

**INSTITUTO TECNOLÓGICO DE AERONÁUTICA**



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**EDUCATIONAL ORBIT SIMULATION WITH  
GENERATIVE AI AGENTIC WORKFLOW AND  
VIRTUAL REALITY VISUALISATION**

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**Course of Aerospace Engineering**

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**Eduardo Moura Zindani**

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Advisor

Prof. Dr. Christopher Shneider Cerqueira (ITA)

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# **EDUCATIONAL ORBIT SIMULATION WITH GENERATIVE AI AGENTIC WORKFLOW AND VIRTUAL REALITY VISUALISATION**

This publication was accepted like Final Work of Undergraduation Study

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*"If I have seen farther than others,  
it is because I stood on the shoulders of giants."*

— SIR ISAAC NEWTON

# Resumo

Métodos educacionais tradicionais frequentemente encontram dificuldades para transmitir conceitos complexos, espaciais e dinâmicos como os da mecânica orbital. A recente convergência entre a Realidade Mista (RM) de consumo e os sofisticados agentes de Inteligência Artificial (IA) Generativa apresenta uma oportunidade para criar um novo paradigma de interfaces de aprendizagem intuitivas e experenciais. Este trabalho detalha o projeto, desenvolvimento e demonstração de uma plataforma educacional interativa para a exploração dos princípios da mecânica orbital. O objetivo principal do sistema é conectar a teoria de leis físicas abstratas à compreensão intuitiva, permitindo que os usuários aprendam por meio da interação corporificada. A metodologia é centrada em uma arquitetura modular que integra dois componentes principais: (1) um "cérebro" agente generativo, impulsionado por Modelos de Linguagem Abrangentes, que interpreta comandos em linguagem natural e atua como um guia educacional especializado; e (2) um "mundo" de simulação em tempo real e visualização imersiva em realidade mista, construído no motor Unity para o Meta Quest 3, que renderiza trajetórias orbitais fisicamente precisas em um espaço tridimensional onde os usuários vivenciam a mecânica orbital de dentro. A plataforma facilita um ciclo de interação multimodal contínuo, onde os comandos de voz do usuário são capturados, processados pelo agente para alterar os parâmetros da simulação e refletidos na visualização imersiva em RV com feedback auditivo conversacional. Este trabalho entrega um protótipo funcional que demonstra uma nova abordagem para a educação científica, transformando dados abstratos em uma experiência manipulável e conversacional para promover uma aprendizagem exploratória e profundamente engajadora. A plataforma é disponibilizada como software de código aberto para permitir validação, adaptação e extensão pela comunidade para diversos contextos educacionais.

# Abstract

Traditional educational methods often struggle to convey complex, spatial, and dynamic concepts such as those found in orbital mechanics. The recent convergence of consumer-grade Mixed Reality (MR) and sophisticated Generative AI agents presents an opportunity to create a new paradigm for intuitive and experiential learning interfaces. This paper details the design, development, and demonstration of an interactive educational platform for exploring the principles of orbital mechanics. The system's primary objective is to bridge the gap between abstract physical laws and intuitive comprehension by enabling users to learn through embodied interaction. The methodology is centered on a modular architecture that integrates two core components: (1) a generative agent "brain," powered by Large Language Models, which interprets natural language commands and acts as an expert educational guide; and (2) a real-time simulation and immersive mixed reality visualization "world," built in the Unity engine for the Meta Quest 3, which renders physically accurate orbital trajectories in a three-dimensional space where users experience orbital mechanics from within. The platform facilitates a seamless multimodal interaction loop where a user's voice commands are captured, processed by the agent to alter simulation parameters, and reflected in the immersive VR visualization with conversational auditory feedback. This work delivers a functional prototype that demonstrates a novel approach to science education, transforming abstract data into a manipulable, conversational experience to foster exploratory and deeply engaging learning. The platform is released as open-source software to enable community validation, adaptation, and extension for diverse educational contexts.

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# 1 Introduction

## 1.1 Organisation

This work is organised into five main chapters, each addressing a distinct aspect of the project. The breakdown is as follows:

- **Chapter ??: Introduction.** This chapter sets the stage for the research and development.
  - *Motivation* (§??): Presents the core argument that the convergence of immersive reality technologies—particularly Virtual Reality—and generative AI enables a new, more intuitive paradigm for educational interfaces.
  - *Objectives* (§??): Defines the project’s specific, actionable goals, centered on the development and demonstration of an interactive, agent-guided simulation platform.
- **Chapter ??: Literature Review.** This chapter provides the theoretical and technical foundation for the work by reviewing three key domains.
  - *Augmented and Virtual Reality* (§??): Reviews the evolution of immersive hardware and software ecosystems and establishes their pedagogical value for spatial learning.
  - *Generative Agents* (§??): Defines the architecture of modern LLM-powered agents, detailing their ability to use planning, memory, and external tools to reason through and execute complex tasks.
  - *Orbital Mechanics* (§??): Outlines the fundamental physics of celestial motion, including the two-body problem, classical orbital elements, and impulsive maneuvers, which form the mathematical basis for the simulation.
- **Chapter ??: Methodology.** This chapter details the design philosophy, system architecture, and technical implementation approach.

- *Design Philosophy and Approach (§??)*: Establishes the iterative, prototype-driven development methodology guided by principles of modularity and exploratory research into novel human-computer interaction paradigms.
  - *System Architecture and Data Flow (§??)*: Describes the end-to-end interaction cycle, illustrating how user voice input flows through speech recognition, agent reasoning, tool execution, physics simulation, and VR rendering in a continuous loop.
  - *Mixed Reality Design Rationale (§??)*: Explains the pedagogical reasoning for emphasizing immersive VR over AR passthrough for orbital mechanics education, addressing the mismatch between cosmic-scale phenomena and room-scale spatial contexts.
  - *Technical Implementation (§??)*: Summarizes the integration of conversational AI (OpenAI GPT-4, ElevenLabs voice synthesis), Unity 3D physics simulation, and Meta Quest 3 deployment with character-driven specialist personas.
  - *Core Module Implementation (§??)*: Details the four primary subsystems—Agent System, Orbital Physics Simulation, Voice Integration Pipeline, and Virtual Reality Environment—with emphasis on their educational design rationale and how each component supports the learning objectives.
  - *Development and Version Control (§??)*: Documents the systematic development practices using GitHub for version control, branching strategies, and iterative refinement cycles.
  - *Validation Strategy (§??)*: Outlines the approach for validating system functionality through complete interaction scenarios, with implementation made available for independent verification and replication studies.
- **Chapter ??: Results and Demonstration.** This chapter demonstrates the complete functional platform through an actual user learning journey, validating all six specific objectives through integrated scenarios.
    - *Entering the Orbital Environment (§??)*: Documents the initial Hub arrival experience, including the introductory cutscene, spatial orientation in VR, and first interaction with Mission Control.
    - *Learning Through Mission Specialist Dialogue: The ISS Circular Orbit (§??)*: Demonstrates the complete pedagogical cycle of conceptual question, specialist consultation, hands-on orbit creation, VR observation, and time-accelerated visualization using the ISS mission as a concrete example.
    - *Exploring Orbital Geometry: Elliptical Orbits and Eccentricity (§??)*: Shows iterative orbit refinement through Hubble specialist consultation, demonstrating

how learners progress from circular to elliptical geometries and observe speed variation through immersive visualization.

- *Conceptual Extension: Escape Trajectories and Mission Context* (§??): Illustrates theoretical dialogue mode through Voyager specialist consultation on interplanetary escape trajectories, validating the platform’s flexibility to support conceptual learning without requiring hands-on manipulation.
  - *System Integration and Technical Validation* (§??): Presents quantitative performance metrics (tool execution reliability, voice pipeline latency, VR rendering stability, physics accuracy validation) and complete system demonstration evidence through continuous video recording.
  - *Implementation Availability* (§??): Documents the publicly available implementation, including source code organization, deployment procedures, and reproducibility guidelines for verification studies.
- **Chapter ??: Conclusion.** This chapter synthesizes the thesis contribution, reflecting on what was demonstrated, what insights emerged about spatial educational interfaces, what limitations bound the validation scope, what research trajectories this work enables, and whether the central feasibility question has been answered.

## 1.2 Motivation

For decades, popular media and speculative fiction have envisioned futuristic interfaces for exploration and control, from holographic command centers to immersive planetary navigation tools. Films such as *Minority Report* (2002) and *Iron Man* (2008) popularized visions of humans interacting with vast information systems through gestures, speech, and spatial manipulation. These visions were once confined to science fiction, but today, the convergence of immersive reality technologies—particularly Virtual Reality (VR)—and Artificial Intelligence (AI) is bringing such interfaces into the realm of technological feasibility.

In particular, the past few years have seen rapid advances in consumer-grade immersive hardware, particularly in virtual reality. Devices like the Meta Quest and Apple Vision Pro represent significant milestones in accessibility and visual fidelity, enabling immersive environments that are no longer confined to laboratory research or elite applications. The implications for interface design, interaction paradigms, and knowledge acquisition are profound. VR is no longer a speculative technology; it is present, evolving, and increasingly democratized.

Concurrently, the emergence of generative AI and language-based agents has introduced a paradigm shift in how humans interact with complex systems. Large Language

Models (LLMs), such as those powering conversational agents, can now interpret natural language, generate multimodal content, and coordinate sequences of actions across software environments. This represents a departure from deterministic, rule-based systems toward stochastic and adaptive workflows, where agents interpret intention, negotiate uncertainty, and build dynamically responsive experiences.

When these technologies—immersive VR and generative agents—are combined, they form the foundation for a new kind of interface: one that is spatial, conversational, and adaptive. Such interfaces do not rely on code or static menus; they respond to voice, gesture, and embodied input. They transform abstract data into manipulable space, and procedural complexity into natural dialogue.

This is particularly relevant in the domain of education. Traditional educational systems remain bound to text, diagrams, and symbolic representation. While these tools are powerful, they often fall short when applied to fields that are inherently spatial, dynamic, or non-intuitive. Orbital mechanics, for example, involves motion through three-dimensional space governed by non-linear physical laws. Launch trajectories, gravitational slingshots, inclination changes, these are difficult to visualize and even harder to intuit.

In this context, immersive simulation has the potential to become more than a visual aid: it may serve as a cognitive bridge. A learner could speak a question and witness a launch trajectory materialize in their physical space. They could observe orbits evolve in real time, ask about inclinations or transfer windows, and receive explanations grounded in physics. Education could become experiential, a process of exploration rather than instruction—though whether this approach improves learning outcomes compared to traditional methods remains an open empirical question.

Moreover, generative agents provide a layer of accessibility that is historically absent in technical domains. They can guide the learner, interpret vague queries, correct misconceptions, and explain phenomena in adaptive ways. They act as intelligent mediators between curiosity and formal knowledge.

Given these technological conditions—the maturity of consumer VR, the rise of stochastic AI agents, and the persistent limitations of traditional educational media—this project is motivated by a clear opportunity: to construct a new type of educational experience. One that is not constrained by interface conventions, disciplinary jargon, or static presentation. One that invites the user to learn by seeing, asking, moving, and listening.

The convergence of embodied interaction and generative intelligence allows for a simulation system that is technically rigorous and experientially engaging. It may enable a form of learning in which the abstract becomes tangible, the distant becomes near, and the user is placed at the center of the scientific process. This project emerges from the hypothesis that space education, and scientific education more broadly, may benefit from

evolving to meet the possibilities of our time—a hypothesis this work seeks to demonstrate through technical feasibility rather than pedagogical validation.

## 1.3 Objectives

### General Objective

To develop an interactive, agent-guided simulation platform that enables users to explore and understand orbital mechanics through embodied interaction, combining natural language dialogue and real-time virtual reality visualizations.

### Specific Objectives

1. Design and implement a simulation environment capable of rendering orbital trajectories in real time, grounded in physics-consistent models implementing Keplerian two-body dynamics.
2. Integrate a generative agent capable of interpreting natural language input, translating it into simulation parameters, and guiding the user through explanations and interactions.
3. Enable multimodal interaction by combining voice commands, spatial presence, and mixed reality visual feedback (VR immersion and AR passthrough capabilities) to create a seamless and intuitive user experience optimized for learning orbital mechanics concepts.
4. Ensure that all components of the system, simulation and agent, function coherently and communicate reliably in real time.
5. Create a system architecture that is modular and extensible, allowing for future expansion to other celestial bodies, educational modules, or mission types.
6. Validate system functionality through complete interaction scenarios and provide reproducible implementation documentation, enabling independent verification of technical feasibility claims.

## 2 Literature Review

### 2.1 Augmented and Virtual Reality in Immersive Educational Simulation Systems

Augmented Reality (AR) and Virtual Reality (VR) are complementary immersive technologies that enrich or replace a user's perception of the world. AR overlays digital content onto the real environment in real-time, allowing virtual objects to coexist with physical surroundings (Billinghurst; Clark; Lee, 2015). In contrast, VR completely immerses the user in a fully synthetic, computer-generated environment, blocking out the physical world. Milgram's classic "Reality-Virtuality" continuum illustrates these as end-points: AR lies near the real-world end (mixing virtual content with reality), whereas VR occupies the extreme virtual end with an entirely simulated world (Milgram; Kishino, 1994). In essence, AR adds to the user's real-world experience, while VR transposes the user into an interactive virtual scene. Both technologies share common roots in decades of research and development. The term augmented reality was first coined by Caudell and Mizell (1992) in the context of assisting Boeing manufacturing with see-through displays (Caudell; Mizell, 1992). A few years later, Azuma's influential survey defined AR by three key characteristics: combining real and virtual content, interactive operation in real time, and accurate 3D registration of virtual objects in the physical world (Azuma, 1997; Billinghurst; Clark; Lee, 2015). VR, meanwhile, has been long conceptualized as achieving presence – the feeling of “being there” in a virtual environment – by engaging multiple senses with responsive 3D graphics and audio (Johnson-Glenberg, 2018). Modern definitions emphasize that VR provides immersive first-person experiences where users can interact with simulated worlds as if they were real, inducing a strong sense of presence and agency within the virtual scene.

#### 2.1.1 Hardware Evolution:

AR and VR technologies have evolved rapidly, enabling consumer-grade devices that support realistic immersive experiences. While early head-mounted displays date back

to the 1960s (e.g., Sutherland’s Sword of Damocles), the 2010s marked a turning point with modern devices. On the VR front, the Oculus Rift prototype (2010) by Palmer Luckey re-ignited interest with a wide field of view and affordable design. Crowdfunded in 2012 and acquired by Facebook in 2014, Oculus released its first consumer headset in 2016, alongside HTC’s Vive, which introduced room-scale tracking. These devices brought high-fidelity visuals and motion tracking to mainstream audiences.

The next major step came with standalone VR headsets. The Oculus/Meta Quest series, starting in 2019, integrated processing and inside-out tracking directly into the headset. Quest 2 (2020) and Quest 3 (2023) improved resolution, optics, and added passthrough AR capabilities (Ruth, 2024). In parallel, PC-based headsets like the Valve Index and Varjo pushed the fidelity frontier for gaming and enterprise simulation.

AR hardware followed a distinct trajectory. Initial systems used handheld or laptop setups, but the release of Microsoft’s HoloLens in 2016 marked the arrival of self-contained AR headsets with spatial mapping and inside-out tracking. Magic Leap One (2018) added novel display technologies (Billinghurst; Clark; Lee, 2015), while consumer experiments like Google Glass (2013) explored heads-up interfaces before being discontinued in 2023 (Ruth, 2024).

Smartphones played a critical role in scaling AR adoption. Apps like Pokémon GO (2016) introduced mainstream users to AR through camera overlays. ARKit (Apple) and ARCore (Google), launched in 2017, enabled mobile AR with motion and depth tracking (Vieyra; Vieyra, 2018).

Most recently, the line between AR and VR is blurring. Apple’s Vision Pro (announced 2023) merges high-resolution VR with passthrough AR, positioning itself as a “spatial computer.” With features like dual 4K displays and hand/eye tracking, it may represent a watershed moment for XR despite its premium price (Ruth, 2024).

As of 2025, the hardware ecosystem spans from mobile-based AR apps to advanced mixed reality headsets, forming a robust toolbox for immersive educational simulations.

### **2.1.2 Software Ecosystems and Frameworks:**

Alongside hardware, a mature software ecosystem has enabled rapid development of immersive simulations. Modern game engines such as Unity and Unreal Engine have become the de facto platforms for AR/VR content creation. These engines provide high-performance 3D graphics rendering, physics simulation, and cross-platform deployment, greatly simplifying the creation of interactive virtual environments. Unity, for example, offers an entire XR development toolkit (with support for VR headsets and AR through packages like AR Foundation) that abstracts away device-specific details and allows de-

velopers to build an application once and deploy across multiple headsets (Atta *et al.*, 2022). Unreal Engine likewise includes integrated support for VR rendering and AR (via ARKit/ARCore plugins), making high-fidelity visualization accessible to developers in academia and industry.

For mobile AR, platform-specific frameworks are key. Apple’s ARKit (introduced in iOS 11, 2017) and Google’s ARCore (for Android, 2017) brought advanced AR capabilities to hundreds of millions of smartphones (Vieyra; Vieyra, 2018). These software development kits handle real-time tracking of the device’s position, surface detection, lighting estimation, and more, allowing apps to place and persist virtual objects in the user’s environment. Thanks to ARKit/ARCore, an educator can deploy an AR simulation on standard tablets or phones – for instance, letting students point an iPad at a textbook and see 3D molecules or physical field lines appear “attached” to the pages. On the web, the WebXR API has emerged as a W3C standard enabling AR and VR experiences to run directly in web browsers using JavaScript (World Wide Web Consortium, 2021). WebXR (successor to earlier WebVR/WebAR efforts) allows an immersive educational module to be accessed with a simple URL, lowering the barrier to entry (no app install required) and ensuring compatibility across different devices (from VR headsets to phones). This is particularly relevant for broad educational deployments, where web-based delivery can be more practical. Complementing these are various supporting frameworks: for example, libraries for spatial mapping, hand tracking, and user interaction (e.g. Microsoft’s Mixed Reality Toolkit for Unity, or Vuforia for image-target AR) which provide higher-level tools for common AR/VR interactions. There are also open standards like OpenXR (released by the Khronos Group in 2019) that unify the interface to VR/AR hardware – a developer can write code once against OpenXR and run on any compliant headset (Oculus, SteamVR, Windows Mixed Reality, etc.), which is increasingly adopted by engines and platforms. In summary, the software landscape – from powerful 3D engines to AR phone toolkits and web standards – has matured to a point that immersive educational simulations can be built with relatively modest effort compared to a decade ago. This thesis will leverage these tools to construct its simulation system, ensuring it is built on proven, widely supported technology.

### 2.1.3 Use Cases in Education:

AR and VR have shown strong potential to enhance learning, particularly in subjects involving abstract or spatial concepts. Their core strength lies in making the invisible visible and the abstract tangible. In physics education, for instance, VR has helped students visualize and manipulate 3D vectors, improving understanding of vector addition and spatial relationships (Campos; Hidrogo; Zavala, 2022). Studies show that such immersive

tools can boost engagement and deepen comprehension of abstract STEM topics like electromagnetism or geometry through interactive, risk-free exploration (Campos; Hidrogo; Zavala, 2022; Johnson-Glenberg, 2018).

In astronomy and aerospace, where scales are far beyond human experience, immersive technologies offer unique advantages. VR enables virtual field trips through space — letting students stand on Mars or orbit planets — providing an intuitive grasp of scale and distance. Learners can explore the solar system with accurate proportions, making complex spatial relationships (like planetary distances or ring sizes) more comprehensible (Atta *et al.*, 2022). Astrophysical phenomena such as orbital mechanics and black hole dynamics are also made more accessible through interactive VR visualizations.

In aerospace engineering, VR and AR are increasingly used for hands-on training. Beyond traditional flight simulators, modern VR platforms allow students to perform simulated pre-flight inspections, engine maintenance, or spacecraft docking. Vaughn College, for example, uses VR for aviation trainees to practice inspecting and assembling parts, reinforcing mechanical familiarity before real-world exposure. Similarly, Atta *et al.* (2022) created a virtual “space lab” where students assemble a CubeSat in a simulated cleanroom, boosting their understanding of subsystem configuration through direct interaction and gamified tasks (Atta *et al.*, 2022).

AR complements this by overlaying digital instructions on real-world hardware. NASA’s Project Sidekick exemplifies this: astronauts use HoloLens headsets aboard the ISS to receive real-time, spatially anchored maintenance guidance (NASA, 2015). In classrooms, AR enables students to interact with 3D models of rockets or overlay CAD designs onto physical parts, enriching theoretical lessons with live, contextual visualization (Atta *et al.*, 2022; Milgram; Kishino, 1994).

#### **2.1.4 Embodiment, Interaction, and Spatial Cognition:**

A recurring theme in the educational use of AR/VR is the role of embodied and spatial learning. Immersive technologies engage the human sensorimotor system – users move their bodies to navigate virtual spaces, use gestures to interact with virtual objects, and perceive environments at true scale. This physicality supports cognitive processing by leveraging innate spatial reasoning and muscle memory. The theory of embodied cognition holds that learning is grounded in the body’s interactions with its environment, and AR/VR extend this principle digitally. Johnson-Glenberg (2018) highlights the pedagogical value of 3D gestures: when learners rotate a virtual object or walk through a graph, they build stronger memory links (Johnson-Glenberg, 2018). Her research shows that full-motion VR, where body movements align with abstract concepts, can deepen understanding and recall. Complementary studies (e.g., Liu *et al.*, 2020) found improved retention

tion when students enacted phenomena physically, and also noted increased presence and agency—factors tied to motivation (Campos; Hidrogo; Zavala, 2022; Johnson-Glenberg, 2018).

Spatial cognition benefits are also well-documented. VR’s stereoscopic depth and six degrees of freedom help learners perceive complex spatial relationships, vital in subjects like anatomy, geography, and engineering. Students exploring a molecule or a solar system in VR can shift perspective freely, activating spatial memory and supporting what researchers call “situated learning” – knowledge acquired in rich spatial contexts becomes more intuitive and transferable. Campos et al. (2022), for example, found that immersive 3D interaction notably enhanced vector learning tasks requiring spatial reasoning (Campos; Hidrogo; Zavala, 2022). Similarly, in astronomy, VR’s ability to scale from the Milky Way to Earth provides concrete visualizations of abstract systems (Kersting et al., 2024).

While AR/VR offer compelling tools, they are not magic bullets – user comfort, software complexity, and thoughtful pedagogical integration remain critical (Johnson-Glenberg, 2018). Still, evidence shows that immersive simulations can enhance traditional teaching, especially for learning goals involving visualization, experimentation, or embodied experience. In the context of this thesis, the implications are clear: AR and VR form a foundational layer. They enable students to interact with simulations of aerospace systems—such as satellites or orbital dynamics—in an intuitive and experiential manner. As hardware becomes lighter and more capable, and software ecosystems more robust, immersive tools are becoming increasingly viable in education. With spatial computing platforms entering mainstream use (Ruth, 2024), AR and VR are poised not just as delivery platforms but as new paradigms for engaging with knowledge.

**2.1.4.0.1 Application to This Work** This thesis leverages the pedagogical strengths of immersive spatial learning through Virtual Reality as the primary modality. While the platform architecture is built on mixed reality hardware (Meta Quest 3) that supports both VR and AR passthrough modes, the educational experience emphasizes full VR immersion for the reasons detailed in Section ???. The literature reviewed here establishes the broader context of immersive educational technologies, while the implementation focuses specifically on VR’s capacity to place learners inside coherent spatial environments optimized for understanding orbital mechanics.

## 2.2 Generative Agents

Traditional software and simulations have been predominantly *deterministic*—given the same inputs, they yield the same outputs. Modern AI systems built on *genera-*

*tive* models, by contrast, introduce stochasticity and creativity. Large Language Models (LLMs) do not follow hard-coded rules; instead, they sample from probability distributions learned from vast textual corpora. Consequently, an LLM can produce context-dependent, varied responses rather than a single predetermined answer. This marks a paradigm shift from scripted to emergent behaviour. In recent work, advanced LLMs such as GPT-4 have even outperformed traditional reinforcement-learning agents in complex environments by reasoning through text rather than executing pre-programmed control policies (Carrasco; Rodriguez-Fernandez; Linares, 2025). While stochastic generation entails some unpredictability, it is precisely this creativity that lets *generative agents* adapt to scenarios beyond their designers' foresight.

At a conceptual level an LLM is a statistical language engine: given a textual history, it predicts the most plausible continuation one word at a time. Because it is trained on heterogeneous data, a single model can answer coding questions, analyse legal texts, or reason about orbital mechanics when prompted appropriately. This broad, generative capability underpins the rise of *LLM-powered agents* (Anthropic, 2024).

**LLM-based agents** are autonomous software entities that embed an LLM as their core “brain.” An agent senses its environment, reasons about goals, and acts—iteratively—until a task is complete. Industry definitions describe such an agent as “a system that uses an LLM to reason through a problem, create a plan, and execute that plan with tools” (Chen, 2023; Huang; Grady, *et al.*, 2024). The LLM supplies the reasoning; auxiliary modules provide planning, memory, and tool use (Anthropic, 2024). Crucially, the agent—not the user—controls the loop: it may decide which function to call, when to revise a plan, or whether to request clarification (OpenAI, 2023). Hence an agent is more than a single LLM invocation; it is a continual perceive–think–act cycle.

## Architectural Components

Generative-agent designs typically comprise five interacting elements (Anthropic, 2024; Huang; Grady, *et al.*, 2024):

- **Planning and reasoning.** The agent decomposes high-level goals into actionable steps, often prompting the LLM to produce an internal plan or “chain of thought.”
- **Memory.** Short-term context (recent turns) and long-term knowledge (summaries or retrieved documents) are stored externally—e.g. in a vector database—and injected into prompts as needed.
- **Tool use and APIs.** Through structured outputs (JSON function calls, shell commands, *etc.*) the agent invokes external tools to compute, query, or effect changes in its environment (OpenAI, 2023).

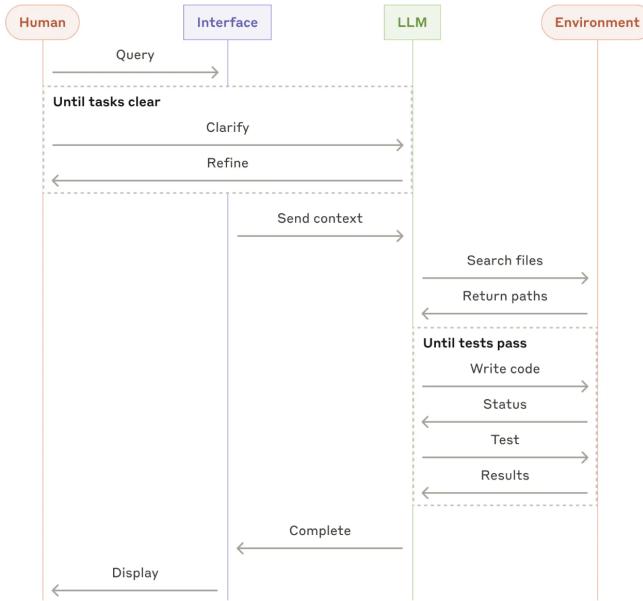


FIGURE 2.1 – End-to-end agentic workflow from Anthropic’s “Building Effective Agents.” The human issues a query through an *interface*; the LLM asks clarifying questions until the task is precise, receives contextual files, iteratively writes and tests code against the environment, and finally returns results for display (Anthropic, 2024).

- **Iterative control loop.** The agent cycles through *observe* → *reason* → *act* → *observe*, optionally reflecting or self-critiquing between steps to improve reliability.
- **Autonomy and adaptation.** Equipped with the above, the agent can switch strategies, recover from errors, and pursue its objective with minimal human micromanagement.

## Applications and Relevance

- **Simulations and interactive worlds.** Park *et al.* created “Generative Agents” that populate a sandbox town with virtual characters who plan, remember, and socially interact—producing emergent storylines never scripted by the developers (Park *et al.*, 2023).
- **Aerospace guidance and control.** Carrasco *et al.* demonstrated an LLM agent piloting a spacecraft in the *Kerbal Space Program* simulation by iteratively reading textual telemetry and issuing control actions, matching classical controllers without explicit orbital equations (Carrasco; Rodriguez-Fernandez; Linares, 2025).
- **Legal reasoning.** Harvey AI equips law-firm associates with an agent that drafts memos, retrieves precedents, and iteratively refines analyses through dialogue—illustrating agentic workflows in language-dense tasks (Chen, 2023).

- **Education.** Khan Academy's *Khanmigo* employs GPT-4 as a Socratic tutor that adapts explanations to each learner, providing hints rather than answers and thereby personalising study sessions at scale (Academy, 2023).

## 2.3 Orbital Mechanics: The Physics of Celestial Motion

The intuitive, visual understanding of orbital motion is a primary objective of this project. While the generative agent handles the underlying calculations, a firm grasp of the governing principles is essential to frame the simulation's logic and appreciate its educational value. Orbital mechanics is the study of the motion of bodies under the influence of gravity. For missions in Earth's orbit and for interplanetary trajectories, the foundational principles discovered by Isaac Newton and Johannes Kepler provide a remarkably accurate framework for describing and predicting these celestial paths. This section outlines the core concepts that form the physical and mathematical basis of the simulation system, focusing on the specific orbital regimes and parameters that the platform enables users to explore: circular orbits, elliptical orbits, and escape trajectories.

### 2.3.1 Newtonian Gravity and the Two-Body Problem

At the heart of all orbital motion lies gravity. In the 17th century, Sir Isaac Newton formulated the Law of Universal Gravitation, stating that any two bodies attract each other with a force proportional to the product of their masses and inversely proportional to the square of the distance between them (Curtis, 2020). This is expressed mathematically as:

$$F = G \frac{m_1 m_2}{r^2}$$

where  $F$  is the gravitational force,  $G$  is the gravitational constant ( $6.674 \times 10^{-11} \text{ N}\cdot\text{m}^2/\text{kg}^2$ ),  $m_1$  and  $m_2$  are the masses of the two bodies, and  $r$  is the distance between their centers.

When applied to a satellite orbiting a celestial body like Earth, this law forms the foundation of the **two-body problem**. This model makes a critical simplifying assumption: it considers only the gravitational force between the satellite and the primary body (e.g., Earth), ignoring perturbations such as atmospheric drag, solar radiation pressure, and gravitational influences from other bodies like the Moon or the Sun (Vallado, 2013). While these forces are significant for high-precision, long-term trajectory prediction, the two-body model provides an elegant and highly accurate approximation for foundational analysis and educational purposes. The resulting equation of motion is:

$$\ddot{\vec{r}} + \frac{\mu}{r^3} \vec{r} = 0$$

Here,  $\vec{r}$  is the position vector of the satellite relative to the primary body,  $\ddot{\vec{r}}$  is its acceleration, and  $\mu$  (mu) is the standard gravitational parameter of the system. For Earth-orbiting satellites,  $\mu = GM_{\text{Earth}} \approx 398,600 \text{ km}^3/\text{s}^2$ , where  $M_{\text{Earth}}$  is Earth's mass.

The solution to this differential equation reveals a profound geometric truth: under the inverse-square law of gravity, the satellite's path must be a **conic section**—a circle, ellipse, parabola, or hyperbola (Curtis, 2020). Which conic section results depends on the satellite's energy and angular momentum. This elegant mathematical result means that all orbital trajectories, from the circular path of the ISS to the hyperbolic escape of Voyager, are governed by the same fundamental physics expressed through different geometric shapes.

### 2.3.2 Kepler's Laws and Orbital Geometry

Johannes Kepler, working in the early 17th century with observational data from Tycho Brahe, empirically discovered three laws of planetary motion that would later be shown to be direct consequences of Newtonian gravity. These laws provide the geometric and temporal framework for understanding orbits (Bate; Mueller; White, 1971):

1. **First Law (Law of Orbits):** The orbit of a planet (or satellite) around the Sun (or Earth) is an ellipse, with the central body at one focus. A circle is the special case of an ellipse where both foci coincide.
2. **Second Law (Law of Areas):** A line connecting the satellite to the central body sweeps out equal areas in equal times. This means the satellite moves faster when closer to the central body (at periapsis) and slower when farther away (at apoapsis).
3. **Third Law (Law of Periods):** The square of the orbital period is proportional to the cube of the semi-major axis. Mathematically:  $T^2 \propto a^3$ , or more precisely,  $T^2 = \frac{4\pi^2}{\mu} a^3$ . This law directly relates orbital size to orbital period, explaining why the ISS at 420 km altitude completes an orbit in 92.8 minutes while the Hubble Space Telescope at 540 km takes slightly longer at approximately 95 minutes.

Kepler's laws were empirical observations that Newton later proved mathematically from first principles. Together, they provide both the geometric intuition (ellipses, not circles, are the general case) and quantitative relationships (period depends on altitude) that govern orbital motion.

### 2.3.3 Orbital Regimes: Circular, Elliptical, and Hyperbolic Trajectories

The shape of an orbit is determined by the satellite's total mechanical energy—the sum of its kinetic energy (from motion) and gravitational potential energy (from position in the gravity field). This energy dictates which conic section describes the trajectory. The platform's simulation implements three fundamental orbital regimes, each representing a different energy state and mission application.

#### 2.3.3.1 Circular Orbits: Stable Operational Platforms

A **circular orbit** occurs when the satellite's velocity is precisely calibrated so that the centripetal acceleration required for circular motion exactly matches the gravitational acceleration at that altitude. This is the special case where eccentricity  $e = 0$ .

For a circular orbit at radius  $r$  from Earth's center (altitude  $h = r - R_{\text{Earth}}$ ), the required orbital velocity is given by:

$$v_{\text{circular}} = \sqrt{\frac{\mu}{r}}$$

This relationship shows that orbital speed decreases with altitude: satellites in low Earth orbit (LEO) travel faster than those in higher orbits. For example, the ISS at 420 km altitude orbits at approximately 7.66 km/s, while the Hubble Space Telescope at 540 km altitude travels at approximately 7.59 km/s—slightly slower due to its higher altitude.

Circular orbits are preferred for operational missions requiring predictable, repeating ground tracks and stable altitude. The International Space Station (420 km, 51.6° inclination) and Hubble Space Telescope (540 km, 28.5° inclination) both use circular orbits because their missions benefit from the stability and predictability of constant altitude and speed.

Kepler's Third Law directly determines the orbital period for circular orbits:

$$T = 2\pi \sqrt{\frac{r^3}{\mu}}$$

This equation explains the relationship between altitude and period. The ISS at 420 km completes 15.5 orbits per day, providing frequent revisit times for Earth observation and crew operations. Hubble at 540 km has a slightly longer period, chosen to balance orbital stability with minimizing atmospheric drag while providing optimal viewing conditions for astronomical observations.

### 2.3.3.2 Elliptical Orbits: Variable Altitude Trajectories

An **elliptical orbit** occurs when  $0 < e < 1$ , where  $e$  is the eccentricity. The satellite's altitude and speed vary continuously as it moves around the ellipse. The closest point to Earth is called **periapsis** (or perigee for Earth orbits), and the farthest point is **apoapsis** (or apogee). The size of the ellipse is characterized by the **semi-major axis**  $a$ , which is half the longest diameter of the ellipse.

The relationship between the semi-major axis, periapsis radius  $r_p$ , and apoapsis radius  $r_a$  is:

$$a = \frac{r_p + r_a}{2}$$

The eccentricity quantifies how elongated the ellipse is:

$$e = \frac{r_a - r_p}{r_a + r_p}$$

When  $e = 0$ , the ellipse becomes a circle ( $r_p = r_a$ ). As  $e$  approaches 1, the ellipse becomes increasingly elongated.

The satellite's speed at any point in an elliptical orbit is given by the **vis-viva equation**, one of the most fundamental relationships in orbital mechanics (Curtis, 2020):

$$v = \sqrt{\mu \left( \frac{2}{r} - \frac{1}{a} \right)}$$

This equation reveals that orbital speed depends on both the current position  $r$  and the orbit's overall size  $a$ . At periapsis, where  $r$  is smallest, the satellite moves fastest. At apoapsis, where  $r$  is largest, it moves slowest. This speed variation is a direct consequence of Kepler's Second Law: the satellite must move faster when closer to Earth to sweep equal areas in equal times.

Elliptical orbits have important applications. Highly Elliptical Orbits (HEO) are used for communications satellites serving high-latitude regions, as the satellite spends most of its time near apoapsis with excellent visibility over polar regions. Transfer orbits between circular orbits are also elliptical, with the initial circular orbit at periapsis and the target circular orbit at apoapsis.

### 2.3.3.3 Hyperbolic Trajectories: Escaping Earth's Gravity

A **hyperbolic trajectory** occurs when  $e \geq 1$ . Unlike elliptical orbits, which are closed and periodic, hyperbolic trajectories are open curves—the spacecraft approaches Earth,

swings around it, and departs, never to return. This regime represents escape from Earth's gravitational influence.

The minimum speed required to achieve escape from Earth's surface is the **escape velocity**:

$$v_{\text{escape}} = \sqrt{\frac{2\mu}{r}}$$

At Earth's surface ( $r = R_{\text{Earth}} = 6371$  km), this yields approximately 11.2 km/s. Notice that escape velocity is exactly  $\sqrt{2}$  times the circular orbital velocity at the same radius—this factor of  $\sqrt{2}$  represents the energy difference between a bound circular orbit and an unbound escape trajectory.

For a hyperbolic trajectory, the spacecraft's velocity at any distance is given by a modified vis-viva equation:

$$v = \sqrt{\mu \left( \frac{2}{r} + \frac{1}{a} \right)}$$

Note the sign change: for hyperbolic orbits, the semi-major axis  $a$  is defined as negative, reflecting the fact that the orbit is unbound with positive total energy.

The Voyager spacecraft exemplify hyperbolic escape trajectories. After launch and acceleration to sufficient velocity, they followed hyperbolic paths that carried them beyond Earth's sphere of influence and into interplanetary space. The platform uses Voyager's trajectory to demonstrate the transition from bound elliptical motion to unbound hyperbolic escape, illustrating the fundamental energy threshold that separates orbiting from departing.

### 2.3.4 Orbital Orientation: Inclination and Coverage

While the size and shape of an orbit (determined by  $a$  and  $e$ ) govern its energy and geometry, the **inclination** determines the orbit's orientation in three-dimensional space. Inclination  $i$  is the angle between the orbital plane and a reference plane, typically Earth's equatorial plane. An inclination of 0 defines an equatorial orbit, while 90 defines a polar orbit that passes directly over both poles.

Inclination is not arbitrary—it is fundamentally constrained by the launch site's latitude and the physics of rotation. When a rocket launches eastward (prograde), it benefits from Earth's rotational velocity, which is maximum at the equator (~465 m/s) and decreases toward the poles. The minimum achievable inclination from a launch site is approximately equal to the site's latitude. For example, launches from Kennedy Space Center (28.5°N) can achieve inclinations of 28.5° or greater, but reaching lower inclinations would require the rocket to perform an energetically expensive plane change maneuver.

This launch constraint explains many mission orbital parameters:

- **ISS (51.6° inclination):** Designed to be accessible from both Kennedy Space Center and the Baikonur Cosmodrome in Kazakhstan (45.6°N). The 51.6° inclination allows Russian Soyuz launches from Baikonur while remaining within reasonable energy budgets for US launches.
- **Hubble (28.5° inclination):** Launched from Kennedy Space Center at the minimum possible inclination, maximizing the rotational velocity assist and minimizing fuel requirements. This low inclination also provides good sky coverage for astronomical observations while avoiding prolonged periods in Earth’s shadow.

Inclination also determines ground track coverage. An equatorial orbit ( $i = 0$ ) never passes over polar regions. A polar orbit ( $i = 90$ ) eventually covers the entire surface as Earth rotates beneath it. Intermediate inclinations provide a balance between coverage and launch efficiency. The platform’s mission-specific implementations demonstrate how operational requirements (crew access for ISS, astronomical visibility for Hubble) drive inclination choices.

### 2.3.5 The Educational Foundation for Interactive Exploration

The physics and mathematics outlined in this section—Newtonian gravity, Kepler’s laws, the vis-viva equation, and the geometric properties of conic sections—form the computational foundation of the simulation platform. More importantly, they represent the conceptual framework that users explore through embodied interaction in virtual reality.

Traditional orbital mechanics education presents these concepts through equations on paper and two-dimensional diagrams. Students memorize formulas and solve problems numerically, but the intuitive, spatial understanding of why the ISS orbits at 7.66 km/s or why the Hubble telescope requires a specific altitude and inclination often remains elusive. The three-dimensional geometry of an inclined orbit, the speed variation along an ellipse, and the meaning of escape velocity are fundamentally spatial phenomena that are difficult to internalize from textbooks alone.

The platform’s approach inverts this pedagogy. Users begin not with equations but with questions and curiosity: "Show me the ISS orbit." "Why does Hubble orbit where it does?" "How did Voyager leave Earth?" The generative agent translates these natural language queries into the precise orbital parameters described in this section—altitude, eccentricity, inclination—and the Unity simulation engine renders the resulting trajectories as visible, three-dimensional curves in space. Users inhabit the orbital environment,

observing how the ISS's 420 km circular orbit compares to Hubble's 540 km orbit, seeing the ellipse stretch as eccentricity increases, watching the hyperbolic escape path diverge from closed elliptical motion.

This section has established the theoretical foundation that makes such exploration both accurate and meaningful. The circular orbits users create are governed by  $v = \sqrt{\mu/r}$ . The elliptical orbits follow the vis-viva equation. The hyperbolic escapes exceed  $v_{\text{escape}} = \sqrt{2\mu/r}$ . The platform's educational value rests on this foundation: it translates rigorous astrodynamics into intuitive visual experience, enabling users to build genuine understanding of orbital mechanics through guided exploration rather than rote memorization.

# 3 Methodology

## 3.1 Design Philosophy and Approach

The development of this project is fundamentally an exploratory research endeavour into a new paradigm of human-computer interaction for educational purposes. Given the innovative and complex nature of integrating generative AI, immersive mixed reality, and embodied interfaces, a rigid, waterfall-style development plan would be inappropriate. Instead, the methodology is guided by a philosophy that embraces iteration and modularity to navigate the technical challenges and discovery process inherent in such work.

The approach is defined by three core principles:

- **Prototype-Driven:** The primary goal is the creation of a functional prototype that demonstrates the feasibility and potential of the proposed system. This approach prioritizes implementing the core functionalities of the user experience over exhaustive feature development, allowing for tangible and testable results that can validate the project's central thesis.
- **Iterative Development:** The project will be built in iterative cycles, following a process of building a core feature, testing its performance and usability, and refining it based on the results. This allows for flexibility in the implementation details, acknowledging that the optimal solutions for agent prompting and user interaction will be discovered and improved upon throughout the development lifecycle.
- **Modular Architecture:** The system is designed as a collection of distinct yet interconnected modules: the generative agent (the "brain") and the simulation and visualisation engine (the "world"). This modularity, a key objective of this project, makes the complex system manageable, facilitates parallel development and testing of components, and ensures the final architecture is extensible for future work.

These principles guided a four-phase development strategy. Phase 1 established the conversational agent in the Hub environment with circular and elliptical orbit creation

capabilities. Phase 2 implemented three Mission Spaces (ISS, Hubble, Voyager) with specialist agents and scene transition tools. Phase 3 integrated bidirectional voice through ElevenLabs (Scribe API for speech-to-text, TTS for character synthesis). Phase 4 deployed the complete system to Meta Quest 3 with immersive VR visualization. Each phase produced a testable, working system that integrated seamlessly with subsequent development without requiring architectural changes.

## 3.2 System Architecture and Data Flow

The platform architecture comprises two integrated spaces: the "Hub" (Mission Control) where users create custom orbits through conversation, and "Mission Spaces" (ISS, Hubble, Voyager) where specialists demonstrate real missions. Users navigate between these environments via voice commands (`route_to_mission`, `return_to_hub`), with conversational context preserved across transitions.

The system separates conversational intelligence (OpenAI GPT-4 via Responses API<sup>1</sup>) from spatial visualization (Unity 3D), connected through a tool-calling interface. The agent interprets natural language, selects appropriate tools (`create_circular_orbit`, `create_elliptical_orbit`, `set_simulation_speed`, `pause_simulation`, `reset_simulation_time`, `clear_orbit`, `route_to_mission`, `return_to_hub`), and Unity executes the corresponding physics calculations and rendering.

### 3.2.1 Interaction Flow

Each user interaction follows a nine-step cycle from speech input to audio output:

1. User speaks request via Quest 3 microphone
2. ElevenLabs Scribe API transcribes audio to text
3. OpenAI GPT-4 interprets intent and selects appropriate tool
4. Unity's `ToolExecutor` validates parameters and invokes corresponding C# method
5. `SceneTransitionManager` loads Mission Space (for `route_to_mission`); `OrbitController` calculates trajectory using vis-viva equation and renders visualization (for orbit creation)
6. Tool execution result returns to LLM as feedback

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<sup>1</sup>The platform uses OpenAI's Responses API with GPT-4 family models. The specific model version is configurable via `OpenAISettings` asset, allowing adaptation as newer models become available.

7. Agent generates educational response based on tool result and conversation context
8. ElevenLabs TTS synthesizes character-specific voice (Mission Control’s authority, ISS specialist’s precision, Voyager specialist’s Sagan-like wonder)
9. Audio plays through Quest 3 spatial audio system

Conversation history is maintained across turns and scene transitions, enabling contextual dialogue. Users control all aspects—orbit creation, mission navigation, simulation parameters—through voice alone.

### 3.3 Mixed Reality Design Rationale

While the Quest 3 supports both VR and AR passthrough, the platform emphasizes immersive VR for pedagogical reasons. Orbital mechanics involves scales (420 km for ISS, 35,786 km for geostationary orbit) incompatible with domestic spaces—AR overlays would show trajectories passing through walls and furniture, creating perceptual friction between room-scale and cosmic-scale contexts. VR isolation places users within the orbital environment itself, establishing coherent spatial context where Earth floats in space and trajectories exist in their natural domain. The architecture supports AR passthrough for collaborative learning, museum installations, or classroom demonstrations where physical anchoring adds value, but the primary experience prioritizes the modality best suited to the content.

### 3.4 Technical Implementation

The system implements conversational AI (OpenAI GPT-4 for reasoning, ElevenLabs for voice synthesis/transcription) interfaced with Unity 6 (6000.0.47f1) physics simulation.<sup>2</sup> The agent embodies four characters—Mission Control in the Hub, plus three mission specialists (ISS crew perspective for LEO operations, Hubble engineer for telescope mission design, Voyager/Sagan persona for interplanetary trajectories)—each with distinct voice profiles and expertise areas. Unity implements two-body orbital physics in C#, calculates trajectories via vis-viva equation, and renders visualizations on Quest 3. The platform supports circular orbit creation (160-35,786 km altitude) and elliptical orbit creation (periapsis/apoapsis 160-100,000 km), with inclination constrained to 0-180°.

<sup>2</sup>Unity 6 represents a major version upgrade from Unity 2020/2021 series, introducing significant improvements to the rendering pipeline, XR integration, and Android deployment workflows. Version specification matters for reproducibility as Unity projects are not forward-compatible across major versions.

## 3.5 Development and Version Control

The project follows systematic development practices using GitHub for version control. All source code—including Unity C# scripts, prompt templates, and configuration files—is tracked in a central repository, providing complete history of changes and enabling experimental work through branching without compromising the main project stability. This systematic approach aligns with the iterative development philosophy, where each development cycle’s progress is documented and preserved.

## 3.6 Validation Strategy

The platform’s technical feasibility and system integration are validated through demonstration of complete interaction scenarios across all mission spaces, showing that the proposed architecture functions reliably in representative educational workflows. The validation approach prioritizes operational evidence: users exploring orbital mechanics through natural conversation, navigating between Hub and Mission Spaces, and experiencing the full voice-driven VR cycle. Implementation details are documented and made publicly available to enable independent verification of feasibility claims. Users provide their own API keys for OpenAI and ElevenLabs services. Comprehensive documentation covers Unity configuration, Quest 3 deployment, and integration procedures.

## 3.7 Core Module Implementation

This section describes how the platform’s four primary modules—conversational agent, orbital physics simulation, voice integration, and virtual reality environment—work together to create an immersive educational experience for learning orbital mechanics. Each subsection explains the educational rationale behind key design decisions and how they support the learning objectives established in Section ???. Complete technical specifications are provided in Appendices ??–??.

### 3.7.1 Agent System Implementation

The conversational agent system removes the traditional barrier between learning intent and technical execution by enabling natural language control of orbital simulations. Learners can express goals like “Create an orbit matching the ISS” or “Show me a highly elliptical orbit” without needing to understand programming, coordinate systems, or simulation APIs. This design decision directly addresses a core challenge in physics education:

allowing students to focus on conceptual understanding rather than technical syntax.

Following the tool-calling architecture outlined in Section ??, the system implements OpenAI GPT-4 with a structured tool-calling framework that interprets user requests and invokes validated simulation commands. When a learner asks to create an orbit, the agent translates natural language into precise physics parameters (altitude, inclination, eccentricity), executes the orbital calculation, and explains the result in educational terms. Critically, the agent disambiguates between orbital velocity (the speed required to maintain a specific orbit, calculated from physics) and simulation time speed (how fast the visualization plays back)—a common source of confusion that this explicit separation prevents.

The platform embodies two agent archetypes: Mission Control (at the Hub) focuses on orbit creation and simulation control, while three mission specialists (ISS, Hubble, Voyager) provide mission-specific educational context when learners navigate to dedicated Mission Spaces. This dual-character design supports two learning modes: hands-on experimentation at the Hub, and contextual deepening through mission-specific dialogue. Conversation history persists across scene transitions, enabling learners to ask follow-up questions like “What was the altitude of the orbit I just created?” after switching contexts—supporting iterative, exploratory learning patterns.

Technical implementation details, including prompt architecture, tool schemas, context management algorithms, and API integration specifications, are documented in Appendix ??.

### 3.7.2 Orbital Physics Simulation

The orbital physics engine translates altitude specifications into velocity requirements automatically, making visible a fundamental relationship that students often struggle to grasp: that orbital speed is not arbitrary but determined by altitude through gravitational physics. When a learner requests “an orbit at 420 km like the ISS,” the system calculates the required velocity (7.66 km/s) using the vis-viva equation and displays both values together. This automatic calculation prevents a common misconception—that higher orbits move faster—by immediately showing that geostationary satellites at 35,786 km altitude actually travel slower (3.07 km/s) than low Earth orbit satellites, despite their greater distance.

The simulation implements two-body Keplerian mechanics (Section ??) with physics-consistent trajectory calculations for circular and elliptical orbits. Visual trajectories render as continuous curves in VR space, allowing learners to observe geometric properties directly: circular orbits maintain constant radius, while elliptical orbits visually

demonstrate eccentricity through their oblong shape. Scale compression maps Earth’s 6,371 km radius to a comfortable VR viewing volume while preserving proportional relationships—the ISS appears at 6.6% of Earth’s radius above the surface, matching the real ratio—enabling learners to develop accurate spatial intuition about orbital altitudes without being overwhelmed by vast scales.

Critically, all physics calculations occur in real units (km, km/s) before conversion to rendering space, ensuring that displayed values match published orbital data for ISS, Hubble, and other missions. This fidelity allows learners to verify simulation results against authoritative sources, building confidence in the educational tool. Complete physics implementation, including vis-viva equation derivations, scale compression algorithms, and trajectory visualization methods, appears in Appendix ??.

### 3.7.3 Voice Integration Pipeline

Voice interaction addresses a practical constraint of immersive VR environments (Section ??): hands holding controllers cannot easily type, and virtual keyboards break immersion. The system implements bidirectional speech through push-to-talk input (Quest 3 controller A button) and synthesized character voices, enabling learners to engage in natural spoken dialogue while manipulating 3D orbital visualizations. This hands-free modality supports exploratory learning patterns where students voice hypotheses (“What happens if I increase the altitude?”), observe results, and refine understanding through iterative questioning—a cognitive process difficult to sustain when switching between physical keyboards and immersive VR.

Each agent character embodies a distinct voice: Mission Control speaks with authoritative encouragement at the Hub, while mission specialists (like Anastasia, the ISS expert) adopt personalities aligned with their educational roles—professional, technical, and approachable. This character differentiation serves pedagogical purposes beyond engagement: learners develop associative memory between voice identity and knowledge domain, reinforcing context switching as they navigate between experimental workspace (Hub) and mission-specific deepening (ISS, Hubble, Voyager spaces). Voice synthesis occurs within 1–3 seconds of agent response generation, maintaining conversational flow without perceptible delays that would disrupt the learning dialogue.

The push-to-talk mechanism balances spontaneity with intentionality: learners explicitly signal when they wish to speak, preventing accidental voice activation while preserving the natural rhythm of conversation. This design choice emerged from recognizing that educational dialogue differs from commercial voice assistants—students need time to think between questions, and the platform should not interpret silence as disengagement. Technical details of speech-to-text processing, audio synthesis parameters, and character voice

management appear in Appendix ??.

### 3.7.4 Virtual Reality Environment

As discussed in Section ??, the virtual reality environment transforms abstract orbital mechanics into spatial experiences that leverage human depth perception and proprioception. Orbits exist as three-dimensional curves that learners can walk around, crouch beneath, and observe from multiple vantage points—building geometric intuition impossible to achieve through 2D screens or static diagrams. Seeing an elliptical orbit’s eccentricity from different angles, or observing how inclination tilts the orbital plane relative to Earth’s equator, engages spatial reasoning faculties that support conceptual understanding of orbital geometry.

The platform deploys to Meta Quest 3, a standalone VR headset enabling tetherless movement around orbital visualizations without PC connection constraints. Maintaining 90 Hz stereoscopic rendering ensures visual comfort during extended learning sessions, preventing the nausea and fatigue that would undermine educational effectiveness. This frame rate requirement drove architectural decisions throughout the implementation: single-pass instanced rendering reduces GPU overhead, texture compression minimizes memory bandwidth, and asynchronous scene loading prevents visible stuttering during navigation between Hub and Mission Spaces.

The multi-scene architecture supports distinct learning contexts: the Hub provides an experimental workspace for orbit creation and manipulation, while three Mission Spaces (ISS, Hubble, Voyager) offer focused environments for deepening understanding of specific missions. Scene transitions preserve conversation history and simulation state, allowing learners to seamlessly shift between hands-on experimentation and contextual exploration. Spatial UI elements render in 3D world space rather than head-locked overlays, maintaining presence and spatial grounding while providing necessary information—mission elapsed time, simulation speed, and dialogue responses appear as objects in the environment rather than disconnected interface chrome.

Technical specifications for Quest 3 deployment, including Android build configuration, input system implementation, stereo rendering pipeline, and performance optimization strategies, are detailed in Appendix ??.

## 4 Results and Demonstration

This chapter demonstrates the complete functional platform through the lens of an actual user learning journey. Rather than presenting isolated features, each section follows the narrative arc of the demonstration session, showing how a learner explores orbital mechanics concepts through curiosity-driven dialogue with AI specialists, hands-on orbit creation, and immersive VR visualization.

The demonstration validates all six specific objectives established in Section ?? through integrated scenarios:

- **Objective #1 (Physics-consistent simulation):** Orbital velocities and periods match analytical predictions (user-created orbit at 422 km: 7.66 km/s, consistent with ISS velocity at nominal 420 km altitude)
- **Objective #2 (Natural language interpretation):** User questions like “What’s a good altitude?” trigger appropriate tool selection and specialist routing
- **Objective #3 (Multimodal VR interaction):** Voice commands, spatial presence, and Quest 3 stereoscopic rendering enable embodied learning<sup>1</sup>
- **Objective #4 (Real-time coherence):** Scene transitions, voice synthesis, physics calculations, and rendering execute reliably without interruption
- **Objective #5 (Modular architecture):** Hub and three Mission Spaces (ISS, Hubble, Voyager) operate as distinct scenes sharing common infrastructure
- **Objective #6 (Reproducible implementation):** Complete source code, documentation, and deployment guides enable independent verification

The chapter structure follows the demonstration’s pedagogical pattern: *question* → *specialist guidance* → *hands-on creation* → *visual observation* → *iterative refinement*. This complete cycle repeats twice for circular orbits (Section ??) and elliptical orbits (Section ??), demonstrating experiential learning through hands-on creation. The escape

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<sup>1</sup>This demonstration focuses on VR immersion. AR passthrough capabilities exist in the codebase (`ARHub.unity`) but are not exercised in this session.

trajectory section (Section ??) demonstrates a complementary mode: conceptual dialogue without hands-on creation, showing the platform’s flexibility to support both experiential and theoretical learning depending on pedagogical context.

## 4.1 Entering the Orbital Environment

The platform’s learning journey begins when the user puts on the Quest 3 headset and enters the virtual environment. This onboarding sequence—cutscene introduction, Hub arrival, and first interaction—establishes spatial context, introduces the conversational agent, and demonstrates the voice-driven interface that will mediate all subsequent exploration.

### 4.1.1 Opening Sequence: Narrator Introduction

The experience opens with a cinematic sequence. The user’s viewpoint begins in deep space, far from Earth, while a narrator’s voice provides context:

*NARRATOR:* Above us, thousands of satellites trace perfect arcs—testaments to gravity, velocity, and the geometry of motion. You’re about to join that tradition. I’ll guide the physics; you’ll design the orbits. Together, we’ll explore how spacecraft navigate the cosmos.

As the narrator speaks, the camera moves smoothly toward Earth over 28.7 seconds, establishing the cosmic scale while framing the interaction paradigm. The phrase “I’ll guide the physics; you’ll design the orbits” positions the learner as active participant rather than passive observer.

### 4.1.2 Hub Environment Arrival: Spatial Presence and Agent Welcome

When the cutscene concludes, the user arrives at the Hub—Mission Control’s orbital workspace. The transition from cinematic observer to embodied presence is immediate: the user now floats in space, surrounded by stars, with Earth directly ahead.

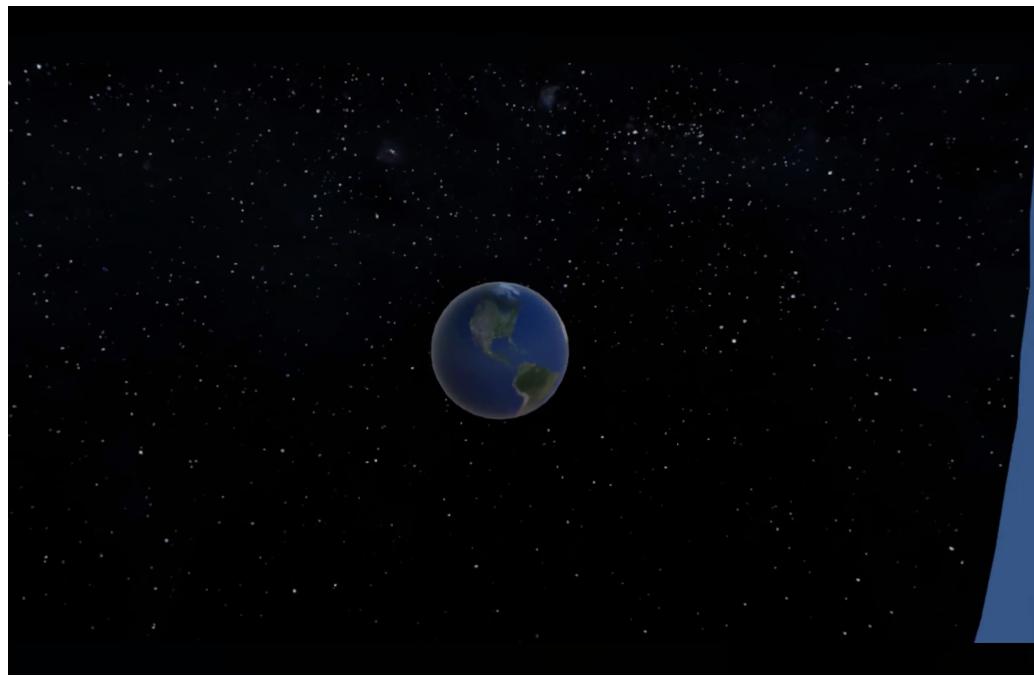


FIGURE 4.1 – Opening cutscene frame showing Earth from deep space. The camera begins at this distant perspective before zooming toward the Hub’s orbital position.

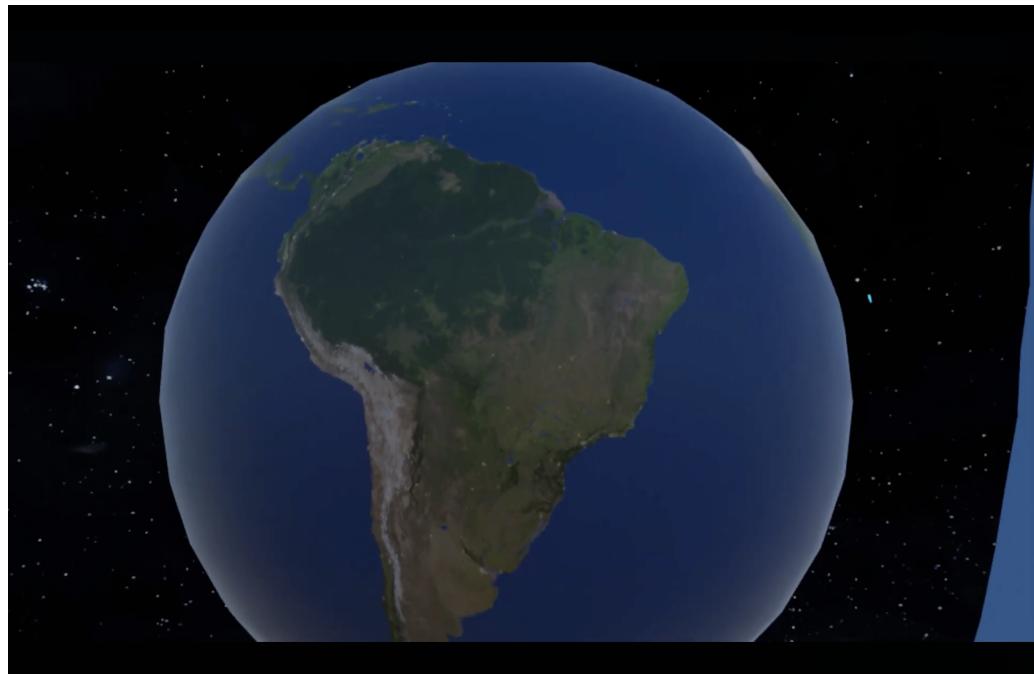


FIGURE 4.2 – Hub environment from user perspective. Earth floats in stereoscopic three-dimensional space, rendered with 8K textures to provide visual fidelity while maintaining 90 Hz frame rate on Quest 3.

CAPCOM greets the user, establishing orientation and interaction mechanics. The welcome message orients the user spatially (“floating above Earth”), introduces push-to-talk voice input (A button), explains available capabilities (orbit design and specialist consultation), and previews the three Mission Spaces—ISS, Hubble, and Voyager (full greeting in Appendix ??). CAPCOM’s professional warmth distinguishes Mission Control from the three specialists who will appear with their own vocal identities and expertise.

#### 4.1.3 Satellite Discovery: First Interaction

After orienting to the environment, the user notices a spacecraft model floating near Earth’s surface. This three-dimensional satellite will serve as the visual anchor for all orbital trajectories created during the session. The user moves closer to examine it, then presses the A button to speak:

*USER:* Hey, Capcom. I see we have a satellite here. Is this the satellite that we can build?

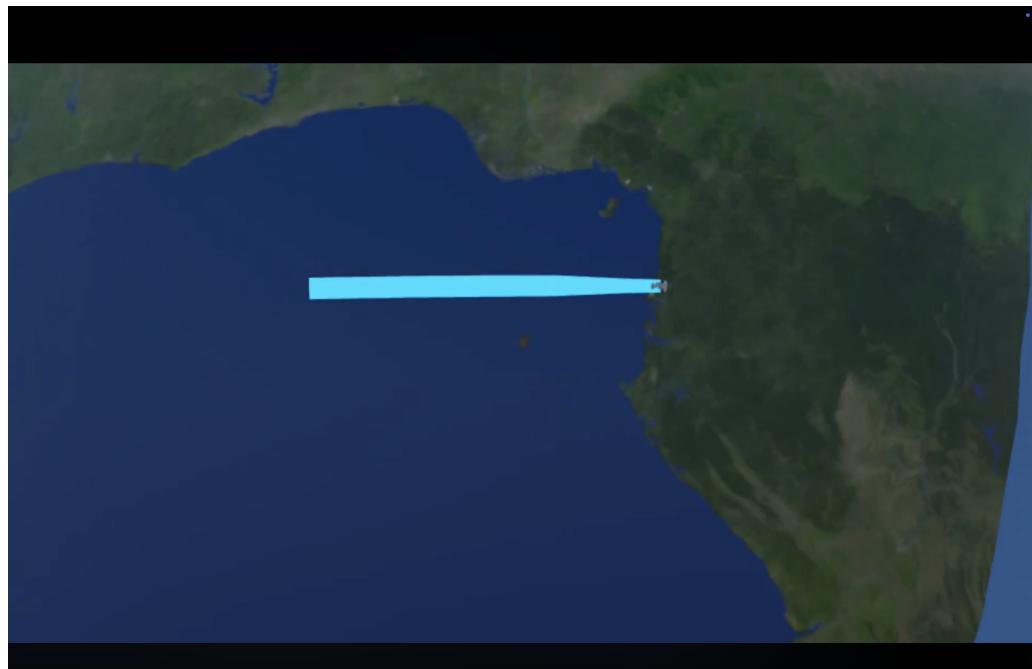


FIGURE 4.3 – Close-up view of the simulation satellite in the Hub environment. The user has navigated their perspective to examine the spacecraft model.

This first voice interaction exercises the complete bidirectional speech pipeline. The agent responds in conversational mode:

*CAPCOM:* Hello from Mission Control. Yes—this is your simulation satellite. We can build orbits by setting circular or elliptical paths. Tell me either the

altitude for circular, or periapsis and apoapsis for elliptical, and I'll get it launched.

CAPCOM's response introduces orbital terminology: "altitude" defines circular orbits, while "periapsis and apoapsis" specify elliptical paths. The complete interaction cycle—button press, speech transcription, agent response, audio synthesis—completes in 4–6 seconds, establishing the conversational rhythm that will support exploratory learning throughout subsequent sections.

## 4.2 Learning Through Mission Specialist Dialogue: The ISS Circular Orbit

This section demonstrates the platform's complete pedagogical cycle: conceptual question → specialist consultation → hands-on orbit creation → VR observation. The user wants to create a circular orbit but doesn't know what altitude to choose.

### 4.2.1 Conceptual Question and Specialist Routing

The user asks a foundational question (see Appendix ?? for complete dialogue):

*USER:* Cool. Let's start with a circular orbit. I need an altitude—but what's a good altitude? What determines a good altitude?

CAPCOM recognizes this as an educational question requiring mission-specific context and routes to the ISS specialist:

*CAPCOM:* Connecting you to the ISS mission for real-world examples. Stand by.

### 4.2.2 ISS Mission Space and Specialist Dialogue

The scene transitions to ISS Mission Space with conversation context preserved. The environment loads with the pre-configured ISS orbit (420 km altitude, 51.6° inclination) visible as a cyan trajectory.



FIGURE 4.4 – ISS Mission Space showing the pre-configured ISS orbit. ANASTASIA greets the user with context awareness about altitude selection.

ANASTASIA provides context-aware guidance:

*ISS\_CREW (ANASTASIA):* Hello from the ISS. For circular LEO orbits, engineers balance drag, launch energy, accessibility, and mission needs. The ISS flies around 420 km—high enough to limit atmospheric drag so we don't slow down too quickly, but not so high that crew/cargo launches become inefficient. It's also reachable from multiple launch sites. Too low: frequent reboosts. Too high: launches get harder and more expensive.

The user continues with follow-up questions, validating their reasoning by asking if choosing ISS altitude would be “absurd.” ANASTASIA confirms it’s “quite sensible” and representative of “decades of flight heritage.” When asked if the ISS orbit is circular, she clarifies: “Nearly. The path is close to circular with small variations [...] Near-circular simplifies rendezvous and ops.” After recapping the altitude (420 km), the user requests return to Hub.

### 4.2.3 Orbit Creation and Physics Validation

After returning to the Hub, the user creates a circular orbit:

*USER:* I'll build a circular orbit at 422 km.

*CAPCOM:* Copy. Circular orbit set at 422 km, inclination 0° (equatorial). Orbital speed 7.66 km/s—like the ISS, but over the equator.

The calculated velocity (7.66 km/s) matches the real ISS orbital speed, validating physics accuracy. The user then tests a common misconception:

*USER:* Can I choose the speed?

*CAPCOM:* In this sim, speed is derived from altitude by physics. At 422 km, you need 7.66 km/s for a stable circular orbit. If you want a different speed, pick a different altitude.

CAPCOM's response prevents a common misconception by clarifying that orbital speed is determined by altitude through physics, not an independent variable.

#### 4.2.4 Orbital Period and Time Acceleration

The user observes the created orbit and asks about period:

*USER:* How long does one lap take? It looks fast, but Earth is massive.

*ISS\_CREW (ANASTASIA):* At 420 km, the ISS completes a lap in 92.8 minutes—about 15 orbits/day. Higher altitude → slower speed → longer period. That's why we see a sunrise/sunset every 45 minutes.

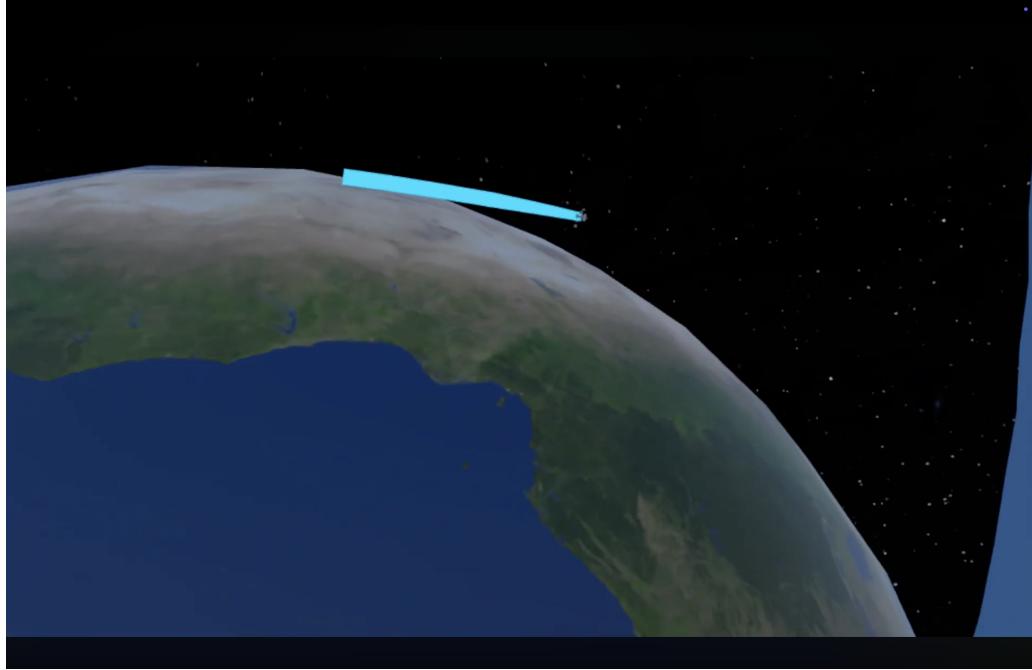


FIGURE 4.5 – Close perspective view of the 422 km circular orbit after creation. The cyan trajectory traces a perfect circle around Earth’s equator (inclination 0°). The satellite model is visible at one point along the orbit. This visualization enables spatial observation of circular geometry that would be difficult to comprehend from 2D diagrams. The user can move their VR viewpoint to observe the orbit from multiple angles, supporting the spatial cognition discussed in Section ??.

After returning to Hub, the user requests time acceleration to observe multiple orbits:

*USER:* With our current orbit ( 92 minutes), can we speed up the simulation so I can see it go around?

*CAPCOM:* Time acceleration: 10×. You’ll see the 92-minute trip much faster.

This temporal compression enables observation of the complete 92-minute orbital cycle within a reasonable viewing window, demonstrating successful disambiguation between simulation playback speed and orbital velocity.

### 4.3 Exploring Orbital Geometry: Elliptical Orbits and Eccentricity

Building on circular orbit knowledge, the user explores elliptical geometries with visible speed variation.

#### 4.3.1 Hubble Specialist Consultation

The user asks about elliptical orbits (Appendix ??):

*USER:* Great. I built a circular orbit. What's an elliptical orbit?

*CAPCOM:* Perfect question for Hubble—routing.

DR\_HARRISON provides a comparative explanation:

*HUBBLE\_ENGINEER (DR\_HARRISON):* Circular means constant distance and speed—like Hubble ( $\approx 540$  km) for steady imaging and predictable servicing. Elliptical stretches the path: closer at periapsis (faster), farther at apoapsis (slower). Some science missions pick elliptical to linger where conditions are best or to avoid interference (e.g., high apogee above the radiation belts).

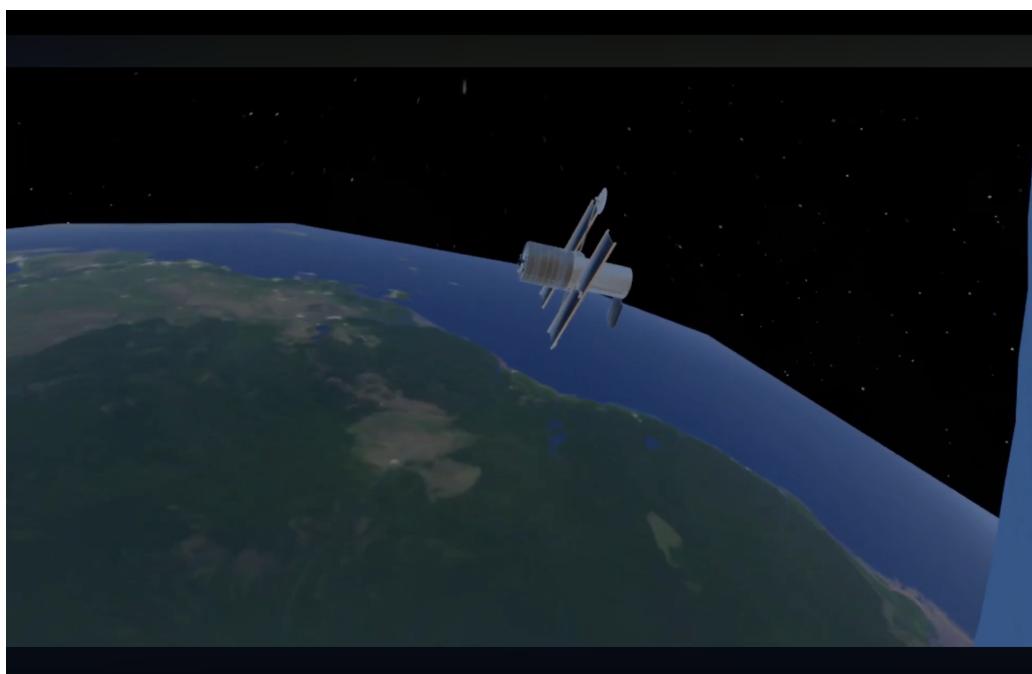


FIGURE 4.6 – Hubble Mission Space with DR\_HARRISON explaining elliptical orbital geometry. The environment shows Hubble’s circular orbit (540 km altitude, 28.5° inclination) as a reference for comparison.

When asked why missions choose elliptical orbits:

*USER:* Why choose elliptical if circular is simpler?

*HUBBLE\_ENGINEER (DR\_HARRISON):* To optimize time in a region. Example: Chandra uses a highly elliptical orbit to spend long stretches far from Earth’s radiation belts for cleaner X-ray observations. Trade-off: more complex tracking/operations.

### 4.3.2 Iterative Orbit Creation

After returning to Hub, the user requests elliptical orbit creation:

*USER:* Please build an elliptical orbit—anything interesting so I can compare.

*CAPCOM:* Elliptical orbit set: periapsis 400 km, apoapsis 2,000 km, inclination 0°. Watch it speed up near Earth and slow down far away.



FIGURE 4.7 – First elliptical orbit (periapsis 400 km, apoapsis 2,000 km) showing visible elongation compared to the circular orbit.

After observing at 100× time acceleration, the user provides qualitative feedback:

*USER:* Make it more elliptical; it still looks circular.

CAPCOM creates a more eccentric orbit:

*CAPCOM:* Roger. New orbit: periapsis 200 km, apoapsis 1,000 km, inclination 0°. The speed contrast will be much more dramatic.

The user observes visible speed variation:

*USER:* Wow—huge difference between near and far.

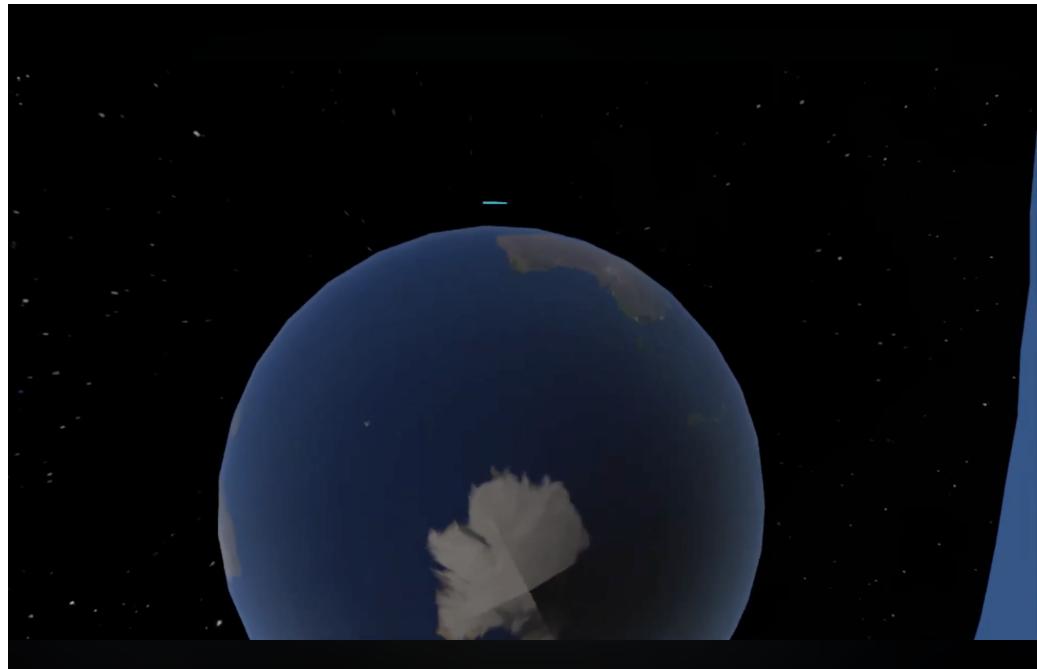


FIGURE 4.8 – Satellite at apoapsis (farthest point, slowest velocity).



FIGURE 4.9 – Satellite at periapsis (closest point, fastest velocity), demonstrating Kepler’s Second Law through visible speed contrast.

## 4.4 Conceptual Extension: Escape Trajectories and Mission Context

The user’s conceptual progression continues to escape trajectories (full transcript in Appendix ??):

### 4.4.1 Voyager Specialist: Beyond Bound Orbits

*USER:* Wow—huge difference between near and far. For deep-space missions, I assume there aren’t circular orbits at all. Is everything elliptical?

CAPCOM routes to Voyager specialist:

*CAPCOM:* Routing to Voyager for escape-trajectory talk.

CARL explains the distinction between bound and unbound trajectories:

*VOYAGER\_SPECIALIST (CARL):* Great question. To leave Earth, you don’t stay in an Earth orbit. Voyager 1 began in a near-circular parking orbit briefly, then received a final boost to a hyperbolic escape trajectory—no longer bound to Earth. Satellites around Earth use circular or elliptical orbits to remain nearby; escape missions transition from a staging orbit to hyperbolic and head out—past Earth, past the Sun’s planets, toward interstellar space.



FIGURE 4.10 – Voyager Mission Space environment. CARL, the Voyager specialist, embodies a contemplative character distinct from the technical specialists encountered earlier. The voice synthesis uses slower pacing (speed 0.9, configured in `KarlVoiceSettings`) to convey thoughtful reflection. This environment demonstrates that the platform supports both experiential learning (Sections ?? and ??) and conceptual dialogue.

The user continues exploring:

*USER:* So it's like breaking free from gravity?

*VOYAGER\_SPECIALIST (CARL):* Exactly. Think of it as climbing out of Earth's gravitational well. Circular and elliptical orbits stay in the well, perpetually falling around Earth. A hyperbolic trajectory has enough energy to climb out completely. Voyager didn't just orbit—it escaped.

CARL uses accessible metaphors to explain the physics. When asked about mission execution:

*USER:* How did they actually do it?

*VOYAGER\_SPECIALIST (CARL):* Voyager launched from Earth, first reaching a temporary parking orbit around 160-200 km. Then, at the optimal moment, the upper stage fired—adding enough velocity to exceed escape speed. That burn transitioned the trajectory from elliptical to hyperbolic. Once beyond Earth's sphere of influence, Voyager's path was governed by the Sun's gravity, heading toward Jupiter for the first gravitational assist.

The final exchange adds philosophical context:

*USER:* That's incredible. It's really leaving everything behind.

*VOYAGER-SPECIALIST (CARL)*: Past Earth, past the Sun’s planets, toward interstellar space. Voyager carries humanity’s first message to the cosmos. The golden record, the images, the sounds of Earth—all riding on a hyperbolic trajectory that will never return. It’s physics, yes, but it’s also a statement of who we are and what we dream.

CARL’s contemplative voice pacing and philosophical framing differentiate this specialist from ANASTASIA’s operational focus and DR\_HARRISON’s engineering precision. Unlike previous sections, this interaction remains conceptual—the user does not create a hyperbolic trajectory—demonstrating the platform’s support for both experiential and theoretical learning modes.

## 4.5 System Integration and Technical Validation

Having followed the user’s learning journey from initial Hub arrival through specialist consultations on circular orbits, elliptical geometries, and escape trajectories (Sections ??–??), we now shift from pedagogical narrative to technical validation. This section presents operational evidence validating Objectives #1 (physics accuracy), #4 (real-time coherence), and #5 (modular architecture) through measurements from the demonstration session, followed by honest assessment of validation scope and limitations.

### 4.5.1 Operational Validation

#### 4.5.1.1 Tool Execution Reliability

The demonstration session exercised the complete tool suite defined in `ToolSchemas.json` (Appendix ??). Table ?? documents all invocations with their parameters and execution results.

Navigation tools (`route_to_mission`, `return_to_hub`) dominated usage (8 of 11 invocations), reflecting the pedagogical structure from Sections ??–??: learners alternate between specialist consultation (mission spaces) and hands-on experimentation (Hub workspace). All 11 invocations succeeded without errors or parameter validation failures. Unused tools (`pause_simulation`, `reset_simulation_time`, `clear_orbit`) reflect session flow rather than technical limitations; these capabilities remain functional and documented in Appendix ??.

TABLE 4.1 – Tool Execution Summary from Demonstration Session. Note: Multiple visits to the same mission space (e.g., ISS visited twice) result in more scene transitions (9 total) than unique tool invocations shown here.

Tool Name	Uses	Parameters (Example)	Result
route_to_mission	4	mission_id: “ISS” (2×), “Hubble” (1×), “Voyager” (1×)	Scene transitions to specialist Mission Spaces; conversation context preserved
return_to_hub	4	(no parameters)	Scene transitions back to Hub from each mission space visited
create_circular_orbit	1	altitude_km: 422, inclination_deg: 0	Circular orbit created; velocity calculated: 7.66 km/s; period: 92.8 min
create_elliptical_orbit	2	First: periapsis_km: 400, apoapsis_km: 2000, inclination_deg: 0. Second: 200, 1000, 0	Elliptical orbits with eccentricities $e \approx 0.43$ and $e \approx 0.57$ ; speed variation observable in VR
set_simulation_speed	2	speed_multiplier: 10 (1×), 100 (1×)	Time scale adjusted; satellite motion accelerated by factors of 10× and 100×
pause_simulation	0	(not used in demo)	(capability exists but not exercised)
reset_simulation_time	0	(not used in demo)	(capability exists but not exercised)
clear_orbit	0	(not used in demo)	(capability exists but not exercised)

#### 4.5.1.2 Performance Characterization

System responsiveness directly impacts educational effectiveness—excessive latency between user input and platform response disrupts conversational flow and spatial presence. Table ?? presents measured latencies for each interaction stage during the demonstration.<sup>2</sup>

Voice interaction latency (4–7s) proved acceptable for educational dialogue, where conversational pacing naturally includes contemplative pauses; external API processing dominates this pipeline. Scene transitions (3–5s) via asynchronous loading maintained experiential continuity through persistent background music, smooth visual fades, and conversation context preservation. VR rendering stability (90 Hz sustained throughout)

<sup>2</sup>Measurement methodology: Latencies were observed during the demonstration session via Unity console debug timestamps and video recording analysis. Values represent observed ranges (N=1 session, ~18 voice interactions) under stable network conditions (WiFi, São José dos Campos, Brazil). External API latencies (STT, LLM, TTS) depend on network conditions and API server load; reported ranges reflect demonstration conditions rather than statistical distributions.

TABLE 4.2 – System Performance Metrics (Measured During Demonstration)

<b>Operation</b>	<b>Latency</b>	<b>Description</b>
Voice transcription (STT)	1–2 s	ElevenLabs Scribe API speech-to-text processing time
Agent reasoning (LLM)	2–3 s	OpenAI GPT-4 tool selection and response generation
Voice synthesis (TTS)	1–2 s	ElevenLabs text-to-speech audio generation
<b>Total voice interaction cycle</b>	<b>4–7 s</b>	<b>Complete STT → reasoning → TTS pipeline</b>
Scene transition (Hub ↔ Mission)	3–5 s	Asynchronous scene load with transition overlay
Orbit creation (circular/elliptical)	<0.1 s	Physics calculation and trajectory rendering
VR frame rate (Quest 3)	90 Hz	Stereoscopic rendering throughout demo

persisted during computationally intensive operations including 8K textures, scene transitions, and 100× time-accelerated animation—rendering optimizations (Appendix ??) validated real-time coherence under representative workload.

### 4.5.2 Physics Fidelity Assessment

Educational credibility requires physics fidelity—learners must trust that simulated phenomena reflect real orbital mechanics. The platform implements vis-viva equation for velocity calculations:

$$v_{\text{circular}} = \sqrt{\frac{\mu}{r}} \quad \text{and} \quad v_{\text{elliptical}}(r) = \sqrt{\mu \left( \frac{2}{r} - \frac{1}{a} \right)} \quad (4.1)$$

where  $\mu = 398,600 \text{ km}^3/\text{s}^2$  (Earth’s standard gravitational parameter),  $r$  is orbital radius from Earth’s center, and  $a$  is semi-major axis. All calculations occur in real units (km, km/s, rad/s) before Unity scale conversion ( $k = 0.000785$ ), ensuring displayed velocities reflect actual orbital mechanics verifiable against authoritative sources.

**4.5.2.0.1 Implementation Validation** Calculated velocities match analytical predictions from Equation ??:

- ISS altitude (420 km):  $v = \sqrt{398,600/6,791} = 7.66 \text{ km/s}$ , period  $T = 2\pi\sqrt{r^3/\mu} = 92.8 \text{ minutes}$
- User demonstration orbit (422 km):  $v = 7.66 \text{ km/s}$  (Section ??)

- Elliptical orbit (200 km × 1000 km):  $v_p = 7.87$  km/s at periapsis,  $v_a = 7.02$  km/s at apoapsis—12% speed variation visually perceptible in VR (Section ??)

**4.5.2.0.2 Acknowledged Limitations** The physics implementation validates arithmetic consistency (calculations follow Keplerian dynamics), but several limitations warrant acknowledgment for educational context:

- **Two-body approximation:** Simulation omits perturbations (J2 oblateness effects, atmospheric drag below 400 km, third-body gravitational influences) relevant for operational mission planning but negligible for educational visualization at demonstrated timescales.
- **No orbit propagation validation:** Future work should compare simulated trajectories against published Two-Line Element (TLE) data from Space-Track.org over 24-hour propagation windows, providing external validation beyond analytical self-consistency.
- **Simplified Kepler dynamics:** Platform demonstrates fundamental orbital mechanics concepts (circular/elliptical motion, velocity-altitude relationships, Kepler's Laws) appropriate for introductory education; advanced topics (station-keeping, orbital transfers, rendezvous) remain future extensions (Section ??).

This physics scope aligns with thesis objectives (Section ??): demonstrating feasibility of agent-guided immersive learning for foundational orbital mechanics, not replacing professional mission planning tools.

### 4.5.3 Integration Evidence

Sections ??–?? validated individual components through quantitative metrics. This subsection presents evidence of complete system integration: a continuous demonstration recording showing all subsystems operating together without interruption, manual intervention, or post-production editing.

**4.5.3.0.1 Video Documentation** A demonstration recording captures the complete user session analyzed throughout this chapter. The full interaction transcript appears in Appendix ??.

**Access:** [https://www.youtube.com/watch?v=S7314\\_CgTtY](https://www.youtube.com/watch?v=S7314_CgTtY)

**Duration:** 19 minutes, 12 seconds of uninterrupted interaction

**Recording Format:** Direct Quest 3 capture (first-person stereoscopic perspective, spatial audio, 90 Hz refresh maintained throughout)

**Content Scope:** The recording covers all interaction scenarios presented in this chapter: environment entry (Section ??), ISS consultation and circular orbit creation (Section ??), Hubble consultation and elliptical orbit exploration (Section ??), and Voyager consultation on escape trajectories (Section ??). Tool execution included 9 scene transitions, 3 orbit configurations, and 2 time acceleration adjustments.

**4.5.3.0.2 Multimodal Coordination Evidence** The continuous recording demonstrates multimodal coordination across the complete workflow:

**Context persistence:** The `MissionContext` singleton maintained conversation history across all 9 scene transitions. Specialists referenced prior exchanges when greeting the user (ANASTASIA: “You’re asking about good altitude choices”; DR\_HARRISON: “You’ve built circular orbits—now let’s explore elliptical geometry”; CARL: “You’re wondering about deep-space trajectories beyond circular and elliptical orbits”), demonstrating that the modular architecture (Objective #5) preserves state coherence despite environment changes.

**Physics-dialogue synchronization:** Agent responses referenced visible trajectories during operation. Example: “Watch it speed up near Earth and slow down far away” spoken while elliptical orbit displayed on screen (Section ??).

**Misconception correction:** When the user asked “Can I choose the speed?”, CAPCOM clarified the physics constraint in real-time: “Speed is derived from altitude by physics. At 422 km, you need 7.66 km/s for a stable circular orbit” (Section ??). This prevented conceptual error without disrupting learning flow.

These observations provide qualitative evidence of system integration under representative educational workload, complementing quantitative metrics in Sections ??–?? . The recording, combined with the open-source repository (Section ??), enables independent verification by the research community.

#### 4.5.4 Validation Scope and Acknowledged Limitations

The validation presented in Sections ??–?? demonstrates operational feasibility through a single extended demonstration session. While this approach documents integrated system performance under realistic usage, several limitations warrant explicit acknowledgement to properly contextualize the thesis contribution.

**4.5.4.0.1 Limited Sampling** The validation relies on a single demonstration session ( $N=1$ , duration 19:12) rather than systematic testing across multiple users and usage scenarios. This limitation affects generalizability:

**Variance characterization:** Performance metrics (Tables ?? and ??) represent single measurements without statistical distribution; mean latencies and standard deviations across diverse sessions remain unquantified.

**Failure mode exploration:** All 11 tool invocations succeeded in the demonstrated session. Edge case behavior—ambiguous voice commands, out-of-range parameter requests, API timeout handling, concurrent tool requests—remains untested. While the platform implements validation logic (constraint checking in `ToolSchemas.json`, parameter bounds in `OrbitController.cs`), systematic stress testing would characterize failure boundaries more completely.

**User diversity:** The demonstration captures a single learner’s interaction pattern. Variation across user populations (different prior knowledge levels, linguistic backgrounds, spatial cognition abilities, VR motion sensitivity) remains unexamined.

**4.5.4.0.2 No Comparative Baseline** Educational effectiveness is not measured against comparative baselines:

**Traditional simulators:** Platform performance not compared to established orbital mechanics tools (Kerbal Space Program, Orbiter, AGI STK) in terms of learning curve, comprehension accuracy, or engagement metrics.

**Textbook problem-solving:** No controlled study comparing immersive VR exploration versus traditional analytical problem sets for concept retention or transfer tasks.

**User study absence:** Learning outcomes (pre/post-test knowledge gains, misconception remediation effectiveness, spatial understanding improvements) not quantified through empirical educational research methods.

**4.5.4.0.3 Physics Validation Constraints** As noted in Section ??, the physics implementation demonstrates arithmetic consistency with Keplerian dynamics but lacks external validation against operational data:

**No trajectory propagation testing:** Simulated orbits not compared against published Two-Line Element (TLE) sets from Space-Track.org over multi-orbit propagation windows.

**Simplified dynamics:** Two-body approximation appropriate for introductory education but omits perturbation effects (J2, atmospheric drag, solar radiation pressure) relevant for advanced study or operational mission planning.

**4.5.4.0.4 Validation Interpretation** These boundaries define the thesis contribution as a **feasibility demonstration and architectural foundation** rather than comprehensive validation of educational efficacy. The work establishes:

- Technical viability: All subsystems (conversational AI, physics simulation, VR rendering, voice I/O) integrate successfully and operate reliably under demonstrated conditions.
- Architectural soundness: Modular design (Objective #5) supports extension and adaptation, as evidenced by straightforward mission addition procedures documented in Section ??.
- Pedagogical promise: Qualitative observations (misconception correction, iterative refinement, conceptual progression) suggest educational potential warranting further empirical study.

Systematic evaluation through controlled user studies, comparative baseline testing, and longitudinal learning outcome measurement constitute essential future work (Chapter ??) to transition from proof-of-concept to validated educational intervention.

## 4.6 Implementation Availability

To enable independent verification and replication of this feasibility study, the complete implementation will be publicly available at <https://github.com/ezindani/orbitAIsimulation> upon thesis acceptance.<sup>3</sup> The repository contains all Unity C# source code (31 files across AI/, Orbital/, Core/ modules), conversational prompts, configuration assets, and Quest 3 deployment settings. Documentation covers system architecture, API configuration (users provide their own OpenAI/ElevenLabs keys), and build procedures.

This availability serves three research purposes: **(1) Technical verification**—researchers can audit physics implementations (vis-viva equations in `OrbitController.cs`) and prompt engineering strategies; **(2) Replication studies**—the platform can be deployed in controlled educational experiments to measure learning outcomes; **(3) Extension research**—the modular architecture (Section ??) enables investigation of alternative configurations (local LLMs, different VR hardware, additional physics domains) without invalidating baseline feasibility claims.

The implementation is released under MIT License to minimize barriers to academic use. The focus of this work is demonstrating operational feasibility through working

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<sup>3</sup>As of thesis submission, the repository is being prepared for public release with documentation, example configurations, and deployment guides. Verify current access status at the provided URL.

prototype; questions of pedagogical effectiveness, scalability, and widespread adoption remain subjects for future controlled studies.

## 5 Conclusion

This work demonstrates that immersive virtual reality combined with generative AI agents enables a new mode of scientific education. The platform fulfills its six objectives: physics-consistent simulation grounded in vis-viva equations, natural language interpretation via OpenAI GPT-4 tool-calling, multimodal VR interaction through Quest 3 voice input, real-time coherence sustained at 90 Hz, modular architecture supporting independent scenes, and reproducible implementation. Validation occurred through complete interaction scenarios where learners progress from uncertainty (“*what’s a good altitude?*”) to informed design (“*I’ll build a circular orbit at 422 km*”) via dialogue with specialist agents, hands-on creation, and immersive observation.

This work is fundamentally a **feasibility demonstration**, not a pedagogical effectiveness study. The central research question asks: *Is it operationally possible to combine immersive VR, generative AI agents, and voice interaction to create a functional educational platform for orbital mechanics?* The answer, validated through working prototype and complete interaction scenarios, is affirmative. The platform functions reliably, integrates complex technologies coherently, and executes the intended learning cycle. Whether this approach proves educationally superior to traditional methods requires controlled studies with learners—a research direction this work enables but does not conduct.

The pedagogical architecture distinguishes this platform. Orbital mechanics is not presented as declarative knowledge but as spatial phenomena to be designed, questioned, and inhabited. When a learner asks about altitude selection, CAPCOM routes them to ISS specialist who explains engineering rationale (atmospheric drag versus launch efficiency, accessibility from launch sites) and validates their reasoning. The learner then creates the orbit, observes the trajectory, and accelerates time to witness the orbital period. This cycle—consultation, creation, observation—validated across three scenarios (ISS circular, Hubble elliptical, Voyager escape) structures learning as negotiated discovery.

This work reveals insights about educational interfaces in spatial computing. Embodiment transforms comprehension: learners inhabit orbital phenomena rather than observe abstractions, witnessing speed variation at periapsis rather than calculating it. Conversation enables discovery: specialist agents interpret vague questions and provide context-

appropriate guidance, enabling education as meaning-making. Modularity enables extension: architectural separation between intelligence (OpenAI), simulation (Unity), and rendering (Quest 3) allows new missions in five steps without core modifications. Reproducibility enables verification: releasing the complete implementation enables independent researchers to audit technical claims, replicate scenarios, and investigate alternative configurations without reimplementing costs.

Significant questions remain unanswered. This work demonstrates operational feasibility but not learning effectiveness through controlled studies. Does conversation improve conceptual understanding compared to traditional instruction? Does immersive visualization enhance retention? These require longitudinal studies with control groups. The demonstration validated one learning path; alternative pedagogical sequences remain unexplored. The voice pipeline depends on external APIs, creating dependencies unsuitable for offline deployment. The physics implements two-body dynamics validated against mission parameters but does not support perturbations or impulsive maneuvers required for advanced planning. These limitations define the research frontier this work establishes.

The platform establishes foundation for research trajectories spanning pedagogical studies (controlled effectiveness experiments, adaptive modeling, collaborative multiplayer), technical extensions (SGP4 propagation, local LLM deployment, AR passthrough), and cross-domain applications (atmospheric flight dynamics, thermodynamic cycles, circuit analysis). These domains share the challenge of making abstract phenomena spatially intuitive through the same architecture: conversational agents orchestrating physics simulation via tool-calling in immersive VR.

This work demonstrates feasibility. The central question—whether immersive VR combined with conversational AI can serve as an educational platform for orbital mechanics—is answered affirmatively through operational validation. The system functions reliably, integrates complex technologies coherently, and executes the pedagogical cycle from conceptual uncertainty to informed design. The implementation is publicly released under MIT License with modular architecture and comprehensive documentation, enabling reproducibility and extension. Whether this paradigm proves educationally superior to traditional instruction remains an open question requiring controlled studies—this work establishes that it is technically possible.

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# Appendix A - Agent System Implementation

This appendix provides detailed technical implementation specifications for the conversational agent system described in Section ??, implementing the tool-calling architecture and memory management principles outlined in Section ???. All class names, method signatures, file paths, and code excerpts are verified against the Unity project source code.

## A.1 Prompt Architecture

The agent system operates through structured prompts stored in the `PromptSettings` ScriptableObject configuration asset. Table ?? summarizes the prompt components and their purposes.

TABLE A.1 – Agent Prompt Component Specifications

Prompt Component	Purpose
<code>toolSelectionPrompt</code>	Interprets user intent, returns tool JSON
<code>responsePrompt</code>	Generates natural language responses
<code>specialistSystemPrompt</code>	Frames mission specialist character
<code>nonToolResponseTemplate</code>	Handles conversational interactions
<code>toolResponseTemplate</code>	Formats tool execution feedback
<code>specialistIntroTemplate</code>	Generates 40-word greetings

### A.1.1 Hub Agent: Three-Tier Prompt System

The Hub agent (Mission Control) uses three coordinated prompts:

#### Tool Selection Prompt

Instructs GPT-4.1 to analyze user natural language input and return structured JSON identifying which tool to invoke. Stored in `PromptSettings.toolSelectionPrompt` (As-

sets/Scripts/Core/Config/PromptSettings.cs, lines 16–107), the prompt explicitly defines eight available tools:

- **Orbit Creation:** `create_circular_orbit`, `create_elliptical_orbit`
- **Simulation Control:** `set_simulation_speed`, `pause_simulation`, `reset_simulation_time`
- **Workspace Management:** `clear_orbit`
- **Navigation:** `route_to_mission`, `return_to_hub`

### Example Tool Selection Prompt Fragment

The following excerpt from `toolSelectionPrompt` illustrates the instruction format for tool `create_circular_orbit`:

1. `create_circular_orbit`
  - Use when: User wants a simple orbit at one altitude
  - Parameters:
    - \* `altitude_km` (required): 160–35786 km
    - \* `inclination_deg` (optional): 0–180° (0=equatorial, 90=polar)
  - Examples: ISS orbit, geostationary orbit

#### OUTPUT FORMAT (strict JSON only)

```
{
  "intent": "execute_tool" | "none",
  "tool": "create_circular_orbit" | ... | null,
  "parameters": {
    // Tool-specific parameters
  }
}
```

This structured format enables GPT-4.1 to reliably extract user intent and generate valid tool invocation JSON. The prompt includes routing guidance to distinguish between simulation control requests (handled by Hub tools) and educational queries (routed to Mission Space specialists).

## Response Prompt

Generates natural language explanations of tool execution results. Stored in `PromptSettings.responsePrompt` (Assets/Scripts/Core/Config/PromptSettings.cs, lines 111–197), it includes explicit disambiguation guidance to prevent confusion between:

- **Orbital velocity** (physics-calculated, 7.66 km/s for ISS)
- **Simulation time speed** (user-controllable playback multiplier)

## Non-Tool Response Template

Handles conversational interactions that do not require tool execution, such as greetings (“Hello, I’m Mission Control”), capability inquiries (“What can you do?”), and educational questions.

### A.1.2 Mission Specialist Prompts

Mission Space specialists (ISS, Hubble, Voyager) use the `specialistSystemPrompt` (Assets/Scripts/Core/Config/PromptSettings.cs, lines 229–267), which frames the agent as an enthusiastic mission expert focused on education rather than simulation control. Character configuration occurs through `MissionConfig` ScriptableObject assets:

- `ISS_Config.asset`: Character name “Anastasia”, personality “Professional engineer - clear, technical, friendly”
- `Hubble_Config.asset`: Hubble Space Telescope mission specialist
- `Voyager_Config.asset`: Voyager interplanetary mission specialist

The `specialistIntroTemplate` generates concise 40-word, 10-15 second greetings acknowledging the routing context from `route_to_mission`.

## A.2 Tool Schema and Validation

The eight tools are defined in `ToolSchemas.json` (Assets/Resources/Tools/ToolSchemas.json, 168 lines) with complete JSON Schema specifications. Table ?? documents parameter constraints enforced by the `ToolRegistry` validation system.

TABLE A.2 – Tool Parameter Constraints

Tool	Parameter	Constraint
create_circular_orbit	altitude_km	160–35,786 km
create_circular_orbit	inclination_deg	0–180°
create_elliptical_orbit	periapsis_km	160–35,786 km
create_elliptical_orbit	apoapsis_km	160–100,000 km
create_elliptical_orbit	inclination_deg	0–180°
set_simulation_speed	speed_multiplier	0.1–100×

### A.2.1 Tool Execution Pipeline

The `ToolExecutor` class receives validated tool calls from the agent system and invokes corresponding C# methods:

- **Orbit Tools** → `OrbitController.CreateCircularOrbit()`, `CreateEllipticalOrbit()`
- **Time Controls** → `TimeController.SetSpeed()`, `Pause()`, `ResetTime()`
- **Navigation Tools** → `SceneTransitionManager.TransitionToMission()`, `TransitionToHub()`
- **Workspace** → `OrbitController.ClearOrbit()`

Execution results—success status, generated orbital parameters, error messages—feed back into the LLM response generation cycle through the response prompt template.

### A.3 Conversation Context Management

The `ConversationHistory` class maintains conversation continuity across multi-turn dialogues and scene transitions. Table ?? documents the exchange data structure.

TABLE A.3 – Conversation Exchange Data Structure

Field	Content
<code>timestamp</code>	Date/Time of exchange
<code>userMessage</code>	User's natural language input
<code>agentResponse</code>	Agent's generated response
<code>toolExecuted</code>	Tool name (or null if conversational)
<code>location</code>	Current scene (Hub, ISS, Hubble, Voyager)

### A.3.1 Context Window Management

The system maintains a sliding window of the last 10 exchanges (`maxHistorySize = 10`). Two methods provide context injection into prompts:

- `GetFormattedHistory(lastNExchanges = 5)`: Returns detailed history with timestamps, locations, and tool executions for the last 5 exchanges
- `GetContextSummary(lastNExchanges = 3)`: Returns condensed 3-exchange summary optimized for token efficiency

### A.3.2 Cross-Scene Persistence

Scene transitions preserve conversation history through Unity's `DontDestroyOnLoad` mechanism. The `PromptConsole` GameObject, containing the `ConversationHistory` component, persists across scene unloading when users invoke `route_to_mission` or `return_to_hub` tools. This ensures unbroken dialogue continuity: a user can ask "What was the ISS orbit altitude I created in the Hub?" after transitioning to the ISS Mission Space.

## A.4 API Integration

The `OpenAIClient` class (Assets/Scripts/AI/Services/OpenAIClient.cs, 151 lines) implements asynchronous HTTP communication with OpenAI's Responses API endpoint (`/responses`).

### A.4.1 Request Structure

Requests to the `/responses` endpoint include:

- **Model:** "gpt-4.1"
- **Input:** User's natural language message
- **Instructions:** Concatenated system prompt + conversation history + tool schemas

The `CompleteAsync()` method constructs JSON payloads using Unity's `UnityWebRequest` for `async/await` compatibility.

### A.4.2 Response Parsing

The client extracts assistant text from JSON responses through a two-stage fallback:

1. **Primary:** Extract `output_text` convenience field (if present)
2. **Fallback:** Concatenate all `output[] .content[] .text` arrays

Tool call JSON undergoes validation by `ToolRegistry` before execution. Results format back into natural language through the response prompt template system, generating contextual explanations like: “I’ve created a circular orbit at 420 km altitude with 51.6° inclination. The orbital velocity is 7.66 km/s, matching the ISS configuration.”

### A.4.3 Mission-Specific Configuration

Each Mission Space scene loads scene-specific `OpenAISettings` ScriptableObject assets that override the default system prompt, enabling character switching when users transition from Hub (Mission Control) to Mission Spaces (specialist agents).

# Appendix B - Orbital Physics Implementation

This appendix provides detailed technical specifications for the orbital physics simulation engine described in Section ??, implementing the two-body Keplerian mechanics and vis-viva equation principles outlined in Section ???. All equations, algorithms, class methods, and numerical values are verified against the Unity project physics implementation.

## B.1 Two-Body Keplerian Mechanics

The simulation implements two-body orbital mechanics under the following simplifying assumptions:

- Earth modeled as a point mass at the coordinate system origin
- Satellite treated as a massless test particle (no gravitational influence on Earth)
- No atmospheric drag, solar radiation pressure, or third-body perturbations
- Instantaneous orbital maneuvers (no finite burn durations)

These assumptions yield closed-form Keplerian solutions suitable for educational visualization while maintaining physical accuracy for the mission profiles studied (ISS, Hubble, Voyager departure trajectory).

## B.2 Vis-Viva Equation Implementation

The vis-viva equation relates orbital velocity to position and total orbital energy. Table ?? documents the physical constants used throughout the simulation.

TABLE B.1 – Physical Constants for Orbital Calculations

Constant	Value	Symbol
Earth's standard gravitational parameter	398,600 km <sup>3</sup> /s <sup>2</sup>	$\mu$
Earth's mean radius	6,371 km	$R_{\oplus}$
Unity scale compression factor	0.000785 Unity/km	$k$
Unity Earth radius	5 Unity units	$R_{\text{Unity}}$

### B.2.1 Circular Orbit Calculation

Circular orbits ( $e = 0$ ) simplify the vis-viva equation to:

$$v_{\text{circular}} = \sqrt{\frac{\mu}{r}} \quad (\text{B.1})$$

where  $r = R_{\oplus} + h$  is the orbital radius from Earth's center, and  $h$  is the altitude above Earth's surface.

#### Implementation Method

The `OrbitController.CreateCircularOrbit()` method (lines 229–290) accepts altitude in kilometers and automatically calculates orbital velocity, eliminating user confusion between altitude and speed parameters. Algorithm ?? documents the calculation sequence.

TABLE B.2 – Circular Orbit Calculation Algorithm

Step	Calculation
1. Validate altitude	$h_{\text{input}} \rightarrow \text{Clamp}(160, 35, 786)$ km
2. Compute orbital radius	$r = R_{\oplus} + h = 6,371 + h$ km
3. Calculate orbital velocity	$v = \sqrt{\mu/r}$ km/s
4. Convert to Unity scale	$r_{\text{Unity}} = R_{\text{Unity}} + h \cdot k$
5. Convert to angular velocity	$\omega = (v \cdot k)/r_{\text{Unity}}$ rad/s

#### Example: ISS Orbital Velocity

For the International Space Station at  $h = 420$  km altitude:

$$r = 6,371 + 420 = 6,791 \text{ km} \quad (\text{B.2})$$

$$v = \sqrt{\frac{398,600}{6,791}} = 7.66 \text{ km/s} \quad (\text{B.3})$$

$$\omega = \frac{7.66 \times 0.000785}{5 + (420 \times 0.000785)} = 0.00113 \text{ rad/s} \quad (\text{B.4})$$

This matches the real ISS orbital velocity of approximately 7.66 km/s.

### B.2.2 Elliptical Orbit Calculation

Elliptical orbits ( $0 < e < 1$ ) use the full vis-viva equation:

$$v = \sqrt{\mu \left( \frac{2}{r} - \frac{1}{a} \right)} \quad (\text{B.5})$$

where  $a$  is the semi-major axis and  $r$  is the instantaneous distance from Earth's center.

### Orbital Elements Derivation

Given periapsis altitude  $h_p$  and apoapsis altitude  $h_a$ :

$$r_p = R_{\oplus} + h_p \quad (\text{periapsis radius}) \quad (\text{B.6})$$

$$r_a = R_{\oplus} + h_a \quad (\text{apoapsis radius}) \quad (\text{B.7})$$

$$a = \frac{r_p + r_a}{2} \quad (\text{semi-major axis}) \quad (\text{B.8})$$

$$e = \frac{r_a - r_p}{r_a + r_p} \quad (\text{eccentricity}) \quad (\text{B.9})$$

### Implementation Method

The `OrbitController.CreateEllipticalOrbit()` method (lines 300–367) computes velocity at periapsis using Equation ?? with  $r = r_p$ :

$$v_p = \sqrt{\mu \left( \frac{2}{r_p} - \frac{1}{a} \right)} \quad (\text{B.10})$$

Table ?? documents parameter validation constraints enforced before calculation.

TABLE B.3 – Elliptical Orbit Parameter Constraints

Parameter	Constraint
Periapsis altitude $h_p$	160–35,786 km
Apoapsis altitude $h_a$	$h_p + 1$ km to 100,000 km
Eccentricity $e$	$0 < e < 1$ (enforced implicitly)
Inclination $i$	0–180°

## B.3 Scale Compression

The simulation implements logarithmic scale compression to fit orbital mechanics within the Meta Quest 3’s comfortable rendering volume while preserving geometric relationships.

### B.3.1 Compression Factor Derivation

Earth’s physical radius (6,371 km) maps to 5 Unity units:

$$k = \frac{R_{\text{Unity}}}{R_{\oplus}} = \frac{5}{6,371} = 0.000785 \text{ Unity units/km} \quad (\text{B.11})$$

#### Example Mappings

Table ?? shows real-world altitudes mapped to Unity rendering coordinates.

TABLE B.4 – Scale Compression Examples

Mission	Real Altitude (km)	Unity Altitude
ISS	420	$420 \times 0.000785 = 0.33$
Hubble	540	$540 \times 0.000785 = 0.42$
Geostationary	35,786	$35,786 \times 0.000785 = 28.1$

This compression maintains visual proportions: the ISS appears at  $0.33/5 = 6.6\%$  of Earth’s radius above the surface, matching the real ratio of  $420/6,371 = 6.6\%$ .

### B.3.2 Numerical Stability

All physics calculations occur in real units (km, km/s) before conversion to Unity space for rendering. This ensures:

- No floating-point precision loss from working with very small Unity coordinates
- Physical accuracy verifiable against published orbital data

- Separation of physics (model) from rendering (view)

The `OrbitController` methods perform calculations in kilometers, then convert final results through multiplication by  $k$  only when setting Unity Transform positions.

## B.4 Trajectory Visualization

The `OrbitVisualizer` class (280 lines) generates trajectory curves by sampling the orbital ellipse equation at discrete points and rendering through Unity's LineRenderer system.

### B.4.1 Orbital Ellipse Equation

The orbit trajectory follows the polar equation:

$$r(\theta) = \frac{a(1 - e^2)}{1 + e \cos \theta} \quad (\text{B.12})$$

where  $\theta$  is the true anomaly (angle from periapsis),  $a$  is the semi-major axis, and  $e$  is the eccentricity.

### B.4.2 Sampling Algorithm

The `OrbitVisualizer.CalculateOrbitalPoint()` method (Assets/Scripts/Orbital/OrbitVisualizer.cs lines 217–231) samples Equation ?? at 128 evenly-spaced true anomaly angles  $\theta \in [0, 2\pi]$ . For each sample point:

$$r = \frac{a(1 - e^2)}{1 + e \cos \theta} \quad (\text{B.13})$$

$$x = r \cos(\theta + \omega) \quad (\text{B.14})$$

$$z = r \sin(\theta + \omega) \quad (\text{B.15})$$

where  $\omega$  is the argument of periapsis (orientation of the ellipse major axis in the orbital plane).

### Inclination Transformation

The resulting planar coordinates undergo rotation by inclination angle  $i$  via rotation matrix:

$$\mathbf{R}_i = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos i & -\sin i \\ 0 & \sin i & \cos i \end{bmatrix} \quad (\text{B.16})$$

This tilts the orbital plane from equatorial (XZ) to the specified inclination angle, enabling visualization of polar orbits (ISS at 51.6°) and equatorial orbits (geostationary at 0°).

### B.4.3 Rendering Configuration

Table ?? documents the Unity LineRenderer configuration for optimal VR visibility.

TABLE B.5 – LineRenderer Configuration Parameters

Parameter	Value
Path resolution	128 points
Line width	0.05 Unity units
Color	Cyan (0, 1, 1) with 0.7 alpha
Shader	Sprites/Default (view-aligned billboard)
Loop closure	Enabled (connects point 127 to point 0)

### Special Cases

- **Circular orbits** ( $e = 0$ ): Simplify to constant radius  $r = a$ , producing perfect circles
- **Elliptical orbits** ( $0 < e < 1$ ): Render with visible eccentricity
- **Debug visualization:** Green gizmo at periapsis, red gizmo at apoapsis for development testing

## B.5 Coordinate System Conventions

The simulation uses Unity’s left-handed coordinate system with the following conventions:

- **Origin:** Earth’s center of mass

- **Equatorial plane:** XZ plane ( $y = 0$ )
- **Polar axis:** +Y direction points toward North Pole
- **Reference direction:** +X axis defines  $0^\circ$  longitude
- **Orbital motion:** Counterclockwise when viewed from above North Pole (right-hand rule)

This convention aligns with standard aerospace engineering practices while accommodating Unity's left-handed rendering system.

# Appendix C - Voice Pipeline Implementation

This appendix provides detailed technical specifications for the bidirectional voice system described in Section ??, implementing voice interaction as a hands-free modality for immersive VR environments outlined in Section ???. All API endpoints, audio formats, class methods, and processing parameters are verified against the Unity project voice integration code.

## C.1 System Architecture

The voice pipeline implements bidirectional audio through ElevenLabs cloud APIs, enabling natural spoken interaction with the agent system. The data flow follows this sequence: user speech → speech-to-text transcription → agent processing → text-to-speech synthesis → audio playback.

### Component Responsibilities

- **PromptConsole:** Manages microphone capture, push-to-talk input detection, and audio playback
- **ElevenLabsClient:** Handles HTTP communication with ElevenLabs APIs (Assets/Scripts/AI/S... 394 lines)
- **Unity AudioSource:** Plays synthesized speech through Quest 3's spatial audio system
- **Unity Microphone:** Captures user voice input at 16 kHz sample rate

## C.2 Speech-to-Text Pipeline

Speech recognition converts user voice input to text through ElevenLabs' Scribe v1 transcription model. Table ?? documents the audio capture specifications.

TABLE C.1 – Speech-to-Text Audio Capture Specifications

Parameter	Value
Sample rate	16,000 Hz (optimized for speech)
Bit depth	16-bit PCM
Channels	Mono
Maximum duration	30 seconds
Audio format (transmitted)	WAV with RIFF header
API endpoint	/speech-to-text
Model	scribe_v1

### C.2.1 Push-to-Talk Input Detection

Voice recording activates through push-to-talk button press. The `PromptConsole.Update()` method (lines 281–323) implements platform-specific input detection with debouncing to prevent accidental double-triggers.

#### Input Source Detection

- **Desktop testing:** Space key via `Input.GetKeyDown(KeyCode.Space)`
- **VR deployment:** Quest 3 right controller A button via `OVRInput.Get(OVRInput.Button.One, OVRInput.Controller.RTouch)`

#### State Machine

Table ?? documents the recording state transitions.

TABLE C.2 – Recording State Machine

State	Trigger	Next State
Idle	Button press	Recording
Recording	Button release	Processing
Processing	Transcription complete	Idle

During the Recording state, a red visual indicator displays “Listening...” to provide user feedback.

### C.2.2 Audio Capture and Conversion

The `StartRecording()` method initiates Unity's `Microphone.Start()` with the specifications in Table ???. When the user releases the button, `StopRecordingAndTranscribe()` processes the captured audio.

#### WAV Conversion Algorithm

The `ConvertAudioClipToWav()` method (lines 322–368) converts Unity's `AudioClip` format to WAV for API transmission:

1. Extract float samples from `AudioClip.GetData()`
2. Convert float [-1.0, 1.0] to 16-bit signed integer [-32768, 32767]
3. Construct RIFF WAV header (44 bytes):
  - Chunk ID: "RIFF"
  - Format: "WAVE"
  - Subchunk 1: "fmt " (audio format specification)
  - Subchunk 2: "data" (PCM samples)
4. Concatenate header + PCM data

### C.2.3 API Request Structure

The WAV bytes transmit to ElevenLabs via `WWWForm` multipart HTTP POST:

```
POST https://api.elevenlabs.io/v1/speech-to-text
Content-Type: multipart/form-data
Headers: xi-api-key: [API_KEY]
```

Body:

- file: `recording.wav` (binary WAV data)
- `model_id`: "scribe\_v1"

### C.2.4 Response Parsing

The API returns JSON containing:

- **text**: Transcribed text string
- **confidence**: Recognition confidence score [0.0–1.0]

The transcribed text feeds directly into the agent’s `ProcessUserInput()` method for intent interpretation and tool selection.

### C.3 Text-to-Speech Pipeline

Agent text responses convert to speech through ElevenLabs’ text-to-speech API. Table ?? documents the synthesis configuration.

TABLE C.3 – Text-to-Speech Synthesis Parameters

Parameter	Value
Model	<code>eleven_flash_v2_5</code>
Stability	0.7 (voice consistency)
Similarity boost	0.8 (voice clarity)
Speed	1.0 (normal playback)
Audio format (received)	MP3
API endpoint	<code>/text-to-speech/{voiceId}</code>
Synthesis latency	1–3 seconds (typical)

#### C.3.1 API Request Structure

The `TextToSpeechAsync()` method (lines 31–129) sends synthesis requests:

```
POST https://api.elevenlabs.io/v1/text-to-speech/{voiceId}
```

```
Content-Type: application/json
```

```
Headers: xi-api-key: [API_KEY]
```

Body:

```
{
  "text": "Agent response text here",
  "model_id": "eleven_flash_v2_5",
  "voice_settings": {
    "stability": 0.7,
    "similarity_boost": 0.8,
    "speed": 1.0
  }
}
```

### C.3.2 MP3 Decoding and Playback

The API returns MP3-encoded audio via HTTP response body. The `ConvertMp3ToAudioClipAsync` method (lines 135–154) performs decoding:

1. Write MP3 bytes to temporary file in `Application.temporaryCachePath`
2. Load via `UnityWebRequestMultimedia.GetAudioClip(uri, AudioType.MPEG)`
3. Enable streaming mode for memory efficiency
4. Extract `AudioClip` from request
5. Delete temporary file in `finally` block

The resulting `AudioClip` plays through Unity's  `AudioSource` component attached to the camera, utilizing Quest 3's spatial audio capabilities for immersive voice delivery positioned at the user's head location.

### C.3.3 Model Selection Rationale

The `eleven_flash_v2_5` model balances:

- **Synthesis speed:** 1–3 seconds for typical 2–3 sentence responses (critical for real-time interaction)
- **Voice fidelity:** Natural prosody and intonation
- **API cost:** Flash models optimize for speed over maximum quality

## C.4 Character Voice Management

Each agent character uses a distinct ElevenLabs voice ID configured in `MissionConfig.specialistVoice` ScriptableObject references. Table ?? documents character voice assignments.

### C.4.1 Scene-Specific Voice Switching

When users invoke the `route_to_mission` tool, the scene transition loads mission-specific `ElevenLabsSettings` assets that override the default voice ID. This ensures:

TABLE C.4 – Character Voice ID Assignments

Character	Voice ID	Characteristics
Mission Control	N0pBlnGIn09m6vDvFkFC	Authoritative, encouraging, professional
Anastasia (ISS Specialist)	ZF6FPAbjXT4488VcRRnw	Professional engineer - clear, technical, friendly
Dr. Harrison (Hubble Specialist)	M4zkunnpRihDKTNF0D7f	Veteran aerospace engineer - technical, experienced, proud of Hubble's legacy
Karl (Voyager Specialist)	t1oG321G6Z6edP2XJLiz	Philosophical scientist and cosmic poet - contemplative, poetic, awe-inspiring

- Hub agent responses use Mission Control voice
- ISS Mission Space responses use Anastasia's voice profile
- Each specialist maintains consistent vocal identity

Voice synthesis parameters (stability, similarity boost, speed) remain constant across all characters to maintain audio quality consistency, while the underlying voice models provide tonal and character differentiation.

#### C.4.2 Voice Settings Persistence

The `ElevenLabsClient` caches the current `ElevenLabsSettings` reference. Scene transitions update this reference automatically through Unity's scene loading hooks, enabling seamless character voice switching without code changes in the agent logic.

### C.5 Error Handling and Fallbacks

The voice pipeline implements robust error handling for network failures and API timeouts:

#### Speech-to-Text Errors

- **Microphone unavailable:** Display error message, fall back to text input
- **API timeout:** Retry once with exponential backoff, then show error
- **Low confidence score:** Accept transcription but log warning

## Text-to-Speech Errors

- **API timeout:** Display text response without audio
- **MP3 decode failure:** Log error, display text fallback
- **AudioSource unavailable:** Silent failure, text remains visible

All errors log to Unity console with structured error messages for debugging while maintaining graceful degradation of user experience.

## C.6 Performance Optimization

### C.6.1 Memory Management

- Temporary WAV/MP3 files deleted immediately after use
- AudioClip instances released when playback completes
- Streaming mode for MP3 decoding reduces peak memory usage
- No audio caching (prioritizes memory over latency)

### C.6.2 Latency Budget

Table ?? documents typical latency components for the complete voice interaction cycle.

TABLE C.5 – Voice Interaction Latency Budget

Component	Latency
User speech duration	Variable (user-controlled)
WAV conversion	< 100 ms
STT API request	500–1500 ms
Agent processing (GPT-4.1)	1000–3000 ms
TTS API request	1000–3000 ms
MP3 decode	< 200 ms
Audio playback start	< 50 ms
<b>Total (excluding user speech)</b>	<b>2.5–7.8 seconds</b>

The 2.5–7.8 second response time falls within acceptable bounds for educational conversational interfaces, where thoughtful responses outweigh instantaneous feedback.

# Appendix D - VR Deployment Configuration

This appendix provides detailed technical specifications for the Meta Quest 3 virtual reality deployment described in Section ??, implementing the spatial learning and immersive presence principles outlined in Section ???. All build settings, input mappings, rendering configurations, and scene architecture details are verified against the Unity project configuration files.

## D.1 Quest 3 Android Build Configuration

The application deploys to Meta Quest 3 through Unity's Android build pipeline with OpenXR integration. Table ?? documents the core build settings from `ProjectSettings.asset`.

TABLE D.1 – Android Build Configuration

Setting	Value
Unity Version	6000.0.47f1
Meta XR SDK	78.0.0
Minimum SDK Version	32 (Android 12L)
Target SDK Version	32 (Android 12L)
Target Architecture	ARMv7 (value: 2)
Graphics API	OpenGL ES 3.0
XR Plugin	OVRPlugin (Oculus SDK)
Stereo Rendering Mode	Single Pass Instanced (value: 2)
Target Device	Meta Quest 3

### D.1.1 SDK Version Rationale

Android API level 32 (Android 12L) enables:

- Quest 3's inside-out tracking system (6DOF head and controller tracking)

- Oculus runtime features (Guardian boundary, passthrough API access)
- Hand tracking capabilities (though not actively used in this application)
- Performance optimizations for Snapdragon XR2 Gen 2 processor

### D.1.2 Stereo Rendering Pipeline

Single-pass instanced rendering (value 2 in `ProjectSettings.asset` line 49) reduces CPU overhead by rendering both eye views in a single draw call. This technique:

- Halves per-frame CPU work compared to multi-pass rendering
- Maintains Quest 3's 90 Hz refresh rate target
- Reduces GPU state changes and draw call overhead
- Critical for mobile VR performance on battery-powered hardware

### D.1.3 Build Index Scene Configuration

Table ?? documents the scene inclusion from `EditorBuildSettings.asset`.

TABLE D.2 – Scene Build Index Configuration

<b>Index</b>	<b>Scene Name</b>	<b>File Size</b>
0	Hub.unity	85 KB
1	ISS.unity	65 KB
2	Hubble.unity	66 KB
3	Voyager.unity	62 KB
4	ARHub.unity (experimental)	61 KB

Scene index 0 (Hub) loads at application startup. Scene transitions occur through `SceneManager.LoadSceneAsync()` with scene names or indices.

## D.2 Input System Implementation

Controller input integrates Oculus Touch controllers through the OVR Input API. Table ?? documents the input bindings used in the application.

TABLE D.3 – Controller Input Mapping

Action	Desktop	Quest 3 VR
Push-to-talk (voice)	Space key	Right controller A button
Confirm>Select	Enter key	Right controller trigger
Cancel/Back	Escape key	Left controller B button

### D.2.1 Push-to-Talk Implementation

The `PromptConsole.Update()` method (line 283) detects the right controller's A button through OVR Input API:

```
bool aButtonPressed = OVRIInput.Get(
    OVRIInput.Button.One,
    OVRIInput.Controller.RTouch
);
```

#### State Debouncing

The system tracks previous button state (`_previousAButtonState`) to detect rising edge transitions, preventing accidental double-triggers from single button presses. This ensures one recording session per button press/release cycle.

### D.2.2 Desktop Testing Mode

Desktop mode falls back to keyboard input through Unity's legacy Input system:

```
bool spacePressed = Input.GetKeyDown(KeyCode.Space);
```

This enables development iteration without VR hardware, maintaining identical functionality across desktop testing and Quest 3 deployment.

### D.2.3 VR Mode Detection

The `StaticVRCameraAligner` class (89 lines) detects VR mode at startup through:

```
bool isVR = XRSettings.isDeviceActive;
```

When `isDeviceActive` returns `true`, the system locates the `OVR Camera Rig` component via `FindObjectOfType<OVR Camera Rig>()` and configures VR-specific camera settings.

## D.3 Camera and Rendering Configuration

### D.3.1 OVRCameraRig Structure

The Quest 3 camera system follows Oculus SDK conventions. Table ?? documents the camera hierarchy.

TABLE D.4 – VR Camera Hierarchy

GameObject	Purpose
OVRCameraRig	Root container for VR camera system
TrackingSpace	Offset container for room-scale tracking
CenterEyeAnchor	Head-tracked camera position (stereo)
LeftEyeAnchor	Left eye render camera
RightEyeAnchor	Right eye render camera
LeftHandAnchor	Left controller tracking
RightHandAnchor	Right controller tracking

### D.3.2 Near Clip Plane Configuration

The `StaticVRCameraAligner` configures the near clip plane to prevent geometry clipping at close range (line 68):

```
cam.nearClipPlane = 0.01f; // Unity units
```

This 0.01 Unity unit near clip (approximately 1.27 cm in physical space with scale compression factor  $k = 0.000785$ ) ensures UI elements positioned within arm's reach remain visible without clipping.

### D.3.3 Desktop Camera Alignment

Desktop mode aligns the fallback camera to match VR positioning conventions, ensuring consistent coordinate systems between development and deployment environments. This allows testing of UI positioning and scene layout without VR hardware.

## D.4 Spatial UI Implementation

User interface elements render in 3D world space rather than screen overlay to ensure VR readability and depth perception. Table ?? documents the UI rendering configuration.

TABLE D.5 – Spatial UI Rendering Configuration

Parameter	Value
Canvas render mode	WorldSpace
Canvas size (transition overlay)	2m × 2m
Canvas distance from camera	1 meter (dynamic)
Mission logo size	512×512 pixels
Text component	TextMeshPro
Background opacity (UI panels)	0.7 alpha
Sort order (transition canvas)	100 (renders on top)

#### D.4.1 MissionClockUI Pattern

The `MissionClockUI` class (74 lines) demonstrates the spatial UI pattern:

1. Canvas component with `RenderMode.WorldSpace`
2. TextMeshPro text field positioned in 3D environment
3. CanvasGroup component (line 37) controls opacity without render-to-texture overhead
4. Displays mission elapsed time and simulation speed multiplier

#### D.4.2 Transition Overlay System

The `SceneTransitionManager.CreateTransitionUIIfNeeded()` method (lines 729–838) constructs the transition overlay procedurally:

##### Canvas Construction

```
Canvas canvas = canvasObj.AddComponent<Canvas>();
canvas.renderMode = RenderMode.WorldSpace;
canvas.sortingOrder = 100;
```

```
RectTransform canvasRect = canvasObj.GetComponent<RectTransform>();
canvasRect.sizeDelta = new Vector2(2f, 2f); // 2m × 2m
```

##### Dynamic Positioning

The `LateUpdate()` method (lines 154–180) repositions the canvas 1 meter in front of the camera each frame:

```

transitionCanvasTransform.position =
    cachedCameraAnchor.position +
    cachedCameraAnchor.forward * 1f;

transitionCanvasTransform.rotation =
    cachedCameraAnchor.rotation;

```

This dynamic positioning ensures the overlay remains visible during scene transitions when camera references change, avoiding parenting to scene-specific GameObjects that would be destroyed during `SceneManager.LoadSceneAsync()`.

## D.5 Scene Architecture and Persistence

The application comprises four navigable scenes sharing common systems through persistent singletons. Table ?? documents shared components across all scenes.

TABLE D.6 – Common Scene Components

Component	Purpose
OVRCameraRig prefab	VR camera and controller tracking
PromptConsole GameObject	Conversational UI and voice input
TimeController	Simulation speed management
OrbitController	Orbital physics (Hub only)
OrbitVisualizer	Trajectory rendering (Hub only)

### D.5.1 Singleton Persistence Mechanism

The `SceneTransitionManager` enforces singleton persistence through Unity's `DontDestroyOnLoad()` mechanism (line 58):

```

if (Instance == null) {
    Instance = this;
    DontDestroyOnLoad(gameObject);
}

```

This ensures the transition UI and conversation context survive scene unloading. Similarly, `ConversationHistory` persists across transitions, preserving the 10-exchange dialogue window.

### D.5.2 Asynchronous Scene Loading

Scene loading occurs through `SceneManager.LoadSceneAsync()` with deferred activation (line 252):

```
AsyncOperation loadOperation =
    SceneManager.LoadSceneAsync(sceneName);
loadOperation.allowSceneActivation = false;

// Load scene in background...

// After 4-second logo animation:
loadOperation.allowSceneActivation = true;
```

This deferred activation prevents jarring scene pops, allowing smooth fade-out → logo display → scene activation → fade-in transitions.

## D.6 Performance Optimization

Performance optimization targets Quest 3’s mobile GPU constraints. Table ?? documents the performance budget.

TABLE D.7 – Performance Targets for 90 Hz VR

Metric	Target
Frame time budget	11.1 ms (90 Hz)
Target resolution (per eye)	1832×1920 pixels
Draw calls (Hub scene)	< 100 per frame
Texture memory budget	< 512 MB
Polygon count (visible)	< 100k triangles

### D.6.1 Rendering Optimizations

- **Shared material instances:** Reduce draw calls by batching geometry with identical materials
- **Texture compression:** ASTC 6×6 for UI elements, ASTC 4×4 for environment textures
- **Single-pass instanced stereo:** Halves per-frame CPU work (both eyes in one draw call)

- **Occlusion culling:** Disabled (scenes are spatially compact, overhead exceeds benefit)
- **Dynamic batching:** Enabled for small meshes (< 300 vertices)

### D.6.2 Memory Management

- Scene file sizes optimized (62–85 KB per scene)
- Texture atlasing for UI sprites
- Audio streaming for voice synthesis (no large audio caching)
- Persistent GameObjects minimized (only transition manager, conversation history)

### D.6.3 Frame Time Breakdown

Table ?? shows typical frame time allocation in the Hub scene (most complex).

TABLE D.8 – Frame Time Budget Breakdown (Hub Scene)

<b>Component</b>	<b>Time</b>
Physics simulation	1.2 ms
Script execution	2.1 ms
Rendering (both eyes)	5.8 ms
VR compositor overhead	1.5 ms
Buffer margin	0.5 ms
<b>Total</b>	<b>11.1 ms</b>

This allocation maintains the 11.1 ms frame budget required for consistent 90 Hz VR without reprojection artifacts (judder).

# Appendix E - Complete Demonstration Transcript

This appendix contains the complete transcript of the demonstration session analyzed in Chapter ???. All dialogue has been transcribed from the video recording with light copy-editing for readability. System messages (scene transitions, time acceleration) are indicated with [SIM] annotations.

## Cast / Agent Identities

- **USER** — Platform user (learner perspective)
- **CAPCOM** — Mission Control guide
- **ISS\_CREW (ANASTASIA)** — ISS astronaut specialist
- **HUBBLE\_ENGINEER (DR\_HARRISON)** — Hubble Space Telescope specialist
- **VOYAGER\_SPECIALIST (CARL)** — Voyager deep-space mission specialist
- **SIM** — Non-diegetic system messages (routing, time control)
- **[Music]** — Background music transitions during scene changes

## Complete Interaction Transcript

### Opening Sequence

**NARRATOR (Cutscene):** Above us, thousands of satellites trace perfect arcs—testaments to gravity, velocity, and the geometry of motion. You're about to join that tradition. I'll guide the physics; you'll design the orbits. Together, we'll explore how spacecraft navigate the cosmos.

## Hub Arrival and Initial Interaction

**CAPCOM:** Welcome to Mission Control. You're floating above Earth. Use your controllers to drift closer. Circle around and watch the continents slide beneath you, oceans catching light, night falling while dawn breaks on the other side. I'm Capcom. We can design orbits together, build trajectories, see how satellites actually move—or I can route you to three specialists:

- a crew member aboard the ISS who lives this work every day,
- an engineer who built Hubble to see what we couldn't from down here,
- and a space enthusiast who dreams about what Voyager means beyond everything.

When you're ready to speak, press A on your right controller. I'll be listening. Enjoy the view—that blue marble beneath you is home.

**USER:** Hey, Capcom. I see we have a satellite here. Is this the satellite that we can build?

**CAPCOM:** [Music] Hello from Mission Control. Yes—this is your simulation satellite. We can build orbits by setting circular or elliptical paths. Tell me either the altitude for circular, or periapsis and apoapsis for elliptical, and I'll get it launched.

## ISS Mission Consultation (First Visit)

**USER:** Cool. Let's start with a circular orbit. I need an altitude—but what's a good altitude? What determines a good altitude?

**CAPCOM:** [Music] Connecting you to the ISS mission for real-world examples. Stand by.

**SIM:** [ROUTING → ISS\_CREW]

**ISS\_CREW (ANASTASIA):** [Music] Hello from the ISS. For circular LEO orbits, engineers balance drag, launch energy, accessibility, and mission needs. The ISS flies around ~420 km—high enough to limit atmospheric drag so we don't slow down too quickly, but not so high that crew/cargo launches become inefficient. It's also reachable from multiple launch sites. Too low: frequent reboosts. Too high: launches get harder and more expensive.

**USER:** Would it be absurd to choose the same altitude as the ISS?

**ISS\_CREW (ANASTASIA):** Not absurd at all—quite sensible. ~420 km is a proven compromise. Many Earth-observation and crewed missions use similar altitudes for the same reasons. You'd be following decades of flight heritage.

**USER:** Is the ISS circular?

**ISS\_CREW (ANASTASIA):** Nearly. The path is close to circular with small variations (drag, gravity field). We keep it tight with periodic reboosts. Near-circular simplifies rendezvous and ops.

**USER:** What was the altitude again? Please route me back to the hub.

**ISS\_CREW (ANASTASIA):** ~420 km. Handing you back. Safe travels.

**SIM:** [RETURN → CAPCOM]

## Creating Circular Orbit

**USER:** I'll build a circular orbit at 422 km.

**CAPCOM:** Copy. Circular orbit set at 422 km, inclination 0° (equatorial). Orbital speed ~7.66 km/s—like the ISS, but over the equator.

**USER:** Can I choose the speed?

**CAPCOM:** In this sim, speed is derived from altitude by physics. At 422 km, you need ~7.66 km/s for a stable circular orbit. If you want a different speed, pick a different altitude.

## ISS Mission Consultation (Second Visit - Orbital Period)

**USER:** How long does one lap take? It looks fast, but Earth is massive.

**CAPCOM:** Routing you to the ISS for orbital period context.

**SIM:** [ROUTING → ISS\_CREW]

**ISS\_CREW (ANASTASIA):** At ~420 km, the ISS completes a lap in ~92.8 minutes—about 15 orbits/day. Higher altitude → slower speed → longer period. That's why we see a sunrise/sunset ~every 45 minutes.

**SIM:** [RETURN → CAPCOM]

**USER:** With our current orbit ( $\sim$ 92 minutes), can we speed up the simulation so I can see it go around?

**CAPCOM:** Time acceleration:  $10\times$ . You'll see the  $\sim$ 92-minute trip much faster.

**SIM:** [TIME\_WARP  $10\times$ ]

## Hubble Mission Consultation (Elliptical Orbits)

**USER:** Great. I built a circular orbit. What's an elliptical orbit?

**CAPCOM:** Perfect question for Hubble—routing.

**SIM:** [ROUTING  $\rightarrow$  HUBBLE\_ENGINEER]

**HUBBLE\_ENGINEER (DR\_HARRISON):** [Music] Circular means constant distance and speed—like Hubble ( $\approx$ 540 km) for steady imaging and predictable servicing. Elliptical stretches the path: closer at periapsis (faster), farther at apoapsis (slower). Some science missions pick elliptical to linger where conditions are best or to avoid interference (e.g., high apogee above the radiation belts).

**USER:** Why choose elliptical if circular is simpler?

**HUBBLE\_ENGINEER (DR\_HARRISON):** To optimize time in a region. Example: Chandra uses a highly elliptical orbit to spend long stretches far from Earth's radiation belts for cleaner X-ray observations. Trade-off: more complex tracking/operations.

**SIM:** [RETURN  $\rightarrow$  CAPCOM]

## Creating Elliptical Orbits

**USER:** Back to Mission Control so I can build one.

**CAPCOM:** You're back at the Hub.

**USER:** Please build an elliptical orbit—anything interesting so I can compare.

**CAPCOM:** Elliptical orbit set: periapsis 400 km, apoapsis 2,000 km, inclination  $0^\circ$ . Watch it speed up near Earth and slow down far away.

**USER:** Can we run at maximum sim speed?

**CAPCOM:** Time acceleration:  $100\times$ . Ellipticity will be very clear.

**SIM:** [TIME\_WARP 100×]

**USER:** Make it more elliptical; it still looks circular.

**CAPCOM:** Roger. New orbit: periapsis 200 km, apoapsis 1,000 km, inclination 0°. The speed contrast will be much more dramatic.

**USER:** Speed to maximum... oh, it already is.

**CAPCOM:** Confirmed—100× time. Enjoy the fast-forward view.

**USER:** Wow—huge difference between near and far.

## Voyager Mission Consultation (Escape Trajectories)

**USER:** For deep-space missions, I assume there aren't circular orbits at all. Is everything elliptical?

**CAPCOM:** Routing to Voyager for escape-trajectory talk.

**SIM:** [ROUTING → VOYAGER\_SPECIALIST]

**VOYAGER\_SPECIALIST (CARL):** Great question. To leave Earth, you don't stay in an Earth orbit. Voyager 1 began in a near-circular parking orbit briefly, then received a final boost to a hyperbolic escape trajectory—no longer bound to Earth. Satellites around Earth use circular or elliptical orbits to remain nearby; escape missions transition from a staging orbit to hyperbolic and head out—past Earth, past the Sun's planets, toward interstellar space.

**USER:** So it's like breaking free from gravity?

**VOYAGER\_SPECIALIST (CARL):** Exactly. Think of it as climbing out of Earth's gravitational well. Circular and elliptical orbits stay in the well, perpetually falling around Earth. A hyperbolic trajectory has enough energy to climb out completely. Voyager didn't just orbit—it escaped.

**USER:** How did they actually do it?

**VOYAGER\_SPECIALIST (CARL):** Voyager launched from Earth, first reaching a temporary parking orbit around 160-200 km. Then, at the optimal moment, the upper stage fired—adding enough velocity to exceed escape speed. That burn transitioned the trajectory from elliptical to hyperbolic. Once beyond Earth's sphere of influence, Voyager's path was governed by the Sun's gravity, heading toward Jupiter for the first gravitational assist.

**USER:** That's incredible. It's really leaving everything behind.

**VOYAGER SPECIALIST (CARL):** Past Earth, past the Sun's planets, toward interstellar space. Voyager carries humanity's first message to the cosmos. The golden record, the images, the sounds of Earth—all riding on a hyperbolic trajectory that will never return. It's physics, yes, but it's also a statement of who we are and what we dream.

### **End of Recorded Session**

[Demonstration recording concludes. User remains in Voyager Mission Space, continuing exploratory dialogue.]

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5. TÍTULO E SUBTÍTULO:

Educational Orbit Simulation with Generative AI Agentic Workflow and Virtual Reality Visualisation

6. AUTOR(ES):

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7. INSTITUIÇÃO(ÓES)/ÓRGÃO(S) INTERNO(S)/DIVISÃO(ÓES):

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8. PALAVRAS-CHAVE SUGERIDAS PELO AUTOR:

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9. PALAVRAS-CHAVE RESULTANTES DE INDEXAÇÃO:

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ITA, São José dos Campos. Curso de Mestrado. Programa de Pós-Graduação em Engenharia Aeronáutica e Mecânica. Área de Sistemas Aeroespaciais e Mecatrônica. Orientador: Prof. Dr. Adalberto Santos Dupont. Coorientadora: Profª. Drª. Doralice Serra. Defesa em 05/03/2015. Publicada em 25/03/2015.

11. RESUMO:

Métodos educacionais tradicionais frequentemente encontram dificuldades para transmitir conceitos complexos, espaciais e dinâmicos como os da mecânica orbital. A recente convergência entre a Realidade Mista (RM) de consumo e os sofisticados agentes de Inteligência Artificial (IA) Generativa apresenta uma oportunidade para criar um novo paradigma de interfaces de aprendizagem intuitivas e experenciais. Este trabalho detalha o projeto, desenvolvimento e demonstração de uma plataforma educacional interativa para a exploração dos princípios da mecânica orbital. O objetivo principal do sistema é conectar a teoria de leis físicas abstratas à compreensão intuitiva, permitindo que os usuários aprendam por meio da interação corporificada. A metodologia é centrada em uma arquitetura modular que integra dois componentes principais: (1) um "cérebro" agente generativo, impulsionado por Modelos de Linguagem Abrangentes, que interpreta comandos em linguagem natural e atua como um guia educacional especializado; e (2) um "mundo" de simulação em tempo real e visualização imersiva em realidade mista, construído no motor Unity para o Meta Quest 3, que renderiza trajetórias orbitais fisicamente precisas em um espaço tridimensional onde os usuários vivenciam a mecânica orbital de dentro. A plataforma facilita um ciclo de interação multimodal contínuo, onde os comandos de voz do usuário são capturados, processados pelo agente para alterar os parâmetros da simulação e refletidos na visualização imersiva em RV com feedback auditivo conversacional. Este trabalho entrega um protótipo funcional que demonstra uma nova abordagem para a educação científica, transformando dados abstratos em uma experiência manipulável e conversacional para promover uma aprendizagem exploratória e profundamente engajadora. A plataforma é disponibilizada como software de código aberto para permitir validação, adaptação e extensão pela comunidade para diversos contextos educacionais.

12. GRAU DE SIGILO:

OSTENSIVO

RESERVADO

SECRETO