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Hybrid SPECT–Optical Fusion with Augmented Reality Overlay for Quantitative Sentinel Lymph Node Localization

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A B S T R A C T

Accurate intraoperative localization of sentinel lymph nodes (SLNs) remains critical for oncologic staging and surgical precision. While preoperative SPECT/CT imaging provides high-sensitivity nodal detection, spatial translation of nuclear imaging data to the surgical field may introduce registration error. This study presents a hybrid SPECT–optical fusion framework integrated with augmented reality (AR) visualization to enhance real-time SLN localization accuracy. Three-dimensional SPECT/CT volumes were segmented using a semi-automatic intensity–gradient clustering method and converted into surface meshes. Optical surface tracking was performed using a structured-light depth sensor mounted on a head-mounted AR display. A surface-constrained rigid registration algorithm aligned nuclear imaging coordinates to patient anatomy, followed by real-time refinement through iterative surface matching. Validation was conducted on 14 human cadaveric specimens injected with technetium-99m radiotracer and 8 synthetic phantom models (total 22 datasets). Mean target localization error was 2.96 mm using standard projection alignment and decreased to 1.38 mm with the proposed fusion framework. Overlay stability during 4-minute motion simulation showed drift below 1.12 mm. Detection concordance with gamma probe verification reached 95.6%. These findings demonstrate that hybrid SPECT–optical fusion significantly improves AR-based SLN localization accuracy while maintaining intraoperative usability

INTRODUCTION

Sentinel lymph node (SLN) mapping plays a central role in oncologic surgery, as nodal status directly determines disease staging, treatment strategy, and prognosis. Although SLN biopsy has become a standard procedure in multiple cancer types, its clinical accuracy remains strongly dependent on precise intraoperative localization. Failure to identify relevant nodes may lead to under-staging and suboptimal treatment planning, whereas overly extensive dissection increases surgical morbidity and operative time. Recent clinical studies have focused on improving tracer protocols, imaging workflows, and intraoperative detection strategies to enhance both reliability and procedural efficiency [1,2]. At the same time, emerging navigation approaches integrating advanced imaging and visualization technologies have shown potential to further improve localization accuracy. In particular, recent augmented reality–assisted SLN

localization studies have demonstrated that fusing preoperative imaging with real-time visualization can enhance spatial perception and reduce search effort in controlled experimental settings, supporting the feasibility of image-guided lymphatic navigation [3]. Preoperative SPECT/CT imaging has become a widely adopted modality for SLN mapping due to its high sensitivity and ability to provide three-dimensional anatomical context compared with conventional planar lymphoscintigraphy. By combining functional tracer uptake with anatomical localization, SPECT/CT enables more accurate identification of draining lymph nodes and their spatial relationships to surrounding structures [4,5]. However, a major limitation lies in the translation of preoperative imaging information into the intraoperative environment. Differences in patient positioning between scanning and surgery, soft-tissue deformation, and the absence of direct visual correspondence often reduce spatial consistency between image space and the surgical field. As a result, surgeons frequently rely on handheld gamma probes and mental reconstruction of three-dimensional structures from two-dimensional displays, which increases cognitive load and introduces operator-dependent variability [6,7]. These limitations highlight the need for methods that can directly bridge preoperative imaging and intraoperative spatial perception. Augmented reality (AR) has been increasingly investigated as a solution to this image-to-patient translation problem. By projecting imaging-derived targets directly into the surgeon's field of view, AR systems can provide intuitive spatial guidance without requiring attention shifts between displays. Rapid advances in head-mounted displays, projection-based systems, and video see-through platforms have enabled a range of navigation applications in surgical oncology [8,9]. In the context of SLN procedures, early feasibility studies indicate that three-dimensional visualization of nuclear imaging targets can improve spatial understanding and reduce node localization time under controlled conditions [10,11]. However, most existing studies are limited by small sample sizes, simplified experimental setups, or lack of rigorous quantitative validation, which restricts their generalizability to routine clinical workflows [12,13]. In addition, variability in system design and evaluation protocols makes it difficult to directly compare reported performance across studies. A key technical challenge in AR-guided SLN localization is accurate and stable image-to-patient registration. Marker-based registration methods can achieve high alignment accuracy but require additional hardware, increase setup complexity, and may be affected by occlusion during surgery. Markerless approaches based on surface reconstruction and optical tracking reduce hardware burden and improve usability, yet their performance depends heavily on reliable depth sensing, robust tracking, and accurate surface matching [14,15]. Recent work using RGB-D cameras and structured-light systems has demonstrated promising accuracy in selected navigation scenarios, suggesting that markerless approaches can support clinically acceptable guidance under controlled conditions [16,17]. Even so, reported accuracy varies widely due to differences in validation protocols, target definitions, and evaluation metrics. Factors such as temporal drift, motion robustness, and segmentation uncertainty are often not systematically analyzed, despite their significant impact on overall localization performance [18,19]. Another limitation of current AR-based SLN systems is the lack of comprehensive quantitative validation. Many studies focus primarily on feasibility, usability, or qualitative improvement in visualization, while detailed analysis of localization error remains limited. In particular, the contributions of segmentation error, registration inaccuracy, and tracking drift are rarely separated, making it difficult to understand the dominant sources of deviation. Motion testing is often restricted to short or simplified scenarios, and validation against intraoperative ground truth—such as gamma probe measurements—is not consistently performed [20,21]. For SLN localization, where millimeter-level accuracy is clinically relevant, these gaps hinder the translation of AR systems from experimental demonstrations to reliable surgical tools. There is therefore a clear need for an integrated framework that minimizes manual intervention, maintains spatial consistency under motion, and provides reproducible quantitative evaluation of localization accuracy. Beyond registration accuracy, spatial stability during intraoperative interaction is an equally important requirement. Small patient movements, respiratory motion, or instrument contact can introduce

misalignment between the virtual overlay and physical anatomy. Without appropriate compensation mechanisms, such deviations may accumulate over time and reduce the reliability of AR guidance. Furthermore, inconsistencies between segmented structures in preoperative images and their intraoperative counterparts may introduce systematic bias that propagates through the registration pipeline. Addressing these issues requires not only improved alignment algorithms but also a unified consideration of segmentation quality, tracking robustness, and real-time spatial update strategies. The present study develops a hybrid SPECT–optical fusion framework integrated with augmented reality overlay for quantitative SLN localization. The proposed approach combines semi-automatic segmentation of SPECT/CT data with surface-based optical tracking using a structured-light depth sensor, enabling direct alignment between preoperative imaging and intraoperative anatomy. A surface-constrained rigid registration is first applied to establish initial correspondence, followed by iterative surface refinement to maintain alignment during real-time interaction. In addition, a quantitative evaluation scheme is introduced to assess localization accuracy against gamma probe measurements, allowing systematic analysis of error sources and motion effects. The objective of this work is to reduce image-to-patient translation error, improve overlay stability under short-term motion, and provide reproducible evidence of millimeter-level localization performance. By integrating imaging, registration, and validation into a unified framework, this study aims to advance the practical reliability of AR-guided SLN mapping and support its translation toward routine clinical use.

2.Materials and Methods

2.1 Sample and Study Setting

The study included 22 datasets, consisting of 14 human cadaveric specimens and 8 synthetic torso phantom models. Cadaveric specimens were obtained through a formal body donation program. All specimens were adult and showed no previous surgical intervention in the target regions. Technetium-99m radiotracer was injected at standardized superficial depths of 5–10 mm to simulate clinical sentinel lymph node (SLN) mapping. Phantom models were made of tissue-like materials and contained embedded radiotracer sources positioned at depths between 8 and 25 mm. All procedures were performed in a laboratory environment arranged to resemble an operating room. Room lighting, temperature, and equipment placement were kept constant during all sessions to reduce environmental effects on optical tracking and imaging consistency.

2.2 Experimental Design and Control Protocol

A controlled comparison was conducted to evaluate localization accuracy. The control workflow used standard projection alignment. In this setting, SPECT/CT images were manually aligned to visible anatomical landmarks without surface-based refinement. The experimental workflow applied the hybrid SPECT–optical fusion framework, which included surface-based rigid registration and iterative surface matching. Each dataset was processed using both workflows. The order of processing was randomized to reduce sequence effects. Localization error, overlay stability, and detection agreement were measured using the same verification procedure under both conditions. This design enabled direct comparison while maintaining consistent imaging input and evaluation criteria.

2.3 Measurement Procedure and Quality Control

SPECT/CT imaging was performed using a dual-head gamma camera equipped with low-energy high-resolution collimators. Image reconstruction was carried out with ordered-subset expectation maximization and attenuation correction. SLN regions were segmented using an intensity–gradient clustering method. Three-dimensional surface meshes were generated from the segmented volumes. Optical tracking was achieved using a structured-light depth sensor integrated into a head-mounted augmented reality device. Surface point clouds were captured at 30 Hz and processed with statistical filtering to remove outliers. Registration accuracy was verified using embedded radiopaque fiducial markers in phantom models and clearly defined anatomical landmarks in cadaveric specimens. A handheld gamma probe was used as the reference standard for target confirmation. Each localization measurement was repeated three

times, and mean values were calculated. Sensor calibration was performed before each session using a standard checkerboard-based intrinsic calibration procedure to maintain measurement consistency.

2.4 Data Processing and Model Formulation

Target localization error (TLE) was defined as the Euclidean distance between the AR-indicated target position and the reference position confirmed by gamma probe measurement. The error was calculated as

$$TLE=\sqrt{(x_{AR}-x_{ref})^2+(y_{AR}-y_{ref})^2+(z_{AR}-z_{ref})^2}$$

where (x_{AR},y_{AR},z_{AR})represents the AR-derived coordinate and $(x_{ref},y_{ref},z_{ref})$ represents the reference coordinate. Overlay drift during motion simulation was defined as the mean displacement over time:

$$D_{drift}=\frac{1}{N}\sum_{i=1}^{N}\| P_i(t)-P_i(t_0)\|$$

where $P_i(t)$is the registered target position at time t, $P_i(t_0)$ is the baseline position, and N is the number of sampled frames. Data normality was assessed before statistical testing. Paired t-tests were used to compare experimental and control conditions, with a significance level of $p<0.05$. All statistical analyses were conducted using MATLAB R2023b (MathWorks, Natick, MA, USA).

3.Results and Discussion

3.1 Localization accuracy and practical significance

In 22 datasets, the hybrid SPECT–optical fusion reduced the mean target localization error from 2.96 mm under standard projection alignment to 1.38 mm. This reduction indicates that surface-based registration improves the transfer of SPECT/CT targets to the surgical field. Earlier AR studies for SLN mapping reported larger discrepancies between virtual targets and reference positions, especially when alignment relied on manual landmark matching or simplified phantom conditions [22]. The present results fall within the lower millimeter range and therefore approach the accuracy levels considered acceptable for image-guided soft-tissue procedures. These findings are consistent with reports showing that registration accuracy has a stronger influence on navigation precision than visualization mode alone [23].Fig.1. System architecture of a tracked AR navigation platform showing component relationships and coordinate coupling.

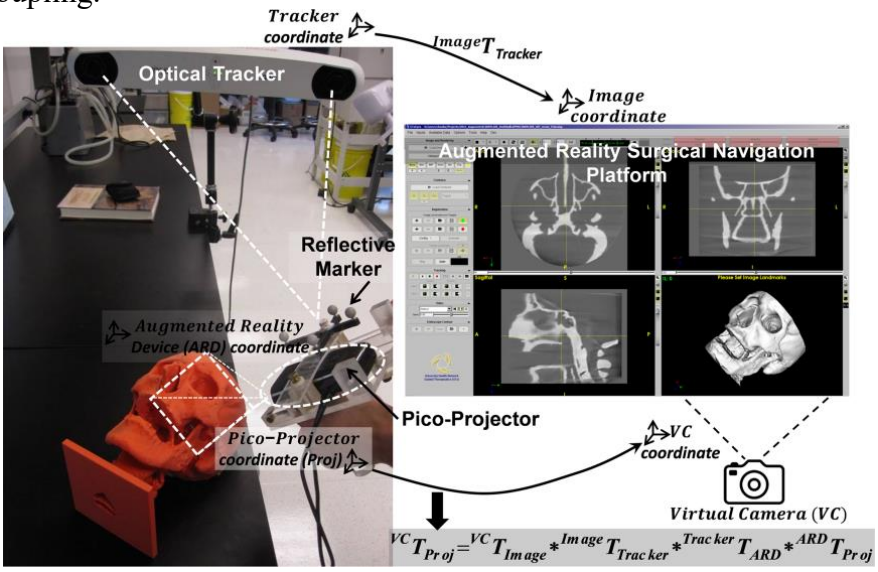


Fig.1.**Workflow of the SPECT–optical fusion system showing SPECT/CT segmentation, surface registration, and real-time AR target display for sentinel lymph node localization.**

3.2 Overlay stability and motion-related effects

During the 4-minute motion simulation, overlay drift remained below 1.12 mm. Stable overlay is essential because small tracking errors may accumulate during routine head movement or patient repositioning. The low drift observed here suggests that iterative surface updates can correct minor pose changes when sufficient depth data are available. Previous AR navigation studies have reported that depth noise, partial surface visibility, and latency in pose updates are common sources of error [24,25]. In comparison, the present framework maintained stable alignment under controlled motion. However, longer procedures or larger surface occlusion may reduce stability and require re-registration or additional tracking support.

3.3 Detection agreement and comparison with related SLN guidance systems

Gamma-probe verification showed 95.6% detection concordance. This level of agreement indicates that the AR overlay was consistent with the standard intraoperative confirmation method. Several AR-based SLN guidance studies have focused on feasibility and user experience but have provided limited quantitative validation against probe-confirmed targets. In contrast, the present data provide direct comparison between AR-indicated positions and reference measurements. Other navigation systems, including projector-based or robotic image-guided platforms, have demonstrated improved visualization but often report limited accuracy metrics under controlled conditions [26,27]. The current results suggest that surface-based fusion can maintain high detection agreement while reducing localization error.Fig.2. Projector-based AR navigation configuration and coordinate unification for precise overlay.



Fig.2.**Setup of the projector-based augmented reality navigation system illustrating coordinate alignment and target projection within the surgical field.**

3.4 Interpretation, limitations, and future validation

The combined reduction in localization error and low short-term drift indicates that integrating SPECT segmentation with optical surface tracking can improve image-to-patient alignment in SLN guidance. The results support the view that accurate registration and continuous surface correction are central to AR surgical navigation performance. Nevertheless, limitations remain. Cadaveric models do not fully reflect tissue deformation, bleeding, or dynamic changes during live surgery. The motion simulation was short in duration and may not represent extended operative scenarios. In addition, segmentation quality of SPECT volumes can influence mesh accuracy and therefore affect registration outcomes. Future work should include prospective clinical validation with standardized error metrics, longer motion assessment, and structured reporting of failure cases to enable comparison with existing AR SLN and image-guided navigation systems [28].

4.Conclusion

The present study shows that combining preoperative SPECT/CT imaging with optical surface tracking and augmented reality display improves quantitative localization of sentinel lymph nodes. The hybrid fusion framework achieved millimeter-level accuracy, reduced alignment error compared with standard projection-based methods, and maintained stable overlays during short-term motion. Compatibility with conventional gamma probe verification was preserved, confirming practical consistency with current clinical workflow. These findings indicate that surface-based registration with continuous refinement can effectively improve the transfer of nuclear imaging data to the surgical field. The approach may support more precise intraoperative guidance, reduce target search time, and help avoid unnecessary tissue removal in oncologic surgery. However, several limitations should be noted. The evaluation was performed on cadaveric specimens and phantom models rather than live patients. Motion assessment was limited in duration, and segmentation quality in SPECT images may influence registration performance. Future clinical studies under routine operative conditions are

required to evaluate robustness to tissue deformation, longer procedure times, and variable surgical environments, and to establish standardized accuracy benchmarks for AR-guided sentinel lymph node localization.

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