Visual-Inertial 6D Object Pose Tracking for Orthopedic Surgical Training

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1 Introduction and Contributions

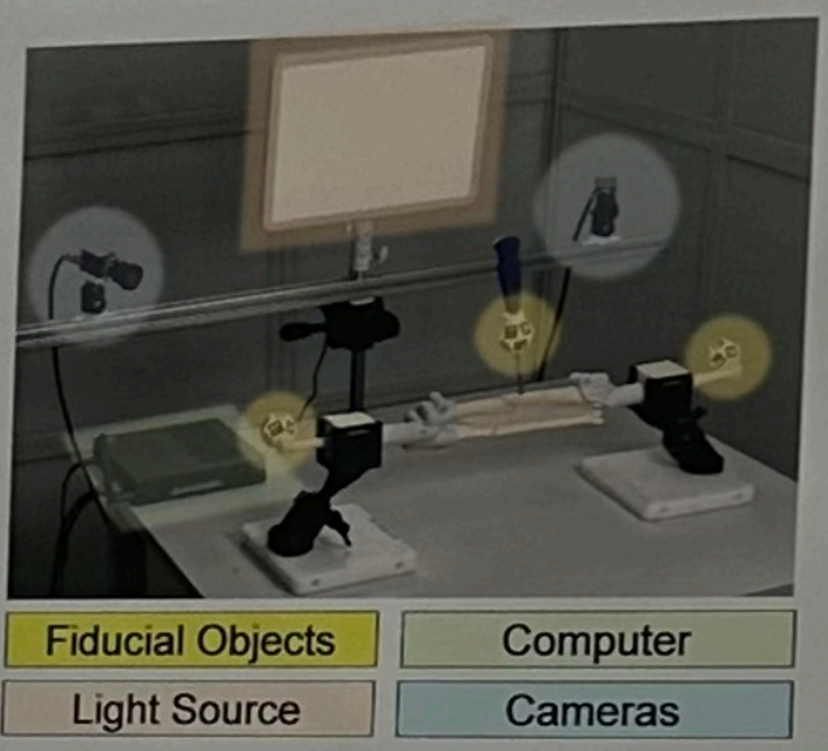
Digital orthopedic simulators are becoming essential for **risk-free, standardized surgical training**. To achieve realistic haptic feedback, **accurate real-time tracking** of tools and anatomy is required. Current surgical-grade tracking systems are **expensive and occlusion-prone**, while affordable RGB-based alternatives are difficult to integrate due to lack of **accuracy, robustness, and scalability**.

In this work, we propose **a novel visual-inertial tracking system tailored for orthopedic surgical training.** Our main contributions are:

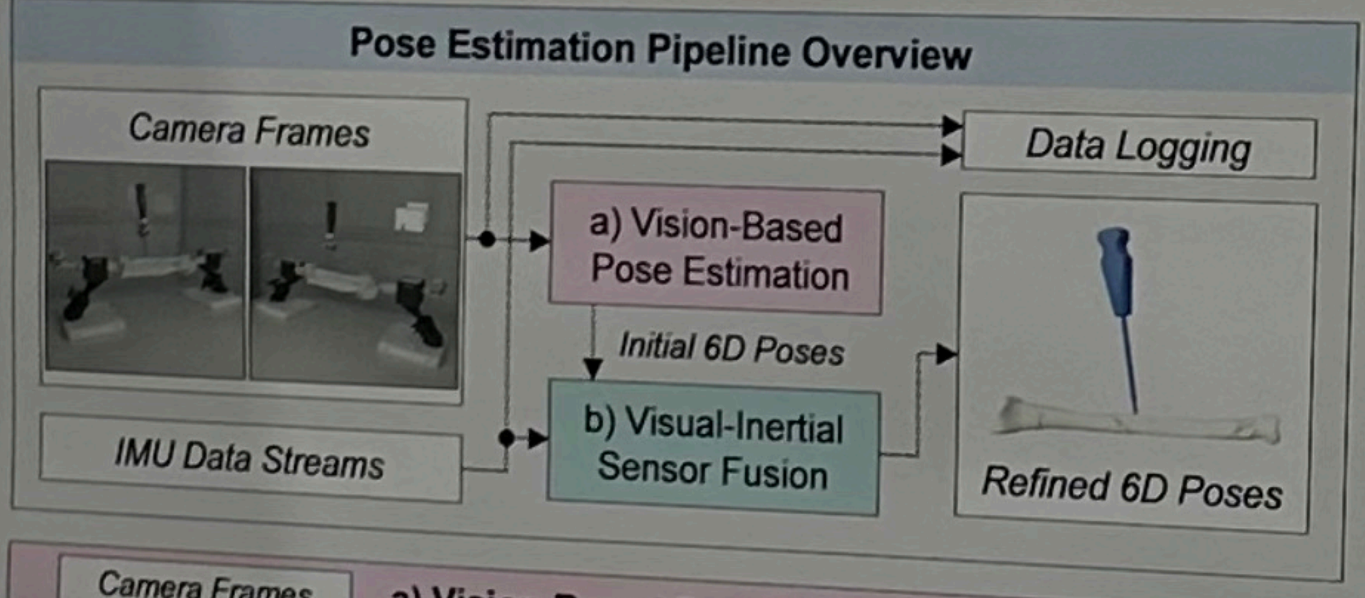
- A **custom fiducial object** combining planar markers with an inertial measurement unit (IMU)
- A **dual-camera vision pipeline** with **IMU fusion** for drift-free 6D pose estimation
- A simple **calibration framework** for time shift and coordinate alignment

2 System Overview

Our system consists of a **dual camera setup (right)** that tracks the **custom fiducial objects (left)** equipped with IMUs

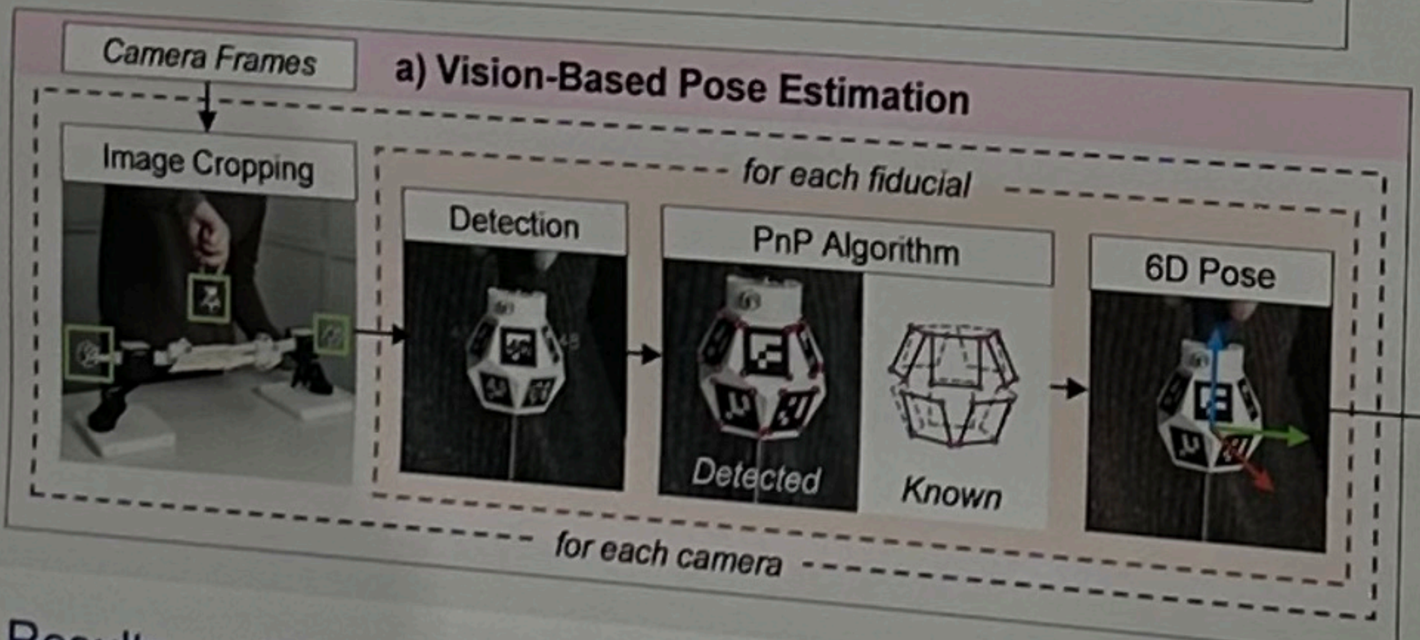


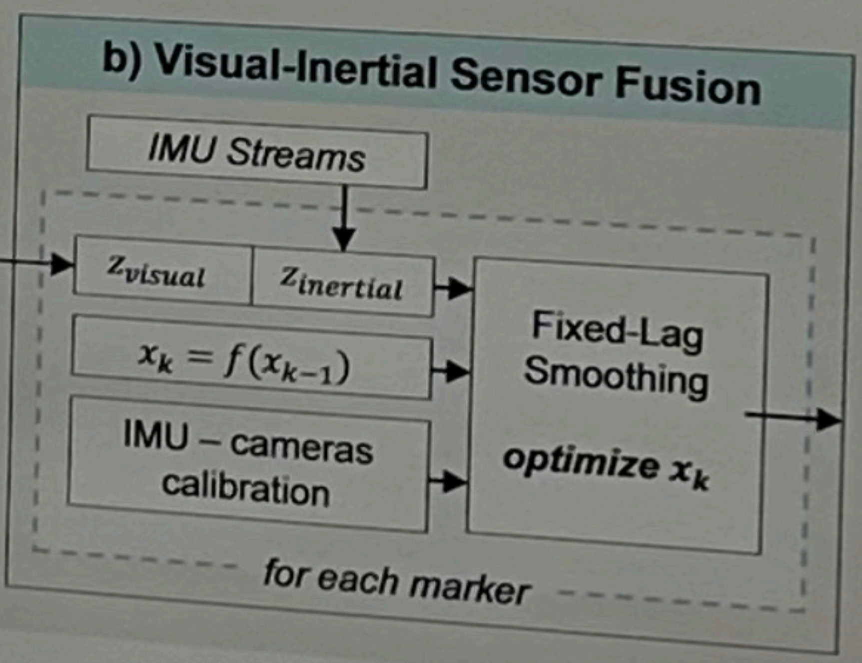
3 Method



An overview of the **pose estimation pipeline** is shown on the left. It consists of two sub-components:

- **Vison-step (a):** The camera frames are first independently scanned for ArUco markers to maintain tracking **during partial occlusions**. An **outlier-sensitive** PnP algorithm then calculates initial 6D poses
- **Fusion step (b):** The initial poses are combined with high-frequency IMU data using a **fixed-lag smoother**. An **integrated calibration algorithm** aligns coordinate frames and synchronizes sensor timing, resulting in **drift-free 6D multi-object pose tracking in real time.**



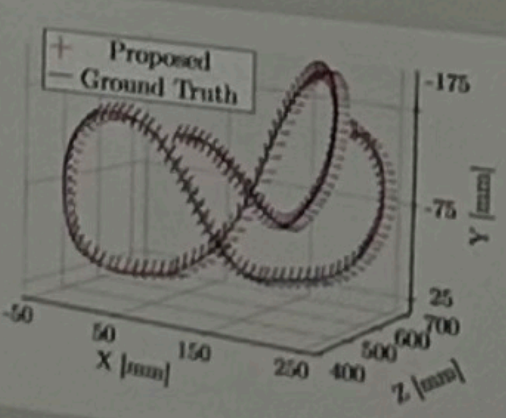


Link to Code Repository

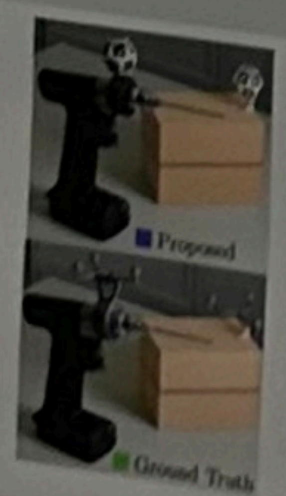
4 Results and Discussion

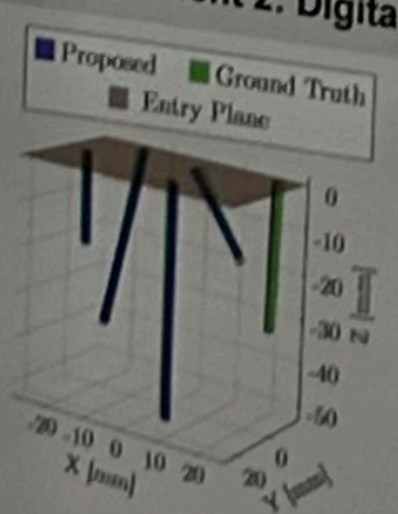
Experiment 1: Accuracy of Fiducial Object

The fiducial object was tracked simultaneously with our system and a surgical-grade optical tracker (Atracsys fusionTrack 500) for accurate ground truth. Using two cameras + IMU across varied motions, our method achieves **0.9 mm positional** and **0.5° angular error** with **low occlusion rates.**



Experiment 2: Digital Twin of Mock Surgery





A drill and foam block were tracked while drilling holes into a biomechanical block using our system. To evaluate, we traced these drilled holes using the ground truth optical tracker. The reconstructed drill holes from our system had average offsets of **1.7 mm in position, 2.0° in angle, and 1.0 mm in length** compared to the ground truth, while **no tracking losses** occurred.

The achieved metrics meet reported surgical accuracy thresholds of **1-2 mm in position and 3-5° in angle** for orthopedic procedures, demonstrating that the is suitable for training across a wide range of orthopedic interventions.

5 Conclusion

We propose a **novel visual–inertial tracking system** for orthopedic surgical training. In a mock surgery, drill hole errors remained within **1–2 mm and ~2°**, satisfying reported surgical accuracy thresholds. The system further demonstrated **occlusion robustness, cost-effectiveness, and ease of use**, confirming its clinical relevance and suitability for **scalable training simulators.**

Key References

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