Evaluation of surgeons' performance on three robotic surgical systems

Andrea Roberti[1], Maria Bencivenga[2], Simone Giacopuzzi[2], and Riccardo Muradore[1]

[1]*Department of Engineering for Innovation Medicine, University of Verona, Italy*

[2]*Department of Surgery, Dentistry, Pediatrics and Gynaecology, University of Verona, Italy*

INTRODUCTION

Minimally invasive surgery (MIS) has become a standard technique due to its benefits over traditional open procedures, such as reduced infection risk and faster recovery. However, it presents challenges including limited dexterity, poor depth perception, and steep learning curves [1]. Robotic systems and computer-assisted surgery (CAS) have been introduced to address these limitations, offering enhanced control, precision, and visualization. Accurate 3D tracking of instruments during procedures is key to enabling effective feedback, dynamic constraints, and objective skill assessments. Traditional tracking methods often require external hardware, while recent trends in computer vision enable image-based solutions using only surgical video data [2], [3].

This study proposes a methodology to estimate the 3D pose of surgical instruments using a visual segmentation model, Segment Anything 2 (SAM2) [4], in combination with feature tracking. The system extracts high-fidelity masks and applies the Perspective-n-Point (PnP) [5] algorithm with known CAD geometries to estimate 3D instrument pose. Validation includes performance evaluation across three robotic systems: the da Vinci Surgical System [6], Hugo RAS System [7], and Versius Surgical Robotic System [8], during the anastomosis phase of a gastrectomy procedure.

MATERIALS AND METHODS

The proposed framework is built upon three essential components:

- instrument segmentation using SAM2,
- feature point tracking,
- 3D pose estimation via the PnP algorithm.

Instrument Segmentation: SAM2 is employed to perform promptable visual segmentation on surgical videos. Initial masks are generated on the first frame using interactive prompts, and segmentation is propagated throughout the video sequence using temporal continuity and iterative refinement.

Feature Tracking: We apply two strategies for tracking: centroid-based tracking and ORB-based feature tracking. The latter improves robustness, especially during occlusions and varying orientations. Tracked features serve as prompts for SAM2 in subsequent frames, ensuring consistent segmentation.

Pose Estimation: We extract 2D features from segmented masks and match them with 3D CAD coordinates. The PnP algorithm estimates the instrument's pose by solving for rotation and translation parameters that minimize reprojection error. The system was validated using the da Vinci Research Kit (dVRK) where the kinematic data are available and used as ground truth, and then applied to compare the three robotic platforms during the anastomosis phase of a gastrectomy.

EXPERIMENTAL VALIDATION

In the dVRK evluation test, the PSM1 is autonomously controlled along a spiral trajectory within the robot's workspace, ensuring visibility through the endoscope. Figure 1 shows the reference trajectory in red and the estimated pose obtained using our approach in blue. The overall root mean square error (RMSE) of the estimation is $0.0062m$, demonstrating the accuracy of our method. However, since the pose estimation relies on images using the PnP method, its accuracy depends on the correct recognition and matching of 2D image features. This can introduce noise, especially in the z-axis, where depth estimation is less due to perspective projection.

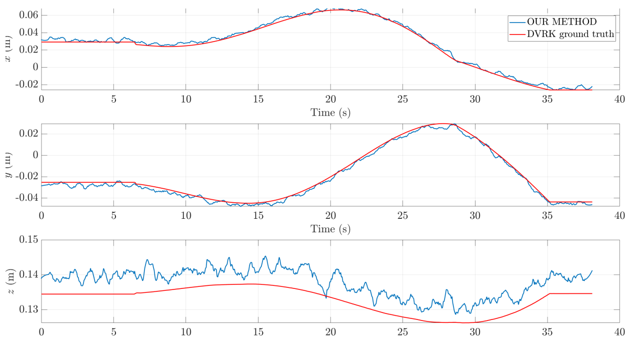

Fig. 1. Instrument position estimation: reference trajectory (red) vs. our approach (blue).

To evaluate further our method and compare surgeon performance across three robotic systems, we analyzed instrument kinematics during the anastomosis phase of a gastrectomy procedure. The platforms, shown in Figure 2, are the:

- da Vinci Surgical System,
- Hugo™ RAS System, and
- Versius Surgical Robotic System.

The metrics used to evaluate the task performance of surgeons are determined in collaboration with expert surgeons and are the duration of the task in terms of time,

(a) da Vinci by Intuitive

(b) Hugo by Medtronic

(c) Versius by CMR

Fig. 2. Most common robotic surgical systems. The figures in this paper are reproduced from external sources. All copyrights remain with their respective owners.

the total distance traveled by the instruments during the anastomosis phase, the number of clutch activations, and the time the endoscope is in use. Other important data points include how often the instruments move out of the camera's field of view and the percentage of usage for each instrument to assess whether the surgeon is optimizing the operation. The preliminary results are listed in Table I providing a comparative analysis of three robotic surgical systems across various performance metrics.

The da Vinci system showed the shortest task duration and best field-of-view maintenance. Versius excelled in bimanual instrument coordination but had the most frequent camera misalignment. Hugo showed balanced performance, though it required more frequent repositioning (clutching), potentially increasing surgeon fatigue.

Metric	Da Vinci	Hugo	Versius
Task duration (min,sec)	11,21	17,37	19,01
Total distance: dx (m)	0.8029	0.8275	0.8164
Total distance: sx (m)	0.7219	0.8032	0.8452
# Clutch	7	11	6
Endoscope motion (s)	11	12	18
Out of FOV: dx (s)	5 (0.7%)	7 (0.6%)	23 (2%)
Out of FOV: sx (s)	3 (0.4%)	11 (0.9%)	36 (3.2%)
Both instrument motion	96%	93%	99%

TABLE I

Comparison of robotic surgical systems based on various metrics.

CONCLUSIONS AND DISCUSSION

This study highlights the strengths and weaknesses of three major robotic surgical systems based on quantitative performance metrics. Our approach using SAM2 and PnP-based pose estimation enables a robust, image-based method to analyze real surgical procedures.

da Vinci Surgical System demonstrates the highest efficiency with the shortest task time, fewer clutches, and minimal instrument occlusion. Its high level of integration and mature control interfaces offer superior surgeon ergonomics and precision.

Hugo RAS System shows a good balance in metrics, with strong visualization and modular arm flexibility. However, it required the highest number of clutch activations, which may suggest less fluidity in instrument control or increased repositioning demands.

Versius Surgical System excels in bimanual coordination and adaptability, but struggled with camera tracking, showing the highest out-of-view time. This could impact surgical precision and indicate a steeper learning curve or less intuitive control feedback.

In conclusion, while each platform demonstrates unique advantages, the da Vinci system leads in overall operational efficiency under our evaluation metrics. The SAM2-based tracking pipeline proves to be a valuable tool for benchmarking robotic systems in surgical contexts. Future work will aim to refine real-time feedback, depth estimation, and extend testing in clinical settings.

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