様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費 KAKENHI

科学研究費助成事業　　研究成果報告書

令和　６ 年　５ 月 ２８ 日現在

機関番号：１２６０１
研究種目：若手研究
研究期間：2020～2023
課題番号：２０Ｋ１４６９１

研究課題名（和文）Automatic Optimal Design of a Visual-based Stiffness Sensor and real-time Colour-coded Stiffness Map for Minimally Invasive Procedures.

研究課題名（英文）Automatic Optimal Design of a Visual-based Stiffness Sensor and real-time Colour-coded Stiffness Map for Minimally Invasive Procedures.

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交付決定額（研究期間全体）：（直接経費）　　3,200,000円

研究成果の概要（和文）：本研究は、低侵襲手術の安全性と精度を向上させるセンサーを開発しました。センサーは軽量ロボットと統合され、遠隔操作とリアルタイムの剛性フィードバックが可能です。Meta Quest 3で制御と視覚化を強化しました。
主な成果は、ロボットを正確に遠隔操作するナビゲーションアルゴリズムの開発です。収集された情報はリアルタイムのカラーコード付き剛性マップの作成に使用でき、手術の精度と安全性を向上させます。

研究成果の学術的意義や社会的意義
This technology enhances surgical procedures by providing real-time stiffness information during minimally invasive surgeries, improving the quality of outcomes. By increasing surgical precision and safety, it contributes to better patient recovery and overall healthcare quality.

研究成果の概要（英文）：This research developed a sensor to enhance the safety and accuracy of minimally invasive surgeries. The sensor was integrated with a lightweight robot, allowing for remote operation and real-time feedback on tissue stiffness. Control and visualization were enhanced using the Meta Quest 3.

Key achievements include the development of a navigation algorithm for precise remote control of the robot. The information collected can be used to create a real-time color-coded stiffness map, improving the precision and safety of surgeries.

研究分野：Robotics

キーワード：Visual-based sensing　Optimal design　MIS　Medical Robotics　Remote palpation　Stiffness sensing　Topological optimization　Optimal 3D design

１．研究開始当初の背景

Minimally invasive surgery (MIS) has revolutionized the field of surgery by allowing complex procedures to be performed through small incisions. This technique offers numerous benefits over traditional open surgery, including reduced pain, shorter recovery times, and less scarring ①. Despite these advantages, MIS presents significant challenges in terms of precision and safety. Surgeons rely heavily on tactile feedback to differentiate between various tissue types and navigate delicate anatomical structures ②. In traditional open surgery, surgeons can use their hands to feel tissue stiffness, which is crucial for identifying abnormalities such as tumors. However, this critical feedback is significantly reduced or entirely absent in MIS ③.

The lack of real-time stiffness information in MIS can make it difficult for surgeons to accurately identify and differentiate between healthy and diseased tissues. This limitation increases the risk of accidental tissue damage and reduces the effectiveness of the surgery, particularly in identifying problems like cancer, where tissue hardness is a key indicator ④. Traditional MIS tools do not provide adequate feedback, leading to a higher reliance on visual cues alone, which can be insufficient in complex surgical scenarios ⑤.

To address these challenges, a visual-based stiffness sensor was developed by the principal investigator (PI) prior to this project. This sensor is attached to the endoscopic camera used in surgical procedures, eliminating the need for additional instruments. The current research aimed to optimize this sensor and integrate it with a remote robotic platform to enhance its functionality and effectiveness. By providing real-time feedback on tissue stiffness, the system would allow surgeons to perform more accurate and safer operations. The integration of advanced technologies, such as virtual reality, was also explored to improve the overall control and visualization of the surgical process.

The motivation for this research stems from the need to address the limitations of current MIS techniques and to leverage advancements in robotics and sensor technology to create a more effective surgical system. With the increasing prevalence of MIS procedures worldwide, there is a critical need for innovations that can improve surgical outcomes and patient safety ⑥. This research aimed to bridge this gap by developing a comprehensive system that enhances the capabilities of surgeons performing MIS.

２．研究の目的

The primary objectives of this research were centered on providing stiffness sensing information in minimally invasive surgery (MIS) procedures through the development and optimization of advanced sensor technology for the endoscopic camera, integrated with a robotic platform that can provide stiffness distribution information to remote operator. This integration aimed to enhance the surgeon’s ability to differentiate tissue types and improve the precision and safety of surgical procedures. A graphical representation of the overall system is shown in Figure 1.

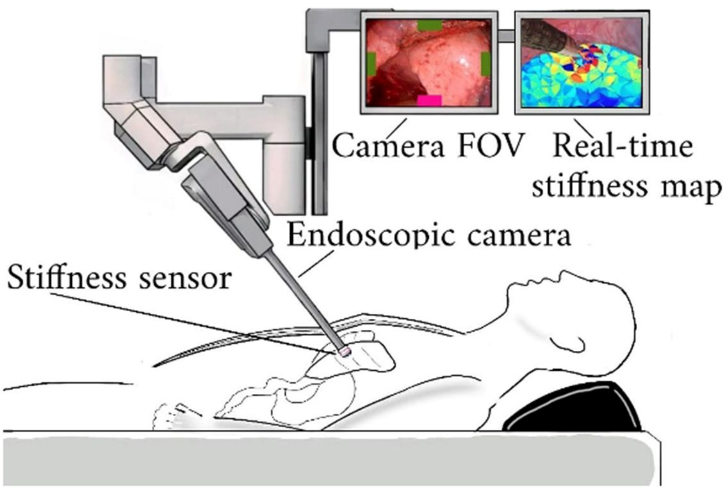


Figure 1. Proposed sensory system: the endoscopic camera is equipped with the stiffness sensor providing to the clinical team real-time images of the anatomical areas as well as the stiffness

Specifically, the objectives were:

- **Optimization of the Visual-Based Stiffness Sensor:**
  To refine the existing sensor, originally attached to the endoscopic camera by the principal investigator, for better performance. This included optimizing its sensitivity, durability, and integration capabilities using the advanced design tool Fusion 360 ⑦. The

enhancement aimed to provide real-time stiffness feedback, addressing the critical need for tactile information that is absent in traditional MIS.

- **Integration with a Lightweight Robotic Platform:**
  To integrate the optimized sensor with the UFactory Lite6, a lightweight six-degree-of-freedom robotic arm. This integration allowed precise control and manipulation during surgery, enabling the surgeon to receive real-time feedback and make informed decisions.
- **Remote Operation Capability:**
  To enable the robot to be controlled remotely by the surgeon, ensuring accurate and responsive movements during complex procedures. This capability was designed to enhance the surgeon's ability to perform delicate tasks with greater precision and safety.
- **Development of a Semi-Autonomous Navigation Algorithm:**
  To develop a navigation algorithm using the Robot Operating System (ROS) and Moveit framework ⑧, allowing the robot to follow a planned path while providing the capability for real-time adjustments by the surgeon. This algorithm aimed to improve the robot's adaptability and precision during surgery.
- **Enhancement of Control and Visualization through Virtual Reality:**
  To utilize the Meta Quest 3 virtual reality system to improve the control and visualization capabilities of the surgeon. This included providing an immersive interface where the surgeon can visualize the surgical environment and interact with the robotic system in real-time. The VR system aimed to enhance the overall surgical experience, providing a more intuitive and effective control mechanism.

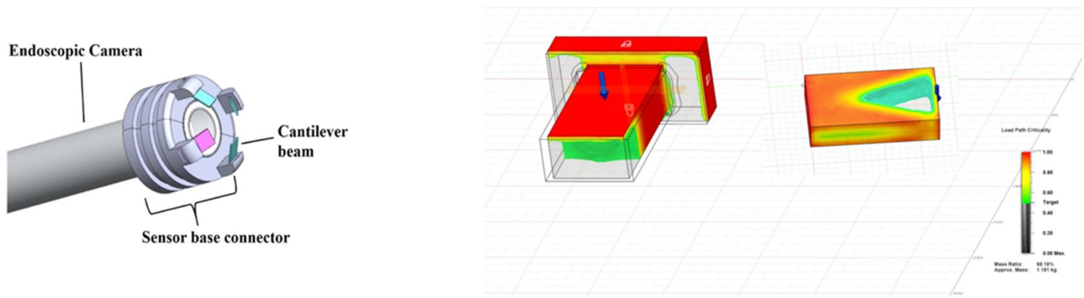
These objectives aimed to address the limitations of current MIS techniques by providing surgeons with critical stiffness information, enhancing the functionality of the endoscopic camera, and leveraging the latest advancements in robotics and virtual reality technology. The goal was to improve the precision and safety of MIS, leading to better patient outcomes and more efficient surgical diagnostic procedure.

３．研究の方法

The research methodology involved several key steps to develop and optimize the visual-based stiffness sensor, integrate it with a robotic platform, and enhance control and visualization using virtual reality.

(1) SENSOR OPTIMIZATION

The first step was to optimize the existing visual-based stiffness sensor, originally attached to the endoscopic camera. This optimization was conducted using Fusion 360, a computer-aided design (CAD) tool. The process involved a series of shape optimization studies where different shapes and materials were tested under various simulated conditions. Specifically, cantilever beam configurations were analyzed by applying forces to assess their performance. The goal was to identify the optimal design that balanced sensitivity and durability. Although these simulations provided valuable insights, limitations in 3D printing capabilities prevented the fabrication of the best sensor design. Therefore, the previous clip-on stiffness sensor for endoscopic camera developed by the principal investigator was used for integration.



(a) (b)

Figure 2. Clip-on stiffness sensor for endoscopic camera (a). Shape optimization studies (b)

(2) ROBOTIC INTEGRATION
The UFactory Lite6, a lightweight six-degree-of-freedom robotic arm, was used for this integration. The Robot Operating System (ROS) facilitated the interfacing and control of the robotic arm, allowing for real-time data processing and control.
A simple navigation method was developed within ROS to control the robotic arm. This method allowed the robot to follow pre-defined paths and make real-time adjustments based on feedback from the sensor. The navigation algorithm ensured that the robotic arm could move accurately and safely within the surgical environment, which was essential for performing delicate tasks and avoiding accidental tissue damage.

(3) VIRTUAL REALITY INTEGRATION
To enhance the control and visualization capabilities, the Meta Quest 3 virtual reality system was integrated into the setup. Unity Developer Hub ⑨ and Meta Quest Developer Hub ⑩, were used to connect ROS and the Meta Quest 3, creating a cohesive VR environment . A model of the robotic arm was imported into the VR environment, allowing the surgeon to visualize the robotic arm and the surgical field in real-time. The VR system provided an immersive experience, making it easier for the surgeon to control the robot remotely.

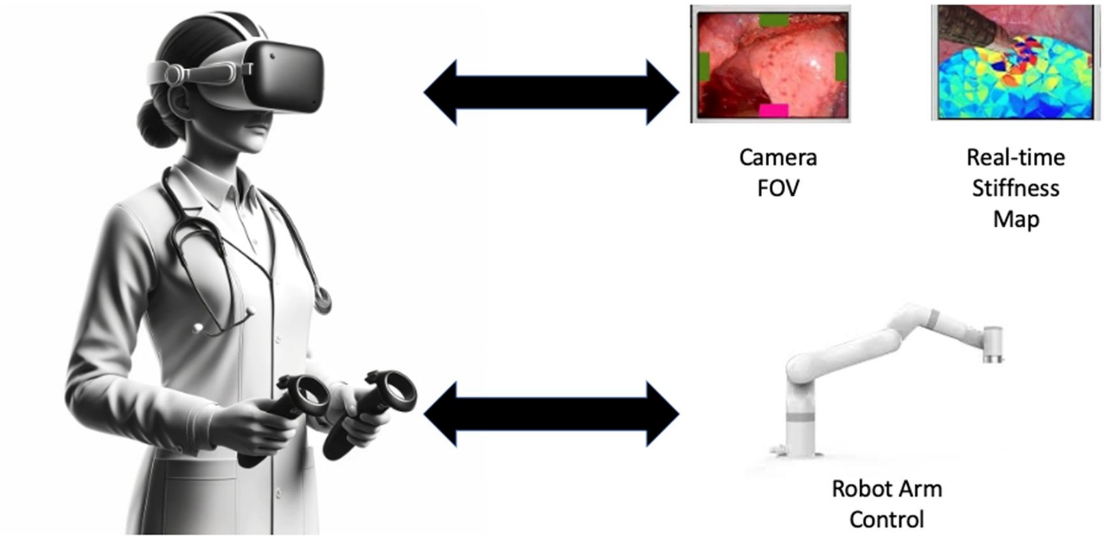


Figure 3. Schematic of the System: Surgeon using Meta Quest VR system to control the robot arm and visualize the camera FOV and real-time stiffness map.

The VR interface was designed to display real-time data from the sensor, including stiffness information. This setup enabled the surgeon to interact and control the robotic system intuitively, using visual and haptic feedback to guide their actions. The integration of VR helped bridge the gap between the physical operation of the robot and the surgeon's perception, enhancing the overall effectiveness of the system. A schematic overview of the system is shown in Figure 3.

４．研究成果
The research conducted yielded several important findings and advancements in the field of minimally invasive surgery (MIS), particularly in the optimization of stiffness sensing and the integration of advanced control and visualization systems. Although the project encountered some limitations, the outcomes achieved provide a solid foundation for future work.
The optimization studies focused on refining the design of the visual-based stiffness sensor, originally developed by the principal investigator. Various shapes and materials were tested through simulations to determine the optimal configuration. The cantilever beam design was identified as particularly effective, showing that it can be automatically optimized and customized based on the required range of force and stiffness calculations. These findings suggest that with further development, the cantilever beam sensor could be tailored to meet specific surgical needs, enhancing its applicability in MIS.
The existing stiffness sensor was integrated with the UFactory Lite6 robotic arm using the Robot Operating System (ROS). A simple navigation algorithm was developed within ROS, enabling

the robotic arm to follow pre-defined paths and make real-time adjustments based on sensor feedback. The integration process demonstrated that the system could effectively provide real-time stiffness data, which is crucial for differentiating between healthy and abnormal tissues during surgery.

The Meta Quest 3 virtual reality system was integrated to enhance control and visualization capabilities. Using Unity, a cohesive VR environment was created that allowed the surgeon to visualize and control the robotic arm and the surgical field in real-time. The VR system provided an immersive experience, facilitating intuitive control of the robotic arm. The interface displayed real-time data from the sensor, including stiffness information, which helped bridge the gap between the physical operation of the robot and the surgeon's perception.

Key Findings

Optimization Insights: The study demonstrated that the cantilever beam design could be effectively optimized using advanced CAD tools, paving the way for customizable sensors tailored to specific surgical needs.

Feasibility of Integration: The successful integration of the stiffness sensor with the robotic arm and VR system highlighted the feasibility of providing real-time feedback and control in MIS.

Enhanced User Interaction: The use of VR for control and visualization was shown to significantly improve the surgeon's ability to perform delicate procedures with greater accuracy and confidence.

Future Directions

Fabrication and Testing: Future efforts should focus on overcoming current 3D printing limitations to fabricate the optimized sensor designs and conduct comprehensive evaluation tests.

Advanced Navigation Algorithms: Developing more sophisticated navigation algorithms will enhance the system's precision and adaptability, ensuring safer and more efficient surgical procedures.

Clinical Validation: Extensive clinical trials are necessary to validate the system's effectiveness in real surgical settings, aiming to translate these technological advancements into improved patient outcomes.

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１．著者名 Faragasso Angela	４．巻 30
２．論文標題 The IEEE Robotics and Automation Society Automation Technical Committee Cluster Holds Its Inaugural Forum at the 2023 International Conference on Robotics and Automation on Pioneering Visions for a Sustainable Society [TC Spotlight]	５．発行年 2023年
３．雑誌名 IEEE Robotics & Automation Magazine	６．最初と最後の頁 113～116
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/MRA.2023.3322919	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

１．著者名 Faragasso Angela、Bonsignorio Fabio	４．巻 10
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/LSENS.2023.3240745	査読の有無 有
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.ifacol.2022.12.060	査読の有無 無
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Robot navigation in crowds via deep reinforcement learning with modeling of obstacle uni-action	2022年
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10.1080/01691864.2022.2142068	無
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10.1109/LCSYS.2020.2997741	無
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.ifacol.2020.12.846	査読の有無 無
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4．発表年 2022年

1．発表者名 Angela Faragasso
2．発表標題 Smart design of effective robot mechanisms and devices
3．学会等名 International Workshop on Embodied Intelligence（国際学会）
4．発表年 2022年

1．発表者名 Angela Faragasso
2．発表標題 Reproducibility and Benchmarking in Robotics for Healthcare and Nuclear Decommissioning
3．学会等名 Joint Workshop on AI Driving Olympics and Steps Towards Widespread Reproducibility of Research and Objective Performance Evaluation of Intelligent Robotic Systems（国際学会）
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1．発表者名 Angela Faragasso
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1．発表者名 Angela Faragasso
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Angela Faragasso

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Reproducibility and Benchmarking in Medical Robotics: How to manufacture effective devices

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３．学会等名
IEEE/RSJ IROS 2020 Workshop on "Robot-assisted Medical Examination Training（国際学会）
４．発表年
2020年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関