[Blue Owl Solutions]

Inside-Out Tracking Sensor Suite for Virtual Reality Applications

Version 0.0

[17/05/2025]

Presented by:
Erhan Alpan
Utku Yabacı
Arda Denizci
Emir Sencer Özdemir
Muhammed Ahmet Dinç
Oğuzhan Oğuz

Table of Contents

Company Information

Blue Owl Solutions include engineers with experience in embedded systems, signal processing, computer vision, sensor fusion, and control systems, making the company well-suited to develop the product.

Utku Yabacı
With a strong background on embedded systems and IMU integration, Utku led the hardware selection process. He also took part in writing the code for processing the information from the IMU and carried out research on Kalman Filter.

Arda Denizci
Arda mainly worked on processing the image from the camera. Also, he has experience in sensor fusion. He also co-developed the IMU data processing code and helped fusing the information from the camera and the IMU.

Muhammed Ahmet Dinç
Muhammed focused on writing the Kalman Filter algorithm and sensor fusion. He also wrote the IMU processing code. He also explored state-of-the-art visual algorithms for the camera.

Erhan Alpan
Collaborating closely with Muhammed, Erhan contributed to the development and optimization of the Kalman Filter. He also researched power-management solutions and determined the project’s power supply design.

Oğuzhan Oğuz
Oğuzhan designed the low-latency wireless link between the SBC and an external computer. He also implemented real-time rendering of the 3D head model and assisted with image processing.

Emir Sencer Özdemir
Emir fabricated lightweight housings for hardware used in the project. He also supported development of the IMU data processing code and helped with image processing.

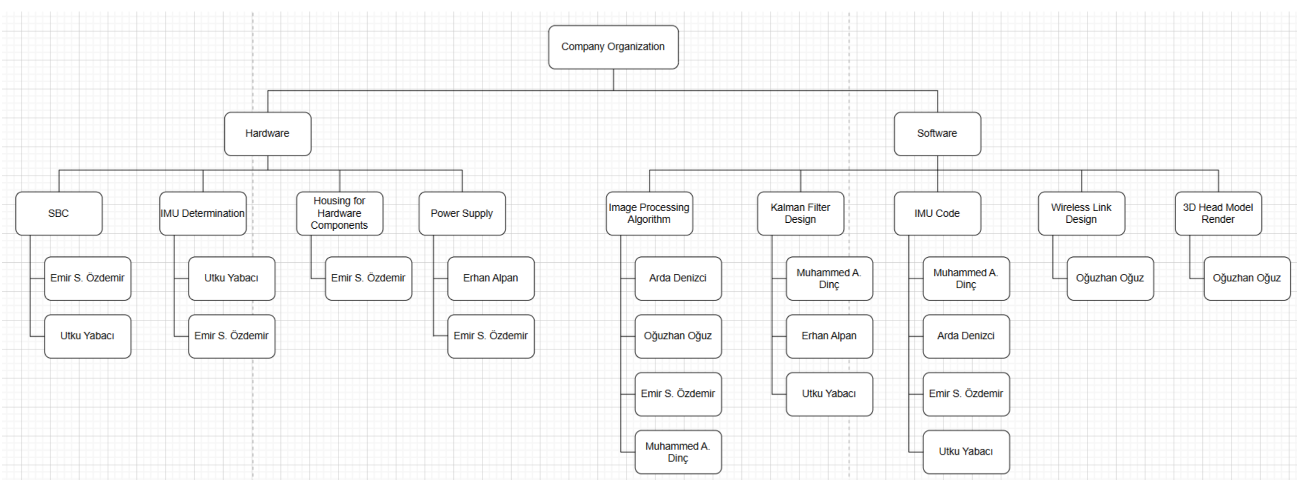

Figure 1. Company organization

Executive Summary

The Inside-Out Tracking Sensor Suite for Virtual Reality Applications project aims to revolutionize VR technology by eliminating the need for external sensors and provide users with an immersive experience. VR technology is becoming more widespread in sectors such as entertainment and education. For this reason, the need for portable, flexible systems that can work integrated with many systems is increasing day by day. Traditional VR technologies use external sensors in a fixed space, which limits user movement, increases dependency on specific environments, and causes hardware complexity. In this project, Blue Owl Solution company is trying to prevent this problem by using inside-out tracking with sensor fusion technology.

The design aims to achieve 6-DoF tracking and visualization of the user head position using a real-time model on the computer with minimum latency and error. To achieve this goal, data from Raspberry Pi Camera and the inertial measurement unit BNO055 will be integrated using sensor fusion. More advanced rotational estimation will be done using BNO055. Position estimation will be done by applying Kalman Filter to information from Raspberry Pi camera and BNO055. Wi-Fi technology and User Datagram Protocol (UDP) technique are used for communication between sensors and computers. In this way, fast and efficient communication occurs between the hardware and the computer. Rendering is performed on the computer using data sent to the computer via UDP. Python is used for this.

Engineers working at Blue Owl Solutions have theoretical and practical experience in the fields of sensor fusion, embedded systems, communication, image processing and control theory. They have gained this experience both in their academic careers and through industry-specific internships and candidate engineering experiences. In recent months, the team has completed the integration of data from the IMU and camera. Using both data, the Kalman filter can achieve advanced results. The data obtained was sent to the computer via UDP and the rendering process was completed. All of these systems were tested successfully. The project was created with a budget of approximately $300 and a total of seven months were spent.

At the end of the project, the user will have a system that is securely mounted on the VR set, processes the data from the IMU and the camera and sends it to the computer. With special software, a system that performs precise and low-latency head position estimation will be obtained.

Through this project, Blue Owl Solutions aims to redefine the VR experience with a versatile, cost-effective tracking solution that enhances freedom of movement and extends VR's applications across various fields, ultimately contributing to a more accessible and immersive digital future.

Introduction

Statement of the project

Virtual reality technologies are rapidly spreading in entertainment, education and industrial sectors. Therefore, the demand for portable, flexible and immersive VR systems is increasing. Current VR systems usually use external sensors, which restricts the user's freedom. The Inside-Out Tracking Sensor Kit for Virtual Reality Applications project aims to overcome this problem by switching to an inside-out tracking system. In this way, it can achieve the goals of providing users with more immersive and free virtual environments, encouraging innovation and increasing the accessibility of VR for wider applications.This project aims to provide a portable, flexible, and immersive VR experience by implementing an inside-out tracking system that uses sensor fusion techniques to accurately track head movements using a camera and IMU.

Current status of your project work

Within the scope of the project, 6 degrees of freedom data from Raspberry Pi Camera and BNO055 IMU have been successfully obtained and comprehensive tests have been carried out. The camera system has been tested with ORB-SLAM3 algorithm for high-resolution image acquisition and environmental mapping and the accuracy of the location data has been verified. Both systems have been integrated to Raspberry Pi and sensor fusion has been performed. Later, the results obtained have been improved by using Kalman filter. The obtained results have been sent to the computer via UDP and the rendering process has been successfully carried out on the computer via Python. All necessary tests have been carried out.

Scope and organization (of the report)

This Critical Design Review Report for the “Inside-Out Tracking Sensor Kit for Virtual Reality Applications” project provides a comprehensive evaluation of the system’s readiness. And ensures to move into fabrication, demonstration, and testing, ensuring that all performance requirements are met within the established cost, schedule, and other system constraints. The report opens with an abstract and introduction that detail the project’s context, rationale, and current status, setting the stage for a detailed analysis of the design. The subsequent sections define the engineering challenges and performance targets, and describe the system design by detailing the interactions between various subsystems. And define the design principles that guarantee the robustness of the system, with the understanding that essential design elements will remain unchanged after the review. Furthermore, the test results, planning, and risk analysis sections outline the validation methods, timeline, and potential risks. And ensure collectively affirming the system’s ability to meet its stated requirements.

System Design

The main goal of our solution is to develop a portable and cost-effective system that provides precise and real-time 6-degree-of-freedom (6-DoF) tracking for virtual reality (VR) applications. Our design is based on the fusion of data obtained from an inertial measurement unit (IMU) and a Raspberry Pi Camera module. The integration of these sensors ensures both high-resolution rotational and linear (translational) tracking capabilities. The fusion of data is mainly achieved by the Kalman Filter Algorithm. Apart from that our system uses advanced algorithms for sensor fusion and environmental mapping; for example, the ORB-SLAM3 algorithm is implemented for the camera. This approach ensures both precision and computational efficiency. The head orientation is obtained in terms of euler angles by using the quaternion coefficients obtained by the IMU. The communication between the headset and the external computer is carried out using the low-latency UDP protocol. In this way, the user's head position and orientation are transferred to the 3D model created in the computer environment in real time.

The hardware design focuses on lightness and ergonomic use. The total weight of the headset, including the camera and Raspberry Pi 5, is approximately 300 grams, which ensures user comfort even during long-term use. The system is powered by a power bank capable of operating for more than four hours with optimized power management. Thanks to the strategic placement of sensors, the headset is resistant to dynamic movements and provides stability and safety for the user.

The modular architecture offers scalability and adaptability, allowing for future developments, such as increased fidelity and increased interactivity. This solution addresses the shortcomings of current VR systems and offers a portable, efficient and cost-effective alternative. A functional flow diagram of the overall solution is provided in Figure 2.

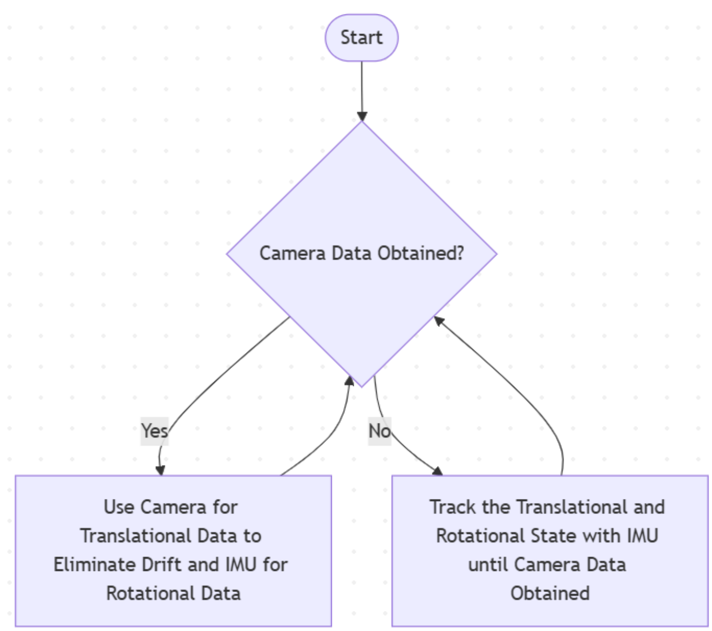

Figure 2. Functional flow diagram of the solution

Sensor data fusion is central to our system's ability to accurately provide 6-DoF head tracking. To achieve this goal, we combine cyclic motion information (pitch, roll, yaw) from the BNO055 IMU with positional data from the Raspberry Pi Camera using the ORB-SLAM3 algorithm. This dual-source approach compensates for the limitations of individual sensors: the IMU suffers from drift over time, while the camera is more prone to positional errors in low-light or visually deficient environments.

The data fusion process uses a Kalman filter to transform sensor outputs into a single representation of head position and orientation. The Kalman filter minimizes noise and drift by continuously updating incoming measurements. This ensures robust tracking even during rapid head movements or in environments with variable lighting conditions.

Additionally, combining camera and IMU data results in ±10° orientation accuracy and ±10 cm positional error. These performance measurements have been validated through rigorous testing under various operating conditions.

Thanks to these methods, our sensor fusion algorithm ensures high reliability and precision, creating a solid foundation for an immersive and responsive VR experience.

A 3D drawing of the physical design is given in Figure 3 and Figure 4.

Figure 3. 3D drawing of the design

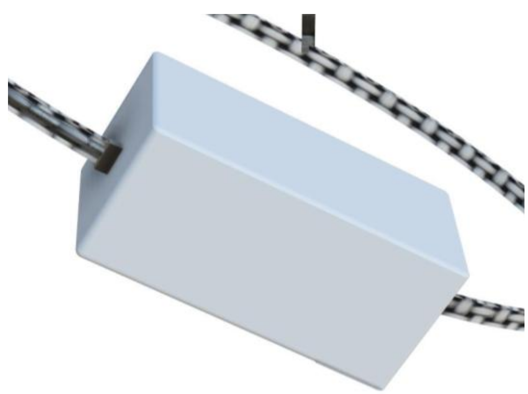

Figure 4. Power bank enclosure

The physical system consists of three enclosures, first one holding the camera on the forehead of the user, the second one holding the SBC and the IMU sensor, and the third one holding the powerbank on the belt. The connection in between these three enclosures is going to be realized by the necessary cables, as seen in the figures, from the back of the user. This design choice is made so that the wiring between the enclosures does not prevent convenient and comfortable use. The headset enclosure is going to be discussed in the future parts of this report, namely in the Sensor Suite Subsystem section. The other enclosure, which is to hold the SBC is estimated to be 37x61x95 mm(yeni değere güncellenecek) in dimensions with a wall thickness of 2 mm and weight around 100 grams. The powerbank used in the product is approximately 400 grams and the SBC (Raspberry Pi 5 16 GB) is around 50 grams.
The block diagram of the system, describing it overall, is given in Figure 5 and 6.

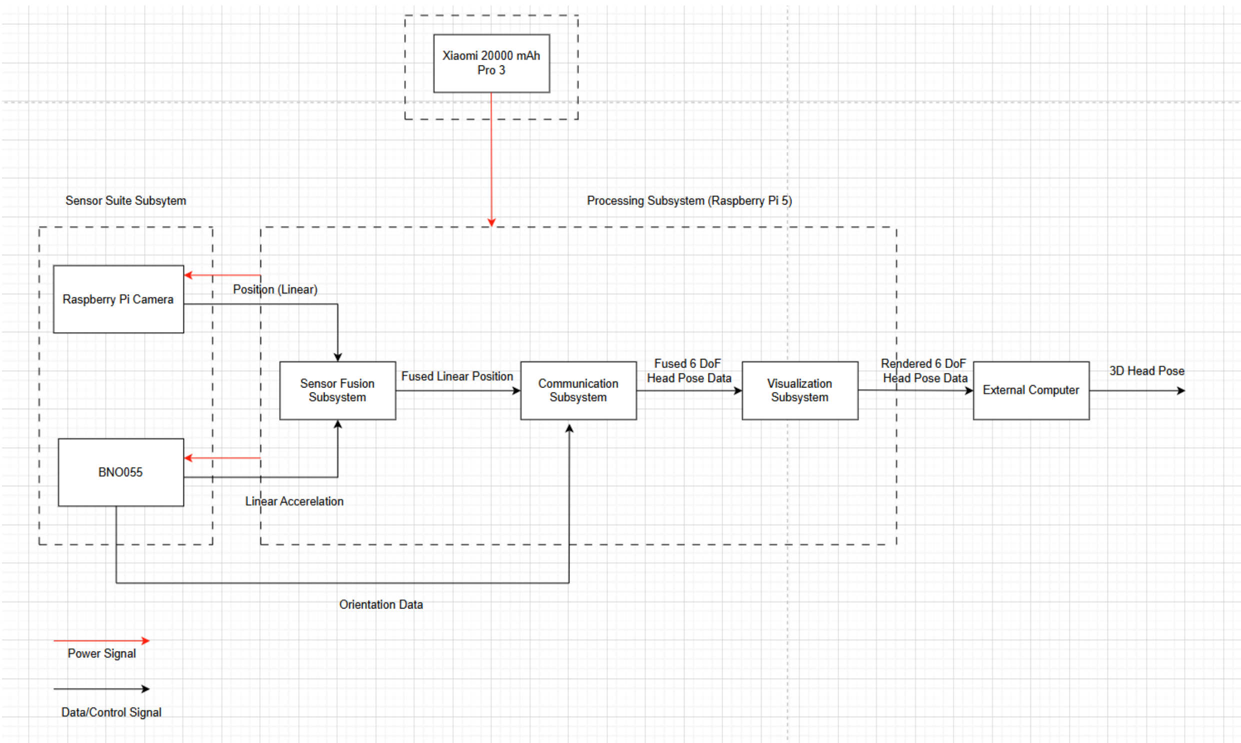

Figure 5. System Level Block Diagram

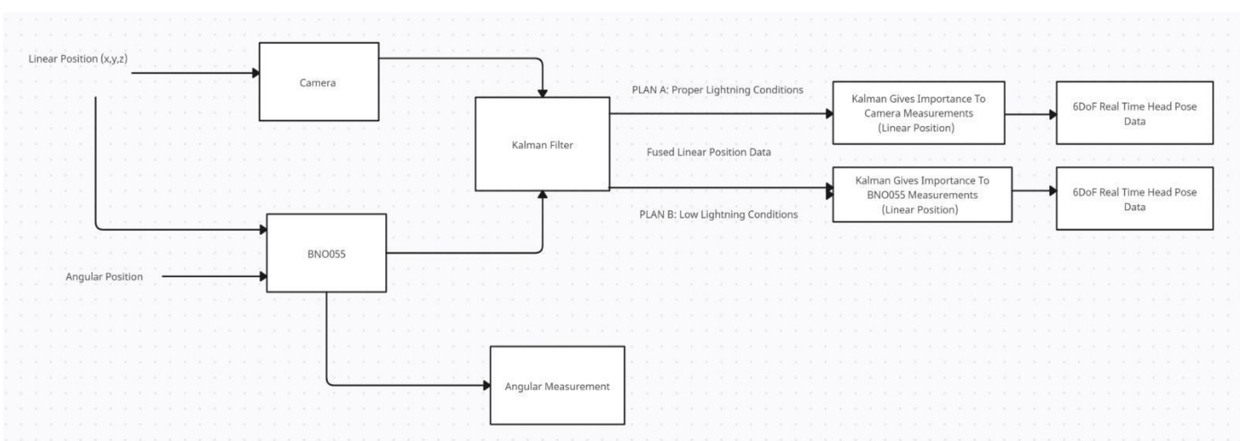

Figure 6. Plan A and Plan B Figure

Subsystems

Sensor Suite Subsystem

The Sensor Suite Subsystem is designed to provide precise and real-time 6-DoF tracking of the VR headset by collecting data from the sensors. The location and orientation information data were collected by IMU and a camera. The fusion of these sensors enables the system to achieve highly accurate object tracking while addressing challenges such as the drift problem of IMU position tracking. The gathered data is processed using Kalman Filter [10]. The IMU module is expected to meet the system level requirement of determining the orientation of the head, with an error less than ±10°, by itself.

IMU (Inertial Measurement Unit)

The BNO055, Intelligent 9-axis absolute orientation sensor [2], used in the project provides critical data for estimating the 6-degree-of-freedom (6-DOF) head pose. The sensor combines accelerometer, gyroscope and a geomagnetic sensor to provide both raw data such as linear acceleration and angular velocity and fused data in quaternion [5] and Euler angle [6] formats for real-time orientation tracking. By providing fused data and therefore eliminating the need for excessive external computation, this integration reduces computation load on the host processor, making it suitable for real-time applications in VR.

Since position of the head can not be simply obtained from the accelerometer data from IMU due to the drift problem, a Kalman Filter will be applied. With the filter, more reliable position information will be obtained.

Camera

In our project, Raspberry Pi's PiCamera module plays a critical role in determining the 6-degree-of-freedom (6-DOF) head position and orientation. The camera provides a real-time high-resolution video stream, forming the basis for processing visual data. The basic algorithm used for image processing is ORB-SLAM3 [1] (Oriented FAST and Rotated BRIEF Simultaneous Localization and Mapping), which allows us to obtain both position and orientation information precisely.

The ORB-SLAM3 algorithm detects and tracks prominent feature points (keypoints) in the images captured by the camera, allowing the mapping of the environment and the determination of the 3D position of the camera. This algorithm is highly effective not only in determining head orientation, but also in precisely determining the environmental position of the head. The algorithm can analyze head movements by tracking the movement of visual features over time. It also increases the accuracy of the camera position by combining visual odometry with environmental map data.

The image data provided by PiCamera is combined with angular velocity and acceleration measurements from the IMU, resulting in a more robust system. In particular, sensor fusion methods such as the Kalman filter minimize possible interruptions in the camera’s image capture or uncertainties resulting from rapid head movements. Tests have shown that the precision provided by the ORB-SLAM3 algorithm, when combined with IMU data, significantly increases the overall accuracy and reliability of the system.

The operation flow of the sensor data processing and fusion is given in Figure 7.

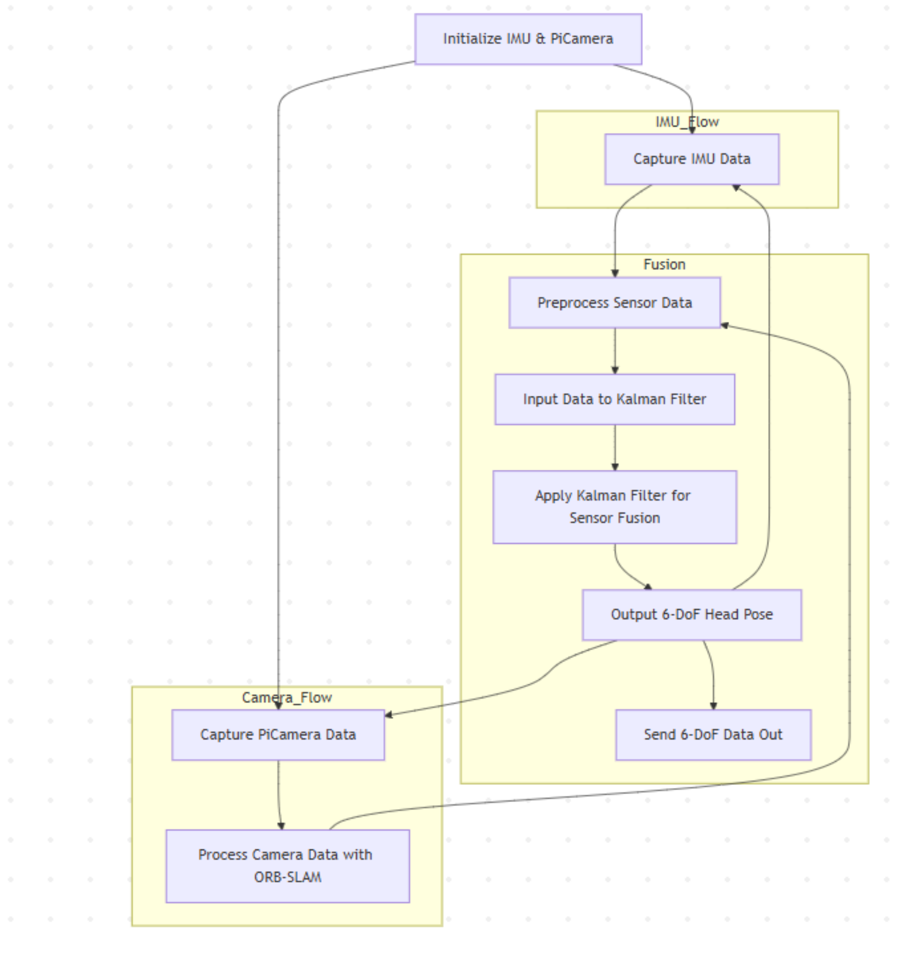

Figure 7. Sensor Data Process and Fusion Steps

Headset

The headset in the system is designed to meet the system level requirements of functionality, comfort, and stability. With a lightweight construction, the case itself weighs only around 100 grams, minimizing user fatigue during extended use. The total weight of the headset is estimated to be around grams with the addition of components, straps and cables. It is designed to maintain stability during dynamic movements, securely mounted for rotations up to ±90°.

Hereby, the headset is expected to meet the system level requirements of being lightweight, convenient and comfortable. The camera sensor will be strategically placed on the users forehead with a specifically designed case that will ensure their stable operation. This case will be secured in its place with the help of straps. Efficient cable management will be implemented in order to avoid restricting user's movements. The cables are going to be guided towards the nape of the user by using the top strap in the headset and then will be guided downwards from the back of the user to the powerbank, which is carried on a belt. With its sleek, professional design, the headset not only enhances functionality but also reflects the innovative and professional nature of the VR tracking system.

The case that is going to hold the Raspberry Pi 3 Camera Module is planned to have the dimensions of 4.3x4.0x2.5 cm with a wall thickness of 0.2 cm. This case will be 3D printed, using PLA as the filament, resulting in a very lightweight product, approximately 25 grams. The interior of the case will be specifically designed to tightly secure both the camera and the IMU, preventing any movement or vibration that could affect sensor accuracy or alignment. Then the straps are going to be connected to the case to ensure that the case itself will be stable on the forehead of the user. A 3D drawing of the Headset is shown in Figure 8.

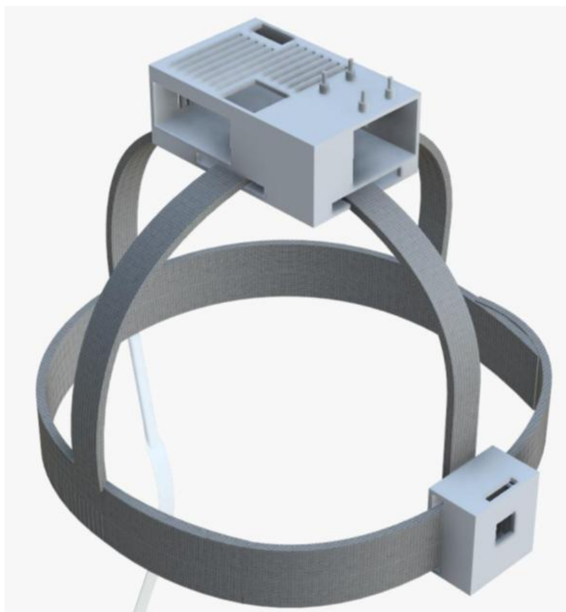

Figure 8. 3D design of the Headset

Sensor Fusion Subsystem

In our project, data obtained from both the IMU and the camera are fused via a Kalman filter algorithm. This approach combines the strengths of both sensors to achieve minimal error and real-time 6-DOF tracking of the VR headset and solves some problems, such as drift in the IMU. The accelerometer data from the IMU may drift over time because a slight bias or error may accumulate and cause significant positional errors due to integral error (drift). In contrast, the camera provides stable global position information by utilizing environmental reference points detected through methods such as the ORB-SLAM3 algorithm. Thus, the IMU does not provide reliable and stable positional data, and the camera continuously corrects errors to solve the drift problem inherent in using the IMU alone.

The Kalman filter operates on a 9×9 state vector that includes the system's position, velocity, and acceleration for each axis. On the prediction update, the model errors are used by the process noise matrix to predict the next state. In the next update, separate measurement updates are performed: The camera is good at delivering high-accuracy location information, especially in slow or stationary conditions through environmental mapping via an ORB-SLAM3 algorithm. The IMU is sensitive to fast movements and vibrations, offering low-latency motion data. This combination allows the system to perform 6-DOF tracking of the user's head movements even during rapid changes. These fused measurement updates allow the system to maintain both sensitivities to rapid movements and overall stability in tracking.

Overall, by integrating the IMU's fast and instantaneous motion data with the camera's robust environmental position data through a Kalman filter, the sensor fusion subsystem minimizes drift and measurement errors across the system, delivering real-time, high-precision head pose tracking.

Processing Unit Subsystem

The processing unit sub-system is composed of an SBC. SBC handles the processing of the data obtained from sensors. The main solution for this subsystem includes a Raspberry Pi 5 16 GB. Due to the high memory of Raspberry Pi 5, the processing unit subsystem can hold sufficient data obtained from sensors. Processing unit subsystem with Raspberry Pi 5 16 GB meets the system level requirements of processing the data from sensors via an SBC with memory higher than 4 GB.

SBC

Raspberry Pi 5 16 GB is chosen as SBC for the project. Its high memory enables holding enough data to obtain 6-degree-of-freedom head pose information. 2.4 GHz Quad core Cortex A-76 CPU integrated within the Raspberry Pi 5 allows running image processing algorithms on the SBC. Existence of onboard WiFi eliminates the need for an extra WiFi module.

Power Subsystem

The Raspberry Pi 5 has a 5V DC input voltage and enables it to draw up to a maximum of 5A current. In the most stress tests it is shown that the board has 10.75W of power [11] under full load. 5V with 10.75W corresponds to 2.15A current which is drawn by the board solely under full load. The BNO055 draws 12 mA of current at 3.3V (in normal mode). BNO055 is connected to the 3.3V pin of the Raspberry Pi. Apart from that, the Raspberry Pi Camera Module 3 [3] module draws approximately 300mA [4] at 5V DC. As the board and its peripherals are sensitive to voltage fluctuations, the voltage supplied to the board must be strictly 5V DC. The total current, i.e. the sum of currents of the board and its peripherals is 2.46A.Due to heavy computing of the board and unexpected loads this current may rise up to 2.75-2.80A.Thus, to be on the safe side the 3A will be the maximum reference value for the current to compute the operation time. The Xiaomi 20000 mAh 3 Pro Type-C Powerbank will be used as the portable power supply. This supply has an output pin of 5V and 3A(max) which is suitable for the board and peripheral supply requirements(5V/3A). Like typical power banks, the Xiaomi 20000 mAh 3 Pro has a nominal voltage rate of 3.7V. The total energy stored in the power bank is 3.7V *20Ah=74Wh. The power supply has a step-up converter inside such that its efficiency is around %85. Therefore its effective energy that can supply is 74Wh*85/100=63Wh. The board and its peripherals draws maximum of 15W under full load (heavy computation and peripheral load).The effective amp-hour power capacity is 63Wh/5V=12.6Ah. The board takes 3A as the input current such that the operation time is 12.6Ah/3A=4.2 hours approximately for the full load case. If the computational and peripheral load is not that heavy, the board will draw less than 15W and the operation time will increase.

The power ratings and connections of the devices are given in Figure 9. The project's resource management diagram can be seen in Figure 10. Optional case fan can be used against heating situations. All necessary tests have been done and explained in the power management analysis section.

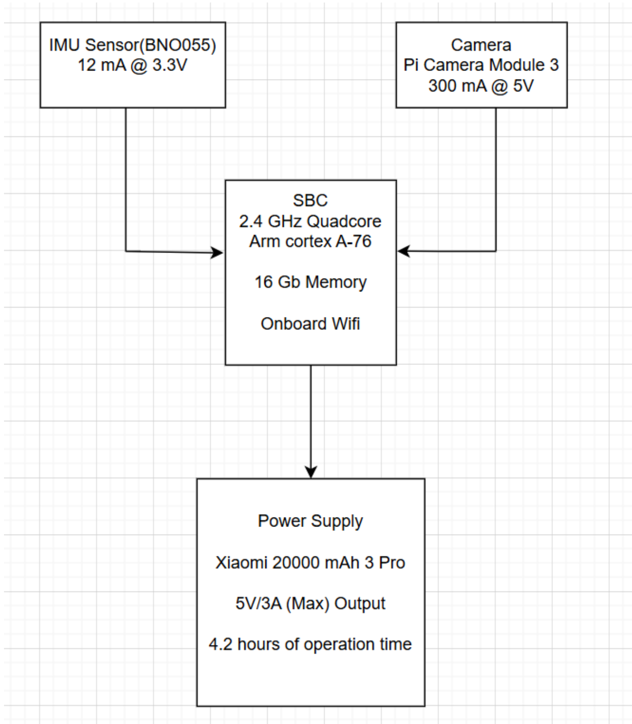

Figure 9. Power Ratings of the Devices

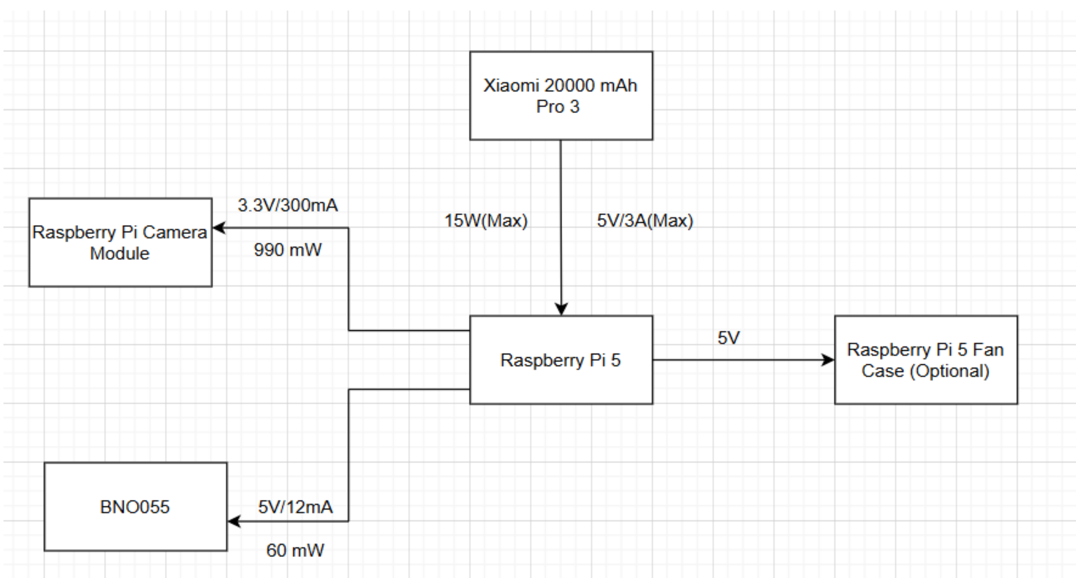

Figure 10. Power distribution diagram.

Communication Subsystem

Figure 10 shows the communication subsystem. Figure 11 shows the flowchart of the communication subsystem. Wi-Fi [7] will be used to communicate between the headset we will create and the computer. Since the Raspberry Pi hardware is compatible with 2.4/5G technology, low-latency and high-speed communication will be provided with the direct connection (P2P) method. UDP (User Datagram Protocol) [8][9] will be used for communication in the project and a client-server structure will be created. Raspberry Pi will process the data it receives from the IMU and camera as a client, and will calculate the 6-DoF head position in real time by running translational and rotational pose estimation algorithms. The client will package this data wirelessly in binary data format and send it to the server on the computer. Raspberry Pi will send an average of 10 data packets per second to the computer's IP address and the specified port via UDP sockets; The computer will listen to the data coming to this port. Packets will include information such as "time stamp, x/y/z positions, qx/qy/qz/qw values". Timestamps will be used to provide low latency and maintain synchronicity. All of these operations will be performed with Python. Thus, fast, reliable and real-time communication will be established between the head and the computer. In this way, the transmission of the information in a wireless function is fulfilled.

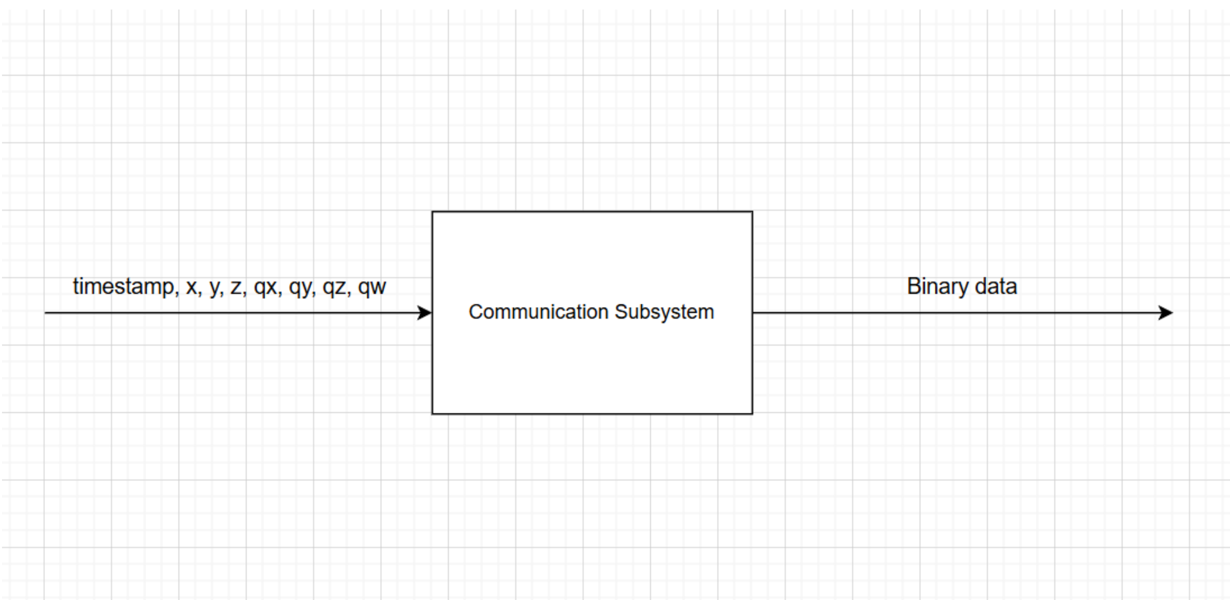

Figure 11. Block diagram of communication subsystem.

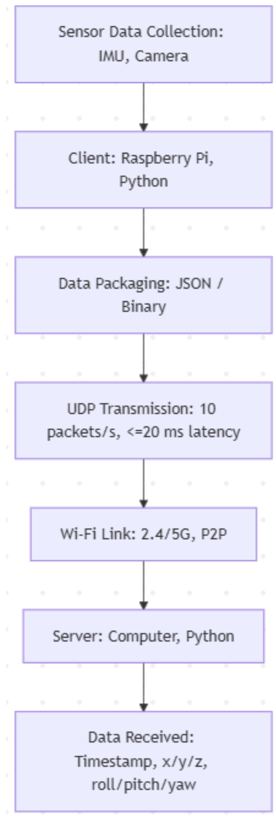

Figure 12. Flowchart of the communication subsystem.

Visualization Subsystem

The visualization subsystem is used to process the 6-degree-of-freedom head position in real time on a computer according to the data collected from the sensors. The subsystem ensures that the processed data from the sensors is converted into an accurate and interactive 3D model. Therefore, it will allow users to clearly understand the movements being monitored. Python VTK library will be used for ease of operation and minimum latency. The application will process the head model according to the processed data at a target frame rate of 15-20 FPS. The 3D head model will be designed to be lightweight and the algorithm will be optimized to maintain minimum latency and smooth visualization. Therefore, the visualization will not only increase user interaction, but also help us verify the accuracy of the fusion algorithm. The flow chart of the visualization subsystem can be seen in Figure 13. An example image for the visualization interface can be seen in Figure 14.

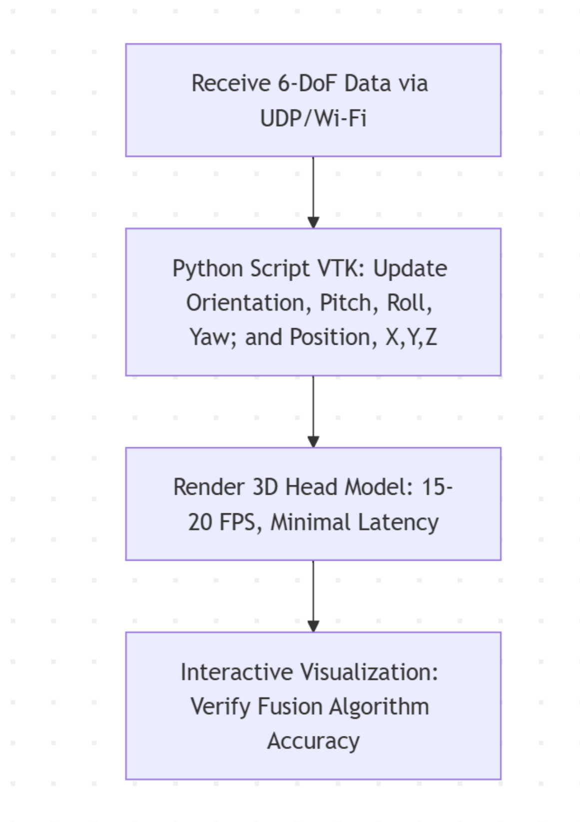

Figure 13. Flowchart of the visualization subsystem.

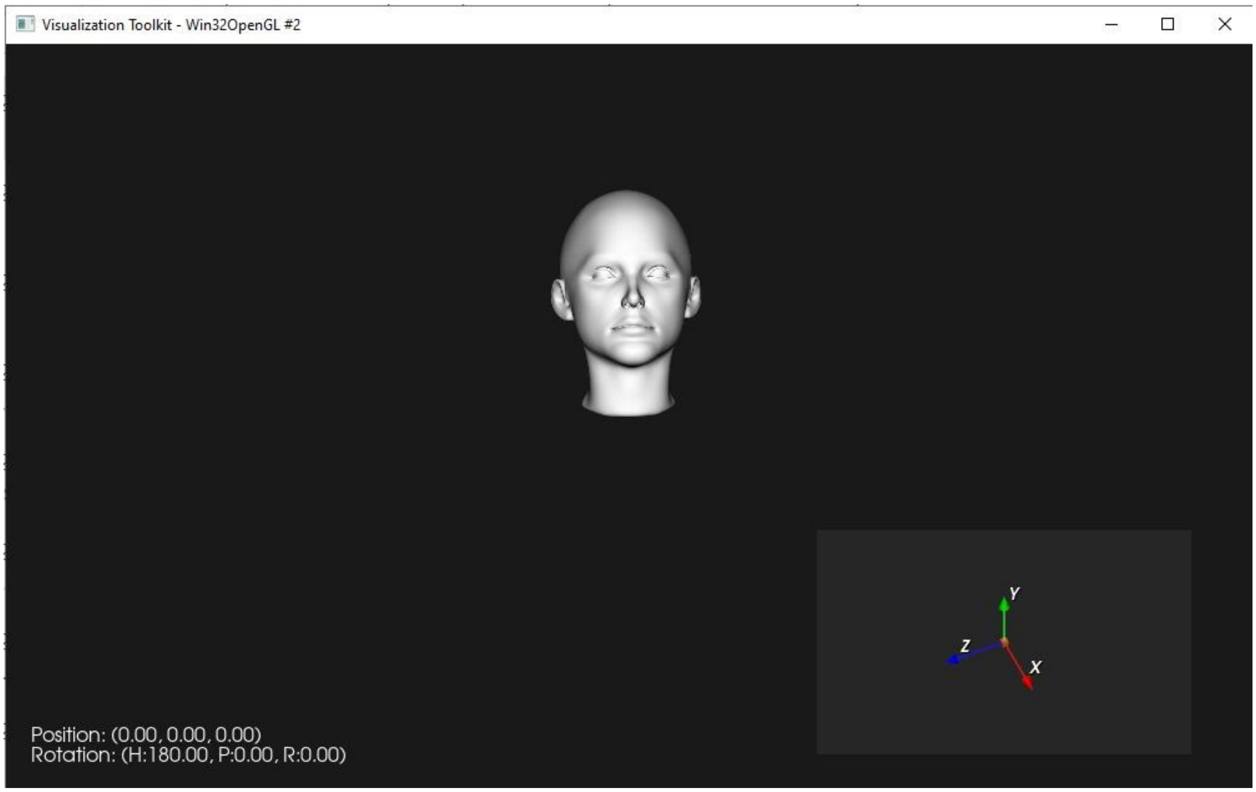

Figure 14. Visualization subsystem.

Requirements

At the system level, delivering accurate orientation and position tracking within defined error margins, real-time responsiveness, low latency, and portable power efficiency, all while maintaining a fully inside-out tracking architecture is the focus. These system level requirements are fulfilled by clearly defined subsystem level requirements covering sensor accuracy, data fusion consistency, power stability and more. Each of the requirements mentioned are quantitative and aligned with the functional and performance constraints of the system. As a whole, a structured base for implementation, testing, and validation is provided by these requirements. Overall, to ensure that the project's goals are met, the system and subsystem level requirements of the VR tracking solution are explained in detail.

SYSTEM LEVEL REQUIREMENTS

The system level requirements in the project can be itemized as:

- The system shall perform tracking without reliance on external base stations or anchors.
- The system shall estimate headset orientation with an error margin not exceeding **±10 degrees**.

- The system shall provide positional tracking with an error less than **±10 cm** within a 2x2 meter environment.
- To ensure real-time response, data from the Raspberry Pi will have a maximum delay of 20 ms.
- The maximum delay at the end of rendering will be 200 ms.
- The system shall operate continuously for at least **4 hours** on portable battery power.
- The physical system should be lightweight, comfortable and convenient.

SUBSYSTEM LEVEL REQUIREMENTS

The requirements are itemized and listed in a clear aspect for every subsystem as:

Sensor Suite Subsystem

- The IMU is supposed to estimate the orientation of the user head with less than ±10° error.
- The camera and IMU fused data should be able to estimate the user head position with ± 10 cm error.
- The headset weight is approximately 50 grams.
- The I²C (Inter-Integrated Circuit) standard (IEC 60255-24) is used for communication between the IMU sensor and the processing unit, enabling reliable, low-power, short-distance communication within the compact wearable system.

Sensor Fusion Subsystem

- The fused translational position information should have less than ±10 cm error. The fused orientation information should have less than ±10° error.

Processing Unit Subsystem

- The SBC should have a memory greater than 4 GB to ensure that the sensor fusion algorithm can run smoothly.

Power Subsystem

- The powerbank used shall enable stable operation for at least 4 hours.

Communication Subsystem

- Approximate latency is 20 ms in transmission. Resulting in a total system latency (from data acquisition to rendering) to be smaller than 200 ms.

- UDP/IP is used for communication between the SBC and the external computer responsible for rendering the user's head movements. This ensures low-latency, connectionless data transmission, which is crucial for real-time responsiveness in the VR tracking system.

Visualization Subsystem

- The application should create renders at 20 FPS and smaller delay than 2 seconds.

Compatibility Analysis of Subsystems

- Interface Compatibility Analysis

  The subsystems of the VR tracking system are designed for seamless integration through well defined electrical and data interfaces. The sensor to SBC connection employs clearly defined signal interfaces. The BNO055 IMU communicates via I²C at 3.3V. The Raspberry Pi Camera Module 3 uses a CSI interface with a 5V DC supply. This explicit definition of signal interfaces ensures reliable data transmission. It facilitates future upgrades without significant modifications.

- Software Version Compatibility Analysis

  Consistency across software versions is maintained by strict version control and standardized operating environments. The Raspberry Pi operates on a Linux-based OS with Python 3. It is utilizing libraries such as OpenCV and PySerial for sensor data processing and communication. This approach guarantees that firmware updates. And changes in individual software components do not disrupt the overall system performance. It is ensuring that sensor fusion, data acquisition, and communication algorithms remain compatible over time.

- Timing and Synchronization Analysis

  Real-time performance is achieved through precise timing and synchronization protocols. The sensor suite continuously samples data with a processing delay of about 20 ms. It is ensuring timely data fusion before transmission. Packets, complete with time stamps and 6-DoF parameters, are sent via UDP over a direct Wi-Fi connection. They are maintaining an end-to-end latency of under 200 ms. This rigorous timing strategy is crucial for synchronizing sensor data with the visualization subsystem. Thereby delivering a stable and responsive VR experience.

- Relevant Standards and Justifications

  Adherence to industry standards is critical for ensuring overall system compatibility. The use of IEEE 802.11 guarantees reliable high-speed Wi-Fi communication. I²C/SPI protocols standardize sensor communication, making the system adaptable to various components. The UDP/IP protocol is selected for its minimal overhead and fast transmission capabilities. It is meeting the low-latency demands of real-time applications. Additionally, maintaining a 5V/3A power supply standard ensures consistent and stable operation. They are providing a robust framework for both current and future system enhancements.

Compliance with Requirements

Design Decisions Based on Requirements

Design choices are optimized to meet the specified system and subsystem requirements. The basic conditions are explained below:

- No External Sensor (Inside-Out Tracking):

  Requirement: The system must operate without relying on external base stations.
  Design: IMU and camera data are connected to the independence of the external sensors.
  Test Result: -

- Low Error Margins (±10° Angular error, ±10 cm Positional error):

  Requirement: positional error < ±10 cm and Angular error < ±10°
  must be satisfied.
  Design: IMU drift is minimized with Kalman Filter, and camera positional accuracy is increased.
  Test Result: As it can be seen from the test results, error requirements are satisfied.

- Low Latency (<200 ms System Latency):

  Requirement: Total processing and processing latency must be less than 200 ms. o
  Design Decision: UDP provided data transmission in less than 20 ms, and Python VTK enabled fast processing.
  Test Result: The average latency was 200 ms.

- Portability, Wearability, and Long Battery Life (4+ Hours):

  Requirements: The system should not be heavy. In addition, it should have at least 4 hours battery life on running the system.
  Design: Using a Xiaomi 20000 mAh power bank and a suitably ergonomic design.
  Test Result: More than 4 hours of working time was achieved. In addition, the total weight of the system is 0.9 kg

Conflicting Requirements

- Low Cost and High Accuracy: Using a better camera sensor can increase accuracy. However, the cost may increase due to camera prices.

- Long Battery Life and Performance: When performance increases, such as high processing power usage, it leads to high energy consumption. Therefore, battery durability may decrease.

Best Solution

Kalman Filter-based sensor fusion and ORB-SLAM visual odometry are intentionally combined in our optimized system design to meet the conflicting demands of high tracking accuracy, low power consumption, and cost-effectiveness. This method maintains strong 6-DoF tracking performance without the need for costly Time-of-Flight (ToF) sensors. Table 1 shows the crosscheck table for requirements and design decisions.

Table 1. Crosscheck Table for Requirements and Design Decisions.

Requirements / **System Design**	Using kalman filter instead of TOF sensor	The renewed physical system design	Choosing pyhton VTK instead of blender	Using Xiaomi 20000mAh instead of complex	Using UDP protocol for communication	Using IMU and Camera for sensors
No external sensors	✓					✓
Orientation error ≤ 3°	✓					
Positional error ≤ 5 cms	✓					
Transmission latency ≤ 20 ms					✓	
Total latency ≤ 200 ms	✓		✓		✓	
Battery run time duration ≥ 3 hours				✓		
Ligthweight, comfortable and convenient product		✓				

Potential Failure Points and System Robustness

- IMU Drift

  One of the biggest problems in inertial measurement systems is the drift that is caused by the integral term. It can lead to cumulative errors in the linear position over a long time measurement. In the proposed design, this problem is addressed by continuously correcting the visual feedback from the camera, and by integrating the IMU and camera data via a Kalman Filter. It provides a dynamic correction via time and measurement updates.

- Camera Measurement Insufficiency at Low Light Conditions

  Visual tracking systems are sensitive to environmental factors such as illumination. For example, in low-light scenarios, tracking performance reduces significantly. To address this, the system temporarily compensates for these visual disruptions, and the Kalman filter algorithm makes the IMU measurements more prominent. This sensor redundancy ensures smooth motion estimation until the visual data becomes reliable again, allowing the system to operate continuously even in difficult lighting conditions.

Budget

Table 2. Cost Analysis

Category	Item	Quantity	Unit Cost	Total Cost
Sensor	BNO055 (9-DOF)	1	$47.666	$47.666
Sensor	Raspberry Pi 3 Camera Module	1	$47.553	$47.553
Microcontroller	Raspberry Pi 5 16 GB	1	$161.18	$161.18
Connection	Long Cable For Headset	1	$4.9	$4.9
Power Source	Xiaomi 20000 mAh 3 Pro Type-C Powerbank	1	$40.274	$40.274
Memory	Micro SD Card	1	$7.114	$7.114
Cooling	Raspberry Pi 5 Cooling Fan + Heat Sink	1	$6.515	$6.515
Wearable	Headset Design	1	$7.73	$7.73

Total Cost	**$324.99**

The updated cost breakdown is given in Table 2. It reflects the cost of each component for the project. As a result of the analysis, each component was selected to provide the most optimum performance within the budget. The cost of each component was also updated according to current market prices. Although there were cheaper alternatives, functionality and reliability influenced the choices. Choices were made to ensure system stability and longevity. And choices were made that would make significant contributions to the success of the project.

Results and Analyses of Performance Tests

- Sensor Suite Subsystem Test Result Analysis:

  By looking at these results, with the help of the Kalman filter algorithm we achieved much better performance on the linear position data of the user's head with respect to previous test results that have been done without the Kalman filter. Therefore, the Kalman filter successfully fuses the linear position data coming from the camera and the IMU. Also, the linear position error requirements were satisfied. Apart from that the orientation test results show that the BNO055 measures 3 angles (yaw, pitch, roll) in a precise manner with an error of less than 10 degrees. Overall, these test results show that the overall design of the full system operates successfully while meeting the design requirements.

- Power Subsystem Test Procedure:

  In each power test, we recorded the input voltage and current of each component (the board, camera module, BNO055) via multimeter. By using these values, power of each component was measured. The operation time is recorded via a simple chronometer.

- Power Management Analysis:

  The Raspberry Pi 5 draws 5V DC input and can draw up to 5A (25W) under full load, which includes heavy computation and peripheral usage. In our case, the expected maximum current is 3A, so the expected maximum power drawn by the board, and its peripherals is 15W. In power tests, the system was powered by a Xiaomi 20000 mAh 3 Pro Type-C Powerbank that has nominally 74 Wh at the nominal voltage of 3.7V. It corresponds to 63 Wh due to %85 efficiency of the step-up converter. Effective amp-hour capacity is calculated as 63Wh/5V=12.6 Ah. From the theoretical point of view, the operation time of the system is 12.6 Ah/3A= 4.2 hours. In our experiments, we conducted five cases and observed slight deviations from the expected operation time. In Case 1, the board was measured at 5.01V drawing 2.25A (11.27 W), the BNO055 sensor drew 12.1 mA at 3.3V, and the Camera Module 3 drew about 305 mA at 5V, resulting in an operation time of 4.93 hours. In Case 2, we measured 5.02V as the input voltage and 2.30A as the input current for the board. It corresponds to 11.55W of input power. The BNO055 drew 11.80 mA and the camera module current was measured as 302 mA, leading to an operation time of 4.81 hours. Case 3 yielded 4.99V and 2.45A for board corresponding to 12.23W of input power. The BNO055 current was recorded as 12.20 mA. The camera module current was measured as 310 mA. The operation time is recorded as 4.72 hours. In Case 4, the board had an input voltage of 5.02V with a current draw of 2.40A which corresponds to 12.048W of input power. IMU sensor drew 11.70 mA and the camera current was recorded as 295 mA resulting in an operation time of 4.68 hours. Finally, Case 5 showed a slightly higher current draw for each component. The board drew 2.70A at 5V, which corresponds to 13.5W of input power. IMU sensor had a 12.10 mA of input current and the camera drawing was 315 mA. The operation time was recorded as 4.18 hours. Note that these runtimes under full load are slightly larger than our theoretically calculated operation time (4.2h). This is mainly due to the fact that the board draws less than 3A in all cases. However, the theoretical value is calculated by considering the worst case (the board draws the maximum current that the power supply can provide (3A))

The test results are tabulated at Table 3.

Table 3. Power Subsystem Test Results

Tests	BNO055 (V/mA)	BNO055 (mW)	Camera (V/mA)	Camera (mW)	Board (V/A)	Board (W)	Operation Time (h)
Test 1	3.3V/12.1mA	39.93mW	5V/305mA	1525mW	5.01V/2.25A	11.27W	4.93h
Test 2	3.3V/11.80mA	38.94mw	5V/302mA	1510mW	5.02V/2.30A	11.55W	4.81h
Test 3	3.3V/12.20mA	40.26mW	5V/310mA	1550mW	4.99V/2.45A	12.23W	4.72h
Test 4	3.3V/11.70mA	38.61mW	5V/295mA	1475mW	5.02V/2.40A	12.05W	4.68h
Test 5	3.3V/12.10mA	39.93mW	5V/315mA	1575mW	5V/2.70A	15.44W	4.18h

Measures of Success: Operation time > 4h

- Communication Subsystem Test:

  Since there is no handshake in the UDP protocol, it is quite difficult to measure latency. Therefore, the latency values of the TCP protocol, which has more latency, will be measured. For this, the return time of the information sent from the client to the client will be found. This value is equal to the RTT value. The RTT / 2 value is approximately the latency value of the information sent from the TCP client to the server. These values will be made for thirty seconds for ten different servers. The results obtained and the average of the results will be reported. This obtained result is more than the UDP protocol, so the requirements value will be controllable.

  Measures of Success:

  Wireless latency approximately 20 ms.

- Communication Subsystem Test Results:

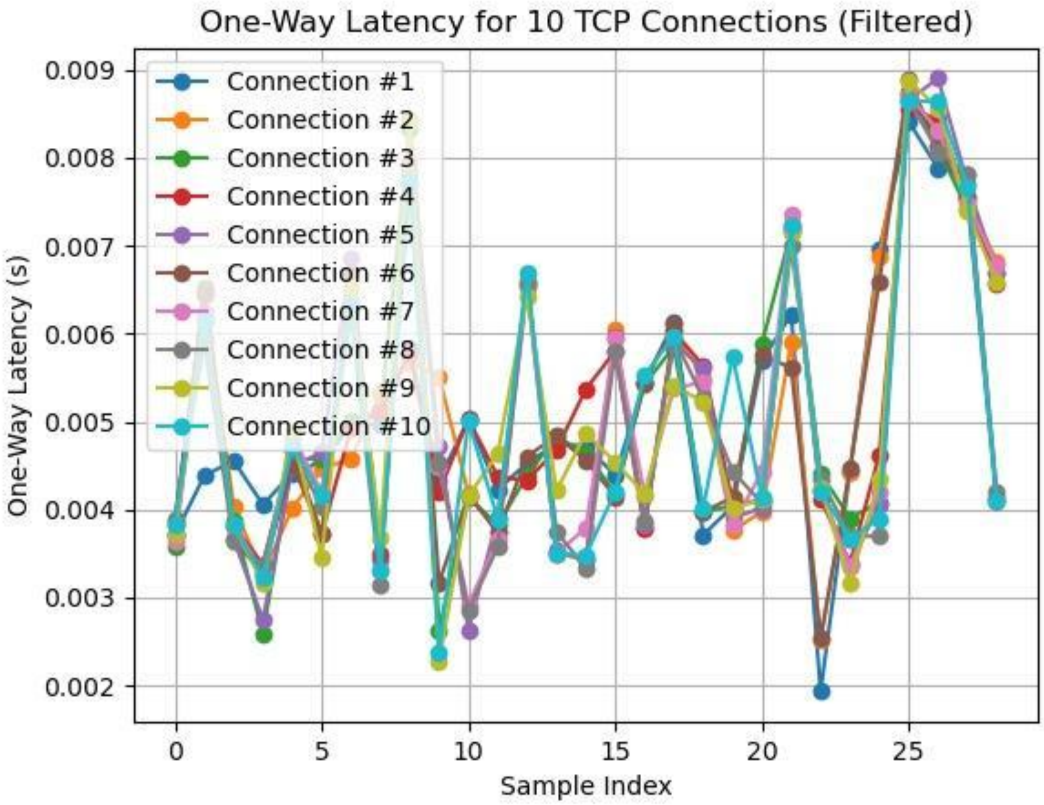

Figure 15. One way latency for 10 TCP connections

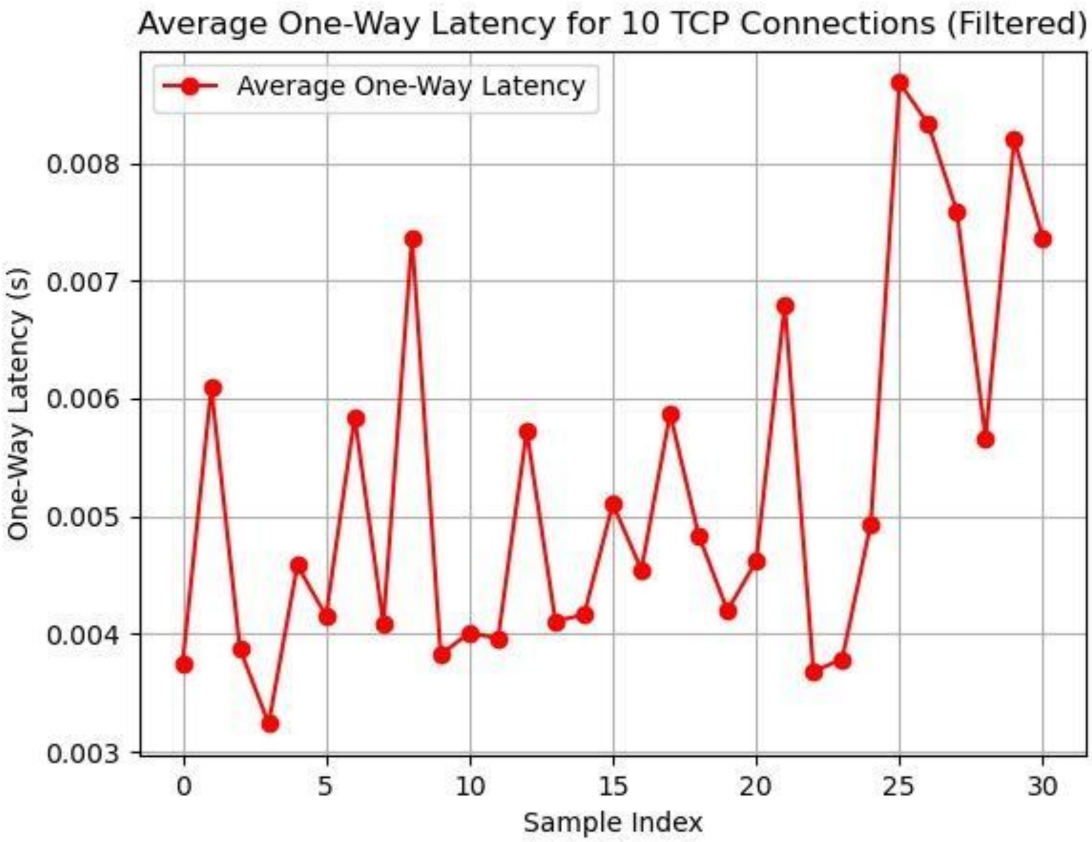

Figure 16. Average one was latency for 10 TCP connections

UDP protocol is faster than TCP protocol. This is because there is no handshake. Therefore, it is quite difficult to measure the latency of UDP protocol. When the time synchronization between two devices is not complete, the real latency value cannot be measured. In order to measure a more accurate latency value, a test was made on TCP protocol. The latency of TCP protocol is higher than UDP protocol. Figure 15 shows the latency values of ten TCP protocols. Figure 16 shows the average of these values. The minimum latency is 4 ms, and the maximum latency is 8 ms. The average can be said to be 6 ms. Therefore, the latency value of the UDP protocol is lower than 6 ms on average. This is much lower than the 20 ms value specified in the requirements. Therefore, the communication subsystem meets the requirement.

- Visualization Subsystem Test:

  Again, since there is a problem in the communication test, tests will be performed over the TCP protocol. This time, as in the communication latency test, the latency until the end of rendering will be measured. The incoming data will be randomly generated, so only the speed of the subsystem can be measured. The values obtained will be added to the report in a table. In addition, the FPS test will be performed. In VTK, the update_transform function will be planned to be called approximately every 20 milliseconds using CreateRepeatingTimer(20). However, due to the actual rendering process and system delays, this interval may not be fully implemented. Each time this function is called, the global frame_count counter will be increased by one. Every 1 second, the difference between the current time and the last_fps_time will be taken and the FPS, that is, the number of frames rendered per second, will be calculated with the formula frame_count / (current_time - last_fps_time). The calculated FPS value will be added to the fps_samples list together with the transition time, then the frame_count will be reset and the last_fps_time will be updated. The results obtained for FPS will also be added to the report.

Measures of Success:

Rendering frame rate ≥ 20 FPS.

Total system latency (from data acquisition to rendering) < 200 ms.

- Visualization Subsystem Test Results:

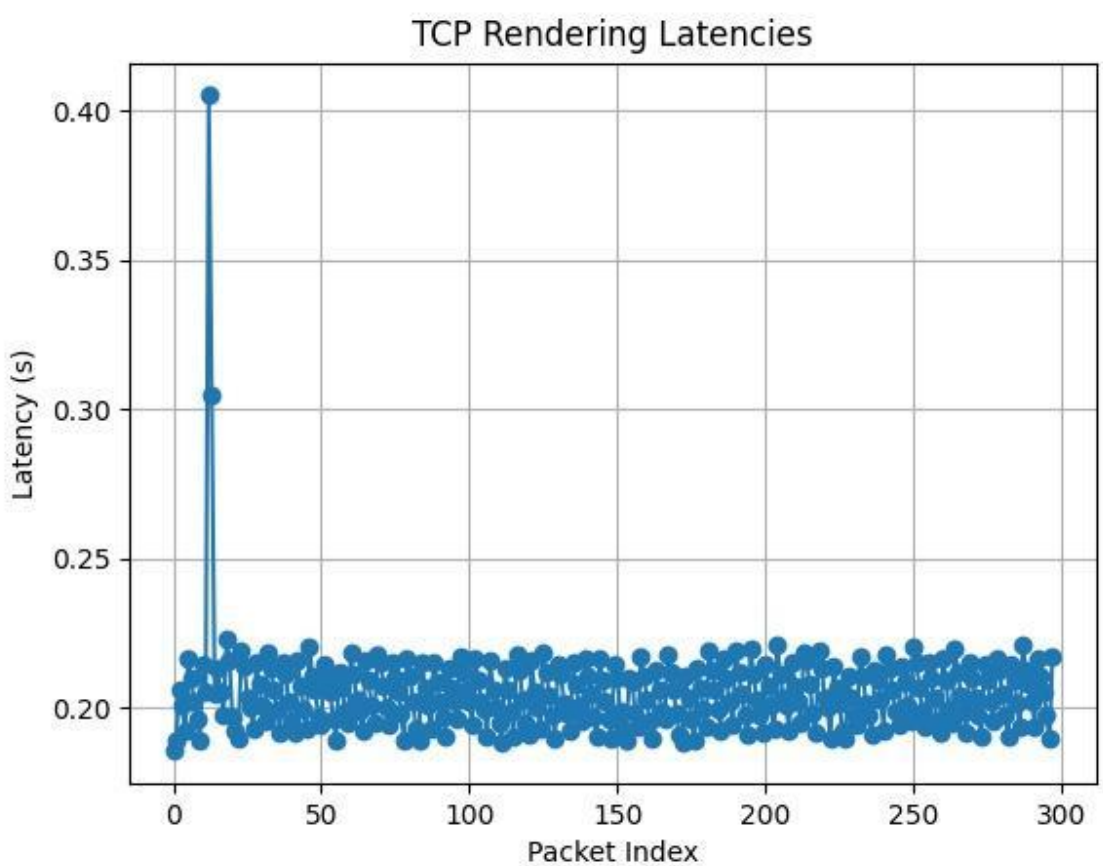

Figure 17. Rendering latency with using TCP protocol

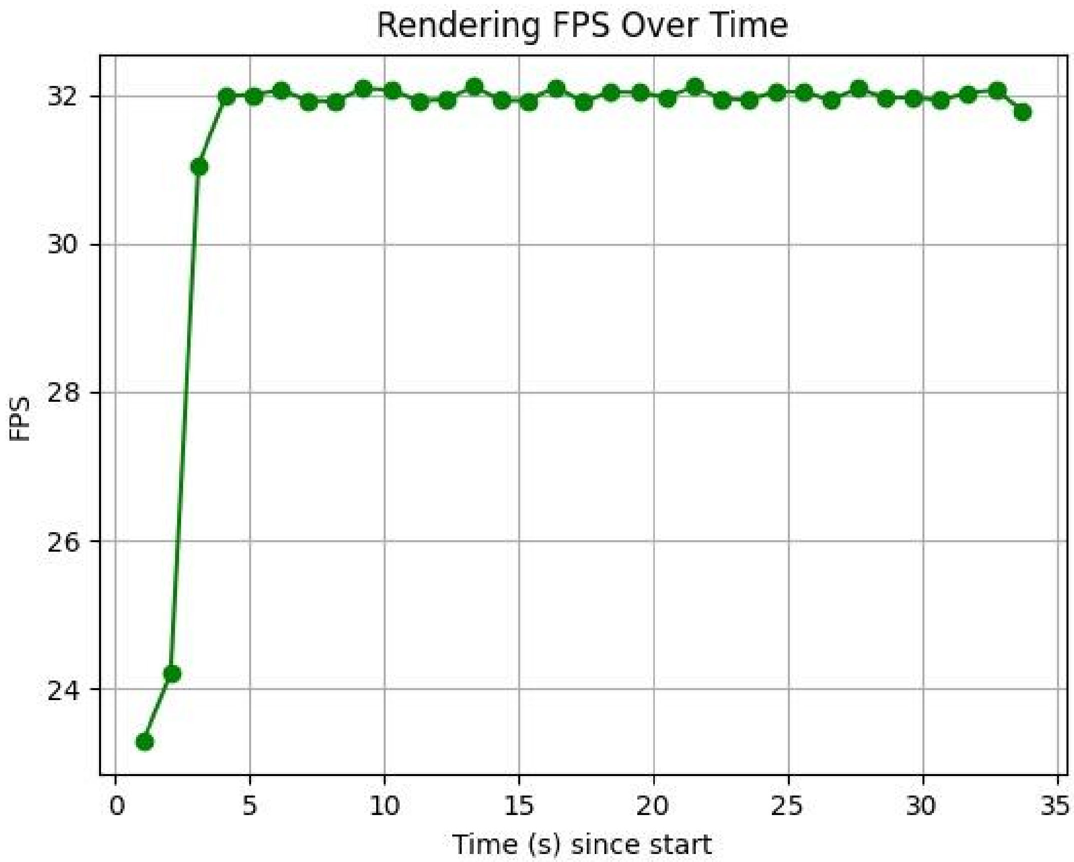

Figure 18. Rendering FPS with using TCP protocol

The obtained latency and fps results can be seen in Figures 17 and 18. The rendering latency value for the TCP protocol is approximately 200 ms. This value is less than the 200 ms value for the UDP protocol. Thus, the maximum 200 ms latency requirement is met. In addition, the FPS value is an average of 32. The 20 FPS requirement is also met.

Table 4. Crosscheck Table for Tests and Requirements

		Tests				
		IMU and Camera Joint Test	Communication Test	Visualization Test	Power Test	General Test
Requirements	No external sensors					✓
	Orientation error ≤ 10°	✓				
	Positional error ≤ 10 cms	✓				
	Transmission latency ≤ 20 ms		✓			
	Total latency ≤ 200 ms			✓		
	Battery run time duration ≥ 3 hours				✓	
	Ligthweight, comfortable and convenient product					✓

The objective of this test procedure is to ensure that the design functions as intended, meeting the aforementioned system level functional and performance requirements. In Table 4, the crosscheck table of the requirements and test results can be seen. Communication, visualization and power subsystem tests were successfully performed. It was seen that the values in the requirement were reached. Communication and rendering latency values reached the targeted value. The power subsystem can also meet the targeted usage time. The tests of the last remaining subsystem will be done as soon as possible.

Expected Deliverables

At the end of the project, the user will be presented with a comprehensive service and product package that allows for analysis of head movements. It is aimed to provide the user with supporting documentation and analysis along with each component. The outputs of the project are listed below:

- **Complete Hardware Suite**
  The tracking module is a compact, lightweight and portable module that is worn on the user's head. It is a tracking module that works integrated with VR. The module is battery powered and contains a processing unit that processes information from the IMU and the camera.

- **Real Time Pose Estimation Software**
  A suitable software solution that can effectively process data and sensor information. The main purpose of this software is to provide real-time 6-Degree-of-Freedom head pose estimation by combining data from the camera and the IMU.

- **Wireless Data Transmission System**
  A wireless communication system that transmits head position data from the hardware package to the computer using Wi-Fi technology and UDP technique. With this system, head movement is transmitted with an error rate close to the target.

- **Synthetic Head Model Visualization**
  A software interface on an external computer that visualizes the user’s head movements in real time through a 3D synthetic head model. This module establishes the pose-tracking system’s capabilities and presents an user-friendly version of the head-pose data.

- **User Manual**
  A detailed user guide that explains how to use the headset,computer programs,and hardware components. In order to provide a safe and fun VR experience the proper usage of headset, belt and extra body related equipments will be explained in detail.

An application of the product and its social impact on society

Our headset inside-out system delivers a smooth, low-latency 6 degrees of freedom of the user’s head. This product can be widely used in the VR game industry. With the help of real-time head pose tracking, every tilt, lean, and step becomes part of the action. For example, in games, players can lean their heads to peek around a virtual wall without lifting a finger, tilt to dodge a fireball hurtling toward them, or they can pull their heads straight back to draw a bowstring. Since all tracking lives inside the headset, there are no base stations or trailing wires to trip over, so you and your friends can leap into the same virtual arena and move together as if you were side by side. As a social impact, the ultimate VR experience creates a social arena where people can enjoy the games while playing together. Another important social impact is who owns the head-motion data, ie, whether it’s the player, the headset maker, or the game developer, and how it’s collected, stored, or sold. In our product, the shared and stored data will be determined by the user's consent so that the protection of the user's privacy can be established.

Potential Environmental of the Product

The headset runs off a standard rechargeable USB power bank, so when the battery runs low user can do fast charging and reuse it again instead of buying a new power unit. Drawing 15 W of electrical power results in low electrical power consumption. Therefore, the cost of powering this product is considerably small, which makes the product cost-efficient on the usage. Also, the heating problem is solved via a DC fan so that the cooling problem is solved without any carbon emissions. We build the electronics with common, RoHS-compliant parts and lead-free solder, and use modular cables and snap-in modules like the camera and battery that make repairs and upgrades straightforward, reducing electronic waste. As the tracking of the user's head happens on the board, there’s no bulky external hardware to manufacture or ship. Taken together, these choices make the headset design environmentally friendly, even its manufactured at a large scale.

Precautions Related with Safety Issues

One of the precautions that is taken is about the cooling problem. In some usage of the product, the board may overheat results in lowering the system’s efficiency. Therefore, a DC fan can be used in order to solve this problem. Another problem might arise from the cables that may restrict the fast and safe movement of the user. To avoid this problem, the board and sensors are mounted on the headset that is carried by the user’s head. Also, the power supply is carried by a belt pack that is mounted on the chest level of the user.The power supply and the board are close to the user body such that these subsystems can be connected with short cables. Using short cables with proper use according to the user manual provides safe head movement for the user. The possible accidents due fast movement or the entangled cables are eliminated with this implementation.

Conclusion

The Inside-Out Tracking Sensor Set for Virtual Reality Applications project was developed to address the portability, flexibility and cost-effectiveness deficiencies of existing VR systems. Thanks to the integration of IMU and camera data, precise and real-time 6-degree-of-freedom head movement tracking without the need for external sensors was targeted. Advanced algorithms such as ORB-SLAM were used to achieve this goal. The camera and IMU subsystems were developed separately. These systems were combined with sensor fusion and the accuracy rate was increased with the Kalman filter. Necessary tests and adjustments were made for both subsystems. The camera and IMU combined system test will be carried out in the future. The data obtained as a result of sensor fusion will be sent to the computer using the Wi-Fi module and UDP protocol. As a result of the renderings made on the computer, head movement tracking will be done instantly. The tests of the UDP and rendering systems were successfully carried out. The targeted delay values were achieved. In this way, communication was provided with a delay below 20 ms with the UDP protocol. Similarly, rendering can be done with a delay below 200 ms. The cost of the system remained below the targeted amount of $300. All these processes can be seen in detail in the written report. Apart from this, the current status of the project is explained in detail. Solution stages and test results are given with the support of block diagrams, tables and figures. Detailed planning stages for the future can also be seen in the report. Both construction and test plans are explained in detail and the tasks in the remaining time are given with a Gantt chart. Cost analysis are performed. The solutions presented in the project are tested and their relationship with the requirements is explained using tables. As a result, the project is approached with a very innovative approach. The customer can benefit from this innovative approach in various ways. First of all, it offers a better VR experience by using 3D visualization and precise, real-time head movement tracking. In addition, the overall system complexity is reduced and accessibility is increased. In addition, installation is facilitated by removing external sensors. Due to its adaptability, VR can be used more widely in areas where user participation and mobility are important, such as education, healthcare and entertainment. In addition, the system achieves environmental sustainability goals. The compact and energy-efficient design minimizes hardware waste and reduces power consumption as it is required for VR systems. Additionally, by using a single-board computer and minimizing physical components, it contributed to a lower environmental footprint. As a result, this project not only highlights current VR limitations, but also suggests a new path for a more environmentally friendly and adaptable VR future, expanding VR's potential for positive social impact.

References

[1] C. Campos, R. Elvira, J. J. G. Rodriguez, J. M. M. Montiel, and J. D. Tardos, “ORB-SLAM3: An Accurate Open-Source Library for Visual, Visual–Inertial, and Multimap SLAM,” *IEEE Transactions on Robotics*, vol. 37, no. 6, pp. 1–17, 2021, doi: https://doi.org/10.1109/tro.2021.3075644.

[2] Bosch Sensortec, "BNO055 Intelligent 9-axis Absolute Orientation Sensor," Datasheet, BST-BNO055-DS000-14, Rev. 1.4, July 2023. [Online]. Available: https://www.bosch-sensortec.com/media/boschsensortec/downloads/datasheets/bst-bno05235-ds000.pdf.

[3] Raspberry Pi Ltd., "Camera Module 3 Product Brief," Version 1, January 2023. [Online]. Available: https://datasheets.raspberrypi.com/camera/camera-module-3-product-brief.pdf. [Accessed: Dec. 27, 2024].

[4] Raspberry Pi Forums, “Re: Powering the Raspberry Pi 4 and peripherals - Forum Discussion,” *Raspberry Pi Forums*, Accessed: Dec. 27, 2024. [Online]. Available: https://forums.raspberrypi.com/viewtopic.php?t=347469

[5] "Quaternions and spatial rotation," *Wikipedia*. https://en.wikipedia.org/wiki/Quaternions_and_spatial_rotation (accessed Dec. 28, 2024).

[6] "Gimbal lock," *Wikipedia*. https://en.wikipedia.org/wiki/Gimbal_lock (accessed Dec. 28, 2024).

[7] Urrea, C., & Kern, J. (2021). Design and implementation of a wireless control system applied to a 3-DoF redundant robot using Raspberry Pi interface and User Datagram Protocol. *Computers and Electrical Engineering*, *95*, 107424.

[8] AL-Dhief, F. T., Sabri, N., Latiff, N. A., Malik, N. N. N. A., Abbas, M., Albader, A., ... & Ghani, A. (2018). Performance comparison between TCP and UDP protocols in different simulation scenarios. *International Journal of Engineering & Technology*, *7*(4.36), 172-176.

[9] Tripathi, S., Gupta, S., Babbar, T., & Gupta, V. (2013). TCP-over-UDP for real time applications. *International Journal of Scientific & Engineering Research-IJSER*, *4*, 357-360.

[10] G. Welch ve G. Bishop, "An Introduction to the Kalman Filter," Department of Computer Science, University of North Carolina at Chapel Hill, 1995. [Online]. Availablei: https://perso.crans.org/club-krobot/doc/kalman.pdf

[11] “Raspberry Pi 5 vs Raspberry Pi 4 Model B – Comparison and Benchmarking,” Core Electronics, published approx. 1.6 years ago. [Online]. Available: https://core-electronics.com.au/guides/raspberry-pi-5-vs-raspberry-pi-4-model-b-comparison-and-benchmarking/. Accessed: May 19, 2025.

Appendices

APPENDIX A. User Manual

1. Introduction

By fusing high-rate inertial data with visual information from a camera, the system delivers precise, low-latency tracking in a lightweight form factor. This manual explains how to set up, operate and maintain the system safely.

2. Package Contents

Quantity	Item	Description
1	Headset Module	Raspberry Pi Camera v3 mounted in a 3-D-printed housing (~50 g)
1	SBC Module	Raspberry Pi 5 16 GB inside a case + BNO055 IMU on the case (~150 g)
1	Power Module	Xiaomi 20000 mAh 3 Pro Type-C Powerbank inside a case (~450g)
1	Head Strap	Adjustable elastic strap
1	User Manual	A user manual for guidance

3. System Requirements

Host PC running Windows 10 or 11 with:

- CPU @3.0 GHz
- 8 GB Ram
- GPU
- Wi-Fi Support

4. Safety Precautions

Read before use. Improper handling may cause injury or equipment damage.
Battery safety. Use only the supplied power bank. Keep away from heat and moisture.
Cable management. Route cables behind the user to avoid tripping.
Motion sickness. If dizziness or nausea occurs, stop use and rest.
Children. Use is not recommended for children under 13 years of age.

5. Quick Start Guide

- Wear the headset and SBC modules. Adjust the straps such that the camera faces forward and is centred on your forehead. The SBC module should be centred over the head.
- Connect the SBC module to the power module via a micro-USB cable. The SBC LED will light up.
- First, you can run the algorithm by connecting the system to the monitor. Or you can run it using ssh via a computer.
- After the algorithm starts, remove the monitor connection. It is ready to use in a 2x2 square meter area.

Points to be noted:

1- When the camera algorithm cannot detect an object, it briefly displays the location at the starting point. After successful object detection, it continues from the last location.
2- Turning the head too quickly may create drift in the angular position.

6. Maintenance & Care

Cleaning: Wipe housings with a soft, dry cloth. Avoid solvents.
Lens Care: Use a microfiber cloth; do not scratch the lens.
Storage: Store in a cool, dry place.

7. Technical Specifications

Parameter	Value
Orientation Accuracy	∓10° (roll/pitch/yaw)
Positional Accuracy	∓10 cm (x,y,z)
Battery life	~4 h for continuous use
Headset weight	~300 g
Total carried weight	~765 g (headset + SBC + power modules)

8. Warranty & Support

This product is warranted against manufacturing defects for **12 months** from the date of purchase.
Warranty is void if the device is opened, modified, or used outside the specifications listed in this manual.

APPENDIX B. Test Results

Table 5: Full System - Translation (X axis)

Parameter Value	Actual Performance	Expected Performance	Error
0 cm	-1.3	0 cm	-1.3
10 cm	7.6	10 cm	-2.4
20 cm	24.1	20 cm	+4.1
30 cm	34	30 cm	+4
40 cm	41.2	40 cm	+1.2
50 cm	47.8	50 cm	-2.2
60 cm	56.3	60 cm	-3.7
70 cm	65.2	70 cm	-4.8
80 cm	75.6	80 cm	-4.4
90 cm	84.4	90 cm	-5.6
100 cm	93.5	100 cm	-6.5

Table 6: Full System - Translation (Y axis)

Parameter Value	Actual Performance	Expected Performance	Error
0 cm	1.4	0 cm	+1.4
10 cm	12.1	10 cm	+2.1
20 cm	23.3	20 cm	+3.3
30 cm	33.4	30 cm	+3.4
40 cm	44.2	40 cm	+4.2

50 cm	54.7	50 cm	+4.7
60 cm	65.2	60 cm	+5.2
70 cm	74.3	70 cm	+4.3
80 cm	84.8	80 cm	+4.8
90 cm	94.6	90 cm	+4.6
100 cm	105.7	100 cm	+5.7

Table 7: Full System - Translation (Z axis)

Parameter Value	Actual Performance	Expected Performance	Error
0 cm	-1.9	0 cm	-1.9
-5 cm	-5.7	-5 cm	-0.7
-10 cm	-10.9	-10 cm	-0.9
-15 cm	-14.1	-15 cm	+0.9
-20 cm	-19.3	-20 cm	+0.7
-25 cm	-23.9	-25 cm	1.1

Table 8: Full System - Rotation (Roll)

Parameter Value	Actual Performance	Expected Performance	Error
0°	0.15	0°	+0.15
10°	10.71	10°	+0.71
20°	18.64	20°	-1.36
30°	26.38	30°	-3.62

-10°	-10.53	-10°	-0.53
-20°	-22.33	-20°	-2.33
-30°	-33.79	-30°	-3.79

Table 9: Full System - Rotation (Pitch)

Parameter Value	Actual Performance	Expected Performance	Error
0°	0.72	0°	+0.72
15°	14.67	10°	-0.33
30°	33.21	30°	+3.21
45°	44.56	45°	-0.44
-15°	-16.72	-15°	-1.72
-30°	-32.12	-30°	-2.12
-45°	-46.22	-45°	-1.22

Table 10: Full System - Rotation (Yaw)

Parameter Value	Actual Performance	Expected Performance	Error
0°	0.65	0°	+0.65
15°	15.76	15°	+0.76
30°	32.14	30°	+2.14
45°	46.12	45°	+1.12
60°	59.66	60°	-0.34
75°	75.45	75°	+0.45

90°	91.34	90°	+1.34
-15°	-14.45	-15°	+0.55
-30°	-32.13	-30°	-2.13
-45°	-44.31	-45°	+0.69
-60°	-61.32	-60°	-1.32
-75°	-76.35	-75°	-1.35
-90°	-90.65	-90°	-0.65

Table 11: IMU - Translation (X axis)

Parameter Value	Actual Performance	Expected Performance	Error
0 cm	0 cm	0 cm	0 cm
10 cm	43 cm	10 cm	33 cm
20 cm	58 cm	20 cm	38 cm
30 cm	61 cm	30 cm	31 cm
40 cm	62 cm	40 cm	22 cm
50 cm	52cm	50 cm	2 cm
60 cm	51 cm	60 cm	-9 cm
70 cm	107 cm	70 cm	37 cm
80 cm	156 cm	80 cm	76 cm
90 cm	162 cm	90 cm	72 cm
100 cm	175 cm	100 cm	75 cm

Table 12: IMU - Translation (Y axis)

Parameter Value	Actual Performance	Expected Performance	Error
0 cm	0 cm	0 cm	0 cm
10 cm	-12 cm	10 cm	-22 cm
20 cm	-17 cm	20 cm	-37 cm
30 cm	15 cm	30 cm	-15 cm
40 cm	28 cm	40 cm	-12 cm
50 cm	46 cm	50 cm	-4 cm
60 cm	98 cm	60 cm	38 cm
70 cm	53 cm	70 cm	-17 cm
80 cm	70 cm	80 cm	-10 cm
90 cm	75 cm	90 cm	-15 cm
100 cm	83 cm	100 cm	-17 cm

Table 13: IMU - Translation (Z axis)

Parameter Value	Actual Performance	Expected Performance	Error
0 cm	0 cm	0 cm	0 cm
10 cm	11 cm	10 cm	1 cm
20 cm	2 cm	20 cm	-18 cm
30 cm	-2 cm	30 cm	-32 cm
40 cm	1 cm	40 cm	-39 cm
50 cm	24 cm	50 cm	-26 cm

Table 14: IMU - Rotation (Roll)

Parameter Value	Actual Performance	Expected Performance	Error
0°	0.52	0°	+0.52
15°	14.58	15°	-0.42
30°	28.93	30°	-1.07
45°	40.1	45°	-4.9
60°	52.6	60°	-7.4
75°	73.6	75°	-1.4
90°	84	90°	-6
105°	111	105°	-4
120°	119.9	120°	-0.1
135°	132.2	135°	-2.8
150°	148.3	150°	-1.7
165°	156.18	165°	-3.82
180°	177	180°	-3

Table 15: IMU - Rotation (Pitch)

Parameter Value	Actual Performance	Expected Performance	Error
0°	-3.25	0°	-3.25
15°	16	15°	+1
30°	29.1	30°	-0.9
45°	42.37	45°	-2.63
60°	60.31	60°	+0.31

75°	71.13	75°	-3.87
90°	87.8	90°	-2.2

Table 16: IMU - Rotation (Yaw)

Parameter Value	Actual Performance	Expected Performance	Error
0°	0.25	0°	+0.25
15°	16.06	15°	+1.06
30°	31.13	30°	+1.13
45°	47	45°	+2
60°	64.19	60°	+4.19
75°	78.5	75°	+3.5
90°	92.88	90°	+2.88
105°	112.25	105°	+7.25
120°	123.56	120°	+3.56
135°	138.13	135°	+3.13
150°	152.88	150°	+2.88
165°	167.69	165°	+2.69
180°	183.5	180°	+3.5

Table 17: CAMERA - Translation (X axis)

Parameter Value	Actual Performance	Expected Performance	Error
0 cm	1.4	0 cm	+1.4

10 cm	13.9	10 cm	+3.9
20 cm	24.2	20 cm	+4.2
30 cm	35.2	30 cm	+5.2
40 cm	43.1	40 cm	+3.1
50 cm	52.9	50 cm	+2.9
-10 cm	-13.5	-10 cm	-3.5
-20 cm	-24.6	-20 cm	-4.6
-30 cm	-34.9	-30 cm	-4.9
-40 cm	-44.5	-40 cm	-4.5
-50 cm	-52.2	-50 cm	-2.2

Table 18: CAMERA - Translation (Y axis)

Parameter Value	Actual Performance	Expected Performance	Error
0 cm	0.7	0 cm	+0.7
10 cm	12.2	10 cm	+2.2
20 cm	23.4	20 cm	+3.4
30 cm	33.9	30 cm	+3.9
40 cm	41.4	40 cm	+1.4
-10 cm	-11.2	-10 cm	-1.2
-20 cm	-22.1	-20 cm	-2.1
-30 cm	-34.5	-30 cm	-4.5
-40 cm	-43.5	-40 cm	-3.5

Table 19: CAMERA - Translation (Z axis)

Parameter Value	Actual Performance	Expected Performance	Error
0 cm	1.7	0 cm	+1.07
5 cm	5.4	5 cm	+5.4
10 cm	10.3	10 cm	+0.3
15 cm	17.2	15 cm	+2.2
20 cm	21.1	20 cm	+1.1
25 cm	26.7	25 cm	+1.7
-5 cm	-4.7	-5 cm	+0.3
-10 cm	-10.5	-10 cm	-0.5
-15 cm	-17.6	-15 cm	-2.6
-20 cm	-19.7	-20 cm	+0.3