Research Direction: Constraint-Aware Interactive Systems for Physically Limited Environments

Project Title: ProneVR: Embodied XR Systems for Real-Time, Controller-Free Interaction in Posture-Constrained Environments
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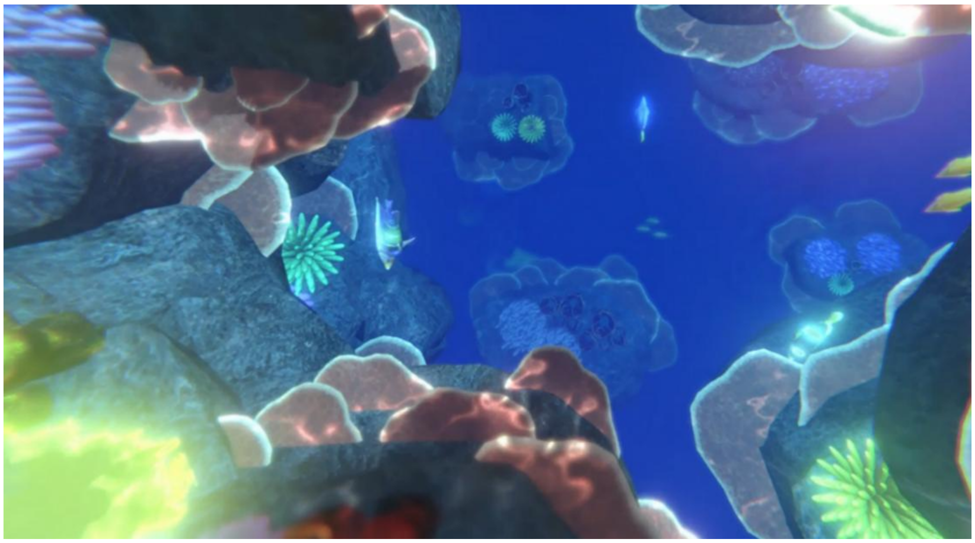

Figure 1: *Prototype interface of ProneVR, an embodied XR system enabling real-time, controller-free interaction for users in prone or otherwise constrained positions. The system integrates head-gaze, body orientation, and low-degree-of-freedom control to support stable, low-effort immersive engagement where traditional VR interaction methods fail.*

1. Research Summary

ProneVR is an XR system enabling constraint-aware, controller-free operation for users under posture constraints (e.g., lying prone for procedures or rehabilitation). Conventional VR systems assume upright posture, handheld controllers, and full arm mobility, making them unusable for individuals in various medical, mobility-restricted, or safety-critical contexts. This work establishes a computational systems framework for constraint-aware immersive systems by introducing a multimodal input pipeline that encompasses head orientation, viewport dynamics, and low-degree body shifts to enable stable, low-effort interaction. This project demonstrates how real-time sensing and constraint-aware control models can be optimized for both interaction stability and safety in physically constrained environments.

2. Motivation

Current VR interaction models are designed around assumptions that break under prone or constrained postures:

- Handheld controllers are inaccessible or ergonomically harmful.
- Gesture recognition requires ranges of motion not physically possible.
- Depth cues and interface elements for forward-facing scenes become disorienting when the user is horizontal rather than upright.
- Existing interactive XR systems lack computational models for interaction stability under constrained physical states.

This gap limits the use of immersive systems in high-value contexts, such as clinical procedures, physical therapy, rehabilitation, safety training, and low-mobility scenarios, where XR has demonstrated potential but remains technically infeasible.

3. Key Technical Contributions

ProneVR introduces several core advances at the intersection of constraint-aware interactive systems, real-time sensing, and high-performance computing:

- A controller-free constraint-aware multimodal input pipeline leveraging head-gaze, micro-movements, and viewport-relative control modeling.
- A constraint-aware stability model that compensates for tremor, drift, and motion limitations inherent to prone posture.
- A depth-stable interface representation that preserves interaction stability and spatial coherence when viewed from non-upright perspectives.
- A system-level real-time control loop optimized for latency, selection precision, and minimal physical input.
- Empirical validation through a multi-stage user evaluation integrating technical performance measures with interaction stability metrics.

These contributions outline a generalizable methodology for constraint-aware interactive systems operating under nonstandard or physically restricted user states.

4. Methodological Approach

The system architecture integrates real-time sensing, constraint-aware modeling, and runtime interface adaptation:

- **Input fusion and filtering:** smoothing of head orientation, micro-movement detection, and viewport-adaptive targeting reduce jitter and stabilize control behavior under constrained conditions.
- **Constraint-aware control model:** combines spatial thresholds, motion envelopes, and dynamic dwell-time strategies tailored to limited-range movement.
- **Depth-stable interface representation:** interface scaling, layout compensation, and parallax optimization maintain spatial readability and prevent distortion in prone environments.
- **Real-time performance pipeline:** ensures low-latency update cycles and control responsiveness through computationally efficient filtering and event routing.
- **Empirical evaluation:** includes prototype deployment, stability and precision measurements, and systematic assessments of interaction stability.

5. Significance

This work advances constraint-aware interactive systems and immersive computing research by:

- Expanding immersive interaction beyond standard upright-controller paradigms through a rigorous constraint-aware computational systems model.
- Demonstrating how multimodal input fusion and stability modeling can support reliable control behavior under minimal physical movement.
- Providing algorithmic and systems-level principles for XR systems intended for prone, seated, or mobility-limited users.
- Enabling new classes of immersive applications in clinical care, rehabilitation, and low-mobility computing, where traditional VR systems are unusable.

Ultimately, ProneVR illustrates interdisciplinary yet deeply technical research bridging systems engineering, visual computing, and real-time immersive computing under physical constraints.

6. Future Extensions

Building on this foundation, ongoing work includes:

- Integrating physiological sensing (breath motion, pressure signatures) to enhance interaction robustness.

- Modeling stability under perceptual constraints imposed by varying head angles.
- Extending the interaction system in XR mixed-reality environments.
- Formal evaluation of adaptive input models across diverse constrained postures and mobility conditions.

7. Role and Leadership

Michael Martin led the design and development of ProneVR. He built the immersive XR environment and implemented the multimodal input pipeline, constraint-aware control model, posture-stability filters, depth-stable interface representation, and real-time event architecture. He integrated real-time rendering, shader effects, spatial audio, and AI-driven agent behaviors, and conducted system instrumentation and quantitative performance evaluation for the UC Davis Pain Clinic pilot study. Dr. Kwan-Liu Ma provided research guidance.

Reference

Martin, M. R., Chan, G., Ma, K.-L. 2025. *ProneVR: Design and Evaluation of a Controller-Free Immersive Virtual Reality System for Pain Management in Prone Procedures***,** Pain Medicine Department, University of California Davis Health, Sacramento, CA, Nov 24, 2025. (Invited Presentation)
https://github.com/MichaelMartinTech/ProneVR-Demo