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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 três 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; (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 ; e (3) uma interface ”corpo” corporificada, consistindo em um globo físico com um sensor rotacional, que permite o controle tangível da simulação. A plataforma facilita um ciclo de interação multimodal contínuo, onde os comandos de voz e as manipulações físicas 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 three core components: (1) a generative agent "brain," powered by Large Language Models, which interprets natural language commands and acts as an expert educational guide; (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 ; and (3) an embodied "body" interface, consisting of a physical globe with a rotational sensor, that allows for tangible control over the simulation. The platform facilitates a seamless multimodal interaction loop where a user's voice commands and physical manipulations 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 multimodal user input is captured, processed by the agent, and rendered in the simulation in a continuous loop.
- *Core Component Implementation* (§3.3): Details the specific development plan and tools for the three primary modules: the Generative Agent ("Brain"), the Simulation and AR Visualisation ("World"), and the Embodied Interface ("Body").
- *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 rotate a globe, speak a question, and witness a launch trajectory materialize. 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 physical manipulation, natural language dialogue, and real-time 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. Develop a physical interface, centered around a globe equipped with sensors, that captures real-world rotational input and transmits it into the simulation system.

4. Enable multimodal interaction by combining physical movement, voice commands, and visual feedback to create a seamless and intuitive user experience.

5. Ensure that all components of the system, simulation, agent, and physical bridge, function coherently and communicate reliably in real time.

6. Create a system architecture that is modular and extensible, allowing for future expansion to other celestial bodies, educational modules, or mission types.

7. 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 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 reten-

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.

2.2 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* $\rightarrow$ *reason* $\rightarrow$ *act* $\rightarrow$ *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.

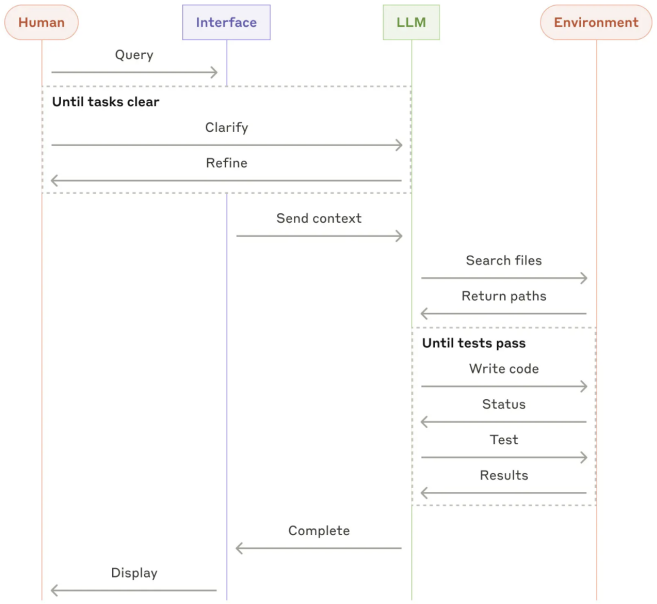

FIGURE 2.1 – End-to-end agentic workflow from Anthropic's "Building Effective Agents." The human issues a query through an *interface*; the LLM asks clarifying questions until the task is precise, receives contextual files, iteratively writes and tests code against the environment, and finally returns 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 sensor integration, 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"), the simulation and visualisation engine (the "world"), and the physical interface (the "body"). 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 outlines the high-level system architecture, describing the flow of information between the user, the physical interface, the software components, and the generative agent. This end-to-end process, or "fluxogram," illustrates how the various components work in concert to create a seamless, real-time interactive experience. The architecture is designed as a continuous "perceive-think-act" cycle, mirroring the agentic workflows described in the literature.

The data flow for a single user interaction can be detailed in the following sequence:

1. **User Input:** The interaction begins with the user issuing a multimodal command, such as speaking a request (e.g., "Show me an orbit with an inclination of 45 degrees") while simultaneously rotating the physical globe to a desired orientation.

2. **Physical Interface Capture:** The system's hardware interfaces capture the raw input data. The microphone on the AR/VR headset records the user's voice, while the Arduino microcontroller reads the rotational data from the sensor attached to the globe.

3. **Data Transmission to Core Application:** The captured audio stream and the serialized rotational data from the Arduino are transmitted in real-time to the central application running in the Unity engine.

4. **The Agentic Core (Reasoning and Planning):** Within Unity, the core logic orchestrates the agent's reasoning process. The application sends the transcribed user query and the relevant contextual data (e.g., globe orientation) to the OpenAI API. The generative agent, guided by its engineered prompt, interprets the user's intent, formulates a plan, and identifies the appropriate "tool" to use—a predefined C# function within the Unity simulation.

5. **Simulation and Visualisation:** The agent invokes the corresponding function in the simulation engine, passing the translated parameters (e.g., $i = 45°$, Ω = calculated_value). The Unity engine calculates the orbital trajectory based on these parameters and renders the path as a 3D visualisation on the Meta Quest 3, correctly synchronised with the virtual Earth's orientation.

6. **Auditory Feedback Loop:** To complete the interaction, the agent generates a textual confirmation or explanation (e.g., "Certainly, here is the 45-degree inclination orbit you requested."). This text is sent to the ElevenLabs API, which synthesizes a natural-sounding voice response that is played back to the user through the headset, providing coherent, conversational feedback (Anthropic, 2024).

3.3 Core Component Implementation

The architecture described above is realized through the implementation of three distinct, yet deeply integrated, core components. This section details the specific role, planned tools, and development process for each component, clarifying how they contribute to the project's objectives.

3.3.1 The Generative Agent (The "Brain")

Role The generative agent serves as the central intelligence of the system. Its primary role is to act as a natural language interface and reasoning engine, translating the user's high-level, often ambiguous, spoken intent into the precise, deterministic commands required by the simulation engine. It functions as an interactive, educational guide for the user.

Tools The agent's capabilities will be powered by a suite of Application Programming Interfaces (APIs). The core reasoning and language understanding will be handled by the **OpenAI API**, leveraging a powerful Large Language Model (LLM) with function-calling capabilities. The agent's voice, providing auditory feedback, will be synthesized using the **ElevenLabs API**, chosen for its ability to generate high-quality, low-latency speech.

Process The development will focus on prompt engineering to define the agent's persona and behaviour as an expert aerospace tutor. The agent will be provided with a schema of the available C# functions within the Unity environment, effectively giving it a set of "tools" it can use. When a user issues a command, the agent will reason about the intent and select the appropriate function to call with the correct parameters. The challenge of LLM hallucination is acknowledged; mitigation strategies, such as providing contextually relevant information within the prompt and validating outputs, will be explored and refined during the iterative development cycles.

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

Role This component is responsible for creating a real-time, physically-grounded, and visually intuitive representation of the orbital environment. It must accurately simulate celestial motion and render the results in an interactive, three-dimensional space for the user.

Tools The simulation and visualisation will be built using the **Unity** 3D development

engine, chosen for its robust cross-platform capabilities and extensive support for XR development. The target hardware for deployment is the **Meta Quest 3**, selected for its high-resolution, full-colour passthrough, which is ideal for Augmented Reality (AR), and its powerful standalone processing capabilities.

Process The simulation's physics will be implemented in Unity using C# scripts. The core logic will be based on the principles of astrodynamics, primarily the two-body problem, to calculate orbital trajectories as described in the foundational literature(Curtis, 2020). The primary development goal is an AR experience, where the orbital visualisations are overlaid onto the user's real-world environment and anchored to the physical globe. The modular nature of the design, however, allows for the future extension to a fully immersive Virtual Reality (VR) mode within the same application.

3.3.3 The Embodied Interface (The "Body")

Role The embodied interface is the physical bridge between the user and the digital simulation. Its role is to capture the user's physical actions—specifically, the rotation of a globe—and convert them into a stream of digital input, enabling a tangible and intuitive method of controlling the simulation's orientation.

Tools The hardware for this interface will consist of a physical **Globe**, an **Arduino** microcontroller (or a compatible equivalent) to process sensor data, and a rotational sensor.

Process A rotational sensor will be physically integrated with the globe's axis of rotation. The initial development will explore the use of a **Potentiometer** for its simplicity in measuring single-axis rotation. Concurrently, an **Inertial Measurement Unit (IMU)** will be investigated as a more capable alternative that could provide multi-axis rotational data (pitch, roll, and yaw), offering a more expressive degree of control. The Arduino will be programmed to read the data from the chosen sensor and transmit it via a serial (USB) connection to the Unity application. This data stream will directly and continuously control the orientation of the virtual celestial body in the simulation, ensuring a one-to-one correspondence between the user's physical action and the digital visualisation.

3.4 Development and Version Control

To ensure a systematic and traceable development process, the project will be managed using modern software engineering practices. The primary tool for this purpose is

GitHub, a distributed version control system. All source code, including the C# scripts for the **Unity** application and the C++ code for the **Arduino** firmware, will be stored in a centralized repository on GitHub. This approach provides a complete history of all changes, facilitates branching for experimental features without compromising the stability of the main project, and establishes a foundation for potential future collaboration. Regular commits will document the incremental progress, aligning with the iterative development philosophy outlined in Section 3.1.

3.5 Evaluation Plan

A critical component of this project is to measure its success, not only as a functional piece of software but also as a potentially effective educational tool. The evaluation plan is therefore designed to address two distinct aspects: the technical validation of the system and a qualitative assessment of its educational potential, directly addressing the final specific objective of this thesis 1.3.

3.5.1 Technical Validation

The first phase of evaluation will focus on verifying that the system's components function correctly, reliably, and efficiently. This involves a series of tests to measure key performance indicators:

- **Agent Accuracy:** Testing the generative agent's ability to correctly parse a range of spoken commands and accurately invoke the corresponding simulation functions with the correct parameters.
- **Simulation Fidelity:** Verifying that the rendered orbital trajectories are mathematically correct according to the implemented physics models.
- **System Latency:** Measuring the end-to-end latency, from user input (voice and gesture) to the corresponding visual and auditory feedback, to ensure the interaction feels responsive and seamless.
- **Interface Precision:** Assessing the accuracy of the physical interface by ensuring that the rotation of the physical globe maps precisely and smoothly to the orientation of the virtual model.

3.5.2 Educational Potential Assessment

The second phase of evaluation aims to gather qualitative data on the platform's potential as a tool for facilitating conceptual understanding of orbital mechanics. This will be achieved through a small-scale, qualitative user study.

Participants A small group of target users (e.g., 3-5 undergraduate students in aerospace engineering or a related field) will be invited to participate.

Procedure Each participant will be given a brief introduction to the system's controls and features. They will then be asked to complete a series of exploratory tasks, such as creating a geostationary orbit, visualizing a polar orbit, or performing a Hohmann transfer between two altitudes.

Data Collection Following the interactive session, feedback will be collected through a semi-structured interview and a short questionnaire. Questions will focus on the user's experience regarding engagement, ease of use, and perceived value. Specifically, participants will be asked whether the platform helped them visualize or understand orbital concepts more intuitively compared to traditional learning methods like textbooks and diagrams.

The goal of this assessment is not to achieve statistical significance, but to gather rich, qualitative insights that can validate the educational premise of the project and inform future improvements.

3.6 Implementation Plan: Sprint-Based Development

This section presents a detailed, sprint-based implementation plan for developing the interactive, agent-guided orbit simulation platform. Replacing the original chronogram, this plan reflects an iterative, prototype-driven methodology that prioritizes core functionality, modularity, and incremental complexity. The development is structured across five distinct sprints, each building upon the foundation laid by the previous phase.

The plan is informed by the principles outlined in Section 3.1: prototype-driven development, iterative refinement, and modular architecture. Each sprint targets a specific component of the system while maintaining integration with the broader ecosystem. This approach enables continuous testing, early validation of design decisions, and flexible adaptation to technical challenges encountered during implementation.

3.6.1 Overview of Sprint Structure

The implementation follows a logical progression from the system's cognitive core (the agent) to its immersive manifestations (simulation, voice, VR, and AR), culminating in a polished, production-ready experience. The six sprints are:

1. **Sprint 1: Agent Intelligence Core** — Establishing the generative agent as the system's "brain," capable of reasoning, memory, tool use, and educational guidance.
2. **Sprint 2: Enhanced Simulation Physics** — Upgrading from simplified circular orbits to physically accurate orbital mechanics based on classical astrodynamics.
3. **Sprint 3: Voice Integration** — Enabling natural spoken interaction through speech-to-text input and text-to-speech feedback.
4. **Sprint 4: VR Deployment and Integration** — Deploying the complete simulation to Meta Quest 3 in fully immersive Virtual Reality mode.
5. **Sprint 5: AR Passthrough and Globe Visualization** — Implementing Augmented Reality mode where orbital visualizations overlay the physical globe in the real environment.
6. **Sprint 6: Polish and User Experience Refinement** — Finalizing visual aesthetics, performance optimization, and conducting user testing.

Each sprint is designed to produce a functional, testable prototype increment that can be independently evaluated and integrated into the broader system. This modularity ensures that delays or challenges in one sprint do not block progress in parallel development tracks.

3.6.2 Sprint 1: Agent Intelligence Core

Objectives

Sprint 1 establishes the conversational agent as the system's intelligent core, enabling users to create and explore orbital visualizations through natural language dialogue. The sprint implements a "Mission Control Theater" architecture where a coordinating agent (CAPCOM) routes user requests to specialist teams, executes simulation functions, and provides educational context. This approach creates the illusion of interacting with a NASA Mission Control team while maintaining a simple, scalable technical implementation.

The primary goal is to deliver a *minimal magical experience*: users speak naturally, receive instant feedback, see orbits appear, and learn why those orbits matter—all within seconds. This sprint prioritizes simplicity and responsiveness over feature breadth, establishing a robust foundation that future sprints can extend without architectural changes.

Key Deliverables

1. **Tool Registry System**
    - Implement a JSON-based tool schema registry that defines available simulation functions, their parameters, and constraints.
    - Design a dynamic loading system where tools are registered at runtime from schema files, enabling future expansion without code changes.
    - Map each tool schema to a corresponding C# method in Unity's `OrbitController`.
    - Provide clear separation between tool definitions (JSON) and tool implementations (C#), ensuring modularity.
2. **Two Core Orbital Creation Tools**
    - **Circular Orbit Tool:** Creates perfectly circular orbits specified by altitude (160–35,786 km) and inclination (0–180°). Used for standard orbital configurations like ISS, GPS, and geostationary satellites.
    - **Elliptical Orbit Tool:** Creates elliptical orbits specified by periapsis altitude, apoapsis altitude, and inclination. Used for specialized orbits like Molniya (communication) or Hohmann transfer trajectories.
    - Both tools validate parameters against physical constraints (minimum altitude for atmospheric stability, maximum altitude for simulation bounds) and return orbital characteristics (period, velocity, eccentricity).
3. **CAPCOM Orchestrator**
    - Develop the central coordination agent ("CAPCOM") responsible for three functions:
        - *Instant acknowledgment:* Provide immediate feedback (<0.5s) to user input via pattern-matched responses, eliminating perceived latency.
        - *Request routing:* Analyze user intent, extract parameters, and route to the appropriate specialist team (Circular or Elliptical Orbit Design).

  - *Educational context:* After tool execution, provide a conversational explanation of what the user sees, why it matters, and relevant orbital mechanics principles.

- Implement sequential processing for multi-step requests: handle one tool invocation at a time, returning control to CAPCOM between steps.

4. **Specialist Response System**

   - Create two specialist team personas that confirm tool execution:
     - **Circular Orbit Specialist:** Young, enthusiastic engineer. Confirms circular orbit creation with brief technical notes. Example: "Circular orbit at 420km established! That's right in the LEO sweet spot."
     - **Elliptical Orbit Specialist:** Experienced, analytical engineer. Confirms elliptical orbit creation with precision. Example: "Elliptical team reporting. Molniya orbit established: 500km periapsis, 40,000km apogee."
   - Specialists operate via distinct prompt templates, creating personality differentiation while using a single underlying LLM.

5. **Minimal Context Manager**

   - Track only essential state information to enable coherent dialogue without overcomplicating the system:
     - *Current simulation state:* List of active orbits with their parameters (altitude, inclination, eccentricity).
     - *Recent conversation history:* Last 2–3 user-agent exchanges to enable contextual references ("as we just discussed...").
     - *Available tools:* Dynamically loaded tool schemas passed to CAPCOM for routing decisions.
   - Deliberately avoid long-term memory, user profiling, or complex state machines to maintain predictability and reduce hallucination risk.

Technical Implementation Details

3.6.2.0.1 Agent Architecture The system is structured as three modular layers:

- **Core Layer:**
  - `AgentOrchestrator.cs` — Coordinates the five-stage interaction workflow, managing transitions between instant acknowledgment, routing, execution, specialist response, and educational context.

  - `PatternMatcher.cs` — Provides instant acknowledgment via local pattern matching (regex-based) for common requests, eliminating API latency for initial feedback.
  - `ContextManager.cs` — Maintains minimal state: active orbits, last 2–3 conversation turns, current tool schemas.

- **Tool Layer:**
  - `ToolRegistry.cs` — Loads tool schemas from JSON files, registers them with the orchestrator, and validates tool invocations.
  - `ToolExecutor.cs` — Invokes Unity C# methods corresponding to tool calls, handles parameter validation and error cases.
  - `ToolSchemas.json` — Defines available tools in a declarative format (tool name, parameters, constraints, specialist persona).

- **Prompt Layer:**
  - `PromptBuilder.cs` — Constructs prompts for CAPCOM and specialist roles, injecting context and tool schemas.
  - `Prompts/CAPCOMRouter.txt` — System prompt for request analysis and routing.
  - `Prompts/CAPCOMEducational.txt` — System prompt for post-execution educational explanations.
  - `Prompts/Specialists/CircularOrbit.txt` — Persona prompt for circular orbit specialist.
  - `Prompts/Specialists/EllipticalOrbit.txt` — Persona prompt for elliptical orbit specialist.

3.6.2.0.2 Five-Stage Sequential Workflow

1. **Stage 1 — Instant Acknowledgment** (<0.5s, local processing):
   - User input captured via text field (voice in Sprint 3).
   - `PatternMatcher` detects common patterns ("show orbit," "create," "explain").
   - Returns immediate canned response: "Roger, analyzing orbital request..."
   - Displayed instantly while subsequent stages process asynchronously.
2. **Stage 2 — CAPCOM Routing** (∼2s, OpenAI API call):

- `PromptBuilder` constructs prompt with: user input, available tools (from JSON), current simulation state, recent conversation.
- OpenAI API returns structured output: tool identifier, extracted parameters, routing message.
- CAPCOM announces routing: "Routing to Circular Orbit Design team for ISS parameters."

3. **Stage 3 — Tool Execution** (<0.1s, Unity local):
   - `ToolExecutor` validates parameters (altitude $\geq$ 160km, inclination $\in [0°, 180°]$).
   - Invokes corresponding C# method: `OrbitController.CreateCircularOrbit(420, 51.6)`.
   - Orbital visualization renders immediately on screen.
4. **Stage 4 — Specialist Confirmation** ($\sim$2s, OpenAI API call):
   - `PromptBuilder` uses specialist persona template.
   - Specialist confirms execution with brief technical note.
   - Example: "Circular orbit at 420km, 51.6° inclination established! ISS orbit is live."
5. **Stage 5 — CAPCOM Educational Context** ($\sim$2s, OpenAI API call):
   - CAPCOM provides educational explanation referencing what user now sees.
   - Example: "There's your ISS orbit. Notice the 51.6° tilt? That allows launches from both US and Russian sites. The station completes an orbit every 90 minutes at 7.6 km/s."
   - Interaction logged in `ContextManager` for future reference.

Total perceived latency: $\sim$5 seconds for simple requests, but user experiences continuous feedback throughout.

3.6.2.0.3 Tool Schema Example

```
{
  "id": "create_circular_orbit",
  "name": "Circular Orbit Design",
  "description": "Creates circular orbit at altitude and inclination",
  "parameters": {
    "altitude_km": {"type": "number", "min": 160, "max": 35786},
```

```
    "inclination_deg": {"type": "number", "min": 0, "max": 180}
  },
  "specialist_persona": "circular_orbit_engineer",
  "unity_function": "OrbitController.CreateCircularOrbit"
}
```

3.6.2.0.4 Prompt Engineering Strategy CAPCOM and specialist personas are carefully designed to create distinct voices while maintaining consistency:

- **CAPCOM (Houston veteran):** Calm, wise, educational. Uses NASA terminology naturally ("Roger," "Copy that"). Explains *why* things matter, not just *what* they are.
- **Circular Specialist (young engineer):** Enthusiastic, quick. Uses exclamations ("Perfect!" "Right in the sweet spot!"). Keeps confirmations under 2 sentences.
- **Elliptical Specialist (experienced analyst):** Analytical, precise. Uses technical terms appropriately. Provides key insights in 2–3 sentences.

All personas avoid jargon overload, maintain encouraging tone, and never say "I don't know" (CAPCOM says "Let me check with the team on that" instead).

3.6.2.0.5 Example Interaction Scenarios Scenario 1: Simple Request (ISS Orbit)

User: "Show me the ISS orbit."

[Stage 1, 0.3s] CAPCOM: "Roger, routing to Orbital Design for ISS parameters."

[Stage 3, instant] [Blue circular orbit appears tilted at 51.6°]

[Stage 4, 2s] Circular Specialist: "Circular orbit at 420km, 51.6° inclination established! ISS orbit is live."

[Stage 5, 2s] CAPCOM: "There's your ISS orbit. Notice the 51.6-degree tilt? That's not random—it allows launches from both Kennedy Space Center and Baikonur Cosmodrome. The station orbits Earth every 90 minutes at 7.6 kilometers per second."

Total time: ∼5 seconds with continuous feedback.

Scenario 2: Ambiguous Request (Requires Clarification)

User: "Create an orbit at 600 kilometers."

[Stage 1, 0.3s] CAPCOM: "Roger, 600km altitude noted. Just to confirm—would you like a circular orbit, or an elliptical orbit reaching 600km?"

User: "Circular."

[Stage 1, 0.3s] CAPCOM: "Copy that, routing to Circular Orbit team."

[Stage 3, instant] [Green circular orbit appears]

[Stage 4, 2s] Circular Specialist: "Circular orbit at 600 kilometers, equatorial inclination. Orbit established!"

[Stage 5, 2s] CAPCOM: "Your 600km circular orbit is active. Satellites at this altitude complete an orbit every 96 minutes. This is a popular altitude for Earth observation satellites—high enough to avoid atmospheric drag, low enough for detailed imaging."

Scenario 3: Error Handling (Impossible Parameters)

User: "Put a satellite at 50 kilometers."

[Stage 2, 2s] CAPCOM: "Houston here. 50 kilometers is inside Earth's atmosphere—satellites can't maintain stable orbits below about 160km due to atmospheric drag. Would you like to try a low Earth orbit at 200km instead?"

User: "Yes."

[Proceeds normally with 200km orbit]

Scenario 4: Multi-Step Request (Sequential Processing)

User: "Show me a polar orbit and then a Molniya orbit."

[Stage 1, 0.3s] CAPCOM: "Roger. Two orbits requested. First, routing to Circular Team for polar orbit."

[Stage 3, instant] [Blue circular orbit appears vertically]

[Stage 4, 2s] Circular Specialist: "Polar orbit at 600km established! 90-degree inclination—passes over both poles every orbit."

[Stage 2, 2s] CAPCOM: "Polar orbit confirmed. Now routing to Elliptical Team for Molniya."

[Stage 3, instant] [Red elliptical orbit appears, highly elongated]

[Stage 4, 2s] Elliptical Specialist: "Elliptical team reporting. Molniya orbit established: 500km periapsis, 40,000km apogee, 63.4° inclination."

[Stage 5, 2s] CAPCOM: "Both orbits active. Notice the dramatic difference? The polar orbit stays at constant altitude, while Molniya swoops close to Earth then climbs to 40,000km—spending most of its 12-hour period over

the northern hemisphere. Russia uses these for communications because the satellite 'hovers' over Siberia for 8 hours per orbit."

Total time: ∼10 seconds for two-orbit sequence.

Success Criteria

Sprint 1 is considered complete when the following criteria are met:

3.6.2.0.6 Technical Performance

- **Tool Selection Accuracy:** CAPCOM correctly identifies the appropriate tool (circular vs. elliptical) for >95% of test commands.
- **Parameter Extraction Accuracy:** Numerical parameters (altitude, inclination) extracted correctly within ±5% tolerance for >90% of natural language inputs.
- **Response Latency:** Total time from user input to final educational response averages <5 seconds for single-orbit requests.
- **System Reliability:** Zero crashes or unhandled exceptions for valid orbital parameters within defined ranges.

3.6.2.0.7 Experiential Quality

- **Perceived Responsiveness:** Users report "instant feedback" in post-interaction surveys (instant acknowledgment eliminates perceived dead air).
- **Conversational Naturalness:** Users describe interaction as "talking to an expert" rather than "using software" in 4 out of 5 test sessions.
- **Educational Value:** Users report learning at least one new orbital mechanics concept during 10-minute exploration sessions.
- **Engagement:** Users naturally ask follow-up questions or request additional orbits without prompting.

3.6.2.0.8 Scalability and Extensibility

- **Tool Addition Time:** Adding a third tool (e.g., Hohmann transfer) requires <2 hours: write JSON schema, implement C# function, create specialist prompt.

- **Persona Modification Time:** Changing specialist personality (e.g., making Circular Specialist more formal) requires <30 minutes of prompt file editing.
- **No Architectural Changes:** System accommodates 2 tools or 10 tools without modifying core orchestration logic.

Timeline and Dependencies

Estimated Duration: 4–5 weeks

Development Breakdown:

- **Week 1–2:** Core five-stage workflow implementation
  - Implement `AgentOrchestrator`, `PatternMatcher`, `ContextManager`
  - Develop basic CAPCOM routing and specialist confirmation flows
  - Integrate with existing `OpenAIClient.cs`
  - Create two Unity functions: `CreateCircularOrbit()`, `CreateEllipticalOrbit()`
- **Week 3:** Tool registry system and JSON schemas
  - Implement `ToolRegistry`, `ToolExecutor`
  - Design and test JSON tool schema format
  - Decouple tool definitions from orchestration logic
  - Validate dynamic tool loading
- **Week 4:** Prompt engineering and persona refinement
  - Craft CAPCOM Router and Educational prompts
  - Design Circular and Elliptical specialist personas
  - Test against edge cases (ambiguous inputs, impossible parameters)
  - Iterate on tone, clarity, and educational effectiveness
- **Week 5:** Testing, iteration, and validation
  - Conduct internal testing with 20+ test scenarios
  - Measure technical metrics (accuracy, latency, reliability)
  - Gather qualitative feedback on conversational naturalness
  - Refine prompts and error handling based on findings

Dependencies:

- Requires existing `OpenAIClient.cs` (already implemented).
- Requires `OrbitController.cs` with basic circular orbit rendering (already exists).
- No external hardware dependencies, enabling desktop-based development.
- No dependencies on subsequent sprints (can begin immediately).

Risks and Mitigation:

- *Risk:* OpenAI API latency exceeds 5s, degrading experience.
- *Mitigation:* Instant acknowledgment masks latency; caching common queries; testing with smaller/faster models if necessary.

3.6.3 Sprint 2: Enhanced Simulation Physics

Objectives

The second sprint upgrades the orbital simulation from simplified circular motion to physically accurate trajectories based on the classical two-body problem and Keplerian orbital elements. This ensures the simulation is not only visually compelling but also scientifically rigorous, enabling realistic orbital maneuvers and educational scenarios grounded in astrodynamics principles (Curtis, 2020).

Key Deliverables

1. **Keplerian Orbital Elements Implementation**
    - Replace the current radius/speed model with the six classical orbital elements:
        - Semi-major axis (a) — defines orbit size and energy
        - Eccentricity (e) — defines orbit shape (circular, elliptical, parabolic, hyperbolic)
        - Inclination (i) — tilt relative to Earth's equator
        - Right ascension of ascending node (Ω) — orientation of orbital plane
        - Argument of periapsis (ω) — orientation of ellipse within plane
        - True anomaly (ν) — position along the orbit
    - Develop conversion functions between Cartesian state vectors (position, velocity) and Keplerian elements.

2. **Two-Body Problem Solver**

   - Implement Kepler's equation solver to compute satellite position at any time t.
   - Calculate velocity vectors corresponding to orbital positions.
   - Support all conic section types: circular, elliptical, parabolic (escape), and hyperbolic (interplanetary).
   - Enable real-time propagation of orbits with configurable time steps.

3. **Orbital Maneuver Calculations**

   - **Hohmann Transfer:** Compute optimal two-burn transfer between circular orbits at different altitudes.
   - **Bi-Elliptic Transfer:** Calculate more fuel-efficient transfers for large altitude changes.
   - **Inclination Change:** Determine delta-V required for orbital plane changes.
   - **Combined Maneuvers:** Optimize maneuvers that change both altitude and inclination simultaneously.
   - **Delta-V Budgeting:** Track cumulative velocity changes for mission planning.

4. **Trajectory Prediction and Visualization**

   - Implement orbit propagation to predict future satellite positions over hours or days.
   - Render orbital paths as 3D curves in Unity, with visual distinction between current orbit and predicted trajectories.
   - Support time-lapse animation to visualize long-term orbital evolution.
   - Display orbital parameters numerically alongside visual representation.

5. **Orbit Comparison and Analysis Tools**

   - Develop functions to compare two orbits quantitatively (differences in altitude, inclination, period, etc.).
   - Visualize relative geometry between multiple satellites.
   - Calculate encounter conditions (closest approach, relative velocity).

6. **Parameter Validation and Physical Constraints**

   - Enforce realistic constraints: sub-orbital detection, escape velocity limits, atmospheric drag thresholds.

- Warn users when requested orbits violate physical laws or practical considerations.
- Implement safety checks for extreme eccentricities or unstable configurations.

Technical Implementation Details

3.6.3.0.1 Mathematical Foundation The simulation will implement the analytical solution to the two-body problem as described in (Curtis, 2020):

- **Orbital Period:** $T = 2\pi\sqrt{\frac{a^3}{\mu}}$ where $\mu = GM$ is Earth's gravitational parameter.
- **Orbital Velocity:** $v = \sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right)}$ (vis-viva equation).
- **Kepler's Equation:** $M = E - e\sin E$ (solved iteratively via Newton-Raphson).

3.6.3.0.2 Code Structure

- `OrbitalElements.cs` — Data structure for storing Keplerian elements.
- `OrbitPropagator.cs` — Computes satellite state at time t given initial elements.
- `ManeuverCalculator.cs` — Implements Hohmann, bi-elliptic, and inclination change algorithms.
- `TrajectoryRenderer.cs` — Visualizes orbital paths using Unity LineRenderer.
- `OrbitComparator.cs` — Analyzes differences between orbits.

3.6.3.0.3 Integration with Agent The enhanced simulation exposes new tools to the agent:

- `CreateOrbitFromElements(a, e, i, Omega, omega, nu)`
- `PropagateOrbit(orbit, duration)`
- `PlanHohmannTransfer(currentOrbit, targetAltitude)`
- `CalculateDeltaV(maneuver)`
- `ShowGroundTrack(orbit, duration)`

The agent can now reason about complex maneuvers and explain the underlying physics to users.

Success Criteria

Sprint 2 is considered complete when:

- The simulation accurately models elliptical orbits with eccentricities $0 \leq e < 1$.
- Hohmann transfer calculations match analytical solutions within 0.1% error.
- Trajectory prediction remains stable over at least 100 orbital periods.
- The agent can successfully plan and execute multi-step maneuvers (e.g., altitude change followed by inclination adjustment).
- All orbital calculations are validated against reference cases from (Curtis, 2020).

Timeline and Dependencies

Estimated Duration: 3–4 weeks

Dependencies: Requires completion of Sprint 1's tool registry system. Can be developed in parallel with Sprint 3 (voice integration).

3.6.4 Sprint 3: Voice Integration

Objectives

Sprint 3 introduces natural spoken interaction, replacing text-based input with speech-to-text recognition and synthesizing agent responses through realistic voice output. This creates a more intuitive, hands-free user experience and moves the interface closer to the conversational paradigm envisioned in the motivation (Section 1.2).

Key Deliverables

1. **Speech-to-Text (STT) Integration**
    - Evaluate and integrate a speech recognition system. Options include:
        - Unity's built-in `DictationRecognizer` (Windows/UWP support)
        - OpenAI Whisper API (cloud-based, high accuracy)
        - Meta's on-device speech recognition (Quest 3 native)
    - Implement continuous listening mode with voice activity detection (VAD).
    - Design wake-word or push-to-talk activation to prevent accidental triggering.

- Handle ambient noise and filtering for optimal recognition accuracy.

2. **Text-to-Speech (TTS) Integration via ElevenLabs**
   - Integrate ElevenLabs API for high-quality voice synthesis (**elevenlabs2024**).
   - Configure voice persona selection (professional mission control, enthusiastic educator, calm professor).
   - Optimize latency: stream audio playback as synthesis completes to minimize delay.
   - Implement SSML support for prosody control (emphasis, pauses, intonation).
3. **Conversational Flow Manager**
   - Design state machine for managing turn-taking between user and agent.
   - Implement interruption handling: allow user to interrupt agent mid-response.
   - Add confirmation prompts for irreversible actions (e.g., "This will consume 3.2 km/s of delta-V. Confirm?").
   - Support multi-turn clarification dialogues ("Which orbit did you mean?").
4. **Voice Command Grammar and Robustness**
   - Define expected command patterns (imperatives, questions, exploratory statements).
   - Implement fallback handling for misrecognized speech ("Did you mean...?").
   - Test with diverse accents and speaking styles to ensure accessibility.
   - Provide visual transcription feedback so users see what the system understood.
5. **Multimodal Feedback**
   - Combine voice output with visual cues (orbital trajectories, highlighted parameters).
   - Use spatial audio (Quest 3's 3D audio) to enhance immersion ("voice from mission control").
   - Display text captions alongside speech for accessibility and comprehension.

Technical Implementation Details

3.6.4.0.1 STT Processing Pipeline

1. User activates voice input (button press or wake word).

2. Audio captured via Quest 3 microphone.
3. Audio stream sent to STT service (Whisper API or native).
4. Transcribed text returned and displayed on-screen for confirmation.
5. Text forwarded to `AgentOrchestrator` for processing.

3.6.4.0.2 TTS Processing Pipeline

1. Agent generates textual response.
2. Text sent to ElevenLabs API with voice ID and settings.
3. Audio stream received and buffered.
4. Audio playback begins as soon as first chunk arrives (streaming mode).
5. Visual indicators (animated waveform, subtitle text) accompany audio.

3.6.4.0.3 Code Structure

- `VoiceInputManager.cs` — Handles STT recording and transcription.
- `VoiceOutputManager.cs` — Manages TTS synthesis and playback.
- `ConversationFlowController.cs` — State machine for dialogue turn-taking.
- `ElevenLabsClient.cs` — HTTP client for ElevenLabs API.

3.6.4.0.4 Example Voice Interaction

[User presses voice button]
User: "Show me a polar orbit."
[System displays transcript: "Show me a polar orbit"]
Agent (voice): "Certainly. A polar orbit has an inclination of 90 degrees, passing over both poles. I'll create one for you now. [Creates orbit] Notice how the satellite covers the entire planet as Earth rotates beneath it."
[Orbital path animates on screen]

Success Criteria

Sprint 3 is considered complete when:

- STT achieves >90% word accuracy on a test set of 50 orbital mechanics commands.
- TTS latency (text submission to audio start) is <2 seconds.
- Users can complete a full mission scenario using only voice input (no manual text entry).
- Interruption handling works reliably (agent stops speaking when user begins).
- At least two distinct voice personas are available and sound natural.

Timeline and Dependencies

Estimated Duration: 2–3 weeks

Dependencies: Requires Sprint 1's agent orchestrator. Can be developed in parallel with Sprint 2 (physics). Requires API access to ElevenLabs and Whisper (or equivalent STT service).

3.6.5 Sprint 4: VR Deployment and Integration

Objectives

Sprint 4 focuses on deploying the complete simulation to the Meta Quest 3 headset in fully immersive Virtual Reality mode. This sprint transforms the desktop-based prototype into a three-dimensional, interactive space environment where users are surrounded by orbiting satellites and can manipulate the simulation through natural head movements, controller input, and voice commands. The goal is to create a seamless VR experience that leverages spatial presence to enhance understanding of orbital mechanics.

Key Deliverables

1. **Meta Quest 3 Build Configuration**
    - Configure Unity project for Android-based Quest 3 deployment.
    - Install and configure Meta XR SDK and OpenXR plugin.
    - Set up build pipeline for APK generation and sideloading via Meta Quest Developer Hub.

- Optimize project settings for mobile VR performance (texture compression, shader variants, lighting baking).

2. **VR Camera and Tracking Setup**

   - Replace desktop camera with XR rig supporting 6-DOF (six degrees of freedom) head tracking.
   - Configure stereo rendering for proper depth perception.
   - Implement comfort settings: adjustable movement speed, snap turning, teleportation.
   - Set up guardian boundary integration to prevent collisions with real-world objects.

3. **Controller-Based Interaction**

   - Map Quest 3 Touch Pro controllers to simulation functions:
     - Trigger: Select satellites or UI elements via ray-casting
     - Grip: Grab and rotate the virtual Earth
     - Thumbstick: Navigate through space (fly closer/farther)
     - Buttons: Time control (pause, speed up, slow down, reset)
   - Implement visual ray indicators showing controller pointing direction.
   - Provide haptic feedback for interaction events (selection, confirmation, warnings).

4. **Spatial UI Design**

   - Redesign flat UI panels for 3D space:
     - Floating orbital parameter displays anchored to satellites
     - Radial menus attached to controllers for quick access
     - Head-locked HUD showing mission objectives and delta-V budget
     - World-locked panels for detailed information (remain fixed in space)
   - Ensure text readability at typical VR viewing distances (1–3 meters).
   - Implement gaze-based interaction as fallback (look at button for 2 seconds to activate).

5. **Immersive Environment Design**

   - Create photorealistic space skybox with high-resolution starfield (using existing 8K Milky Way texture).

- Scale Earth and orbital distances appropriately for VR comfort (compressed scale to fit within comfortable viewing volume).
- Add ambient space audio (subtle background hum, satellite thruster sounds during maneuvers).
- Implement dynamic lighting: sunlight casting shadows on Earth, lens flare effects.

6. **Performance Optimization for Mobile VR**
   - Profile application to achieve stable 72 Hz frame rate (Quest 3 minimum) or 90 Hz (target).
   - Implement aggressive level-of-detail (LOD) systems for distant objects.
   - Use instanced rendering for satellite constellations.
   - Optimize agent API calls to avoid frame drops during LLM queries (asynchronous processing with loading indicators).
   - Reduce draw calls through texture atlasing and mesh batching.
7. **Voice Integration in VR Context**
   - Adapt Sprint 3's voice system for VR: use Quest 3's built-in microphone array.
   - Implement push-to-talk on controller button (e.g., left grip hold + speak).
   - Display voice transcription in spatial UI (floating text panel).
   - Synchronize agent voice output with spatial audio (appears to come from a fixed "mission control" location).
8. **Locomotion and Scale Management**
   - Implement teleportation system for comfortable movement (arc-based targeting).
   - Add "scale modes":
     - **Overview mode:** View entire orbital system from distance
     - **Satellite mode:** Stand "on" a satellite and see Earth below
     - **Earth surface mode:** Experience orbit from ground perspective
   - Enable smooth transitions between scale modes (animated zoom with fade).

Technical Implementation Details

3.6.5.0.1 Unity XR Configuration

- **XR Plugin Management:** Enable OpenXR with Meta Quest feature set.
- **Render Pipeline:** Universal Render Pipeline (URP) optimized for mobile.
- **Target Platform:** Android API level 29+, ARM64 architecture.
- **Texture Settings:** ASTC compression, mipmaps enabled, max resolution 2048x2048.

3.6.5.0.2 Code Structure

- `VRInputManager.cs` — Handles controller input and mapping to simulation actions.
- `VRUIManager.cs` — Manages spatial UI layout and interaction.
- `VRLocomotion.cs` — Implements teleportation and scale transitions.
- `VRPerformanceMonitor.cs` — Tracks frame rate and issues performance warnings.
- `SpatialAudioManager.cs` — Positions 3D audio sources in scene.

3.6.5.0.3 Interaction Flow Example

1. User puts on Quest 3 headset, launches application.
2. Scene loads: user is floating in space, Earth in front, starfield surrounding.
3. User holds left grip button and speaks: "Show me the ISS orbit."
4. Transcript appears floating above left hand, agent responds via spatial audio.
5. ISS orbit materializes around Earth with glowing trail.
6. User points right controller at ISS icon, pulls trigger to select it.
7. Orbital parameters (altitude, speed, inclination) appear in floating panel attached to satellite.
8. User uses thumbstick to fly closer to ISS, experiencing its motion firsthand.

Success Criteria

Sprint 4 is considered complete when:

- Application builds successfully and runs on Meta Quest 3 without crashes.
- Frame rate remains $\geq$72 Hz for >95% of runtime under normal usage.

- All agent functions from Sprints 1–3 are accessible via VR controllers and voice.
- Users can complete a full mission scenario (e.g., Hohmann transfer) entirely in VR.
- No motion sickness reported by at least 5 test users during 15-minute sessions.
- Controller interactions feel responsive (latency <50ms from input to visual feedback).

Timeline and Dependencies

Estimated Duration: 3–4 weeks

Dependencies: Requires completion of Sprints 1–3 (agent, physics, voice). Requires Meta Quest 3 hardware and Meta Quest Developer Hub for deployment. Can proceed independently of Sprint 5 (AR mode).

3.6.6 Sprint 5: AR Passthrough and Globe Visualization

Objectives

Sprint 5 implements Augmented Reality mode, where the simulation overlays the user's real-world environment using Quest 3's high-resolution color passthrough. The key innovation in this sprint is anchoring the orbital visualization to a physical globe in the real world, creating a mixed reality experience where virtual satellites orbit around a tangible Earth. This bridges the digital and physical, enabling users to interact with orbital mechanics while remaining grounded in their physical space.

Key Deliverables

1. **AR Passthrough Activation and Configuration**
   - Enable Quest 3's high-resolution color passthrough mode.
   - Configure passthrough layer ordering: real environment as background, virtual content overlaid.
   - Tune passthrough opacity and color correction for natural blending of real and virtual elements.
   - Implement scene understanding to detect surfaces (tables, floors) for optional UI placement.
2. **Physical Globe Detection and Tracking**

- Implement globe localization strategies:
  - **Method 1 — Marker-Based:** Place a visual marker (QR code, ArUco tag, or custom image target) on or near the physical globe for precise tracking.
  - **Method 2 — Object Recognition:** Use Quest 3's scene understanding to detect spherical objects and infer globe position.
  - **Method 3 — Manual Placement:** Allow user to manually position virtual anchor by pointing controller at globe center.
- Select optimal method based on reliability and ease of setup (likely marker-based for precision).
- Continuously track globe position and orientation relative to user's viewpoint.

3. **Spatial Anchoring and Persistence**

- Use Meta Spatial Anchors API to create a persistent anchor at the globe's location.
- Save anchor to device storage so orbital visualization remains correctly positioned across sessions.
- Implement anchor relocalization: when app restarts, automatically detect and reattach to saved anchor.
- Provide visual confirmation when anchor is successfully locked (brief highlight or checkmark).

4. **Scale-Aware Orbital Rendering**

- Synchronize virtual orbital paths with the physical globe's size and position.
- Implement adaptive scaling: if globe is small (e.g., 20 cm diameter), render satellites proportionally close; if large (e.g., inflatable globe), extend orbital radii.
- Ensure orbital geometry remains physically accurate while being visually comprehensible at real-world scale.
- Allow user to adjust virtual scale factor ("zoom in/out" on orbital distances) without moving the globe anchor.

5. **AR-Specific Interaction Design**

- Adapt VR interaction model for AR context:
  - User physically walks around the globe to view orbits from different angles.
  - Controller ray-casting remains primary selection method.
  - Voice commands adapted for AR ("Show orbit from this angle").

- Implement hand tracking for natural gesture interaction (optional enhancement):
  - Pinch satellite icons to select them.
  - Two-handed pinch-and-spread to adjust time scale.
- Provide haptic and audio feedback when interacting with virtual elements in AR space.

6. **Mixed Reality Visual Design**

- Design orbital trails to contrast with both the physical globe and background environment:
  - Use bright, emissive colors (cyan, magenta, yellow) for visibility.
  - Add subtle glow/bloom effects to make trails pop against real-world lighting.
  - Implement adaptive brightness: dim trails in bright environments, brighten in dark rooms.
- Render satellites as semi-transparent holographic models to distinguish them from physical objects.
- Display floating data labels (altitude, speed) that remain readable against varying backgrounds (use contrasting outlines or background panels).

7. **Occlusion and Depth Management**

- Implement depth occlusion: virtual satellites should pass behind the physical globe when geometrically appropriate.
- Use Quest 3's depth API (if available) or approximate occlusion based on globe anchor geometry.
- Ensure UI panels don't clip through real-world objects (use scene mesh for collision avoidance).

8. **Mode Switching Between VR and AR**

- Provide seamless toggle between VR mode (Sprint 4) and AR mode (Sprint 5) within the same application.
- Implement transition logic:
  - VR $\rightarrow$ AR: Fade in passthrough, shrink space environment to globe-scale, activate spatial anchor.
  - AR $\rightarrow$ VR: Fade out passthrough, expand globe to immersive scale, disable anchor constraints.

- Allow user to choose default mode on startup or switch via in-app menu.

9. **Calibration and Setup Workflow**

   - Design intuitive first-time setup:
     (a) User places physical globe on table.
     (b) App prompts: "Point your controller at the center of the globe and press A."
     (c) System creates spatial anchor at indicated position.
     (d) App prompts: "What is the globe's diameter?" (user selects from presets: 15cm, 20cm, 30cm, or measures manually).
     (e) Orbital visualization scales accordingly and locks to globe.
     (f) Confirmation: "Anchor saved! Orbits will appear here every time you launch the app."
   - Provide recalibration option if globe is moved or replaced.

Technical Implementation Details

3.6.6.0.1 AR Passthrough Configuration

- Enable passthrough via `OVRManager.instance.isInsightPassthroughEnabled = true`.
- Configure passthrough layer: `OVRPassthroughLayer` with color mapping and opacity control.
- Use `OVRSceneManager` for scene understanding and surface detection.

3.6.6.0.2 Spatial Anchor Workflow

- Create anchor: `OVRSpatialAnchor.CreateSpatialAnchor(transform, (anchor, success) => ...)`
- Save anchor: `anchor.Save((anchor, success) => ...)`
- Load anchor on app restart: `OVRSpatialAnchor.LoadUnboundAnchors(...)`
- Localize and bind anchor to world position.

3.6.6.0.3 Marker Tracking (if using markers)

- Integrate Vuforia or OpenCV for Unity for QR/ArUco marker detection.
- Detect marker in camera feed, extract 3D pose (position + rotation).
- Create spatial anchor at marker location for persistent tracking.

3.6.6.0.4 Code Structure

- `ARModeManager.cs` — Manages AR passthrough activation and mode switching.
- `GlobeAnchorController.cs` — Handles spatial anchor creation, saving, and loading.
- `MarkerTracker.cs` (optional) — Detects and tracks visual markers.
- `ARVisualizer.cs` — Adapts orbital rendering for AR context (brightness, occlusion).
- `DepthOcclusionManager.cs` — Implements depth-based occlusion for realism.

3.6.6.0.5 AR Interaction Flow Example

1. User launches app in AR mode, puts on Quest 3.
2. Passthrough activates, user sees their real room through headset.
3. If no saved anchor exists, app prompts: “Point at your globe’s center and press A.”
4. User points controller at physical globe, presses A.
5. Spatial anchor created, orbital visualization appears around globe.
6. User walks around table, viewing ISS orbit from different angles.
7. User says: “Show me a polar orbit.”
8. Agent creates polar orbit, glowing cyan trail appears perpendicular to equator.
9. User physically rotates globe (if on turntable) or walks to opposite side to see orbit’s ground track.

Success Criteria

Sprint 5 is considered complete when:

- AR passthrough mode activates successfully with clear, high-quality real-world view.
- Spatial anchor locks to physical globe with positional drift <2 cm over 10 minutes.
- Orbital visualizations scale correctly relative to globe size (user-verified accuracy).
- Anchor persists across app restarts (user does not need to recalibrate every session).
- Users can walk 360° around the globe and view orbits from all angles without tracking loss.
- Orbital trails remain visible and distinguishable against various background environments (bright/dark rooms).
- Seamless mode switching between VR and AR without crashes or visual artifacts.
- At least 3 beta testers successfully complete AR calibration on first attempt.

Timeline and Dependencies

Estimated Duration: 2–3 weeks

Dependencies: Requires Sprint 4 (VR mode) as foundation. Benefits from but does not strictly require Sprints 1–3. Requires physical globe (any standard classroom/decorative globe, 15–30 cm diameter). Requires Meta Quest 3 hardware.

3.6.7 Sprint 6: Polish and User Experience Refinement

Objectives

The final sprint focuses on transforming the functional prototype into a polished, production-ready educational platform. This involves comprehensive user testing, visual and interaction refinement, performance optimization, accessibility enhancements, and preparation for formal evaluation as outlined in Section 3.5. Sprint 6 ensures the system is not only technically sound but also intuitive, engaging, and pedagogically effective.

Key Deliverables

1. **Visual Effects and Aesthetic Enhancements**

- Refine orbital trail rendering:
  - Gradient fade from bright (recent path) to dim (historical path)
  - Color-coding by orbit type: LEO (blue), MEO (green), GEO (yellow), HEO (red), polar (cyan)
  - Animated particle effects along trajectory showing direction of satellite motion
  - Time-lapse mode with comet-like trails for accelerated playback
- Upgrade satellite models from placeholder spheres to detailed 3D meshes (ISS, Hubble, GPS satellites).
- Implement burn visualization: glowing thrust vector arrows during maneuvers with particle exhaust effects.
- Add atmospheric glow around Earth's limb for realism.
- Create dynamic day/night Earth textures with city lights on night side.

2. **Hand Tracking Integration (Optional Advanced Feature)**
   - Integrate Quest 3's native hand tracking for controller-free interaction.
   - Implement intuitive gestures:
     - Pinch: Select satellites or UI elements
     - Grab (fist): Rotate virtual Earth or camera viewpoint
     - Palm-up: Summon radial menu
     - Two-handed pinch-and-spread: Adjust time scale
   - Provide visual feedback (hand highlights, raycast indicators) for gesture recognition.
   - Ensure smooth fallback to controller input if hand tracking fails.
3. **User Interface and Information Design**
   - Design clean, readable spatial UI:
     - Floating data panels showing orbital parameters (altitude, speed, period, inclination, eccentricity)
     - Mission briefing screens with objectives, hints, and progress tracking
     - Radial menus for quick access to common functions (create orbit, time control, mode switch)
     - Head-up display (HUD) showing delta-V budget, time scale, current mission status

- Ensure text readability: high-contrast fonts, adaptive sizing, background panels for legibility.
- Implement context-sensitive tooltips that appear when user gazes at UI elements.
- Add achievement notifications ("First Hohmann Transfer!", "Orbit Mastery Unlocked!").

4. **Performance Optimization**

   - Profile application using Unity Profiler and Quest 3 performance tools.
   - Achieve and maintain stable 90 Hz frame rate (Quest 3 optimal performance).
   - Optimize rendering:
     - Implement level-of-detail (LOD) for satellite models and orbital trails
     - Use instanced rendering for satellite constellations
     - Reduce draw calls through mesh batching and texture atlasing
     - Optimize shader complexity (avoid expensive operations in fragment shaders)
   - Optimize agent API calls:
     - Cache frequent queries (e.g., "What is the ISS orbit?")
     - Implement request queuing to avoid simultaneous API calls
     - Display loading indicators during LLM processing to manage user expectations
   - Reduce memory footprint: compress textures, unload unused assets, implement object pooling.

5. **Accessibility and Inclusivity Features**

   - Provide text captions for all voice output (essential for hearing-impaired users).
   - Implement colorblind-friendly palettes with alternative trail visualization modes.
   - Support adjustable UI scale and contrast settings.
   - Enable seated vs. standing play modes with appropriate guardian configurations.
   - Provide audio descriptions of visual phenomena ("The satellite is now at apogee").
   - Implement comfort options: vignette during locomotion, reduced particle effects, configurable movement speed.

6. **Educational Content Expansion**

   - Expand mission library to at least 8–10 scenarios:

  - Beginner: ISS Rendezvous, Geostationary Deployment, Polar Observation
  - Intermediate: Molniya Orbit Design, Constellation Planning, Orbital Phasing
  - Advanced: Lunar Transfer, Lagrange Point Navigation, Satellite Rescue
- Refine Socratic tutoring behavior: test with real users and adjust hint/answer balance.
- Add glossary of orbital mechanics terms accessible via voice ("Agent, what is eccentricity?").
- Integrate historical mission examples (Apollo, Voyager, ISS) with narrated context.

7. **Beta Testing and Iteration**

- Recruit 5–10 beta testers from target demographic (undergraduate aerospace students, educators).
- Conduct structured testing sessions:
  (a) Onboarding flow (first-time setup, calibration)
  (b) Mission completion (one beginner, one intermediate scenario)
  (c) Free exploration (15 minutes of unguided interaction)
  (d) Feedback interview (semi-structured, 10–15 minutes)
- Collect qualitative feedback on usability, engagement, learning effectiveness.
- Iterate on identified pain points: confusing UI, unclear instructions, performance issues, etc.

8. **Documentation and Onboarding**

- Create in-app tutorial guiding first-time users through:
  - Basic controls (voice, controllers, hand tracking)
  - Requesting an orbit via agent
  - Understanding orbital parameters
  - Completing a simple Hohmann transfer
- Develop user manual (digital PDF or web page) covering advanced features.
- Record demonstration video showing key interactions for promotional and documentation purposes.

9. **Formal Evaluation Preparation**

- Implement data logging for evaluation metrics:

  - Agent accuracy: log all user commands, agent interpretations, and tool calls
  - System latency: record timestamps for input → response pipeline
  - User actions: track mission completion times, retry counts, help requests
- Prepare evaluation instruments:
  - Pre-test questionnaire: assess prior knowledge of orbital mechanics
  - Post-test questionnaire: measure perceived learning, engagement, usability
  - Semi-structured interview script for qualitative insights
- Conduct pilot evaluation with 1–2 users to validate instruments and refine protocol.

Technical Implementation Details

3.6.7.0.1 Visual Effects Pipeline

- Use Unity's Visual Effect Graph (VFG) for particle systems (thruster exhaust, orbital debris).
- Implement custom shaders for orbital trails with gradient alpha and color blending.
- Apply post-processing stack: bloom for glowing effects, ambient occlusion for depth, color grading for mood.

3.6.7.0.2 Performance Profiling Workflow

1. Run Unity Profiler during typical mission scenario.
2. Identify bottlenecks: CPU-bound (physics, agent logic) vs. GPU-bound (rendering, shaders).
3. Apply targeted optimizations: reduce physics update rate, simplify shaders, cull distant objects.
4. Re-profile and iterate until 90 Hz target achieved.

3.6.7.0.3 Code Structure

- `VisualEffectsManager.cs` — Coordinates orbital trail rendering, particle effects, and animations.
- `HandTrackingController.cs` (optional) — Maps hand poses to interaction events.

- `AccessibilityManager.cs` — Manages captions, colorblind modes, and comfort settings.
- `EvaluationLogger.cs` — Records interaction data for formal evaluation.
- `TutorialManager.cs` — Orchestrates first-time user onboarding sequence.

3.6.7.0.4 Beta Testing Protocol Example

1. Participant arrives, signs consent form, completes pre-test questionnaire.
2. Researcher fits Quest 3 headset, launches application.
3. Tutorial guides participant through basic interactions (5 minutes).
4. Participant attempts "ISS Rendezvous" mission (10 minutes).
5. Participant freely explores (15 minutes), encouraged to ask agent questions.
6. Participant removes headset, completes post-test questionnaire (5 minutes).
7. Semi-structured interview: "What did you find intuitive? Confusing? Engaging?" (10 minutes).
8. Researcher logs observations and feedback for iteration.

Success Criteria

Sprint 6 is considered complete when:

- Application achieves stable 90 Hz frame rate for >95% of runtime.
- At least 5 beta testers complete full mission scenarios without crashes or major bugs.
- User study participants rate usability >4/5 on Likert scale ("easy to use").
- User study participants report increased understanding of orbital mechanics (>70% agree).
- All accessibility features (captions, colorblind mode, comfort settings) function correctly.
- Agent accuracy on validation dataset >95% (correct tool calls for standard commands).
- Documentation (tutorial, manual, demo video) is complete and reviewed.
- Evaluation instruments are validated and ready for formal user study.

Timeline and Dependencies

Estimated Duration: 3–4 weeks

Dependencies: Requires completion of all previous sprints (1–5). Beta testing requires access to target users. Formal evaluation (per Section 3.5) occurs after Sprint 6 completion.

3.6.8 Development Timeline Overview

Table 3.1 summarizes the estimated timeline for the six-sprint development plan. The total development window is approximately 16–23 weeks, with some sprints executable in parallel.

TABLE 3.1 – Sprint-based development timeline overview.

Sprint	Focus Area	Duration (weeks)
Sprint 1	Agent Intelligence Core	4–5
Sprint 2	Enhanced Simulation Physics	3–4
Sprint 3	Voice Integration	2–3
Sprint 4	VR Deployment & Integration	3–4
Sprint 5	AR Passthrough & Globe Visualization	2–3
Sprint 6	Polish & UX Refinement	3–4
Total	**(with parallelization)**	**16–23**

3.6.8.0.1 Parallelization Strategy To optimize the timeline:

- Sprint 1 must be completed first (foundation for all other components).
- Sprints 2 (physics) and 3 (voice) can proceed in parallel after Sprint 1.
- Sprint 4 (VR deployment) requires Sprints 1–3 but can begin as soon as Sprint 3 completes.
- Sprint 5 (AR mode) can be developed concurrently with Sprint 4 since both are independent rendering modes.
- Sprint 6 (polish) requires all previous sprints and should begin when Sprints 4 and 5 reach beta quality.

With efficient parallelization and overlapping work, the realistic timeline collapses to approximately **14–18 weeks** of active development.

3.6.9 Risk Mitigation and Contingency Planning

Identified Risks and Mitigation Strategies

1. **Risk: LLM Hallucination or Incorrect Tool Calls**

   - *Mitigation:* Implement strict validation of agent outputs. Require confirmation for irreversible actions. Provide "undo" functionality. Test extensively with edge cases and adversarial prompts.

2. **Risk: Voice Recognition Accuracy Below Threshold**

   - *Mitigation:* Maintain text input as fallback. Implement confirmation dialogues ("Did you mean...?"). Test with diverse accents and background noise levels. Provide visual transcription feedback.

3. **Risk: API Latency Degrading User Experience**

   - *Mitigation:* Cache frequent queries (e.g., common orbit requests). Implement local processing for deterministic calculations. Display loading indicators and progress feedback during API calls. Consider edge caching or local LLM fallback for critical functions.

4. **Risk: Quest 3 Performance Below 72 Hz (Motion Sickness)**

   - *Mitigation:* Profile early and optimize continuously. Implement aggressive LOD systems. Reduce visual complexity if necessary. Use Unity Profiler and Quest performance overlay to identify bottlenecks. Target 90 Hz but ensure 72 Hz minimum.

5. **Risk: AR Spatial Anchor Drift or Instability**

   - *Mitigation:* Use Quest 3's Scene API for robust environment understanding. Provide manual recalibration option accessible via voice command. Implement visual drift warning ("Anchor stability low - recalibrate?"). Consider marker-based tracking as fallback.

6. **Risk: User Confusion with Complex Interface**

   - *Mitigation:* Design intuitive onboarding tutorial. Implement progressive disclosure (show advanced features only after basics mastered). Conduct early beta testing to identify pain points. Provide in-app help accessible via "Agent, help me with...".

7. **Risk: Quest 3 Hardware Unavailability or Failure**

- *Mitigation:* Maintain desktop VR fallback (SteamVR compatible). Design system to function in "desktop mode" with keyboard/mouse for development without headset access. Ensure project portability to other VR platforms (PCVR, Quest 2).

Contingency Plans

If schedule constraints arise:

- **Priority 1 (Essential):** Sprints 1 and 2 (agent and physics) — these form the core educational value and can function as standalone desktop application.
- **Priority 2 (High Value):** Sprints 3 and 4 (voice and VR) — significantly enhance user experience and demonstrate immersive potential.
- **Priority 3 (Desirable):** Sprints 5 and 6 (AR mode and polish) — can be deferred to post-thesis continuation if necessary. VR-only deployment still fulfills thesis objectives.

Alternative minimum viable product (MVP):

- If VR deployment proves challenging, the system can function effectively as a desktop application with agent, physics, and voice integration (Sprints 1–3).
- If voice integration encounters API limitations, text-based input remains fully functional for all agent interactions.
- If AR mode timeline is constrained, VR-only deployment (Sprint 4) still delivers an immersive, novel educational platform.

The modular architecture ensures that even a partially implemented system delivers meaningful educational utility and can serve as a proof-of-concept for the full vision, with clear pathways for incremental enhancement in future work.

3.6.10 Alignment with Thesis Objectives

This implementation plan directly addresses all specific objectives outlined in Section 1.3:

1. **Physically accurate simulation:** Sprint 2 implements the two-body problem with Keplerian orbital elements, enabling realistic trajectory modeling and maneuver calculations.

2. **Generative agent integration:** Sprint 1 builds the natural language agent with tool use, memory, educational guidance, and Socratic tutoring capabilities.

3. **Physical interface (embodied interaction):** Sprint 5 anchors virtual orbital visualizations to a physical globe in augmented reality, creating a tangible reference point for spatial understanding.

4. **Multimodal interaction:** Sprints 3 (voice), 4 (VR controllers/hand tracking), and 5 (AR physical space) combine spoken dialogue, gestural input, and spatial manipulation for seamless interaction.

5. **Coherent real-time system:** All sprints integrate into a unified platform with continuous agent-simulation-user feedback loops operating at VR-appropriate frame rates.

6. **Modular and extensible architecture:** Each sprint produces standalone modules with clear interfaces, enabling independent testing and future expansion to other celestial bodies or educational domains.

7. **Evaluation as educational tool:** Sprint 6 includes comprehensive beta testing, user study preparation, and formal evaluation instruments (detailed in Section 3.5).

By following this sprint-based plan, the project systematically constructs a novel educational platform that leverages cutting-edge generative AI, immersive VR/AR visualization, and spatial interaction to make orbital mechanics accessible, engaging, and pedagogically effective.

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FOLHA DE REGISTRO DO DOCUMENTO

1. CLASSIFICAÇÃO/TIPO	2. DATA	3. DOCUMENTO Nº	4. Nº DE PÁGINAS
TC	25 de março de 2015	DCTA/ITA/DM-018/2015	69

5. TÍTULO E SUBTÍTULO:

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

6. AUTOR(ES):

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

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8. PALAVRAS-CHAVE SUGERIDAS PELO AUTOR:

AI; VR

9. PALAVRAS-CHAVE RESULTANTES DE INDEXAÇÃO:

AI; VR

10. APRESENTAÇÃO: (**X**) **Nacional** ( ) **Internacional**

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 três 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; (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 ; e (3) uma interface ”corpo” corporificada, consistindo em um globo físico com um sensor rotacional, que permite o controle tangível da simulação. A plataforma facilita um ciclo de interação multimodal contínuo, onde os comandos de voz e as manipulações físicas 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**