behaviour of the flight software (typically autogenerated C code); Processor-in-the-Loop (PIL) tests, used to verify the behaviour of the flight software executed on a representative processor (typically with performance comparable to the spacecraft on-board computer); and Hardware-in-the-Loop (HIL) tests, used to verify the behaviour of the flight software running on a representative processor and interfacing with real hardware (typically physical sensors and actuators) [10].

While MIL and SIL tests require only software, PIL and HIL tests, which are typically conducted no earlier than Phase B of the spacecraft development cycle, require interfacing with physical processor, sensors, and actuators. Therefore, in a traditional V&V approach, these tests cannot be started until the necessary hardware becomes available. As a result, hardware lead times often become a bottleneck for launching PIL and HIL tests, and the GNC V&V campaign becomes time constrained. In the case of IOS missions, where PIL and HIL are complex and constitute critical elements of the V&V campaign, this is highly problematic. A solution is the replacement of physical hardware with NeXosim digital twins.

A. V&V in IOS Missions

V&V of an IOS GNC system, such as the one shown in Figure 2, requires that all phases of the V&V process take into account IOS mission-specific aspects. Examples of these aspects include the interactions between the algorithms controlling rendezvous (i.e. GNC, MVM, and FDIR), the interactions between the ground segment (GS) and the onboard autonomous control system, the six degrees of freedom motion of the servicer and target spacecraft [9], and the transition between orbital navigation and close-proximity operations navigation.

Consequently, to facilitate these tasks, NeXosim enables building digital twins of spacecraft actuators, sensors, and other spacecraft equipment. The NeXosim digital twins replicate functional behaviour of their physical counterparts, by simulating details, such as: telecommand & telemetry protocols, analog &digital interfaces, power bus states, and state machines.

B. NeXosim role in V&V

The representativeness of NeXosim digital twins, means that these models are perfectly suited to support HIL test campaigns. However, a key advantage of NeXosim is that it can be used well before the first hardware is delivered, allowing the HIL test campaign to be launched earlier. A typical approach to using NeXosim for GNC V&V activities is to first construct a fully virtual test bench composed of digital twins. As the on-board computer and GNC peripherals are delivered, these digital components are progressively replaced with actual hardware, resulting in a gradual transition of V&V activities from the virtual to the physical domain.

The above protocol enables the early launch of V&V activities and, instead of relying on a physical HIL test bench from the outset, supports the progressive introduction of HIL testing. Even after the full HIL setup is ready, virtual test benches can remain in use, allowing multiple teams to exercise different scenarios, such as FDIR cases, component configurations, or operational sequences. As a result, the HIL campaign can be divided into smaller, parallel segments, simplifying the verification of complex GNC systems, including autonomous systems used in IOS missions.

IV. NEXOSIM USE CASES

To illustrate the use of NeXosim in practice, two use cases are briefly described: the Asynchronics Hardware-in-the-Loop (HIL) demonstration test bench and the Infinite Orbits Endurance mission use case.

A. Asynchronics Hardware-in-the-Loop Test Bench

The Asynchronics Hardware-in-the-Loop (HIL) test bench is a representative example demonstrating how NeXosim simulation models interact with physical actuators and sensors. The test bench is a stabilization platform that incorporates

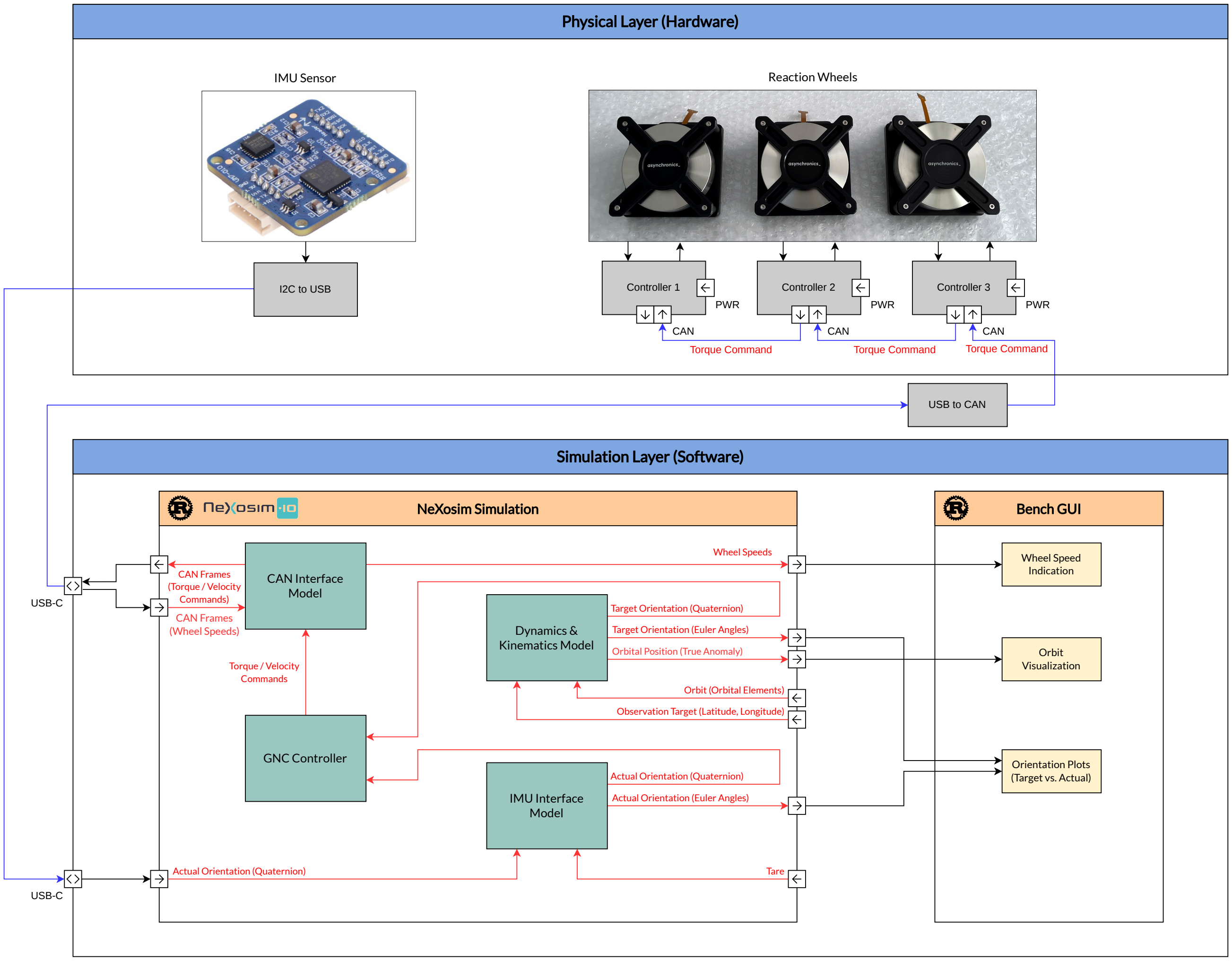

Fig. 3: Asynchronics Hardware-in-the-Loop demonstration test bench block diagram.

three reaction wheels (physical actuators) for attitude control and an inertial measurement unit (physical sensor) for attitude determination.

As shown in Figure 3, which illustrates the test bench layout, the reaction wheels and the inertial measurement unit constitute the physical (hardware) layer. The physical layer interacts with the simulation (software) layer. The simulation layer incorporates NeXosim GNC controller model for orientation control, NeXosim kinematics, dynamics, and environment model for simulating orbital motion, as well as NeXosim CAN and IMU interface models for simulating communication protocols. If additional sensors (e.g., a star tracker or a gyroscope) and actuators (e.g., magnetorquers or reaction control thrusters) are required, the test bench would be expanded. Initially, the new components would be incorporated by integrating their NeXosim models, which would subsequently be replaced with physical hardware.

B. Infinite Orbits Endurance Mission Use Case

The component simulators, as well a full virtual simulation test bench constructed in NeXosim are used by the Infinite Orbits in the V&V campaign of the Endurance mission. The NeXosim virtual test bench, consisting of actuator, sensor, power control & distribution unit, and kinematics, dynamics & environment models, as well as an emulated On-Board Computer (OBC), is used in the V&V activities of the On-Board Software (OBSW).

V. SUMMARY

In-Orbit Servicing (IOS) missions are a particularly challenging class of space missions that require sophisticated Guidance, Navigation & Control (GNC) systems. As the level of autonomy incorporated in the GNC systems grows, so does the demand for comprehensive and rigorous Verification & Validation (V&V) campaigns. To enable the verification of complex state machines, that are usually incorporated in the autonomous systems, and eliminate the risk of undesirable emergent behaviour, such V&V campaigns are primarily based on test activities. NeXosim, an open-source, Rust-based Discrete Event Simulation (DES) framework, allows to launch those test activities earlier than normally and run them in parallel. This is achieved by launching tests in the virtual domain first, and gradually transitioning to the physical domain, as hardware becomes available.

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