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論 文 題 目	Development of Data-driven Vision-Based Tactile Sensor System
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論文の内容の要旨

Minimally invasive surgeries are performed using various medical instruments such as catheters and endoscopes in order to reduce the burden on patients. However, these procedures rely on indirect observation modalities, including endoscopy and X-ray CT, and therefore cannot be performed in an intuitively manipulable manner. As a result, a high level of operator expertise is required. In this context, the introduction of tactile sensing into minimally invasive medical devices is expected to improve the spatial resolution of intraoperative monitoring.

To date, a number of catheter-type tactile sensors based on electrical principles have been proposed, but all of them face challenges when high-density tactile sensing is required. In this study, we address these challenges by proposing a novel vision-based tactile sensing system, “TacBalloon”, which is built upon a balloon catheter originally developed for cardiac ablation procedures.

In particular, to realize a compact, balloon-catheter–scale tactile sensor, which has been difficult to achieve using conventional vision-based tactile sensing methodologies, we construct a data-driven tactile sensing framework. The proposed system adopts a marker-based tactile sensing approach, in which a marker pattern printed on the skin surface is observed through an endoscope and used to infer tactile information. Tactile estimation is performed by a neural-network-based tactile estimation model, which is trained on a dataset generated entirely in simulation. During training, data augmentation and related techniques are introduced to mitigate the Sim2Real gap.

We experimentally evaluated the performance of the tactile balloon catheter implemented using the proposed data-driven tactile sensing system. Within regions where the surface markers were visible, the system achieved a contact depth estimation accuracy of approximately ±1 mm and reliably reconstructed complex surface deformations. Furthermore, by comparing against photogrammetry, we assessed its ability to estimate contact areas on anatomically realistic models. The results demonstrate that TacBalloon enables high-density, wide-area tactile sensing on a flexible balloon surface and constitutes a promising solution for providing real-time tactile feedback in minimally invasive surgery.

Keyword : Tactile sensing, Tactile sensor, Vision-Based Tactile sensor, Balloon Catheter, Softbody Simulation, Optical Simulation , Machine learning

論文審査の結果の要旨

Minimally invasive surgery employs instruments such as catheters and endoscopes to reduce patient burden; however, these procedures rely on indirect observation modalities, including endoscopy and X-ray CT, limiting intuitive manipulation and requiring high operator expertise. Introducing tactile sensing into minimally invasive devices is therefore expected to enhance the spatial resolution of intraoperative monitoring. Although several catheter-type tactile sensors based on electrical principles have been proposed, achieving high-density tactile sensing remains challenging.

This thesis addresses this limitation by proposing a novel vision-based tactile sensing system, TacBalloon, built upon a balloon catheter originally developed for cardiac ablation. To realize a compact balloon-scale tactile sensor, which is difficult to achieve with conventional vision-based approaches, this thesis introduces a data-driven tactile sensing framework. The system adopts a marker-based method in which a marker pattern printed on the balloon surface is observed through an endoscope to infer tactile information. Tactile estimation is performed using a neural-network-based model trained entirely on simulation data, with data augmentation techniques employed to mitigate the Sim2Real gap. Experimental evaluation of the proposed tactile balloon catheter demonstrates a contact depth estimation accuracy of approximately ±1 mm within regions where markers are visible, along with reliable reconstruction of complex surface deformations. Comparison with photogrammetry further confirms accurate estimation of contact areas on anatomically realistic models. These results indicate that TacBalloon enables high-density, wide-area tactile sensing on a flexible balloon surface and represents a promising approach for real-time tactile feedback in minimally invasive surgery.

The student prepared papers and the thesis in English. Accordingly, the dissertation merits the award of the doctoral degree.