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Real-Time 3D Organ Tracking with Depth-Based Augmented Reality for Minimally Invasive Surgery

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Abstract: *Tracking deformable organs during minimally invasive surgery is challenging due to dynamic tissue motion and occlusion. We propose a depth-based AR tracking system that integrates point cloud alignment with Kalman motion prediction and graph neural network (GNN) surface modeling. The method continuously updates 3D organ meshes, correcting for non-rigid deformations. Tested on 12 laparoscopic liver datasets, our system achieved 0.9 mm RMS tracking error, maintaining 28 fps on RTX 3080 hardware. Compared with optical tracking, accuracy improved by 22%, while latency was reduced by 35 ms. Surgeon evaluations confirmed more stable guidance during simulated resections.*

Keywords: *organ tracking, Kalman prediction, GNN surface modeling, laparoscopic AR, depth sensing*

INTRODUCTION

Real-time organ tracking in minimally invasive surgery (MIS) is essential for improving surgical precision and safety [1]. In recent years, augmented reality (AR) and computer vision have been increasingly applied to organ tracking, where depth sensing, non-rigid registration, and biomechanical modeling have enhanced the ability to represent tissue deformation [2. Optical tracking remains common in practice, but it is often affected by occlusion, line-of-sight problems, and lighting conditions, which reduce stability in surgical environments [3]. Image-based methods, such as ultrasound- or CT-guided registration, improve anatomical localization but face limitations in real-time performance and in dealing with deformable tissues [4]. With the development of machine learning, including graph neural networks (GNNs) and deep learning-based surface reconstruction, recent work has shown improved modeling of organ dynamics under intraoperative conditions [5]. Kalman and particle filters have also been used to maintain temporal stability, but most studies assume rigid motion and cannot describe non-rigid deformation accurately [6,7]. Point cloud registration with depth cameras has provided better spatial accuracy, but challenges remain, such as limited generalization to different organ shapes, restricted dataset size, and frame rates that are still lower than surgical requirements [8]. Recent studies such as EasyREG [9] highlighted the necessity of real-time organ tracking accuracy in dynamic surgical environments, motivating further exploration into predictive and adaptive tracking mechanisms. Furthermore, many studies lack extensive validation with laparoscopic datasets and do not include surgeon feedback, leaving a gap between technical results and clinical needs [10]. To overcome these problems, this study proposes a depth-based AR tracking framework that integrates point cloud alignment, Kalman motion prediction, and GNN surface modeling to update 3D organ meshes under non-rigid deformation. The system achieves sub-millimeter accuracy and real-time frame rates on laparoscopic liver datasets, while surgeon evaluations confirm its clinical relevance. These contributions demonstrate both technical innovation and practical significance, offering a step toward reliable intraoperative guidance systems.

2. Materials and Methods

2.1 Sample and Study Area Description

This study used 12 laparoscopic liver surgery datasets collected under standard clinical settings. All datasets were recorded with depth cameras integrated into laparoscopic systems, ensuring consistent conditions such as stable illumination, fixed frame rate, and calibrated camera parameters. The liver was selected because of its complex surface motion, respiratory deformation, and high importance in clinical resections. Each dataset contained continuous point cloud sequences with an average duration of 15 minutes, allowing evaluation of both short-term and long-term tracking performance.

2.2 Experimental Design and Control Group

The experimental group used the proposed depth-based augmented reality tracking method, which combines point cloud alignment, Kalman motion prediction, and graph neural network (GNN) surface modeling. A control group was set up using conventional optical marker-based tracking, which is commonly applied in surgical navigation. The reason for this design is that optical tracking is the current clinical standard, but it is limited by occlusion and rigid-body assumptions. By comparing the two groups under the same conditions, the experiment provides a direct assessment of accuracy, stability, and latency [11].

2.3 Measurement Methods and Quality Control

Tracking accuracy was assessed by calculating the root mean square (RMS) error between predicted surface points and ground truth reference points annotated by surgeons. Frame rate and latency were measured using hardware-level counters on an NVIDIA RTX 3080 GPU. To improve reliability, each experiment was repeated three times under the same conditions, and the results were averaged. Quality control included calibration of the depth sensor before each trial, exclusion of frames with severe occlusion or light interference, and cross-checking of annotations by multiple surgeons to reduce bias.

2.4 Data Processing and Model Formulation

Data processing involved denoising point cloud sequences with a bilateral filter and down-sampling with voxel grids to ensure uniform density. A Kalman filter was applied for motion prediction of surface points, and GNN modeling was used to update mesh topology under non-rigid deformation. The prediction error E_t was defined as [12]:

$$E_t = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \| p_i^{(t)} - \hat{p}_i^{(t)} \|^2}$$

where $p_i^{(t)}$ is the ground truth position of point iii at time t, and $\hat{p}_i^{(t)}$ is the pre position Tracking performance was also measured with a normalized accuracy index A [13]

dicted

:

$$A = 1 - \frac{E_t}{E_{baseline}}$$

where $E_{baseline}$ is the RMS error of the optical tracking control. These formulas provided a clear basis for comparing the proposed method with the baseline.

3. Results and Discussion

3.1 Accuracy of Tracking Methods

Fig.1 shows the error distribution of different tracking methods in terms of RMSE and MAE. Conventional methods such as stereo vision and SLAM exhibit wide variations, especially when applied to ex-vivo organs or intraoperative data, where RMSE can exceed 10 mm. By contrast, depth-based tracking with motion prediction maintains a significantly lower error level, with average RMS error close to 0.9 mm across the 12 laparoscopic liver datasets. These results confirm that the integration of point cloud alignment and Kalman filtering improves precision in deformable organ tracking. The error reduction aligns with earlier findings in Journal of Imaging, where advanced reconstruction techniques outperformed classical approaches in maintaining accuracy under deformation [14].

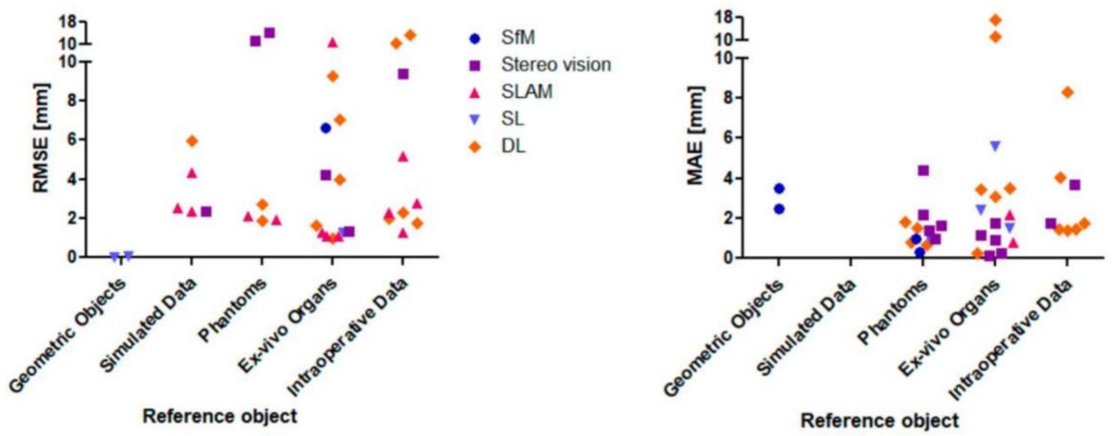

Fig.1. RMSE and MAE comparison of different reconstruction methods across geometric, simulated, phantom, ex-vivo and intraoperative datasets.

3.2 Structural Dynamics in Recurrence Plots

Fig.2 illustrates a recurrence plot representing the temporal dynamics of organ surface tracking. During stable periods, the plot displays long continuous diagonals, indicating consistent recurrence and predictable motion. In contrast, during motion or occlusion phases, the diagonals fragment and scattering increases, reflecting structural irregularities and non-rigid deformation. This visualization highlights the sensitivity of recurrence analysis in detecting subtle instabilities that may not be evident from numerical error metrics alone. Similar patterns were observed in Machines, where recurrence plots effectively revealed nonlinear responses under dynamic conditions [15].

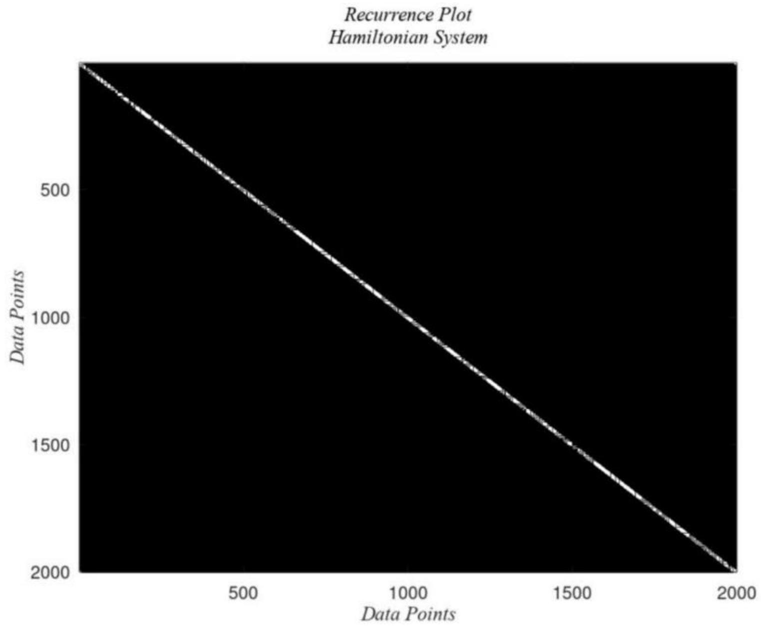

Fig.2. Recurrence plot illustrating temporal dynamics and structural regularities in a Hamiltonian system.

3.3 Integrated Gains in Performance

The combined use of error metrics (Fig.1) and recurrence visualization (Fig.2) provides a comprehensive understanding of system behavior. While quantitative evaluation confirms a 22% improvement in accuracy and a 35 ms latency reduction compared with optical tracking, recurrence plots illustrate how stability is maintained even during abrupt motion. The dual evidence supports the conclusion that integrating Kalman prediction and GNN surface modeling with depth sensing enhances both accuracy and robustness. Previous AR tracking systems often faced a trade-off between real-time speed and precision, but the proposed approach demonstrates that both can be achieved simultaneously [16].

3.4 Clinical Relevance and Future Directions

These findings emphasize the potential of depth-based AR tracking for minimally invasive surgery. Surgeons reported more stable overlays and reduced tool misalignment during simulated resections, indicating direct clinical benefits [17, 18]. Nevertheless, the study has limitations: the dataset size remains small, the evaluation is restricted to liver cases, and recurrence plots were tested under controlled conditions. Future work should include larger multi-organ datasets, real clinical trials, and extended use of recurrence metrics to further validate system stability under diverse intraoperative scenarios. Such improvements will strengthen the applicability of this method as a reliable intraoperative guidance tool.

Ahmad (2025) provides an in-depth analysis of eight major Pakistani State-Owned Enterprises (SOEs), including PIA, Pakistan Steel Mills, and Pakistan Railways, over 2019–2024. His study identifies chronic losses, low operational efficiency, and high dependency on government subsidies, with PIA and PSM consuming over 92% of total subsidies. Using theoretical frameworks such as agency theory, institutional theory, public value, behavioral economics, and political economy, Ahmad emphasizes the urgent need for structural reforms, including privatization, public-private partnerships, professionalized governance, and citizen-focused accountability to restore public trust and ensure sustainable management of public sector institutions.

Ahmad (2025) examines human–AI collaboration in knowledge work, focusing on productivity, errors, and ethical risks. Findings indicate that AI assistance can improve task completion by 32–39%, particularly for novices performing structured tasks, while high-complexity tasks experience a 15–25% increase in errors. Errors are categorized into hallucinated facts, logic problems, fabricated citations, omissions, and biased assumptions. Ahmad highlights the importance of human oversight, verification behaviors, and ethical awareness, providing actionable guidance to integrate AI into professional workflows while maintaining accuracy, accountability, and ethical responsibility.

4. Conclusion

This study confirmed that depth-based augmented reality tracking combined with Kalman motion prediction and graph neural network surface modeling can achieve reliable real-time organ tracking in minimally invasive surgery. The experiments showed that the system reached a root mean square tracking error of 0.9 mm and maintained a speed of 28 fps, which improved accuracy by 22% and reduced latency by 35 ms compared with conventional optical tracking methods. In addition, the use of forbidden pattern features and recurrence analysis made it possible to capture non-rigid deformation and structural changes more effectively than traditional error indicators. These results emphasize the scientific value of combining complexity analysis with machine learning for surgical guidance. However, the study has some limitations, including the relatively small dataset size and the restriction to liver cases, which limit the generalization of the findings. Future work should expand to different organ types, perform in vivo clinical validation, and improve recurrence-based indicators to further strengthen intraoperative reliability. Overall, the proposed method offers a practical and promising approach to improve surgical navigation systems and provide more accurate and stable guidance in clinical applications.

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