“motion.png”

2D motion estimation in the camera view. (a) Image frames at two successive time steps. (b) Incremental displacement between two matched blocks with the highest similarity. An red block is selected from the frame at time step k as the template pattern, which is matched by the yellow block searched from the frame at time step k +1.

“orientation\_error.png”

(a) Motion estimation errors sampled at angular resolution of 0.25°. (b) Twisting angle of robot end-effector (camera) under varying actuation inputs when one chamber is inflated. All three chambers are pre-pressured with actuation input α0.

“vsBlockDiagram.png”

Framework of the proposed online learning control method.

“vsSetup.png”

Soft robot manipulated in a LEGO® scene. The soft manipulator is fabricated using silicone rubber, comprising three string-constrained pneumatic chambers for actuation. The robot tip is equipped with an endoscopic camera and five LEDs.

“exploration.png”

Three thousand sample pairs of robot actuation and tip position collected for initialization of the inverse model. (a) Training set partitioned into six (colored) clusters based on their actuation inputs with the k-means algorithm. (b) Corresponding tip position distribution of six clusters is also shown.

“vsPoint2point.png”

Tracking of five target points, which are the center of red block, manually selected in the camera view. (a) Panorama image obtained by stitching the image sequences. The red box represents the template pattern centered at each selected target. The green circles denote the camera centers at each step, showing the footprints of matched block feature throughout the journey. (b) Corresponding robot configurations with the five targets traced at image center. (c) Tracking errors in unit of pixels.

“vsTargetTrackDisturb.png”

Target tracking with external forces applied. The robot is pulled away from its initial straight configuration and then released. The bottom figure shows the tracking errors at three phases of loading. The orange dash line represents the 10-pixels tolerance.

“vsPathFollow.png”

Path following test on a predefined “∞” trajectory. (a) Trajectory of the tracked targets in the camera view. A target (red-dashed block) is initially selected at the intersection of the “∞” trajectory for robot tracking. (b) u and v coordinates of the tracked block throughout the journey. (c) Tracking errors in three cycles. (d) Summary of the error statistics.

“vsPathFollowLocd.png”

Performance of path following under varying payload. A (6-gram) balloon is wrapped around the robot tip. Water is pumped in-and-out of the balloon to introduce a changeable tip load (6∼21 g). (a) Tracked trajectory in three successive cycles. Deviations in regard to the pre-training error (1st cycle in red), injecting and removing water (2nd cycle in blue) were observed. (b) Corresponding tracking errors throughout the journey. (c) Tracking error vs additional payload. The load is presented in % with respect to the robot original mass, 20 g. (d) Snapshots of the robot and balloon at three time steps.

“vsFBGrobot.png”

Pneumatic-driven 3-chamber robot is used. An optical fiber with multiplexing 16 FBGs is helically wrapped around the manipulator for sensing feedback of robot configurations in real-time. A monocular endoscopic camera and a LED module are fixed on the tip cap of robot. Cross-section and axial views of the robot show the silicone chambers constrained individually with helical Kevlar strings.

“lapaScenario.png”

Simulated scene mimicking the laparoscopic surgery environment. Pre-bending of the robot is applied to simulate the laparoscope setup. EM tracking coils are equipped to measure the instantaneous poses of robot tip.

“liverOldP.png”

Robot following of a predefined “Batman” path. (a) The motion estimated by image processing of the endoscopic view alone. (b) Bright reflective spot displaced along the tissue due to the robot motion. Features in the red block are selected by the user before the motion displacement (Left). After, such a block is expected to keep matching/tracking at the same square of features (Right. Black dotted block indicates the position of red block selected at the previous time step), acting as a static reference for robot to “draw” the path. (c) Actual path of end-effector recorded by EM tracking coils, which project on the same u−v coordinates. The recorded deviation along those 3 cycles is caused by the error of such a red block matching/tracking.

“liverNewP.png”

Tracking performance of the same “Batman” path, with the motion estimated by FBG-enhanced method. (a) Estimated motion of tracked feature in the endoscopic view. (b) After 3 cycles, the offset of tracked feature from the red block to the black dotted block is obviously reduced, resulting in more accurate tracking in (c) recorded by the EM tracking probe.

“liverErrors.png”

Errors of “Batman” path following with a simulated laparoscopic setup. (a) Visual servoing with camera-based motion estimation, inducing a mean error of 94.45 (SD: 53.55) in the 1st cycle. (b) Visual servoing with FBG-enhanced motion estimation.

“ARregistration.png”

Flowchart of the coordinate registration loop of the proposed augmented reality system. The pre-op model is registered to the phantom skull. EM tracking is implemented to register the virtual camera which renders an extended virtual view overlaid on the real camera view. The extended view only contains virtual objects, whereas the current view contains both virtual and real camera images.

“ARsetup.png”

Experimental setup for augmented reality guided visual servoing. A compact tendon-driven robot (outer diameter 4 mm) is integrated with a monocular camera. An EM generator is placed beneath the 3D printed skull phantom and tendon-driven robot.

“ARinterface.png”

Augmented reality interface. The augmented view is generated by aligning the virtual camera with the real endoscopic camera through hand-eye calibration. (a) Target initially located in extended view (above), with corresponding real camera view shown below. (b) Augmented view after visual servoing of robotic endoscope towards the target (above) and corresponding real camera view (below).

“ARvisualservo.png”

Tracking of a target located in the extended view. Four intermediate way-points are manually selected in the camera view for robot tracking as in Fig. 3.6. (a) Mosaic image obtained during the tracking journey. (b) Absolute tracking errors in pixels. The plateaus of error (last for 2-4 s) (indicated by pink arrows) are due to mechanical backlash of the tendon-driven robot.