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