Immersive Realities in Action

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Augmented Reality (AR) enhances real-world environments by overlaying digital information onto physical spaces, creating interactive and immersive experiences. This technology has applications ranging from gaming and education to retail and healthcare. AR enables users to interact with both real and virtual objects seamlessly, offering innovative solutions for visualization, learning, and engagement. Its growing integration into mobile devices and wearable technologies continues to redefine how we experience and interpret the world around us.

Keywords: Real-world environments, seamlessly, visualization, learning, and engagement.

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1 Introduction

The improvement of powerful, ongoing positional global positioning frameworks has been a huge focal point of exploration for a long time, driven by the rising interest for exact and responsive movement following in applications like Normal UIs (NUI), Computer generated Reality (VR), and Expanded Reality (AR). These vivid advances rely vigorously upon the capacity to catch the spatial developments of a client in three-layered space precisely. A critical necessity for these frameworks is the capacity to follow a client's developments progressively, guaranteeing that the connection between the client and the climate stays smooth and normal. With regards to VR and AR, continuous following is basic not exclusively to keep up with the deception of inundation yet in addition to furnish clients with a consistent encounter that emulates normal connection with the virtual world.

All things considered, movement catch frameworks have depended on costly, exceptionally designed spaces furnished with countless cameras and sensors. These frameworks, while exact, presented huge limits concerning versatility, availability, and cost. The necessity for foundation restricted the potential for far reaching reception and impeded the adaptability of these frameworks in different conditions. Be that as it may, late headways moving detecting and following advances have empowered the field to conquer a portion of these hindrances. Remarkably, the presentation of back to front following advances has made it conceivable to decrease the requirement for outside foundation altogether. These advancements have worked with the development of more open and financially savvy movement catch arrangements, especially in VR applications. With these developments, the field has had the option to create some distance from the requirement for costly, devoted following conditions, preparing for more adaptable and reasonable movement global positioning frameworks.

The requirement for additional open and savvy arrangements has been an essential main impetus behind the reception of back to front global positioning frameworks, especially those considering PC vision and Synchronous Limitation and Planning (Hammer) procedures [1], [2]. These techniques permit gadgets to confine themselves without depending on outer cameras or sensors. Back to front global positioning frameworks depend on cameras and sensors mounted on the actual gadget, empowering the gadget to distinguish and plan its current circumstance, and track its position comparative with the environmental elements. One of the critical benefits of this approach is versatility: because every gadget is liable for its own restriction, it can work freely, without the requirement for a decent outer following foundation. This makes it feasible for countless gadgets to coincide and work in a similar space, which is especially valuable in applications where various clients or gadgets should be followed at the same time.

This shift towards back to front following has driven numerous analysts to investigate new strategies for full-body movement following. As opposed to utilizing latent intelligent markers, which require outside sensors to distinguish their situation, the center has moved toward dynamic, back to front gadgets that can autonomously track their own situation and direction [3]. While these advancements have prompted enhancements in adaptability and versatility, there are still difficulties to survive. The essential impediments of current back to front global positioning frameworks relate to the size and exactness of the gadgets. A considerable lot of these frameworks depend on cameras and superior execution processors, which can add huge mass to the gadgets and increment power utilization. These variables might be unrealistic for specific applications, particularly those requiring lightweight, compact gadgets with negligible power necessities.

Considering these impediments, an elective way to deal with movement following has arisen as signal based global positioning frameworks. One such framework is the HTC Vive Beacon, which utilizes a bunch of fixed base stations (otherwise called beacons) to follow the place of items inside the space. The beacons radiate an occasional laser clear across the space at a proper recurrence, and photodiodes put on the followed objects distinguish the laser radiates. By either unraveling data implanted in the tweaked light of the laser or synchronizing with timing heartbeats, the framework can precisely decide the place where the laser bar strikes the item. This empowers the framework to recuperate exact situating data, gave the photodiodes can distinguish the laser beats rapidly enough.

The utilization of reference point based global positioning frameworks like the HTC Vive Beacon offers a few benefits over conventional back to front following strategies. To begin with, the precision of these frameworks is many times prevalent, as they don't depend on the handling impediments of cameras or computationally costly Hammer calculations. Moreover, the utilization of a proper foundation for following intends that there is no requirement for the actual gadgets to incorporate complex sensors or processors, diminishing the size and power prerequisites of the followed objects. The capacity to follow numerous items all the while is one more key benefit, making this approach ideal for VR and AR applications that require the following of different clients or gadgets in a similar space. Be that as it may, the exhibition of guide put together frameworks is yet subordinate with respect to the speed and precision with which the photodiodes can identify the laser clears, which forces specific imperatives on the general framework plan.

While back to front following and reference point-based frameworks each have their own arrangement of benefits and impediments, the two strategies address critical progressions in the field of movement following. Back to front frameworks offer unmatched adaptability and versatility, empowering continuous following in conditions where different clients or gadgets should be followed all the while. Then again, guide-based frameworks give a more exact and effective following arrangement, particularly in controlled conditions where exact positional information is required. The decision between these two methodologies eventually relies upon the necessities of the application, including elements like versatility, exactness, and framework intricacy.

All in all, the field of movement following has developed fundamentally as of late, with headways in both back to front and reference point based global positioning frameworks offering additional opportunities for constant following in VR, AR, and NUI applications. The advancement of versatile, savvy, and precise following arrangements is urgent to the proceeded with development of vivid innovations, and progressing research in this space will without a doubt prompt further advancements that work on the exhibition and openness of movement catch frameworks.

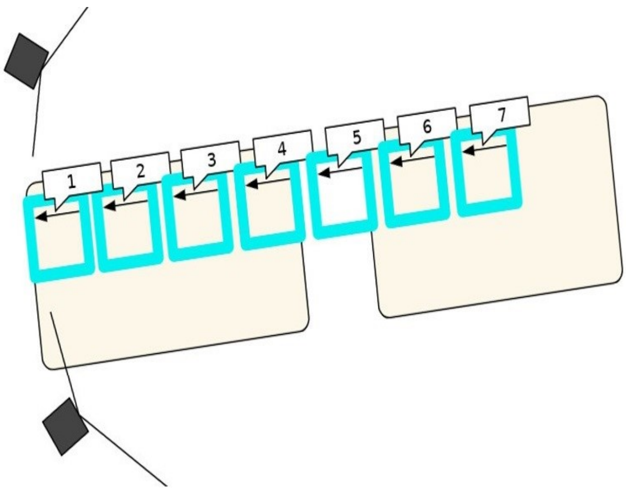

Figure 1. Characterization jig: each numbered square is a position of the CNC.

This interface can be tested and modified from our repository1. This will enable mobile applications such as smartphone web apps for motion capture or augmented reality.

[1] Web app Repository: http://github.com/hivetracker/hivetrackerjs

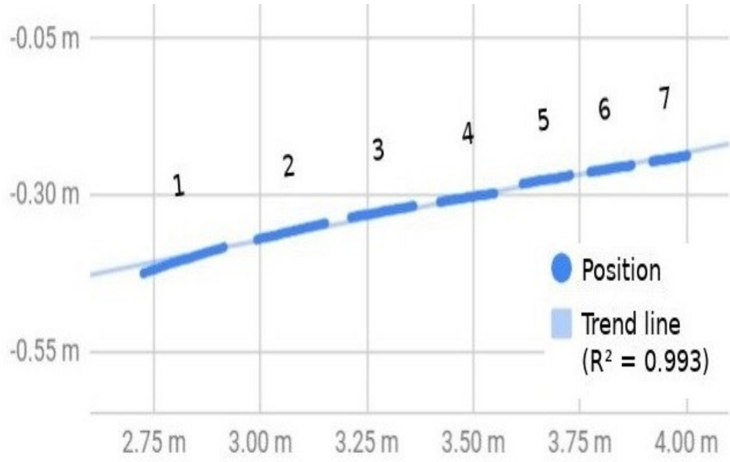

Figure 2. Characterization result: each numbered line is a measurement of a 300mm distance.

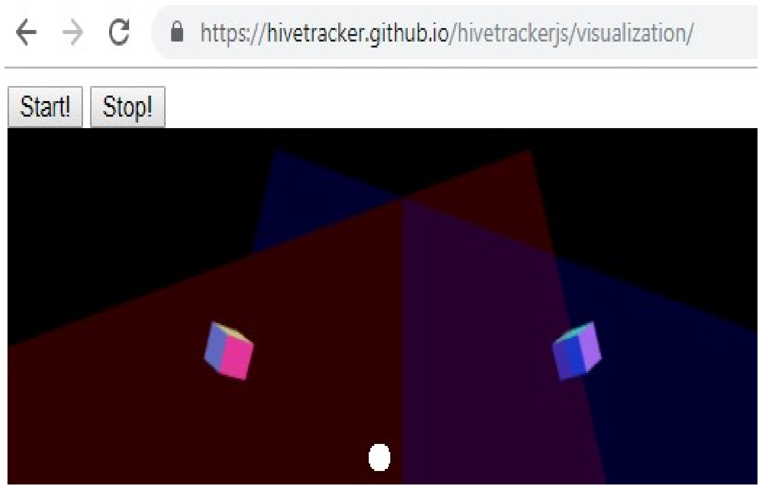

Figure 3. Web app showing the 2 base stations (cubes) and the tracker (sphere).

2 Contributions

In previous work, we introduced the first prototype of HiveTracker2[4], an innovative system that leverages the rare real-time and parallel processing capabilities of the nRF52 microcontroller developed by Nordic Semiconductor. By sensing lighthouse light sweeps without the need for expensive and bulky FPGA hardware, HiveTracker presented a significant breakthrough in affordable, small-

[2]https://hivetracker.github.io

scale, and accurate full body motion tracking. The initial prototype utilized up to five photodiodes, offering a cost-effective solution for motion tracking on a larger scale, especially in applications requiring real-time, high-precision tracking.

In our prior work, we demonstrated that full-body motion tracking could be achieved without relying on traditional, expensive infrastructure such as high-end cameras or FPGAs. The concept behind HiveTracker was to make motion capture systems not only affordable but also scalable for diverse applications. The miniaturized form factor and the use of low-power components such as the nRF52 microcontroller set HiveTracker apart from existing systems, allowing for greater flexibility in deployment while maintaining high accuracy.

Building on the success of this initial prototype, this paper describes the key advancements made in miniaturizing the HiveTracker device, improving its usability, and overcoming significant hardware and software challenges. Our goal was to enhance the accessibility and usability of the system, addressing limitations identified in the proof-of-concept phase, and pushing the boundaries of what was achievable with the HiveTracker platform. This paper focuses on improving the ease of use, scalability, and accuracy of the system, expanding its potential for adoption in both research and real-world applications.

Through detailed analyses and experiments, we aim to provide comprehensive insights into the technical innovations that drive the improvements in HiveTracker. We cover topics such as optical distortion characterization, firmware development, Bluetooth Low Energy (BLE) communication integration, and the development of real-time visualization systems, providing an in-depth look at how these elements work together to create a seamless and scalable motion tracking system.

2.1 Optical Distortion Characterization

One of the most significant challenges in motion tracking systems is understanding and mitigating optical distortion. Optical distortion arises when the sensors or tracking system fail to record the exact position of an object in space due to various factors, including environmental influences, sensor alignment, and system configuration. These distortions can significantly affect the accuracy of the tracking data, especially in systems where precise measurements are essential.

In this paper, we describe a method for characterizing and mitigating optical distortion in the HiveTracker system. The objective of this characterization was to quantify the distortion in the system and develop methods to correct it, ensuring that the motion tracking system performs as accurately as possible across the entire operating range.

1. Test Jig Design and Setup: To properly assess the distortion, we created a custom test jig designed to precisely measure translations across a working space. This test jig was designed to simulate a wide range of real-world motion tracking scenarios. The jig was intended to help us validate the linearity of the tracking system by verifying whether the HiveTracker could consistently measure a coherent 10 mm translation across the entire working zone.

   To achieve this, we used a CNC system3to precisely move the test jig along a predefined linear path. The CNC machine was chosen because it provided precise control over movement, ensuring that the position data collected from the system was consistent and reliable. This setup allowed us to sample measurements at seven different locations along the linear path, with data being collected every 10 mm at each position. Each measurement point was sampled 30 times to ensure statistical reliability and consistency.

[3] XY-plotter by Makeblock: http://www.makeblock.com

For comparison purposes, we used the HTC Vive positioning system, which is known for its accuracy and is commonly used in virtual reality (VR) applications. The HTC Vive system was used as a baseline to evaluate the performance of HiveTracker, as it provides a high level of precision and is widely used in the motion tracking community.

In the experimental setup, instead of orienting the base stations in the standard configuration (where the stations face one another), we placed both base stations in the same direction, as shown in figure 1. This configuration was chosen because it better simulates the potential challenges users might face when positioning the base stations in a real-world environment, where optimal placement might not always be possible.

2 Results and Analysis: The results of our characterization tests, shown in figure 2, revealed that the HTC Vive positioning system displayed significant non-linear behavior in the configuration used. We observed that measuring a distance of 300 mm near the base stations did not produce the same result as when measuring the same distance at a further point. This behavior suggests that the system exhibits optical distortion that varies with distance from the base stations.

These findings highlighted the need for calibration in our tracking system. The non-linearity we observed indicates that the system's measurements are not purely geometric, and corrections are needed to account for these distortions. The characterization data we collected is invaluable, as it allows us to create a distortion map that can be used to compensate for these inaccuracies in future measurements. This calibration map will enable us to refine the accuracy of the HiveTracker system, ensuring that measurements taken in real-world environments are as precise as possible.

Moving forward, we plan to implement a real-time distortion correction mechanism, where the system will automatically calibrate itself based on the characteristics of its operating environment, further improving its accuracy and ease of use.

2.2 Firmware Development

The firmware for the HiveTracker system plays a critical role in ensuring that the system operates efficiently and reliably. One of our main goals for this development was to make the firmware as accessible and user-friendly as possible. As part of this initiative, we decided to open-source the firmware to allow researchers, developers, and hobbyists to easily modify, extend, and integrate the system into their own applications. The open-source nature of the project ensures that the system will continue to evolve through contributions from the wider community.

To achieve compatibility with the broad Arduino ecosystem, we made the decision to design the firmware to be compatible with Arduino boards, specifically the Arduino "Nano 33 BLE" model. The reason for selecting this model was that it uses the same nRF52 microcontroller as the HiveTracker prototype. This commonality allows for a seamless transition from development to deployment, as users can leverage existing libraries and resources available for the Arduino platform. Moreover, it guarantees long-term support for the system, as the Arduino community is large and continuously evolving.

In the development of the firmware, we focused on optimizing power consumption and improving real-time data processing capabilities. The nRF52 microcontroller's built-in Bluetooth Low Energy (BLE) capabilities were utilized to implement a lightweight BLE protocol, ensuring that the system can interface with a wide range of devices. This BLE communication interface was specifically designed to allow easy pairing and data streaming directly from WebBLEenabled browsers, making it easier for users to interface with the HiveTracker system without the need for additional software installations.

2.3 Bluetooth Low Energy (BLE) Communication Integration

An important feature of the HiveTracker system is its ability to communicate wirelessly with other devices using Bluetooth Low Energy (BLE). BLE is ideal for low-power, real-time communication, making it a perfect fit for the HiveTracker system, which needs to be energy-efficient while providing real-time tracking data.

One of the key advantages of BLE is its low power consumption, which extends the battery life of embedded devices. This is critical for motion tracking systems, which often need to operate for long periods of time. BLE also allows for easy pairing with smartphones, tablets, and computers, enabling users to interact with the HiveTracker system in a seamless and user-friendly way.

The integration of BLE into the firmware allows for the creation of wireless motion tracking systems that do not require physical connections to operate. This enhances the flexibility of the system and makes it more versatile for a variety of applications. Additionally, BLE enables multiple HiveTracker devices to be paired together, allowing for large-scale motion tracking in environments where numerous sensors are needed, such as full-body motion capture for virtual reality, gaming, or performance analysis.

2.4 D. Real-Time Visualization in a Web Application

In addition to improving the hardware and communication protocols, we also focused on making the HiveTracker system easier to use and test by developing a real-time visualization framework. This framework built using the Three.js library4, allows users to visualize the tracked positions of objects in three-dimensional space in real time. By using a web-based interface, we make the system highly accessible and cross platform, as it can run on any modern device with a web browser, including desktops, laptops, and mobile devices.

The real-time visualization tool provides immediate feedback on the accuracy and performance of the tracking system, enabling developers to quickly identify and address any issues that may arise. This is particularly useful for testing and prototyping, as users can easily see how the system is performing in a dynamic, interactive environment.

This interface also supports mobile applications, allowing developers to integrate the HiveTracker system into mobile based motion capture or augmented reality applications. The web-based visualization framework is open-source, and users can access the code from our GitHub repository5. This further promotes the accessibility and adaptability of the HiveTracker system, allowing it to be used across a wide range of industries and research fields.

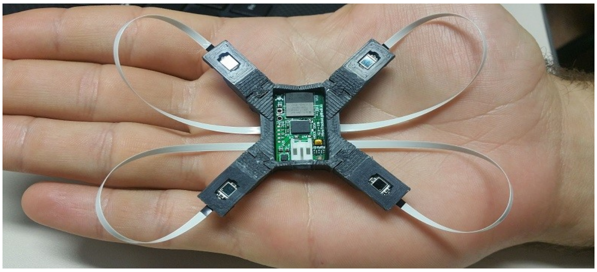

Figure 4. Squared structure used for calibration.

[4] Three.js library: https://threejs.org/

[5] Web app Repository: http://github.com/hivetracker/hivetrackerjs

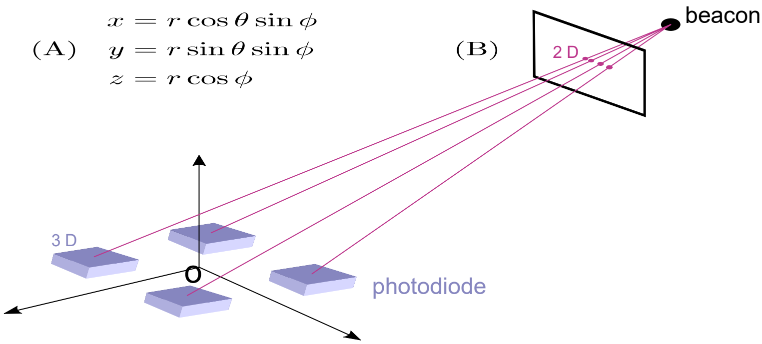

Figure 5. Schematic of reconstruction procedure. (A): Relation of polar coordinates to cartesian coordinates, where θ and ϕ are the angles recovered from the device. (B): Projection of angles into fixed distance plane to generate 2D/3D correspondences.

3 Discussion

3.1 Adaptive Alignment and 3D Reconstruction

The course of movement following includes precisely deciding the place of sensors comparative with a reference outline, frequently alluded to as the "beginning" of the framework. In our ongoing work, we keep on expanding upon the establishments laid in our past review [4], where we straightforwardly utilized the SteamVR alignment methodology to extricate the area of base stations in outright VR world directions. While this strategy functioned admirably for applications coordinated with augmented reality (VR) frameworks, it was compelled by its dependence on SteamVR, making it unacceptable for free movement catch frameworks that require full remote activity without a PC or VR headset.

In this paper, we propose an elective way to deal with adjustment, where the HiveTracker gadget itself fills in as the beginning of the global positioning framework. The gadget is furnished with four photodiodes organized in a known planar setup (showed in Figure 4), empowering the recuperation of position information in a free reference outline. This opens a great many applications where a totally remote and independent movement global positioning framework is required, for example, in remote detecting, field-based examination, or portable VR conditions where the utilization of a fixed base station isn't doable.

To play out the alignment, we depend on sets of photodiode hits from a similar base station. Each hit addresses a communication between the photodiode and a laser pillar produced by a base station, permitting us to compute two points, from which we can recreate a line from the photodiode to the base station's starting point. This cycle is outlined in Figure 5A. These lines are then projected onto a proper distance plane before the signal, recuperating 2D places of focuses that lie on the outer layer of the guide plane, as displayed in Figure 5B.

The critical benefit of this approach is that we can characterize the 3D directions of these 2D focuses on the beginning gadget. This outcomes in a bunch of correspondences (N =4) somewhere in the range of 2D and 3D focuses that can be utilized to process the place of the beginning gadget comparative with the reference point. The hidden numerical issue here is the Viewpoint N-Point (PnP) issue for planar fiducial markers, which is all around concentrated on in the PC vision local area [5], [6]. By applying proficient PnP calculations, we can reproduce the overall places of the photodiodes and the base station in a computationally effective way.

Nonetheless, the PnP issue can be inclined to mistakes because of clamor or blunders in estimation. To address this, we apply progressed streamlining strategies, explicitly pack change techniques like the Levenberg-Marquardt calculation [7], to refine the arrangement. Pack change is an integral asset in PC vision and photogrammetry, used to limit the general reprojection blunder across different estimations and work on the precision of the 3D posture assessment. By iteratively changing the places of the photodiodes and the base station, we can accomplish a more exact gauge of the framework's setup.

While the proposed alignment strategy functions admirably with a solitary set of gadgets, further developing exactness in bigger systems can be additionally broadened. For example, by utilizing a framework of gadgets or incorporating different reference focuses, we can utilize progressed streamlining strategies to improve the nature of the assessed guide presents. This could fundamentally work on the general execution of the framework, making it appropriate for enormous scope movement catch arrangements, for example, those necessary in augmented experience or full-body movement following.

3.2 Hardware Prospects Utilizing FPGAs

Up to this point, our plan approach for HiveTracker has zeroed in on keeping up with effortlessness, reasonableness, and versatility. By utilizing the low power nRF52 microcontroller, we accomplished a minimized structure factor that is reasonable for limited scope following applications. Be that as it may, as movement following innovation develops, so do the prerequisites for upgraded execution, more prominent following reach, and the capacity to communicate with fresher advancements. One remarkable improvement in such manner is the arrival of another adaptation of the HTC Beacon base station, which presents a few high-level elements pointed toward lessening the expense of base stations while empowering bigger following reaches utilizing different signals.

The new HTC Beacon variant uses regulated light for correspondence among guides and beneficiaries, which fundamentally changes the detecting design expected to help this innovation. While the nRF52 microcontroller has filled our needs hitherto, it isn't appropriate for this sort of regulated light detecting because of constraints in its handling power and the idea of the light balance utilized by the new base stations. This requires a change in our equipment engineering to oblige the developing necessities of the framework.

To fulfill these new needs, we investigate the utilization of Field Programmable Door Exhibits (FPGAs) for future renditions of the HiveTracker framework. FPGAs offer an extraordinary benefit in that they are profoundly adjustable, giving the adaptability to execute equipment gas pedals for regulated light location, high velocity signal handling, and constant correspondence with various reference points. Besides, FPGAs are known for their low-inactivity and high throughput capacities, causing them ideal for applications that to require quick, constant information handling, for example, movement following.

One of the most encouraging FPGA stages for our utilization case is the Grid iCE40UL-1K. This FPGA offers a reduced 1.4mm x 1.4mm bundle, making it reasonable for scaled down, low-power applications. Notwithstanding its little structure factor, it is equipped for taking care of somewhat complex sign handling assignments and is all around upheld by the open-source local area. The open-source FPGA toolchain [?] further upgrades its availability, empowering engineers to plan custom rationale for movement following applications.

The critical benefit of involving a FPGA in this setting is its capacity to deal with continuous handling of tweaked light signals from the base stations, which is past the abilities of customary microcontrollers. FPGAs can be modified to identify and unravel these regulated signs with high accuracy, considering more precise and solid following over bigger distances. This empowers the utilization of various guides and expanded following reaches, making it conceivable to send the HiveTracker framework in bigger conditions without forfeiting execution.

Furthermore, the utilization of FPGAs opens additional opportunities for sensor incorporation. With the expanded handling power accessible, we can incorporate more photodiodes into the framework, in this manner working on the accuracy of the global positioning framework. This is especially significant for applications that require high-thickness sensor clusters, for example, full-body movement catch or high-level mechanical frameworks.

In rundown, the shift towards FPGA-based equipment in ongoing adaptations of HiveTracker will empower us to help the most recent headways in base station innovation, grow the following reach, and consolidate extra sensors to work on the precision and adaptability of the framework. By consolidating the adaptability of FPGAs with the conservativeness of the nRF52 microcontroller, we expect to make an exceptionally versatile and strong movement global positioning framework that fulfills the developing needs of present-day applications in regions like computer generated experience, expanded reality, mechanical technology, and execution examination.

4 Emerging Applications and Integrations of AR Technologies

The continuous evolution of Augmented Reality (AR) technologies has unlocked opportunities in previously untapped domains. Leveraging advancements in artificial intelligence (AI), cloud computing, and edge processing, AR systems are becoming more robust, scalable, and accessible.

4.1 AR and Artificial Intelligence (AI)

Integration of AI into AR systems enhances contextual understanding and dynamic interaction. By combining real-time object recognition with natural language processing, AR devices can deliver personalized and adaptive experiences. For instance:

- Healthcare: AR-assisted surgeries now incorporate AI driven decision-making tools to visualize anatomical structures and predict surgical outcomes in real-time.
- Retail: Virtual try-on experiences are made possible by AI models trained on user preferences and AR's spatial overlay capabilities.

4.2 Cloud and Edge Computing for AR Scalability

Cloud computing enables AR systems to process and store vast amounts of data. However, latency challenges in real-time applications have led to the adoption of edge computing. By distributing computational tasks between the cloud and edge devices:

- Urban Planning: AR applications assist city planners in overlaying 3D building models onto real environments, using edge devices for instant rendering.
- Remote Collaboration: Teams can collaborate in a shared virtual environment, leveraging low-latency communication powered by edge nodes.

4.3 Expanding AR Interfaces with Haptics

The development of haptic feedback systems complements AR visual interfaces, creating a multisensory interaction model. For example:

- Education: AR applications with tactile feedback enable users to "feel" virtual objects, enhancing learning in fields such as anatomy and engineering.
- Entertainment: Immersive gaming experiences integrate haptics for a richer sense of presence and interaction.

4.4 Interoperability and Open Standards

To foster innovation, AR technologies are moving towards interoperability through open standards like WebXR. These frameworks:

- Simplify AR application development for multiple platforms.
- Enable seamless transitions between AR and VR ecosystems.
- Encourage cross-industry collaboration by establishing common protocols.

5 Conclusion

In this work, we presented a novel, versatile, remote 3D GPS beacon that presents energizing opportunities for various applications, including movement catch, conduct studies, athletic execution examination, imaginative undertakings, and clinical diagnostics. The essential inspiration driving this improvement was to make an incorporated framework that joins both equipment and programming based upon open and available principles. Thusly, we expect to expand the scattering of this cutting-edge innovation and make it accessible to a wide scope of specialists, experts, and enterprises.

The excursion to accomplish this degree of usefulness has been nowhere near basic, as we experienced various specialized difficulties all through the improvement interaction. These difficulties went from the intricacies of exact movement following and adjustment, to streamlining framework execution, to guaranteeing that our equipment and programming engineering could be effectively adjusted and scaled for different use cases. Notwithstanding these obstacles, we have exhibited that it is to be sure conceivable to foster a powerful, remote global positioning framework that addresses the issues of requesting applications, and we have done as such with parts that are either broadly accessible or as of now part of the open-source biological system.

In this paper, we introduced a methodology that use the adaptability of current FPGA innovation, the proficiency of low-power microcontrollers, and the exactness of cutting-edge alignment strategies. We additionally talked about how joining these advances could empower future cycles of the framework to help bigger scope applications, for example, full-body movement catch or huge region following. We trust that this mix of openness, versatility, and execution makes our global positioning framework a promising answer for the fate of movement investigation.

Be that as it may, despite the headway made, there is still a lot of work to be finished. We perceive that the momentum framework is just the start, and that there are a few roads for additional exploration and refinement. These incorporate working on the precision of the global positioning framework through cutting edge calculations and AI methods, upgrading the power and adaptability of the equipment, and growing the product environment to help more different applications. Moreover, as new headways in detecting and correspondence advancements arise, we plan to ceaselessly emphasize on our plan to guarantee that it stays at the forefront of the field.

While challenges remain, it means a lot to take note of that the excess strides toward understanding the maximum capacity of this innovation are feasible with right now accessible instruments and assets. The central work has been laid, and the basic following stages principally include refining and scaling the framework to deal with additional mind-boggling situations and more extensive applications. The fruitful mix of numerous reference points, extended following reaches, and upgraded sensor exhibits are all reachable, on account of the progressions in FPGA innovation and other current computational devices.

Our objective with this distribution is to motivate others to join our advancement process. We trust that our open-source approach, straightforward technique, and itemized specialized experiences will act as a significant asset for the more extensive examination local area. Cooperation and the sharing of information are vital for propelling innovation here, and we accept that by cultivating an aggregate exertion, we can drive further developments and make considerably more significant applications later.

All in all, the work introduced here denotes a huge step in the right direction in the improvement of remote 3D following innovation, and keeping in mind that there are as yet numerous valuable open doors for development and improvement, the potential for this framework to change fields going from medical care and sports to computer generated reality and craftsmanship is unquestionable. We are amped up for the eventual fate of this venture and are focused on proceeding with its advancement as a team with the more extensive local area. We trust that through proceeded with exploration, advancement, and joint effort, we can open much more groundbreaking opportunities for this innovation in the years to come.

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