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Design of a Miniature Observation Robot for Light Emitting Diode Irradiation and Indocyanine Green Fluorescence-emission Guided Lymph Node Monitoring in Operating Rooms

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Abstract

Motivation: Typical surgical microscopes used for fluorescence-based lymph node detection experience limitations such as weight and restricted adjustability of the integrated light emitting diode (LED) and camera. This restricts the capture of detailed images of specific regions within the lesion.

Research goal: This study proposes a miniature observation robot design that offers adjustable working distance (WD) and rotational radius, along with zoom-in/zoom-out functionality.

Methods: A five-degree-of-freedom manipulator was designed, with the end effector incorporating an LED and concave lens to widen the beam width for comprehensive lesion illumination. Additionally, a long-pass filter was integrated into the camera system to enhance image resolution.

Experimental results: Experiments were conducted using a fluorescence-expressing phantom to evaluate the performance of the robot. Results demonstrated a captured image resolution of 9600 × 3240 pixels and a zoom-in/zoom-out capacity of up to 3.68 times.

Conclusion: The proposed robot design is cost-effective and highly adjustable, enabling suitability for rapid and accurate detection of fresh lymph nodes during surgeries. The robot's capability to detect small lesions (<1 cm), as validated by phantom tests, holds promise for the detection of minute lymph nodes.

Keywords

phantom test imaging, fluorescence emission-guided robot observation, light emitting diode, infrared camera, zoom-in-out

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Introduction

To facilitate the observation of lymph nodes (LNs) during in vitro extraction in cancer surgery, a procedure involving the injection of indocyanine green (ICG) and light emitting diode (LED) irradiation is employed. This technique enables the visualization of LNs through fluorescence emission under a surgical microscope.[1] However, when examining lesions, it becomes necessary to adjust the working distance (WD) of the camera and its horizontal positioning to capture either the entire area or specific details. Unfortunately, conventional cameras exhibit limitations in terms of their restricted height range (15-30 cm) and rotation angle (30-60°), in addition to being costly and heavy.[2] Moreover, conventional operating microscopes consume significant space within the operating room.[3] To address these challenges, a compact and user-friendly surgical microscope was developed.[4]

In this study, we present a novel design method for a miniaturized, portable fluorescence emission-guided observation robot. This innovative robotic system is designed to swiftly and accurately locate LNs by enabling real-time image storage and facilitating adjustments in parameters such as WD, rotation angle, radius, and zoom level.

Manipulator Design

As illustrated in Figure 1, the proposed manipulator boasts five degrees of freedom (DOF) and is designed to accommodate a shooting range of 290 mm × 210 mm[5].

The control system uses inverse kinematics and trigonometric functions to expedite thread calculations.[6-8] The robot incorporates a 16 MHz single-threaded microcontroller unit (MCU) equipped with a 16-bit oscillator. The real-time motor control, facilitated by timer interrupts, is optimized for streamlined target position calculations.[6] To mitigate these challenges and enhance computation speed, this study employs geometric inverse kinematics.

To facilitate the observation of lymph nodes via ICG, fluorescence emission is induced through LED beam irradiation, as depicted in Figure 1. The fluorescence emission passes through a wavelength filter, enabling high-resolution object monitoring through the camera sensor on the end-effector. A concave lens, affixed to the LED, widens the beam width by over 50% through refraction. Consequently, the observation field for lesions is significantly expanded. Additionally, a stitching method is employed, involving a 9.09° rotation of the LEDs from the vertical. Thus, at a working distance (WD) of 250 mm, the camera is optimally aligned with the center of the illuminated area.

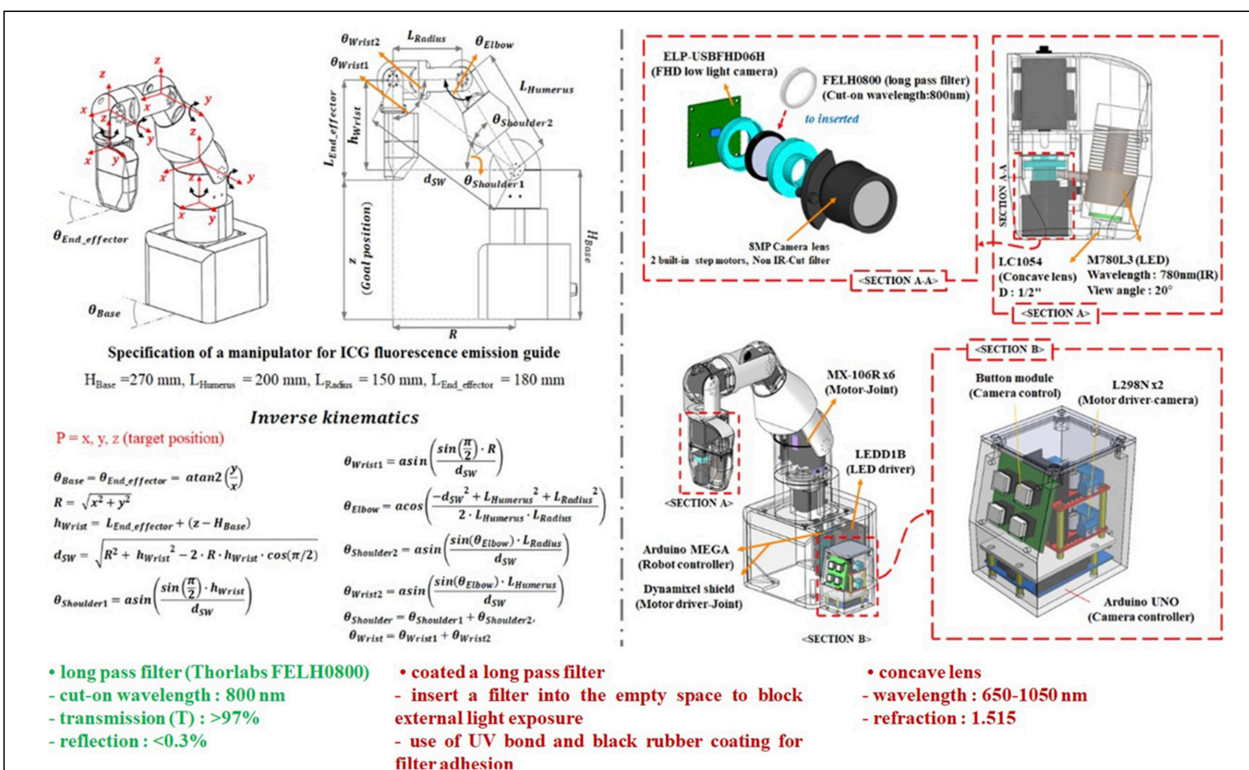

Figure 1. Proposed design of a manipulator.

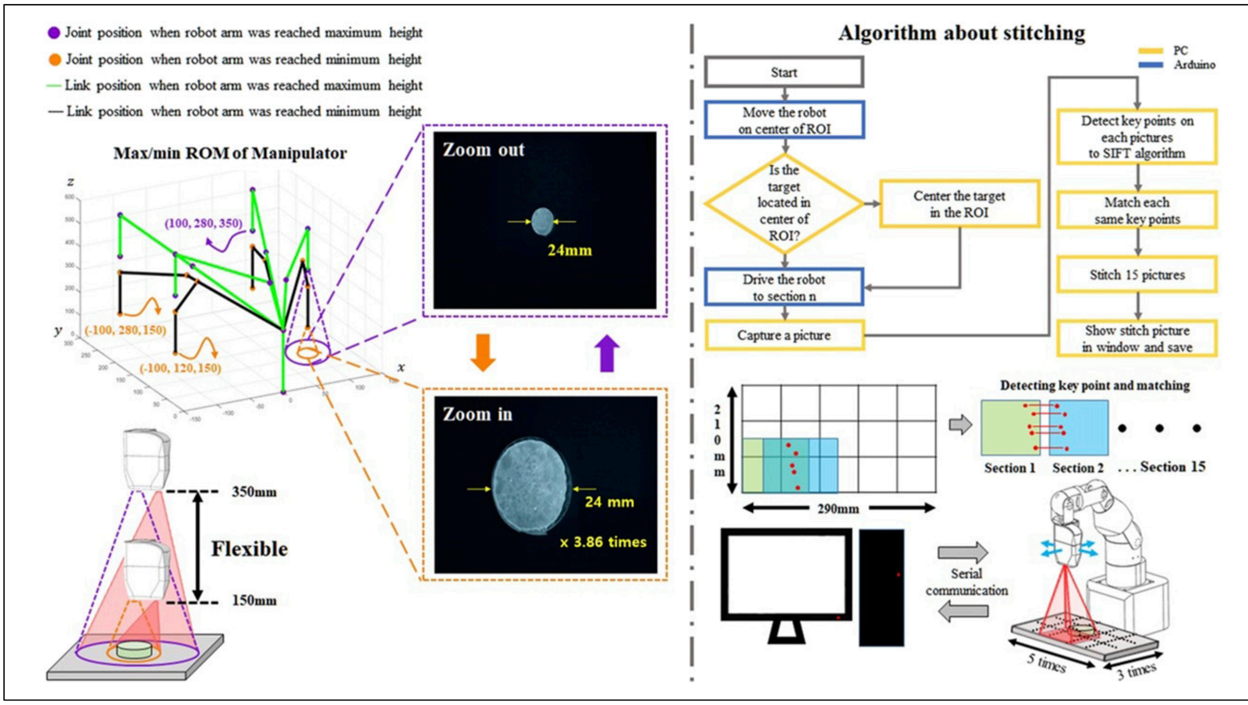

Figure 2. Performance of the system.

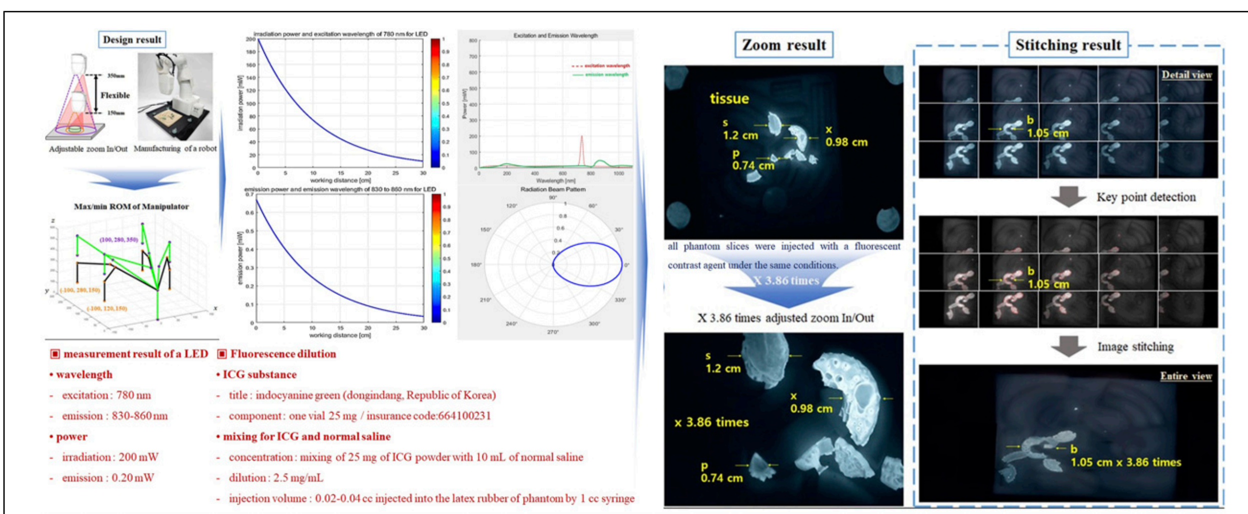

Figure 3. Analysis of the designed system and performance outcome.

System Performance

The designed robot is engineered to navigate along the X-, Y-, and Z-axes, as depicted in Figure 2. The robot's design facilitates comprehensive image capture, achieved by adjusting the Z-axis height and employing the zoom-in/zoom-out functionality of the lens driven by two-step motors. The system is adept at capturing intricate close-up photographs of even minuscule structures. Stitching technology, at a 250 mm Z-axis height, enables high-resolution photography of the entire inspection area with a single-button operation. The robot adopts a ready posture before utilizing the stitching technology, featuring a visible red circle in the center of the real-time image to assist the user in centering the photo. Following the capture of 15 photos, involving movement along the X- and Y-axes in a 5 × 3 pattern, the SIFT algorithm detects feature points for each photo and subsequently merges them into a single image.

Result

In this experiment, the performance of the designed robot was rigorously tested using a phantom model, simulating conditions akin to an animal experiment. Exceptional reliability exceeding 98% was achieved, as demonstrated in Figure 3. The test areas were scrutinized in greater detail through adjustable Region of Interest (ROI) enlargement/reduction, reaching up to 3.86 times magnification. The image resolution was set at 1920 × 1080, and the combination of 15 photos resulted in a final image resolution of 9600 × 3240. The system demonstrated the capability to capture phantoms as small as 1 cm, with the camera adept at zooming in on even smaller phantom components.

Conclusion

Conventional surgical microscopes often lack mobility and do not include a tray. Therefore, it is challenging to observe explanted specimens such as lymph nodes. Moreover, their substantial size poses logistical challenges in narrow operating rooms. The developed observation robot, owing to its compact and agile nature, offers a swift solution to these issues. This observation robot brings multiple advantages, including precise electric manipulation of the robot arm, targeted position control, high-resolution image acquisition, and reduced vibrations and positional errors (<±.007°). Additionally, the robot is proficient in monitoring blood circulation through fluorescence emission, expanding its potential applications in surgical and neurosurgical procedures. Furthermore, this innovative robot for observation is projected to reduce costs significantly, with an estimated unit price approximately 1/6th of that of a surgical microscope (eg, Leica-169: 149,000 USD).[8]

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Author Contributions

Hyeon-Woong Seo worked the study concept and design, and Ki-Cheol Yoon worked the analysis and interpretation. Also, Sangyun Lee worked the simulation and document investigation. Kwang Gi Kim worked for study supervision, and Won Suk Lee worked the providing of clinical informations:

Declaration of Conflicting Interests

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Supplemental Material

Supplemental material for this article is available online.

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