Improving Spatial Consistency and Projection Stability in a Wearable Projection-based Remote Instruction System

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Abstract: Wearable projection systems enable hands-free remote instruction without the fatigue associated with head-mounted displays (HMDs). However, ensuring projection stability during worker movement is a critical challenge for practical deployment. In this study, we propose a wearable projection system integrated with a gimbal to physically dampen body vibrations. The system aims to maintain high spatial consistency for projected visual guidance. We conducted a quantitative evaluation to analyze the relationship between worker motion dynamics (linear/angular velocity) and the positional stability of the projected content. During the evaluation, we observed that high-frequency angular motion often triggers synchronization artifacts (ghosting) between the camera and the laser projector, leading to identification mark failures in non-stabilized setups. The proposed mechanical damping was found to be effective in mitigating these artifacts. Experimental results demonstrate that the gimbal-stabilized system significantly reduces positional jitter and improves tracking reliability compared to a non-stabilized baseline. This work provides a feasibility study and hardware analysis for robust HMD-free remote guidance.

1. Introduction

In recent years, remote collaboration and instruction systems have gained significant traction in fields such as manufacturing and maintenance. These systems aim to enable an instructor to support a remote worker by sharing task-related spatial information. Conventional approaches often rely on head-mounted displays (HMDs) [1] or video conferencing tools [2], [3]. While HMD-based systems allow for hands-free operation, they frequently induce fatigue during prolonged use and restrict peripheral vision. Wearable projection systems [4], [5] offer a promising alternative by projecting information directly onto the physical workspace, preserving natural environmental awareness.

However, a major barrier to the adoption of wearable projection is image stability. Unlike fixed projectors [6], wearable units are subject to the user's continuous body movements. Even minor gait oscillations can cause the projected instructions to drift or jitter, reducing legibility and spatial accuracy. While stabilization has been studied in drone-based platforms [7] or steerable fixed projectors [8], these systems do not account for the specific biomechanical dynamics of a human worker. Software-based methods [9], [10] often fail to correct severe motion blur caused by erratic human motion.

To address these instability issues, we propose a gimbal-augmented wearable projection system. We integrate a 3-axis mechanical gimbal to physically isolate the laser projector from the worker's body oscillations. For this prototype study, we also employ a ceiling-mounted camera to provide the remote instructor's view and to serve as a ground-truth tracking system. While our ultimate goal is a fully self-contained wearable unit, this environmental setup allows us to rigorously evaluate the projection stability in a controlled manner.

The primary contribution of this paper is the quantitative evaluation of the gimbal effectiveness in stabilizing remote guidance. We analyze the time-series correlation between the worker's motion velocity and the positional deviation of the projected guidance. In analyzing the causes of instability, we also discuss the impact of hardware synchronization mismatches (shutter-scan ghosting) observed during rapid movements. Our results confirm that the proposed hardware stabilization significantly improves the consistency of the remote instruction interface by suppressing these motion-induced disturbances.

2. Related Work

2.1 Wearable Projection For Remote Assistance

Remote instruction systems aim to bridge the spatial gap between an expert and a local worker. While video conferencing tools [2], [3] are ubiquitous, they lack spatial context. Head-Mounted Displays (HMDs) have been widely adopted to provide immersive AR guidance [1], [11]. However, HMDs

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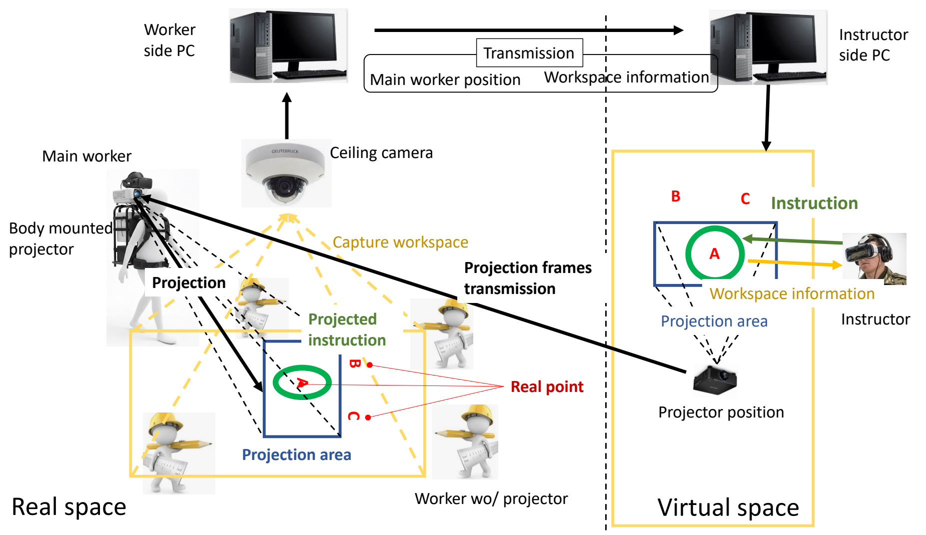


Fig. 1: System Overview. The instructor views the workspace via a ceiling camera. The worker wears a body mounted projector. The projector and Oculus are co-mounted on the gimbal's stabilized platform to ensure synchronized projection.

can isolate the user from their surroundings and induce physical fatigue during prolonged usage.

To address these limitations, wearable projection systems have emerged as a "hands-free, heads-free" alternative. Harrison et al. introduced body-worn projection for on-skin interaction [4], and Murata et al. utilized waist-mounted projectors for gait assistance [5]. Although these systems demonstrate the utility of projecting onto the real world, they primarily focus on local interaction interfaces. Few studies have addressed the challenge of maintaining remote spatial consistency—ensuring that an instructor's annotations remain anchored to the physical world while the worker is moving naturally.

2.2 Projection Stabilization Techniques

Maintaining a stable projection from a moving source is a complex challenge addressed through various approaches.

Actuated Platforms: One approach is to stabilize the projector using external robotic mechanisms. For example, Wilson et al. [8] proposed steerable fixed projectors, and Isop et al. [7] demonstrated stabilization for drone-mounted units using flight dynamics. While effective in their specific domains, these solutions rely on non-human platforms and do not account for the erratic biomechanical oscillations of a walking human.

Digital Stabilization: In the wearable domain, software-based Digital Image Stabilization (DIS) is the most common approach. Methods proposed by Sakata et al. [9] and Tajimi et al. [10] utilize sensors to digitally warp the projected image to counteract jitter. While DIS is effective for smoothing visual trajectories, it typically requires cropping the effective field of view (FOV) and relies on accurate motion estimation models.

Mechanical Damping Approach: Our work investigates a hybrid mechanical strategy specifically for human-worn setups. During locomotion, wearable devices often exhibit imperfect coupling with the body, leading to high-frequency vibrations due to the micro-collisions and looseness between the device and the wearer. By physically isolating the projector with a gimbal, our system aims to absorb these high-frequency disturbances at the source, offering a complementary hardware solution to ensure projection stability.

3. Proposed System

3.1 System Overview

We developed a prototype wearable projection system designed to evaluate the impact of mechanical stabilization on remote instruction. As shown in Fig. 1, the architecture consists of an environmental sensing unit and a wearable projection unit.

3.2 Hardware Configuration

As shown in Fig. 2, the wearable unit is constructed using a custom metal backpack frame to ensure a rigid coupling with the worker's torso. The stabilization hardware follows a hierarchical mounting structure:

Base (Backpack Frame): The gimbal's handle/base is rigidly clamped to the backpack frame, moving directly with the wearer's body.

Stabilizer (Gimbal): We utilize a 3-axis mechanical gimbal equipped with high-frequency IMUs. It acts as the intermediate layer, actively compensating for the base's angular vibrations.

Payload (Projector and Oculus): Crucially, both the Laser Beam Scanning (LBS) projector and the Oculus tracking device are mounted together on the gimbal's stabilizing platform (end-effector). This co-located setup ensures that the Oculus device always tracks the actual pose of the projector, regardless of the gimbal's compensation angle.

3.3 Tracking And Synchronization

The Oculus device serves as the 6DoF pose sensor for the

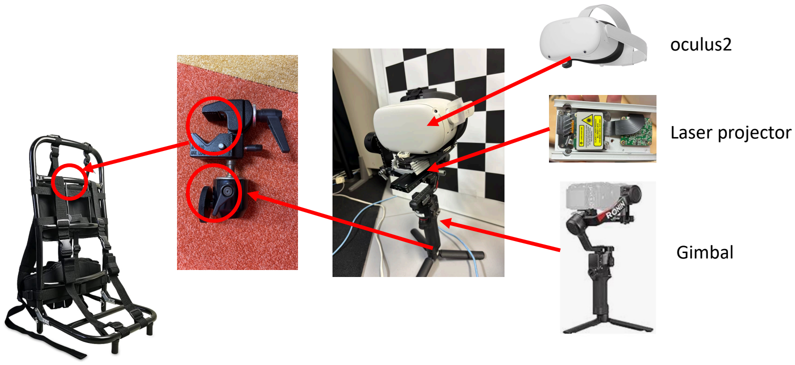
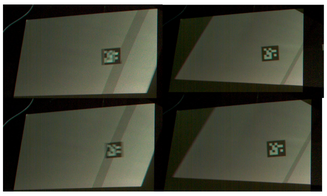
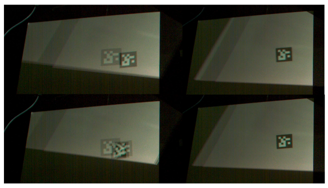


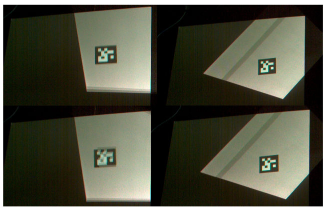
Fig. 2: Wearable Prototype. (a) The metal backpack frame provides a rigid base. (b) The 3-axis gimbal is attached to the frame. (c) Both the Laser Projector and the Oculus tracking device are mounted together on the gimbal's stabilized platform.



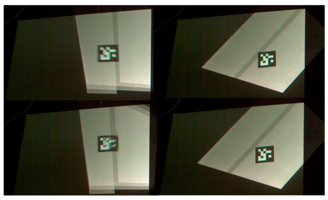
(a) Left: Gimbal OFF — Right:Gimbal ON



(b) Left: Gimbal OFF — Right:Gimbal ON



(c) Left: Gimbal OFF — Right:Gimbal ON



(d) Left: Gimbal OFF — Right:Gimbal ON

Fig. 3: Experimental Comparisons. four image show the corresponding camera views with ghosting artifacts. The left half of each image is Gimbal OFF, The left half of each image is Gimbal ON, Two consecutive frames from top to bottom

projection system. Because it is physically fixed to the projector, it provides real-time, precise data on the projector's optical axis. This pose data is streamed to Unity, allowing the system to render visual content that is perfectly aligned with the projector's current orientation. When the gimbal stabilizes the hardware, the Oculus detects this stable pose, ensuring the projected virtual content remains steady in the physical world.

4. Experiment

4.1 System Latency Characterization

Before evaluating stability, we quantified the end-to-end system latency to establish a performance baseline. We filmed the device rapidly panning and calculated the time it took for the marker to respond to the target's location when the hand moved to the target. Averaged over 20 trials, the system exhibits a latency of 53.0 ms via wired connection and 172.2 ms via wireless streaming.

4.2 Stability Evaluation Protocol

To decouple the effects of different motion types, we designed two distinct movement tasks: Pure Translation and Pure Rotation. The backpack unit was performed reciprocal movements guided by a metronome for 10 seconds per trial.

We placed an AR marker at a location of x=0.5m, z=0.5m in Unity (the Unity world coordination floor plane is on the xz-axis), which corresponds to a real-world detected location of x=0.5m, y=0.5m. We then calculated the current linear speed(m/s) and angular speed(rad/s) using 6-Dof pose obtained from Oculus and the time axis.

1) Translation Task (Linear Motion): The backpack unit was moved forward and backward (Amplitude: 21 cm) along the sagittal plane.

2) Rotation Task (Angular Motion): The backpack was rotated anticlock and clock direction (Amplitude: 32°) around the vertical axis.

Variables: We manipulated two independent variables:

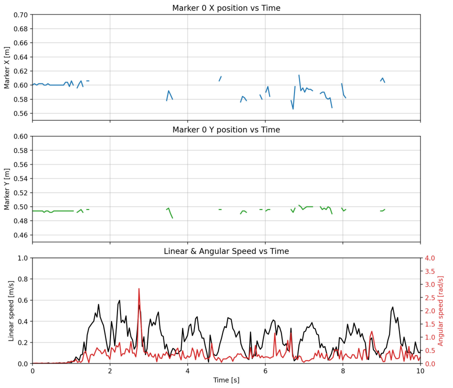
- Stabilization Condition: Gimbal OFF vs. Gimbal ON.
- Movement Frequency:
  (1) Slow (1 Hz): 1 movement cycle per second.
  (2) Fast (2 Hz): 2 movement cycles per second.

4.3 Results

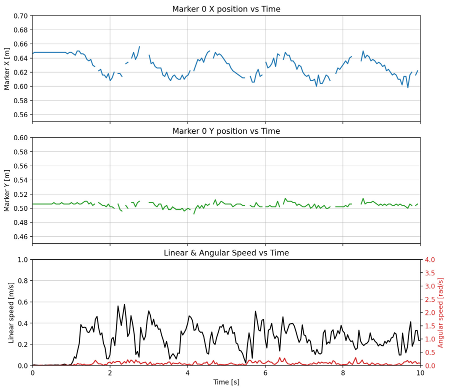
4.3.1 Scenario A: Translation Task (Linear Motion)

In this task, the backpack unit was moved forward and backward (21 cm amplitude).

1) Slow Movement (1 Hz), as shown in Fig. 3a:

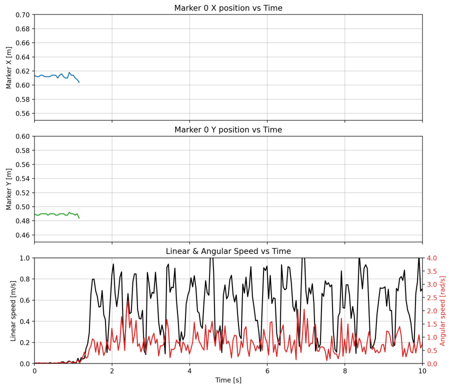


(a) Translation Task (Gimbal OFF – 1Hz)

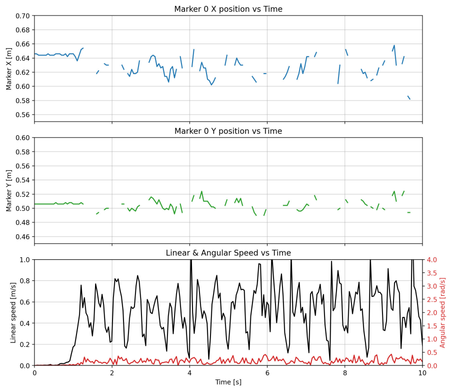


(b) Translation Task (Gimbal ON – 1Hz)

Fig. 4: (a) is a graph obtained at a 1Hz frequency translation movement for Gimbal OFF , (b)is a graph obtained at a 1Hz frequency translation movement for Gimbal ON showing the x-axis, y-axis, linear velocity, and angular velocity from top to bottom.



(a) Translation Task (Gimbal OFF – 2Hz)



(b) Translation Task (Gimbal ON – 2Hz)

Fig. 5: (a) is a graph obtained at a 2Hz frequency translation movement for Gimbal OFF , (b)is a graph obtained at a 2Hz frequency translation movement for Gimbal ON showing the x-axis, y-axis, linear velocity, and angular velocity from top to bottom.

- Gimbal OFF: as show in Fig. 4a, the chart shows numerous breaks, indicating instances where AR markers were not detected, the projection scene motion blur or ghosting during slow movement.
- Gimbal ON: As show in Fig. 4b, the curve is continuous with a few breaks, projection scene, the projected scene remains very clear even during slow movement.

2) Fast Movement (2 Hz), as shown in Fig. 3b:

- Gimbal OFF: As shown in Fig. 5a, except for the initial zero-speed condition, it is almost impossible to detect the marker. High-speed movement produces a strong ghosting and overlay problem.
- Gimbal ON: As shown in Fig. 5b, compared to the 1Hz case, the number of fracture points has increased, and most of the fractures occur in the peak velocity region.

4.3.2 Scenario B: Rotation Task (Angular Motion)

In this task, the backpack unit was rotated anticlock and clock direction (32° amplitude).

1) Slow Movement (1 Hz), as shown in Fig. 3c:

- Gimbal OFF: As shown in Fig. 6a, when rotating slowly, the chart showed slight breaks, but most of the chart remained stable. The recognition failure was likely due to vibration causing blurring or other issues.
- Gimbal ON: As shown in Fig 6b, with a back-and-forth rotation speed of 1fps, the rotation speed of the device mounted on the gimbal becomes very low, resulting in a relatively stable image.

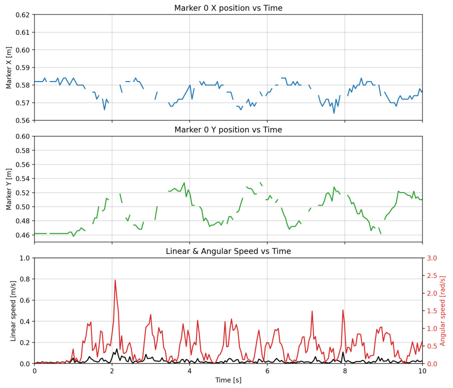
2) Fast Movement (2 Hz)as shown in Fig. 3d:

- Gimbal OFF: as shown in Fig. 7a, the curves in the graph are severely broken, making it almost impossible to identify the markers properly. This demonstrates that at this speed, issues such as ghosting are extremely serious.
- Gimbal ON:as shown in Fig. 7b The system demonstrated its maximum efficacy here. By physically limiting the projector's angular velocity, the gimbal prevented the onset of ghosting.

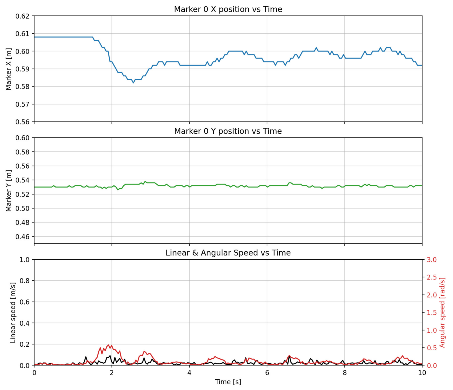
4.3.3 Summary Of Tracking Reliability

A consistent pattern emerged across both Translation and Rotation tasks: speed is the enemy of detection.

- Stabilization Benefit: The gimbal proved effective not just for smoothing motion, but for preserving data integrity. By filtering out high-frequency vibrations, it kept the projection clear enough to be tracked continuously, ensuring the system remained functional for remote guidance.

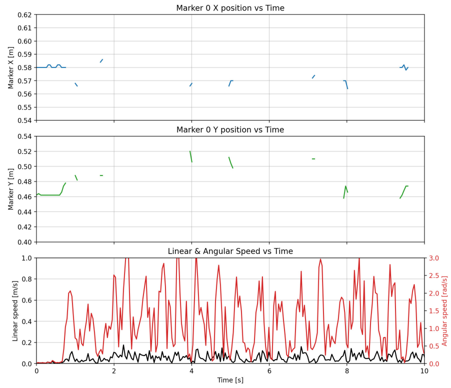


(a) Rotation Task (Gimbal OFF – 1Hz)

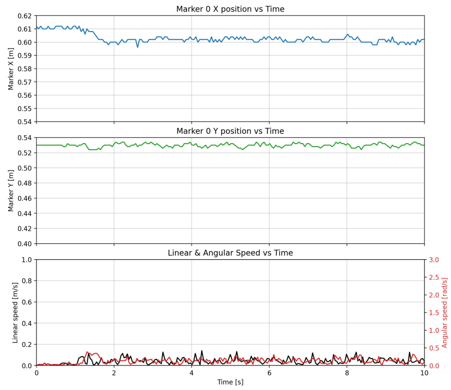


(b) Rotation Task (Gimbal ON – 1Hz)

Fig. 6: (a) is a graph obtained at a 1Hz frequency rotation motion for Gimbal OFF , (b)is a graph obtained at a 1Hz frequency translation movement for Gimbal ON showing the x-axis, y-axis, linear velocity, and angular velocity from top to bottom.



(a) Translation Task (Gimbal OFF – 2Hz)



(b) Translation Task (Gimbal ON – 2Hz)

Fig. 7: (a) is a graph obtained at a 2Hz frequency rotation motion for Gimbal OFF , (b)is a graph obtained at a 2Hz frequency translation movement for Gimbal ON showing the x-axis, y-axis, linear velocity, and angular velocity from top to bottom.

4.3.4 Visual Analysis Of Superimposed Frames

To further analyze the nature of the instability in gimbal on, we generated composite images by superimposing 3 consecutive fast-moving frames. This visualization simulates a “long-exposure” effect to reveal motion patterns.

In the stabilized condition Fig. 8, Fig. 9, (a) shows slight blurring, (b) shows ghosting, and (c) and (d) show stable and clear images. Due to the angular velocity absorption of the gimbal, the velocity ratio of the four experiments is Rotation 1Hz < Rotation 2Hz < Translation 1Hz < Translation 2Hz, A critical observation from our experiments concerns the relationship between movement frequency, effective velocity, and image artifacts. Although both the ”Fast Translation” and ”Fast Rotation” tasks were conducted at the same frequency (2 Hz), the resulting impact on projection stability differed due to the effective speed on the projection plane.Therefore, we can conclude that the threshold velocity for motion blur to occur should be translation 1Hz < *threshold velocity* < translation 2Hz.

5. Experiment Result Analysis

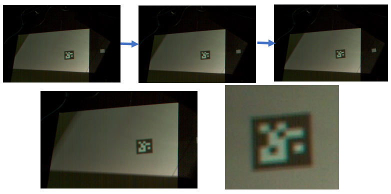
5.1 Summary Of Findings

Our evaluation confirms that wearable projection systems face significant stability challenges during worker locomotion. The experimental results demonstrate a clear dichotomy: while slow movements (1 Hz) are generally manageable, rapid movements (2 Hz)—whether translation or rotation—induce severe tracking failures in non-stabilized setups. The proposed gimbal-augmented system successfully mitigates these failures. By acting as a low-pass filter, the gimbal dampens the high-frequency vibrations that accompany rapid body movements. This ensures that the projector’s motion remains within a manageable threshold, preserving the integrity of the projected markers for continuous tracking. However, the experimental results also show that low-frequency motion blur remains even with the gimbal enabled.

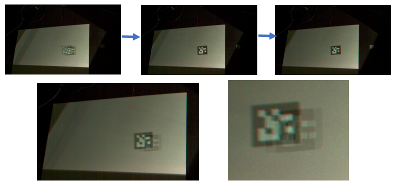
5.2 Analysis Of Ghosting Artifacts

A critical observation in our study is the nature of the image degradation. During high-velocity segments, the tracking loss was caused by discrete ghosting artifacts (double images) rather than continuous motion blur. We attribute this phenomenon to the specific interaction between the vibration dynamics and the hardware characteristics.

1) Shutter-Scan Synchronization Mismatch: The artifacts likely arise from the temporal interference between the camera’s shutter speed (integration time) and the projector’s

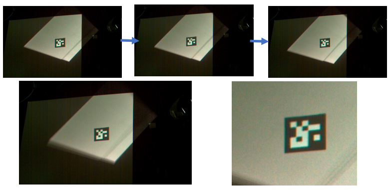


(a) Translation Task (Gimbal ON – 1Hz)

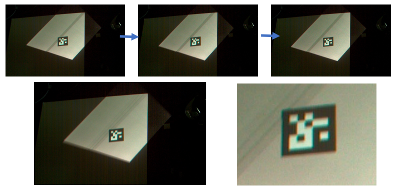


(b) Translation Task (Gimbal ON – 2Hz)

Fig. 8: For each image, the upper half, from left to right, shows two consecutive frames at high speeds.the bottom half shows three overlapping images.(a) is 1Hz translation task, (b) is 2Hz translation task



(a) Rotation Task (Gimbal ON – 1Hz)



(b) Rotation Task (Gimbal ON – 2Hz)

Fig. 9: For each image, the upper half, from left to right, shows two consecutive frames at high speeds.the bottom half shows three overlapping images. (a) is 1Hz rotation task, (b) is 2Hz rotation task

refresh rate. If the projector vibrates significantly within a single camera exposure frame, the camera captures the projection at two distinct positions, resulting in a "ghost" image. This mismatch creates a form of temporal aliasing that disrupts standard marker detection algorithms.

2) LBS Scanning vs. Motion Blur: Standard frame-based displays (e.g., LCD/DLP) typically produce "smearing" or motion blur when moved, as the pixel remains illuminated for the duration of the frame. In contrast, our system utilizes a Laser Beam Scanning (LBS) projector, which draws the image pixel-by-pixel, line-by-line. Because the laser illuminates each pixel for only a microsecond, the effective exposure time for any single point is extremely short. Consequently, even during rapid movement, the individual pixels do not "blur" or smear across the surface. Instead, as the projector vibrates, the scanning pattern shifts spatially between scan lines or refresh cycles, creating sharp, distinct duplicate edges (ghosting) rather than a blurry trail.

6. Conclusion

In this work,we proposed gimbal-augmented system successfully effectively eliminated motion ghosting and blurring caused by high-frequency vibrations. A critical observation from our experiments concerns is that the threshold velocity for motion blur to occur should be translation 1Hz ¡ threshold velocity ¡ translation 2Hz. Currently, our system relies on an environmental ceiling camera for tracking, which restricts the workspace. Future iterations will integrate Visual Odometry (SLAM) directly into the wearable unit. Additionally, while the gimbal effectively suppress high-frequency vibration, but low-frequency motion blur remains. Future work will investigate lighter, custom-designed damping mechanisms optimized specifically for the frequency range of human gait.

Acknowledgment

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