MICCAI2025 Daejeon REPUBLIC OF KOREA

CLINICCAI2025
5TH CONFERENCE ON CLINICAL TRANSLATION OF MEDICAL IMAGE COMPUTING & COMPUTER ASSISTED INTERVENTION
25 SEPTEMBER 2025
DAEJEON CONVENTION CENTER • REPUBLIC OF KOREA

MICCAI

AI based Instrument Motion Detection and Visibility Enhancement in Laparoscopic Video for AR-Guided Surgery

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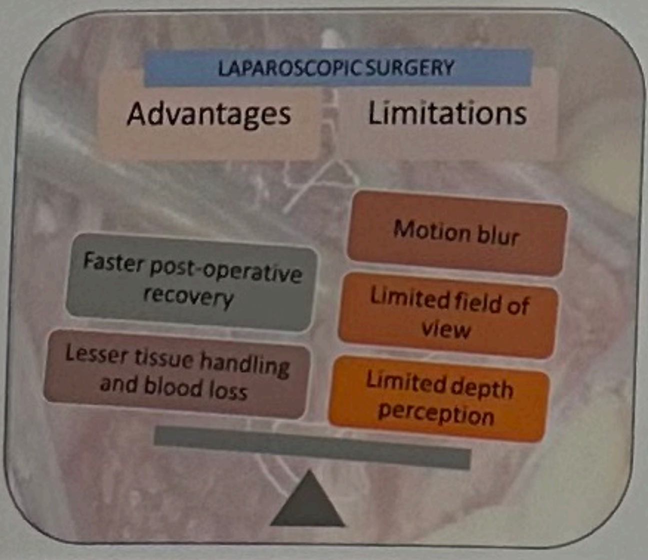


INTRODUCTION

Artificial Intelligence can address key limitations of laparoscopic surgery by enabling real-time detection, tracking, and analysis of surgical instruments, while augmented reality provides contextual overlays on live surgical video to enhance visualization. The integration of AI with AR can stabilize overlays, reduce manual camera control, and provide real-time guidance, thereby minimizing surgical errors and supporting critical decision-making. Furthermore, instrument motion tracking offers objective metrics for surgeon performance, enabling evidence-based training and ultimately improving patient outcomes.

PROPOSED SOLUTION:
Development of a modular AI-enabled AR-guided surgical system from laparoscopic video that combines real-time tool tracking, motion analysis, and blur correction with AR overlays. This system delivers visual alerts, stabilizes live surgical video, and records instrument trajectories to enable objective assessment of surgical skills. By enhancing intraoperative guidance and safety, it has the potential to reduce complications, improve surgical precision, and support both surgical training and clinical decision-making in minimally invasive procedures.

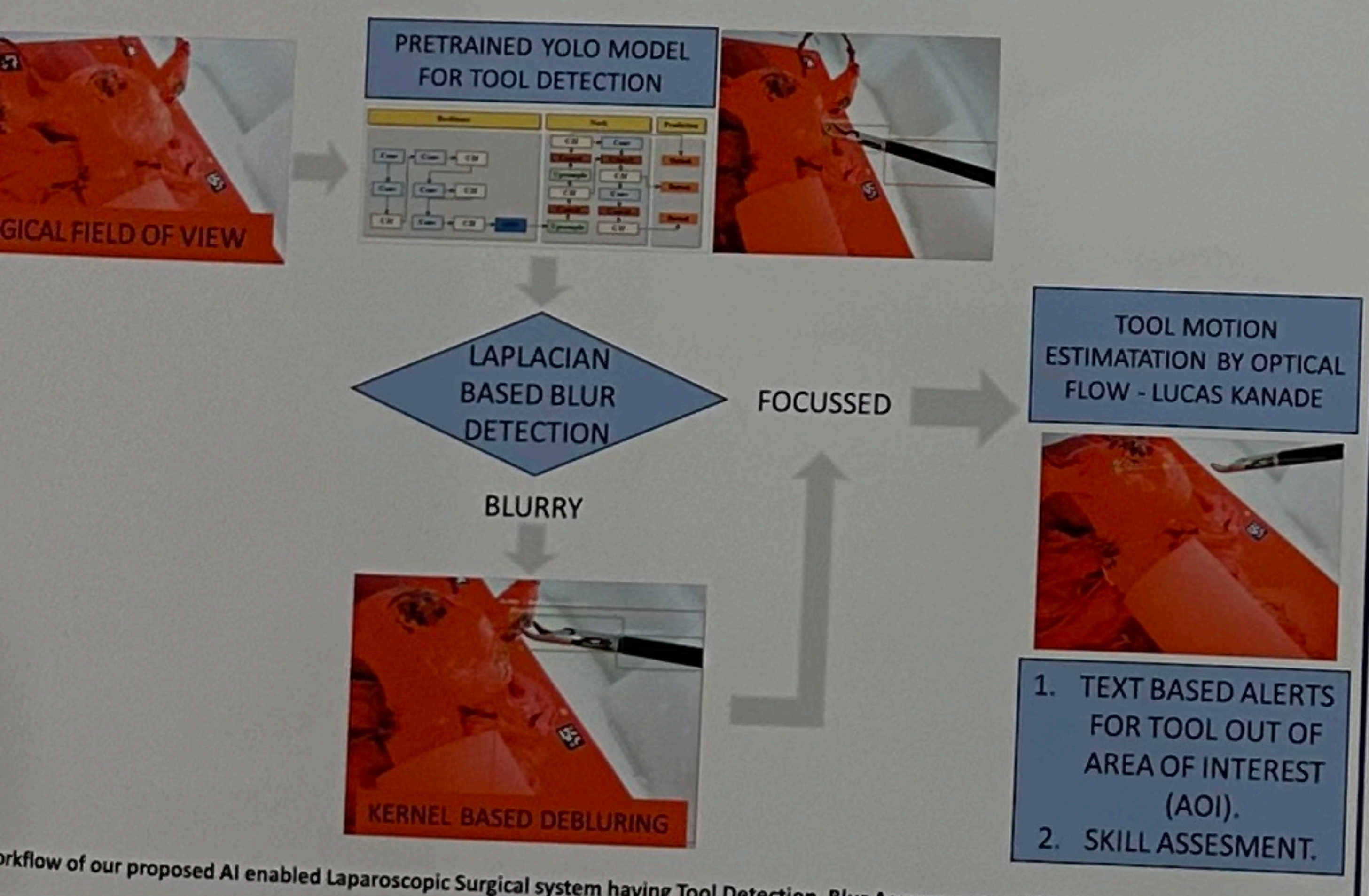
METHODOLOGY

enabled System Development: A modular AI-assisted AR system was developed for real-time surgical idance using laparoscopic video. Validation was performed on a 3D-printed phantom model, enabling ntrolled simulation and iterative refinement.

tem Components:

- **Tool Detection & Tracking:** Tool tip positions were detected using a trained YOLOv8 model, which was trained on the publicly available hSDB Instrument dataset (*Yoon, J. et al. 2021*). containing spatially labeled tool frames from 24 laparoscopic cholecystectomy cases. Following detection, frame-wise tool tip coordinates (x, y) were tracked using the Optical Flow Lucas–Kanade (*B. D. Lucas and T. Kanade 1981*) method to estimate tool motion trajectories (dx, dy). These trajectories were used to provide real-time feedback and were also logged for subsequent surgical skill analysis.
- **Blur Detection & Correction:** Motion blur was detected using a Laplacian-based threshold. On detection, a kernel-based deblurring was applied to that region for visual enhancement.
- **Visual Cues:** Color coded bounding box for detected blur and focussed tool region and tool triggered text based alerts for safe zone (Area of Interest – AOI) violations.

Assessment: Our system was evaluated by three users through a semi-quantitative assessment of cal skills, based on the tool motion trajectories recorded during their procedure on the phantom.



rkflow of our proposed AI enabled Laparoscopic Surgical system having Tool Detection, Blur Assessment and Motion estimation features.

RESULTS

The developed system demonstrated real-time performance with an end-to-end latency of 38.5ms (includes avg. inference time = 10ms per frame), delivering stable AR overlays (TRE ≈ 3 ± 0.5 mm) with tool detection ($mAP_{50} \approx 0.4$) and tracking at 25–30 fps. It enabled detailed motion analysis in x-y directions and quadrant-wise dwell mapping, revealing consistent motion patterns and offering objective metrics for surgeon skill assessment and feedback.

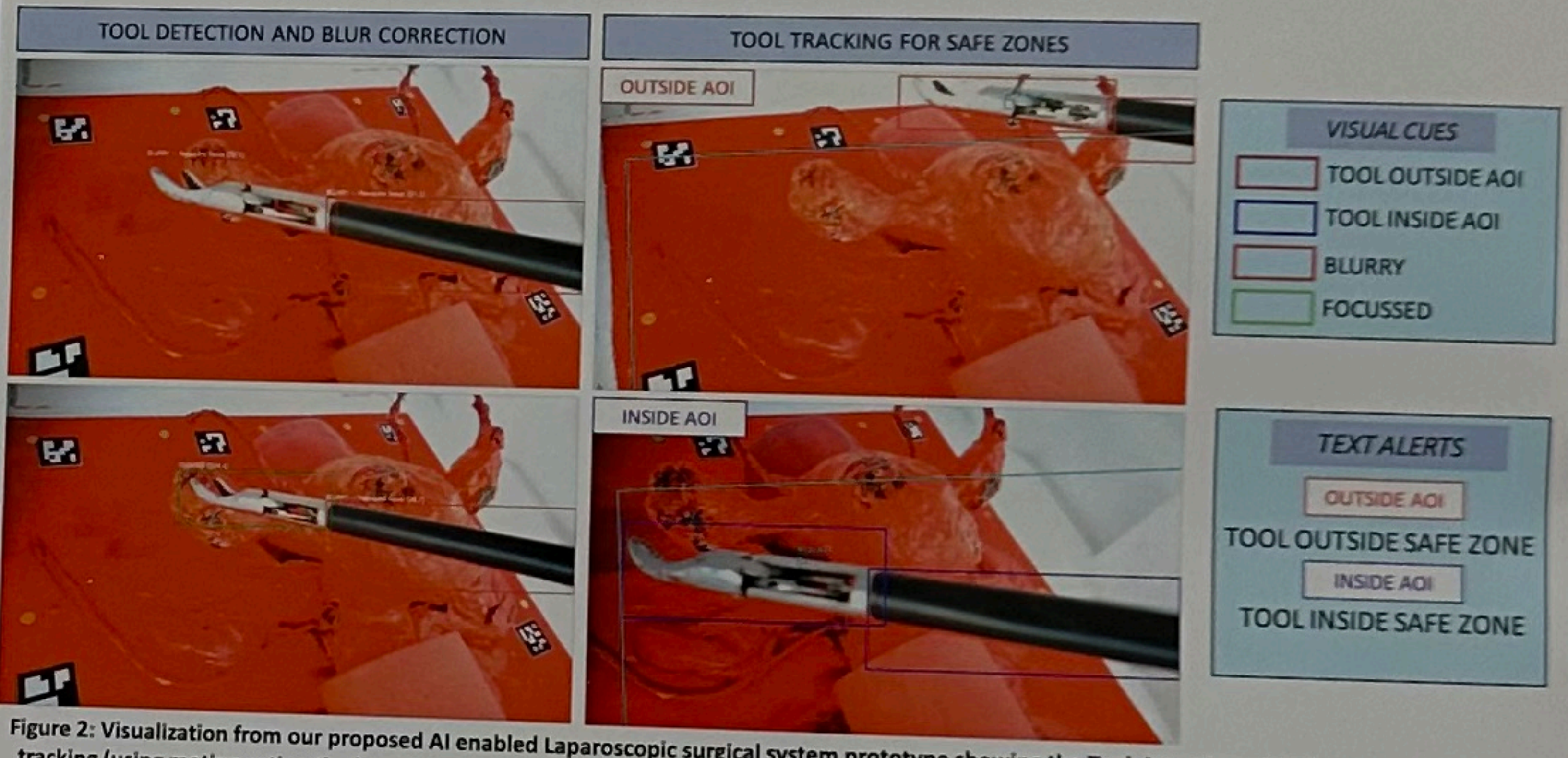


Figure 2: Visualization from our proposed AI enabled Laparoscopic surgical system prototype showing the Tool detection with Blur correction and Tool tracking (using motion estimation) modules along with Visual Cues. This system demonstrated around 38.5ms end to end latency and tool detection accuracy of $mAP_{50} \approx 0.4$ enabling it to operate at 25-30 fps (Frames per second) suitable for real time surgical videos.

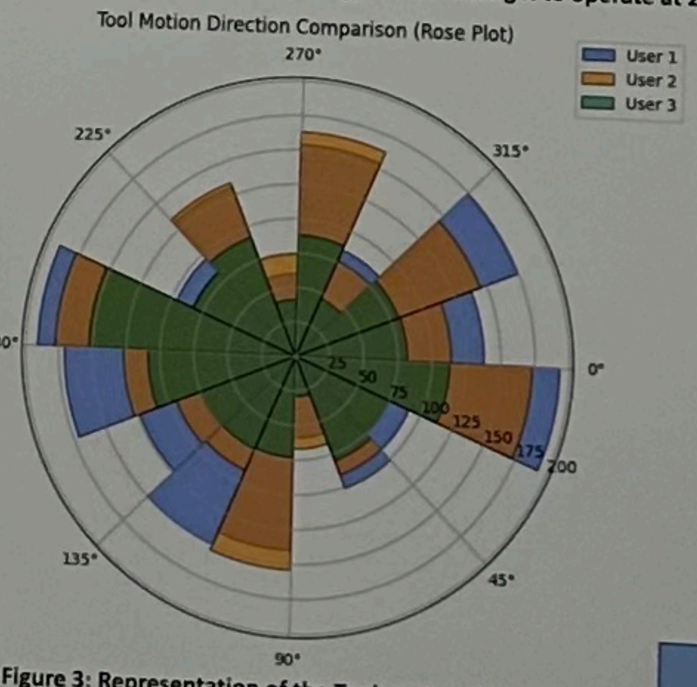
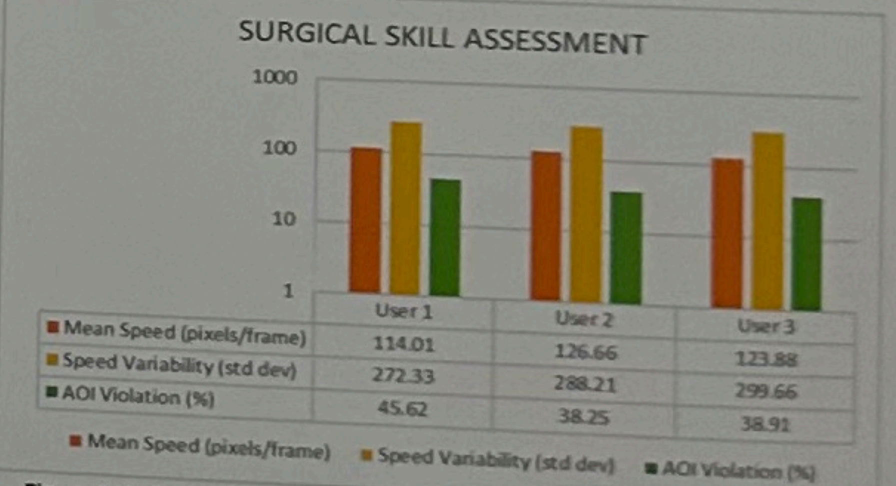


Figure 3: Representation of the Tool motion Trajectories (frequency of the direction changes of tool) logged across the three users



	User 1	User 2	User 3
Mean Speed (pixels/frame)	114.01	126.66	123.88
Speed Variability (std dev)	272.33	288.21	299.66
AOI Violation (%)	45.62	38.25	38.91

Figure 4: Relative comparison of Surgical skill of the three users based on the mean speed, speed variability (speed is number of pixels the tool moves per frame) and AOI Violation (% of frames where the Tool moved out of Area of Interest to an unsafe surgical zone).

INTERPRETATION:
User 1 has relatively higher AOI variation but steady tool movement.
User 3 has relatively lower AOI variation but highly variable tool movement and frequently changing across all directions.

CONTRIBUTIONS

dy provides a novel AI enabled modular pipeline combining tool localization, motion analytics, and uality assessment to enrich AR-based surgical guidance. It enables spatial mapping of instrument for objective skill metrics and shows real-time feasibility on a phantom model in a controlled nent.

y introduces an AI-assisted AR framework that enhances intraoperative safety and decision-by providing real-time tool tracking, motion analysis, and feedback, while also generating objective ance metrics. These metrics can be used for surgeon skill assessment and evidence-based surgical thereby improving precision, consistency, and patient outcomes in minimally invasive surgeries.

CONCLUSION AND FUTURE SCOPE

Our developed system successfully combines AI-based tool detection, tracking and blur detection for real-time surgical guidance. It demonstrated low end-to-end latency which makes it suitable for real-time surgical use with minimal jitter, ensuring consistent guidance during surgical tasks. It integrates tool trajectory analysis by motion estimation, which can assist in semi quantitative skill assessment of surgeons. Overall, this work establishes the feasibility of AI-assisted AR systems to enhance intraoperative safety, feedback, and precision in minimally invasive or robotic-assisted surgeries. Our upcoming work will involve clinical validation, integration with robotic platforms for automated camera control, development of deep learning–based blur classification, and personalized performance profiling across multi-instrument surgical workflows.

CLINICAL APPLICATION PROSPECTS

m has the potential to augment existing laparoscopic and robotic surgical platforms by enhancing intraoperative safety, precision, decision-making, and enabling automated camera control. It can also serve as a training and assessment tool by providing objective performance metrics, thereby facilitating skill development and standardizing surgical training.

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