INSTITUTO TECNOLÓGICO DE AERONÁUTICA

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EDUCATIONAL ORBIT SIMULATION WITH GENERATIVE AI AGENTIC WORKFLOW AND AUGMENTED REALITY VISUALISATION

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EDUCATIONAL ORBIT SIMULATION WITH GENERATIVE AI AGENTIC WORKFLOW AND AUGMENTED REALITY VISUALISATION

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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 Aumentada (RA) 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 experienciais. Este trabalho detalha o projeto, desenvolvimento e avaliação 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 em RA, construído no motor Unity para o Meta Quest 3, que renderiza trajetórias orbitais fisicamente precisas e ancoradas no ambiente do usuário. 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 em RA 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.

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 Augmented Reality (AR) 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 evaluation 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 AR visualization "world," built in the Unity engine for the Meta Quest 3, which renders physically accurate orbital trajectories anchored to the user's environment. 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 AR 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.

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1 Introduction

1.1 Organisation

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

- **Chapter 1: Introduction.** This chapter sets the stage for the research and development.
  - *Motivation* (§1.2): Presents the core argument that the convergence of Augmented Reality and generative AI enables a new, more intuitive paradigm for educational interfaces.
  - *Objectives* (§1.3): Defines the project's specific, actionable goals, centered on the development and evaluation of an interactive, agent-guided simulation platform.
- **Chapter 2: Literature Review.** This chapter provides the theoretical and technical foundation for the work by reviewing three key domains.
  - *Augmented and Virtual Reality* (§2.1): Reviews the evolution of immersive hardware and software ecosystems and establishes their pedagogical value for spatial learning.
  - *Generative Agents* (§2.2): 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* (§2.3): 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 3: Methodology.** This chapter details the practical design, implementation, and assessment of the project.

  – *System Architecture and Data Flow* (§3.2): Describes the end-to-end fluxogram of the system, illustrating how user voice input is captured, processed by the agent, and rendered in the augmented reality simulation in a continuous loop.
  – *Core Component Implementation* (§3.3): Details the specific development plan and tools for the two primary modules: the Generative Agent ("Brain") and the Simulation and AR Visualisation ("World").
  – *Evaluation Plan* (§3.5): Defines the two-pronged approach for assessment, covering the technical validation of the system's performance and a qualitative user study to gauge its potential as an effective educational tool.

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 Augmented Reality (AR), 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 AR/VR hardware. 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. AR and VR are no longer speculative technologies, they are 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 - AR/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 becomes more than a visual aid: it becomes a cognitive bridge. A learner can speak a question and witness a launch trajectory materialize in their physical space. They can observe orbits evolve in real time, ask about inclinations or transfer windows, and receive explanations grounded in physics. Education becomes experiential, a process of exploration rather than instruction.

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 AR/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 not only technically rigorous, but experientially meaningful. It enables 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 belief that space education, and scientific education more broadly, can and must evolve to meet the possibilities of our time.

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 augmented reality visualizations.

Specific Objectives

1. Design and implement a simulation environment capable of rendering orbital trajectories in real time, grounded in physically accurate models.

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 movement, and augmented reality visual feedback to create a seamless and intuitive user experience.

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. Evaluate the platform's potential as an educational tool for facilitating conceptual understanding of orbital mechanics through exploratory learning.

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 endpoints: 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 developers 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 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.

2.2 Generative Agents

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

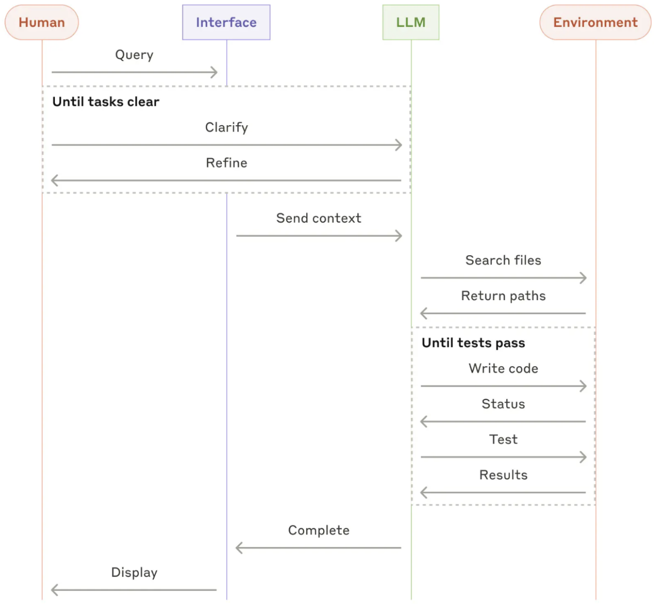

FIGURE 2.1 – End-to-end agentic workflow from Anthropic's "Building Effective Agents." The human issues a query through an *interface*; the LLM asks clarifying questions until the task is precise, receives contextual files, iteratively writes and tests code against the environment, and finally returns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

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 will handle 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 most interplanetary transfers, 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 basis of the simulation system.

2.3.1 The Fundamental Law: 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, 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 simplifies into the cornerstone of astrodynamics: the **two-body problem**. This model makes a critical assumption: it considers only the gravitational force between the satellite and the primary body (e.g., Earth), ignoring all other perturbations such as atmospheric drag, solar radiation pressure, and the gravitational pull 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 most 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 μ (mu) is the standard gravitational parameter of the system ($\mu = G(m_1 + m_2)$). The solution to this equation reveals that the satellite's path must be a conic section: a circle, ellipse, parabola, or hyperbola (Curtis, 2020). For a satellite captured in orbit, its path will be an ellipse, or a circle as a special case of an ellipse.

2.3.2 The Language of Orbits: The Classical Orbital Elements

While the equation of motion describes the physics, it does not provide an intuitive description of an orbit's path. To define the size, shape, and orientation of an orbit in three-dimensional space, a set of six parameters, known as the **classical Keplerian orbital elements**, is used. These elements provide a unique and static description of the orbit that results from solving the two-body problem (Bate; Mueller; White, 1971). They serve as the precise, non-ambiguous instruction set that a generative agent can use to calculate and render any given orbit within the simulation.

The six elements are (Curtis, 2020):

- **Semimajor Axis (a):** Defines the size of the orbit. It is half of the longest diameter of the ellipse.
- **Eccentricity (e):** Defines the shape of the orbit. For a bound orbit, e ranges from 0 for a perfect circle to less than 1 for an ellipse.
- **Inclination (i):** Defines the tilt of the orbital plane with respect to a reference plane (typically Earth's equatorial plane). An inclination of 0° is an equatorial orbit, while 90° is a polar orbit.
- **Right Ascension of the Ascending Node (Ω):** Defines the orientation, or swivel, of the orbital plane in space. It is the angle measured in the reference plane from a reference direction (the vernal equinox) to the point where the satellite crosses the equator from south to north (the ascending node).
- **Argument of Perigee (ω):** Defines the orientation of the ellipse within its orbital plane. It is the angle measured from the ascending node to the orbit's point of closest approach to the primary body (the perigee).
- **True Anomaly (ν):** Defines the position of the satellite along its elliptical path at a specific time. It is the angle from the perigee to the satellite's current position vector.

2.3.3 Changing Orbits: Impulsive Maneuvers and Delta-V

Orbits are not always static. To move a satellite from one orbit to another—for example, from a low parking orbit to a higher operational orbit—it must change its velocity vector ($\vec{v}$). In practice, this is achieved by firing a thruster. For mission planning and simulation, these burns are often modeled as **impulsive maneuvers**, which are assumed to be instantaneous changes in velocity (Bate; Mueller; White, 1971). This simplification is highly effective when the burn time is short compared to the orbital period.

The "cost" of performing such a maneuver is measured by **delta-v** (Δv), which is the total change in velocity required. Delta-v is the fundamental currency of spaceflight; every orbital maneuver has a Δv budget, which ultimately dictates the amount of propellant required (Vallado, 2013).

A classic and highly efficient example of an orbital maneuver is the **Hohmann transfer**, used to move between two circular, coplanar orbits. It consists of two impulsive maneuvers:

1. A first burn (Δv_1) is performed to increase the satellite's speed, placing it into an elliptical transfer orbit that is tangent to both the initial and final orbits.
2. Upon reaching the highest point of the transfer orbit (apoapsis), a second burn (Δv_2) is performed to increase speed again, circularizing the path into the final, higher orbit.

This is precisely the type of task an agent could execute in the simulation: a user could request a transfer between two orbits, and the agent would calculate the required Δv and visualize the two-burn Hohmann transfer trajectory.

2.3.4 The Initial Step: From Surface to Orbit

Before a satellite can orbit, it must first get there. The launch phase involves a complex journey through the atmosphere to achieve the required altitude and velocity for orbit insertion. The fundamental challenge is to provide the launch vehicle with enough energy to overcome two primary obstacles: Earth's gravitational pull and atmospheric drag.

Conceptually, a launch can be viewed as a process of gaining both vertical and horizontal velocity. The vehicle must ascend vertically to clear the densest part of the atmosphere, after which it performs a "gravity turn" to begin building horizontal speed. The objective is to reach a target altitude with a velocity vector that is nearly horizontal and has a magnitude equal to that required for a stable orbit. At this point, known as orbit insertion, the engines cut off, and the spacecraft begins its free-fall journey governed by the principles of orbital mechanics. For the purpose of this simulation, the complex atmospheric ascent can be abstracted, with the interactive experience beginning at the moment of orbit insertion, allowing the user to focus on the orbital dynamics that follow.

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, augmented 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.

3.2 System Architecture and Data Flow

This section describes the system's architecture and how information flows between the user, the conversational agent, and the visualization engine to create an integrated educational experience.

3.2.0.0.1 Architectural Philosophy The system is designed around voice-first interaction because spoken dialogue is the most natural way humans seek and share knowledge. Rather than requiring users to learn complex interfaces or command syntax, the platform allows them to simply ask questions and request visualizations as they would when speaking with a knowledgeable instructor.

The architecture separates conversational intelligence from spatial visualization, enabling each component to excel at its specific purpose. The agent interprets intent, reasons about orbital mechanics, and guides learning through dialogue. The simulation engine translates these conversations into visual demonstrations, rendering orbital trajectories in three-dimensional space where users can observe and explore them.

3.2.0.0.2 Interaction Flow User interactions follow a continuous conversational loop. The user speaks a request—perhaps asking to see a specific orbit or questioning why certain parameters produce particular behaviors. The agent, powered by OpenAI's language models, interprets this natural language input and determines the appropriate response, whether that means creating a visualization, explaining a concept, or routing the user to a relevant learning resource.

When visualization is needed, the agent communicates with the Unity-based simulation engine to generate the requested orbital trajectory. The simulation calculates physically accurate paths using astrodynamics principles and renders them in the virtual reality environment. The user sees the orbit appear in space, anchored to their surroundings through the Meta Quest 3 headset.

The agent then provides spoken feedback via ElevenLabs voice synthesis, confirming what was created and offering educational context. This completes one cycle of the interaction loop, with the user free to ask follow-up questions, request modifications, or explore new concepts.

This architecture enables seamless integration between abstract physics concepts and tangible spatial representations, allowing users to learn through the natural combination of conversation and visual exploration.

3.3 Core Component Implementation

The system architecture is realized through two distinct yet deeply integrated components. This separation enables each component to focus on its core responsibility while working together to create the complete educational experience.

3.3.1 The Generative Agent (The "Brain")

3.3.1.0.1 Purpose and Responsibility The conversational agent serves as the educational intelligence of the platform. Its fundamental purpose is to bridge the gap between natural human communication and precise simulation commands, transforming vague or exploratory questions into specific orbital visualizations and educational explanations.

This component must interpret ambiguous user intent—understanding whether "show me how satellites work" should produce a specific orbit example, route to a mission specialist, or provide a conceptual explanation. It maintains conversational context across multiple turns, remembers what has been discussed, and adapts its guidance to match the user's demonstrated knowledge level.

The agent embodies different characters depending on context: Mission Control in the Hub, or mission specialists in the educational spaces. Each character has distinct personality and expertise, created through careful prompt design that defines their communication style, knowledge domain, and educational approach.

3.3.1.0.2 Technical Foundation The agent's reasoning capabilities are powered by OpenAI's language models, which provide natural language understanding and generation. Voice synthesis through ElevenLabs transforms text responses into spoken dialogue with character-specific voices, creating the auditory personality that makes each character feel distinct and engaging.

The conversational intelligence operates by interpreting user requests, determining appropriate actions (creating orbits, explaining concepts, routing to specialists), and generating educational responses that contextualize what the user sees. This reasoning process must balance precision—ensuring orbital parameters are physically valid—with flexibility to handle the natural variability of spoken language.

3.3.2 The Simulation and AR Visualisation (The "World")

3.3.2.0.1 Purpose and Responsibility The simulation component translates abstract orbital mechanics into tangible visual experiences. Its fundamental purpose is to make invisible physics visible—showing users what a 400 km orbit actually looks like in space, how inclination affects ground coverage, and how different mission requirements manifest as specific trajectory shapes.

This component must render physically accurate orbital paths while presenting them in ways that are visually comprehensible and educationally meaningful. The orbits must be mathematically correct according to astrodynamics principles, yet scaled and styled for effective learning rather than literal representation.

The visualization creates the spatial context where learning happens. By anchoring orbital trajectories to the user's physical environment through augmented reality, or placing users inside immersive virtual space, the component transforms orbital mechanics from equations on paper into three-dimensional phenomena users can walk around, observe from multiple angles, and genuinely inhabit.

3.3.2.0.2 Technical Foundation The simulation is built using Unity, a 3D development engine that provides the tools for calculating orbital trajectories and rendering them in virtual and augmented reality. The physics implementation, written in C#, applies fundamental astrodynamics equations—primarily the two-body problem—to compute satellite positions and velocities over time.

Deployment targets the Meta Quest 3 headset, which enables both immersive VR experiences and AR visualizations through its passthrough camera system. This hardware choice provides standalone wireless operation and sufficient processing power for real-time orbital calculations and high-quality rendering, allowing users to engage with the simulation untethered and freely mobile.

3.4 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.

3.5 Evaluation Plan

3.5.0.0.1 Dual Assessment Rationale The platform's success must be measured along two dimensions: technical functionality and educational effectiveness. Technical validation alone cannot confirm whether the system actually helps users learn, while educational assessment without technical verification cannot determine if observed outcomes result from reliable, consistent system behavior or from chance. This dual approach ensures the platform is both technically sound and pedagogically valuable.

3.5.1 Technical Validation

Technical evaluation verifies that the system performs reliably and correctly. This validation establishes confidence that observed learning outcomes stem from consistent, accurate system behavior rather than from unpredictable or incorrect responses.

Key validation areas include:

- **Conversational Accuracy:** The agent correctly interprets user intent and executes appropriate simulation functions across diverse natural language inputs
- **Physics Fidelity:** Rendered orbital trajectories match validated astrodynamics calculations
- **Interaction Responsiveness:** Voice input to visual and auditory feedback occurs quickly enough to maintain conversational flow
- **Spatial Stability:** Augmented reality visualizations remain properly anchored in the user's physical environment

These technical metrics ensure the platform provides a stable foundation for learning rather than introducing confusion through inconsistent or incorrect behavior.

3.5.2 Educational Effectiveness Assessment

Educational evaluation investigates whether the platform achieves its fundamental purpose: helping users develop genuine understanding of orbital mechanics principles.

This assessment employs a small-scale qualitative study with 3-5 undergraduate students from aerospace engineering or related fields. Participants engage with the platform through exploratory tasks—creating different orbit types, visiting mission showcases, asking questions about observed phenomena—then provide feedback through semi-structured interviews and questionnaires.

The evaluation focuses on whether the platform makes orbital concepts more intuitive and comprehensible compared to traditional learning methods like textbooks and diagrams. Questions probe engagement, ease of use, and most critically, whether users feel they developed better mental models of how orbits work through the interactive, spatial experience.

This qualitative approach prioritizes depth of insight over statistical significance. Rich feedback from a few users who thoughtfully engage with the system provides more actionable understanding of educational effectiveness than surface-level metrics from larger samples. The goal is to validate the core educational premise and identify opportunities for refinement.

3.6 Implementation Plan

This section outlines the implementation strategy for the agent-guided orbital mechanics simulation platform. The development is structured in four focused phases that build from conversational intelligence to immersive virtual reality experience. The approach prioritizes fundamental educational capabilities over feature complexity, ensuring each phase delivers clear value and builds toward a complete learning platform.

The plan reflects the principles established in Section 3.1: prototype-driven development, iterative refinement, and modular architecture. Each phase produces a testable, working system that integrates with subsequent work without requiring architectural changes.

3.6.1 System Architecture Overview

The platform provides two complementary learning experiences:

3.6.1.0.1 The Hub (Mission Control) The Hub serves as the primary workspace where users create and explore custom orbital trajectories. Users interact with Mission Control—a conversational guide with a visionary, encouraging personality—to build circular or elliptical orbits around Earth. The Hub emphasizes focused, hands-on learning by displaying a single orbit at a time, allowing users to understand each configuration deeply before moving to the next.

The decision to support only circular and elliptical orbits is deliberate: these two orbit types are sufficient for understanding fundamental orbital mechanics principles while keeping the system accessible and manageable. Users learn altitude-velocity relationships, inclination effects, and the distinction between circular motion and elliptical trajectories without encountering the complexity of hyperbolic escapes or parabolic paths that would extend beyond the educational scope.

3.6.1.0.2 Mission Showcase Spaces Mission Spaces are dedicated educational environments that display historical space missions with their actual orbital configurations. Each space features a specialist who introduces the mission, explains its orbital characteristics, and answers questions about the underlying physics.

These spaces serve a critical pedagogical purpose: users often struggle to create orbits from scratch without understanding what realistic configurations look like. By exploring ISS, GPS, Voyager, Hubble, and optionally Apollo missions, users see concrete examples of how different orbit types serve different purposes. This experiential learning through real-world cases provides the context needed to successfully create custom orbits in the Hub.

The missions were chosen to represent diverse orbital regimes: Low Earth Orbit (ISS, Hubble), Medium Earth Orbit (GPS), and interplanetary trajectories (Voyager). Each demonstrates different physics principles—inclination requirements, altitude selection rationale, and mission-specific constraints.

3.6.1.0.3 Navigation Between Spaces Users move fluidly between the Hub and Mission Spaces through natural conversation. Mission Control can suggest visiting a specialist when a user's question would benefit from seeing a real example. Users return to the Hub whenever ready to apply what they learned. The system maintains conversational context across transitions, ensuring specialists understand why the user arrived and can provide relevant guidance.

3.6.2 Phase 1: Core Conversational Agent and Hub Experience

Objectives

Phase 1 establishes the conversational AI foundation that powers all user interactions. The goal is to create Mission Control as an intelligent, patient guide capable of helping users build orbits through natural dialogue, whether the user provides precise specifications or needs extensive scaffolding.

Core Capabilities

3.6.2.0.1 Orbit Creation Through Dialogue The system guides users in creating orbital trajectories via multi-turn conversation. Mission Control first determines whether the user wants a circular or elliptical orbit, then collects the necessary parameters through adaptive questioning.

For users who know exactly what they want, Mission Control accepts complete specifications directly and executes immediately. For users exploring or learning, Mission Control asks clarifying questions, provides context about parameter choices, and suggests reasonable values based on the user's stated purpose.

The dialogue system validates all parameters against physical constraints—ensuring altitudes remain above the atmosphere and within simulation bounds, and confirming inclinations fall within valid ranges. When users request impossible configurations, Mission Control explains why and suggests alternatives.

3.6.2.0.2 Single-Orbit Workspace The Hub displays only one orbital trajectory at a time. This intentional limitation focuses attention on understanding each configuration thoroughly rather than managing multiple overlapping paths. Users can clear the current orbit at any time to start fresh, encouraging experimentation without visual clutter.

3.6.2.0.3 Routing to Educational Resources Mission Control recognizes when users would benefit from seeing real-world examples and can suggest visiting Mission Spaces. For instance, if a user asks "what's a good altitude for Earth observation?", Mission Control might respond "The ISS specialist can show you how altitude affects observation capabilities—would you like to speak with them?"

Technical Foundation

The conversational system integrates OpenAI's language models to interpret natural language, reason about user intent, and generate educational explanations. A tool registry defines the available simulation functions—creating circular orbits, creating elliptical orbits, and clearing the workspace. The agent selects appropriate tools based on conversation context and extracted parameters.

The system tracks minimal state: current location (Hub or Mission Space), active orbit parameters if any exist, and recent conversation history to maintain contextual continuity across exchanges.

Success Criteria

Phase 1 is complete when users can successfully create both circular and elliptical orbits through conversation, Mission Control adapts appropriately to different user knowledge levels, parameter validation prevents invalid configurations, and the dialogue remains coherent and educational across multiple turns.

3.6.3 Phase 2: Mission Showcase Spaces

Objectives

Phase 2 creates immersive educational environments where users explore historical space missions and learn orbital mechanics through real-world examples. Each Mission Space demonstrates how theoretical principles manifest in actual spacecraft operations.

Mission Selection Rationale

The platform showcases four to five historically significant missions that collectively demonstrate diverse orbital configurations and mission design principles:

3.6.3.0.1 ISS Mission Space The International Space Station exemplifies Low Earth Orbit at 420 km altitude with a 51.6° inclination. This mission teaches how launch site locations constrain inclination choices and how orbital period relates to altitude. The specialist explains why the station orbits at this specific configuration and what tradeoffs were considered.

3.6.3.0.2 GPS Mission Space GPS satellites operate in Medium Earth Orbit at 20,200 km altitude with 55° inclination. This mission demonstrates constellation design principles—how multiple satellites at specific altitudes and inclinations provide global coverage. The specialist explains the relationship between orbital period (12 hours) and positioning system requirements.

3.6.3.0.3 Voyager Mission Space Voyager's trajectory represents interplanetary travel and escape from Earth's gravity well. Whether modeled as a high elliptical approximation or hyperbolic escape, this mission introduces concepts beyond Earth orbit. The specialist (channeling Carl Sagan's communicative style) explains gravity assists, deep space navigation, and the physics of leaving Earth's sphere of influence.

3.6.3.0.4 Hubble Mission Space The Hubble Space Telescope operates at 540 km altitude with a 28.5° inclination, demonstrating how mission requirements drive orbital choices. The low inclination enables launches from Kennedy Space Center while providing access to large portions of the sky. The specialist explains telescope operational constraints and orbital maintenance needs.

3.6.3.0.5 Apollo 11 Mission Space (Optional) If development time permits, the Apollo lunar mission provides an example of trans-lunar trajectory design. The specialist (channeling Neil Armstrong's calm, precise communication) explains the transfer orbit from Earth to Moon. If implementation proves too complex relative to timeline, this mission can be deferred to future work.

Specialist Interaction Model

When users arrive at a Mission Space, the mission's orbital trajectory immediately appears in the visualization. The specialist greets them with a brief, engaging introduction that provides historical context and highlights the key orbital characteristics they're about to explore.

The specialist then invites questions, responding with mission-specific knowledge and educational explanations. If Mission Control routed the user for a specific reason, the specialist acknowledges this context and addresses the relevant topic.

Users return to the Hub simply by expressing the desire to go back, at which point Mission Control resumes as the primary guide.

Educational Design

These Mission Spaces address a fundamental learning challenge: users often don't know what parameters to choose when creating their first custom orbit. By exploring concrete examples first, they develop intuition about realistic configurations. They see that LEO satellites orbit around 400-600 km, that inclination around 50° enables launches from major spaceports, and that geostationary satellites must be much higher at specific altitudes.

This example-based learning provides the conceptual framework users need to make informed choices when returning to the Hub to create their own orbits.

Success Criteria

Phase 2 is complete when all implemented Mission Spaces display correct orbital configurations, specialists deliver engaging introductions and answer domain-specific questions accurately, users can navigate smoothly between Hub and Mission Spaces, and conversational context is preserved across transitions.

3.6.4 Phase 3: Voice Integration

Objectives

Phase 3 transforms text-based interaction into natural spoken dialogue by synthesizing all character responses with distinct voices and enabling speech input from users. This phase also implements the opening experience that welcomes users to the platform.

Voice Synthesis Strategy

The platform leverages ElevenLabs for text-to-speech synthesis, creating distinct vocal personalities for each character. The conversational intelligence continues to come from OpenAI's language models—voice synthesis adds the auditory layer that brings characters to life.

Mission Control speaks with a visionary leader's voice, authoritative yet encouraging. The ISS specialist sounds like a professional engineer—clear, technical, friendly. The GPS specialist conveys technical expertise with precision. The Voyager specialist channels Carl Sagan's contemplative, poetic communication style. The Hubble specialist speaks with scientific enthusiasm. If implemented, the Apollo specialist echoes Neil Armstrong's calm, confident demeanor.

Voice differentiation ensures users immediately recognize which character is speaking based on voice alone, reinforcing the distinct personalities and expertise areas.

Speech Input

Users provide input through speech recognition, enabling hands-free interaction that feels more natural than typing. The system displays transcribed text visually so users can verify what was understood before the agent processes the command.

A push-to-talk interaction model—activated via controller button in VR—provides clear boundaries between listening and speaking states, preventing accidental triggering.

Opening Experience

The user's first interaction is a 40-second pre-scripted introduction delivered by Mission Control. This welcome sets the tone: physics is beautiful, exploration drives learning, the system is here to guide discovery rather than deliver lectures.

The introduction script is pre-written and synthesized once, ensuring consistent quality and immediate playback without API latency. After the introduction completes, users seamlessly transition to the Hub where interactive exploration begins.

Success Criteria

Phase 3 is complete when all characters speak with distinct, natural-sounding voices, users can reliably interact using voice input, the opening experience delivers an engaging first impression, and the audio-visual experience feels cohesive and immersive.

3.6.5 Phase 4: VR Deployment and Essential Controls

Objectives

Phase 4 deploys the complete platform to Meta Quest 3, creating an immersive virtual reality experience where users physically inhabit the simulation space. This phase also implements essential simulation controls that allow users to manipulate time and manage their workspace.

VR Platform Integration

The Unity project is configured for Meta Quest 3 deployment, enabling the application to run natively on the VR headset. Users don the headset, see Earth floating in space before them, and interact through natural head movements, controller gestures, and voice commands.

The platform can be tested locally during development and deployed as needed for demonstrations or user studies. The modular architecture ensures the same conversational AI and orbital physics work identically whether running on desktop for testing or in VR for the full experience.

Spatial Interaction Design

In VR, interface elements exist in three-dimensional space rather than on flat screens. Orbital parameters float near their corresponding trajectories. Mission briefings appear as spatial panels that remain fixed in the environment. Controllers enable direct interaction through pointing and selection.

The design prioritizes readability and comfort—text appears at appropriate sizes for viewing from typical VR distances, colors ensure visibility against both space backgrounds and Earth, and interaction methods feel intuitive rather than requiring training.

Essential Simulation Controls

Users need basic control over the simulation timeline to observe orbital behavior effectively:

Time can be accelerated to watch multiple orbital periods quickly, allowing users to see how satellites traverse their paths over hours compressed into seconds. The simulation can be paused to examine specific configurations or answer questions without motion distraction. Users can return time flow to normal speed when ready.

The workspace can be cleared to remove the current orbit, providing a fresh start for creating new configurations. This simple reset keeps the interface uncluttered and maintains the focus on one-orbit-at-a-time exploration.

These controls are accessible through both voice commands and controller buttons, providing flexibility in interaction methods.

Immersive Environment

The VR environment creates presence through visual and audio design. Users are surrounded by space—a high-resolution starfield fills the sky, Earth appears as a detailed sphere, and orbital trajectories glow as curves through the void. Ambient audio adds subtle spatial atmosphere.

The scale is adjusted for comfortable VR viewing while maintaining the geometric relationships between Earth and orbits. This compressed scale keeps everything within the headset's optimal rendering volume without sacrificing physical accuracy of the relationships being demonstrated.

Success Criteria

Phase 4 is complete when the application runs smoothly on Meta Quest 3, all conversational features function in VR, users can comfortably interact for extended sessions without discomfort, simulation controls work reliably through voice and controllers, and the immersive environment effectively conveys the three-dimensional nature of orbital mechanics.

3.6.6 Development Timeline

The four-phase structure enables systematic development with clear milestones:

Phase 1 (3-4 weeks): Core conversational agent and Hub orbit creation functionality, tested on desktop with text interaction

Phase 2 (2-3 weeks): Mission Showcase Spaces with specialist characters and routing logic, integrated with Phase 1 foundation

Phase 3 (2-3 weeks): Voice synthesis for all characters and speech input, including opening cutscene creation

Phase 4 (3-4 weeks): VR deployment to Quest 3 with spatial interface and simulation controls

Total development timeline: 10-14 weeks, with phases building sequentially on previous work.

Early phases focus on conversational quality and educational effectiveness through desktop testing, ensuring the core learning experience is solid before adding immersive layers. Voice and VR deployment enhance an already-working system rather than being dependencies for basic functionality.

3.6.7 Evaluation Approach

The platform's effectiveness is assessed through the technical validation and educational evaluation framework detailed in Section 3.5. The implementation ensures all necessary evaluation capabilities are built in:

Conversational accuracy is measured by tracking how reliably the agent interprets user intent and executes correct simulation functions. Educational effectiveness is assessed through user studies comparing comprehension before and after using the platform versus traditional learning methods.

The system logs all interactions—user commands, agent responses, orbit creations, mission visits—providing rich data for analyzing usage patterns and learning pathways.

3.6.8 Technology Stack

The platform integrates several technologies, each selected for its specific strength:

OpenAI: Provides the conversational intelligence that interprets natural language, reasons about orbital mechanics, and generates educational explanations

ElevenLabs: Synthesizes natural-sounding speech for all character responses, creating distinct vocal personalities

Unity: Serves as the 3D simulation engine and VR framework, rendering orbital trajectories and managing the immersive environment

Meta Quest 3: Delivers the virtual reality experience through standalone wireless hardware

This technology combination enables sophisticated conversational AI, emotionally engaging voice interaction, and immersive spatial visualization within a single integrated platform.

3.6.9 Alignment with Project Objectives

This implementation plan directly realizes the objectives established in Section 1.3:

The platform delivers physically accurate orbital simulations using validated astrodynamics equations. The generative agent system interprets natural language and provides adaptive educational guidance. Virtual reality deployment creates immersive three-dimensional visualization. Voice dialogue combined with spatial interaction enables natural, multimodal engagement. The modular four-phase architecture ensures each component can be developed, tested, and refined independently while integrating into a coherent whole.

Most importantly, the design philosophy prioritizes creating magical educational moments over accumulating features. Users experience the wonder of speaking naturally with Mission Control, hearing Carl Sagan explain Voyager's journey, watching orbits materialize in space around them, and developing genuine understanding of orbital mechanics through exploration rather than instruction.

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5. TÍTULO E SUBTÍTULO:

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

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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 Aumentada (RA) 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 experienciais. Este trabalho detalha o projeto, desenvolvimento e avaliação 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 em RA, construído no motor Unity para o Meta Quest 3, que renderiza trajetórias orbitais fisicamente precisas e ancoradas no ambiente do usuário. 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 em RA 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.

12. GRAU DE SIGILO:

(**X**) **OSTENSIVO** ( ) **RESERVADO** ( ) **SECRETO**