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

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研究課題名（和文）Real-time adaptive control of robots for microsurgery: towards submillimeter accuracy without added sensors

研究課題名（英文）Real-time adaptive control of robots for microsurgery: towards submillimeter accuracy without added sensors

研究代表者
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交付決定額（研究期間全体）：（直接経費）　　3,300,000円

研究成果の概要（和文）：手術ロボットを使用することで、成人手術の精度を高めることができるが、狭い作業空間での処置にはロボットを使用することがここまで不可能であった。本研究では、内視鏡画像を用いた手術ロボットの安全性と精度を向上させ、狭隘な場所での手術にロボットを使用できるようにすることを目的とした。

本研究では、外部センサーを用いた作業空間の部分的な測定または完全な計測による手術道具のオンラインキャリブレーションのアルゴリズムの開発を行なった。このようなオンラインキャリブレーションを用いることで、センサーの精度に依存することのみ、非常に高い精度で術具の位置決めを行うことが可能となる。

研究成果の学術的意義や社会的意義
The proposed adaptive control algorithm is the first of its kind and will guide the development in surgical robotics research. It can also be used in other fields of robotics, such as industrial applications. This development will help pave a future for surgeries in challenging scenarios.

研究成果の概要（英文）：Surgeons can use surgical robots to increase their accuracy in adult surgery, but robots are unavailable for procedures in narrow workspaces. This research aims to improve the safety and accuracy of surgical robots using endoscopic images to enable the use of robots for surgeries in narrow regions.

In this project, the online calibration of surgical instruments with partial or complete task space measurements using external sensors was investigated. Using such online calibration makes it possible to have very high accuracy for the positioning of the tools, depending mostly on the accuracy of the sensors. In parallel to the calibration, the investigation of the recognition and tracking of instruments from endoscopic images was also investigated. AI-based methods for tool tracking have been done using advanced simulators that generate convincing computer-generated images. The results are available in high-ranked peer-reviewed publication (also green open-source) and free software.

研究分野：ロボティクス

キーワード：手術ロボット　適応制御　画像処理　ロボティクス　センサ融合

１．研究開始当初の背景

With the advent of the da Vinci Surgical System (Intuitive Surgical, Inc., USA), robot-aided surgery became a reality in thousands of operating rooms worldwide. Robot aid provides higher accuracy, higher endurance, and added 3D vision. The success of the da Vinci in adult laparoscopy has motivated attempts to use it in surgical scenarios with workspaces more constrained than adult laparoscopy, but those attempts were unsuccessful. Microsurgery requires thinner tools (~3mm diameter), the workspace is narrower (>5 times), and collisions can happen inside and outside the field-of-view. In this context, we had been developing a novel surgical and control algorithms for microsurgery. We have had success in providing constrained motion using a technique called vector-field inequalities inside the narrow workspace in the head, based on the robot's encoder information. However, due to interactions with soft tissues in the head the robots' and tools' parameters change over time. Hence, the measurement of tool position based only on encoder information deviates from the actual tool position. This deviation can be over 3 mm, half the size of the workspace, and affects the safety of collision avoidance algorithms.

２．研究の目的

The proposed research can be divided into two interdependent parts that will be combined and validated:

1. develop an image-based tracking of the surgical tools using image processing techniques,
2. develop an adaptive controller which can consider workspace restrictions,
3. combine 1. and 2. to develop a real-time image-based parameter adaptation algorithm, and
4. validate the proposed methodology using realistic surgical models.

３．研究の方法

Concerning (1.), we explored two research fronts:
1.a) The methodology was initially based on preparing synthetic images using the open-source program Blender. The synthetic images were firstly used to recognize only the shaft of the robotic instrument [1]. This was important because the shaft of the instruments is easier to see and recognize on the images. Then, we expanded this to tracking the whole instrument [2]. We used SSD-6D-based AI algorithms for instrument tracking.
1.b) We developed a novel simulator use physics-based rendering [3]. In this work, we generated a large number of images considering also the interaction of the instruments with soft tissues. We evaluated different levels of realism by comparing the results of networks trained with only synthetic images on a test dataset composed of only real images. We used a UNET-based AI algorithm for evaluation.

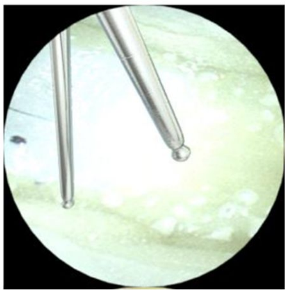

Figure 1 CG image generated in [1]

2.) We developed the worlds-first constrained kinematic adaptive controller [4]. The main idea of the work is to separate the control and adaptation into two optimization algorithms. The first optimization algorithm solves the control problem using vector-field inequalities for collision avoidance. The second optimization algorithm solves the adaptation signal, that is, the change in kinematic parameters to reduce the measurement error, that is the difference between measured tool information and estimated tool information. The second optimization problem has a constraint to guarantee that the task error of the first optimization will never grow, guaranteeing Lyapunov stability.
3.) The combination of these two strategies has been done in the experiments shown in [4]. We first used a high-accuracy sensor (Polaris Vega, NDI, Canada) to quantify the behavior of the controller under differing levels of sensor information. Then, we used a camera-based system.
4.) The validation of each technique using the Bionic Brain surgical model was performed as needed. [1], [2], and [3].

４．研究成果

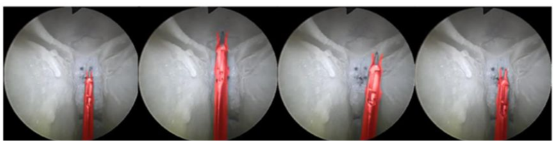

Figure 2 Results of [2].

1.a) We were able to track the complete pose of surgical instruments in the image. The accuracy was better than 1 mm, reaching the original goal of the project.
1.b) We developed a simulator to obtain images in three different levels of realism. We showed that using the proposed physics-based rendering, we can obtain

statistically significant better values for the intersection over union of the semantically segmented images.

2) The most important results of this work have been summarized in [4]. We show that using partial information we can have the adaptive controller reduce the error in that specific dimension. For instance, even with only position measurements we can reduce the translation error. With only orientation measurements we can reduce rotational error. We also show a comparison between our controller and a state-of-the-art constrained kinematic controller. We show that the proposed controller is superior, and we can achieve very high levels of accuracy (much better than 1 mm), depending only on the quality of the sensor measurements.

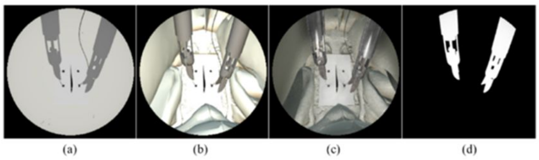

Figure 3 Images generated in [3]

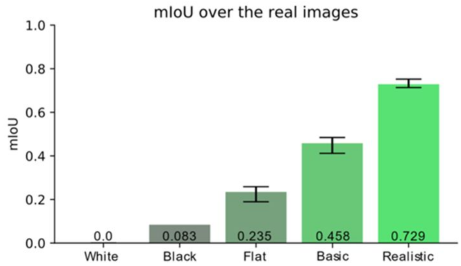

Figure 4 Results of [3].

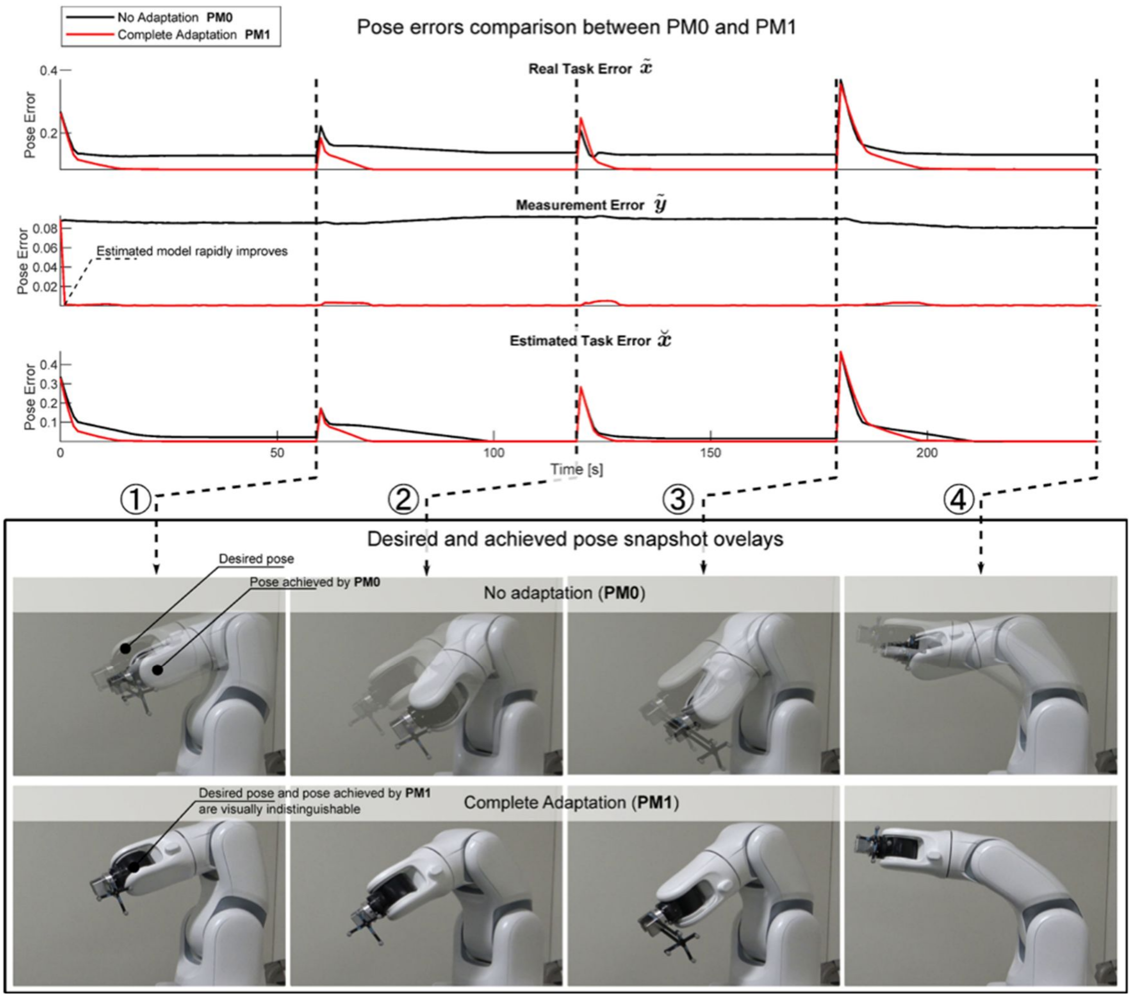

Figure 5 Main results of [4] and of this research project.

References:

[1] Single Shot Pose Estimation of Surgical Robot Instruments' Shafts from Monocular Endoscopic Images. Yoshimura, M.; **Marinho, M. M.**; Harada, K.; and Mitsuishi, M. In 2020 IEEE International Conference on Robotics and Automation (ICRA), pages 9960–9966, May 2020

[2] MBAPose: Mask and Bounding-Box Aware Pose Estimation of Surgical Instruments with Photorealistic Domain Randomization. Yoshimura, M.; **Marinho, M. M.**; Harada, K.; and Mitsuishi, M. In 2021 IEEE International Conference on Intelligent Robots and Systems (IROS), pages 9445–9452, September 2021. IEEE

[3] The Effects of Different Levels of Realism on the Training of CNNs with only Synthetic Images for the Semantic Segmentation of Robotic Instruments in a Head Phantom. Heredia-Perez, S. A.; **Marinho, M. M.**; Harada, K.; and Mitsuishi, M. International Journal of Computer Assisted Radiology and Surgery (IJCARS), 15(8): 1257–1265. August 2020.

[4] Adaptive Constrained Kinematic Control using Partial or Complete Task-Space Measurements. **Marinho, M. M.**; and Adorno, B. V. IEEE Transactions on Robotics (T-RO), 38(6): 3498–3513. December 2022.

５．主な発表論文等

〔雑誌論文〕　計5件（うち査読付論文　5件／うち国際共著　5件／うちオープンアクセス　0件）

１．著者名 Adorno Bruno Vilhena、Marques Marinho Murilo	４．巻 28
２．論文標題 DQ Robotics: A Library for Robot Modeling and Control	５．発行年 2021年
３．雑誌名 IEEE Robotics & Automation Magazine	６．最初と最後の頁 102～116
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/MRA.2020.2997920	査読の有無 有
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 該当する

１．著者名 Heredia Perez Saul Alexis、Marques Marinho Murilo、Harada Kanako、Mitsuishi Mamoru	４．巻 15
２．論文標題 The effects of different levels of realism on the training of CNNs with only synthetic images for the semantic segmentation of robotic instruments in a head phantom	５．発行年 2020年
３．雑誌名 International Journal of Computer Assisted Radiology and Surgery	６．最初と最後の頁 1257～1265
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/s11548-020-02185-0	査読の有無 有
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 該当する

１．著者名 Marinho Murilo Marques、Adorno Bruno Vilhena、Harada Kanako、Mitsuishi Mamoru	４．巻 35
２．論文標題 Dynamic Active Constraints for Surgical Robots Using Vector-Field Inequalities	５．発行年 2019年
３．雑誌名 IEEE Transactions on Robotics	６．最初と最後の頁 1166～1185
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TRO.2019.2920078	査読の有無 有
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 該当する

１．著者名 Marinho Murilo Marques、Harada Kanako、Morita Akio、Mitsuishi Mamoru	４．巻 16
２．論文標題 SmartArm: Integration and validation of a versatile surgical robotic system for constrained workspaces	５．発行年 2020年
３．雑誌名 The International Journal of Medical Robotics and Computer Assisted Surgery	６．最初と最後の頁 e2053
掲載論文のDOI（デジタルオブジェクト識別子） 10.1002/rcs.2053	査読の有無 有
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 該当する

1．著者名 Marinho Murilo Marques、Adorno Bruno Vilhena	4．巻 38
2．論文標題 Adaptive Constrained Kinematic Control Using Partial or Complete Task-Space Measurements	5．発行年 2022年
3．雑誌名 IEEE Transactions on Robotics	6．最初と最後の頁 3498～3513
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TRO.2022.3181047	査読の有無 有
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 該当する

〔学会発表〕　計8件（うち招待講演　0件／うち国際学会　4件）

1．発表者名 Yoshimura, M.; Marinho, M. M.; Harada, K.; and Mitsuishi, M
2．発表標題 MBAPose: Mask and Bounding-Box Aware Pose Estimation of Surgical Instruments with Photorealistic Domain Randomization
3．学会等名 2021 IEEE International Conference on Intelligent Robots and Systems (IROS)（国際学会）
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1．発表者名 Oizumi, S.; Tanaka, M.; Marinho, M. M.; Harada, K.; and Mitsuishi, M
2．発表標題 Preliminary Use of Multi-CycleGAN for Synthetic-to-Real Surgical Instrument Translation in Monocular Endoscope Images
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4．発表年 2021年

1．発表者名 田中 真帆，マルケス マリニョ ムリロ，原田 香奈子，光石 衛
2．発表標題 術具位置推定のための画像生成手法に関する研究
3．学会等名 ロボティクス・メカトロニクス講演会講演概要集 2021
4．発表年 2021年

１．発表者名
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２．発表標題
Single Shot Pose Estimation of Surgical Robot Instruments' Shafts from Monocular Endoscopic Images

３．学会等名
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４．発表年
2020年

１．発表者名
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２．発表標題
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２．発表標題
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３．学会等名
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２．発表標題
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３．学会等名 ロボティクス・メカトロニクス 講演会 2019
４．発表年 2019年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

The DQRobotics webpage. https://dqrobotics.github.io

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