

Visual servoing for tracking cartilage with a robotic endoscope

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Abstract: This paper describes the visual servoing of a robotic endoscope prototype by tracking cartilage in visual feedback from a miniature camera. To track the movement of tissue relative to the camera, three different image processing algorithms were implemented and compared in a first experiment on cartilage of a porcine knee. The experiment showed that tracking cartilage is feasible with a miniature camera and can be used to perform visual servoing with an endoscope.

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I. Introduction

A surgeon requires a broad range of skills. When using a flexible endoscope, the surgeon has to steer the advancement, the rotation and the tip bending of the endoscope, while the actual task is inspecting the surgical site, finding pathologies, or taking biopsies. To simplify flexible endoscope manipulation, robotic endoscopes are a promising solution. While the robot performs endoscope steering, the surgeon could focus more on the tasks that cannot be automated. In arthroscopy for example, robotic endoscope steering could thereby enable the use of more flexible endoscopes that improve the field of view while also decreasing stress applied to surrounding tissue. Maintaining a target structure in the center of the endoscope's view is an endoscope steering task that we consider promising for automation. Visual servoing is an established control approach for robotics in medicine [1] to extract information about the endoscope's pose relative to tissue from the endoscope camera, and to control the endoscope movement based on this information. Previous work applying visual servoing for endoscopes has targeted soft tissue tracking. For example, a miniature camera was used to control an electromagnetically actuated endoscope by estimating the differential kinematics based on the visual feedback obtained during bronchoscopy [2]. A commercially available gastroscope was motorized and visually servoed to compensate for tissue movements [3]. Contrary to these examples, arthroscopic images show bright and homogeneous surfaces, which makes tracking more difficult. In our work, we aim at showing the applicability of visual servoing for arthroscopy with an articulated two-degree-of-freedom robotic endoscope based on images from an integrated miniature camera.

II. Materials and methods

II.1 System description and testing setup

In our setup, a miniature camera (NanEye 2D, ams AG, Premstaetten, Austria) with a resolution of 250x250 pixels

was embedded at the tip of a robotic endoscope. This camera transmitted the image data at a frame rate of 40 fps, to an image acquisition board and from there to a PC (Intel Core i7-7500U @ 2.70 GHz, 2 Cores), where the incoming image data was processed and sent to the control system (control loop running at 1 kHz). The feature error e was used as input to compute the desired motor velocity output v_{des} . To test the visual servoing algorithm, a simple articulated endoscope prototype was built. Two revolute joints allowed the endoscope to tilt in two orthogonal directions α and β in a range of ± 30 degrees. The endoscope was remotely actuated by two pairs of antagonistic tendons, which were attached to the endoscope on one end, and rolled around a winch on the other end. Each winch for one antagonistic pair of tendons was rotated by a motor through a worm gear transmission. Two motors (RE25 DC motors, Maxon Motor AG, Sachseln, Switzerland) were used in velocity control mode provided by the motor drives (Maxon MAXPOS 50/5) (Fig. 1).

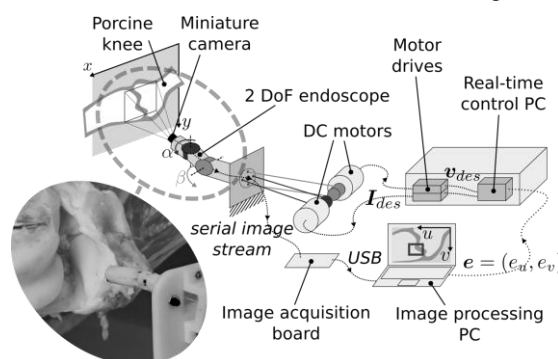


Figure 1: Overview of the visual servoing system

Three different tracking algorithms, all part of the OpenCV library [4], were implemented and compared in an experiment tracking a porcine knee:

- **BLOB:** "SimpleBlobDetector" class [4] detects a manually placed circular marker in every image frame. We considered this robust visual tracking algorithm as a

baseline for the comparison of the other tracking algorithms to show the limitations of real-time control and actuation of our setup.

- **FAST:** Optical flow tracker that uses a variation of the Lucas-Kanade method [5] to compute optical flow, which tracks an initially defined feature. The FAST feature detector [6] was used to find an easily trackable feature close to the desired target on the knee.
- **MOSSE** tracker [7] uses an adaptive correlation filter to track a target region initially defined by a bounding box. If successful, all three trackers continuously yield the position of the tracked target $\mathbf{s} = (u, v)$ in the image coordinates. This position was subtracted from the reference position \mathbf{s}^* to yield the feature error $\mathbf{e} = \mathbf{s}^* - \mathbf{s}$, which was then transmitted to the real-time control system.

II.II Experimental procedure

The endoscope was placed in front of a porcine knee (donated by a local butchery) at a distance of 4 cm. The porcine knee was fixed on a motorized 2D stage at a knee flexion angle of 90 degrees. The same real-time control system was used to control both the 2D stage and the endoscope. A movement following experiment was performed for each of the three trackers described above. After initializing the tracker, the stage was moved 20 mm in x - and 20 mm in y -direction simultaneously. The velocity for each axis was limited to 0.05 m/s. To reduce the error due to varying lighting conditions this procedure was repeated three times for each tracker (3x MOSSE \rightarrow 3x FAST \rightarrow 3x BLOB). The performance of the visual servoing was quantitatively analyzed by computing the following metrics: **latency**, the time it took the image acquisition and processing to detect a feature error greater than one pixel; **overshoot**, the maximal endoscope angles relative to the settled endoscope angles in percent; and **settling time**, the time from when the 2D stage stopped to when both endoscope angles stayed within a tolerance band of 2% around the settled endoscope angles.

III. Results

The reference movement was commanded at $t=0.05$ s and carried out with a maximum stage velocity of 0.05 m/s, thus resulting in a ramped up step (Fig. 2, top).

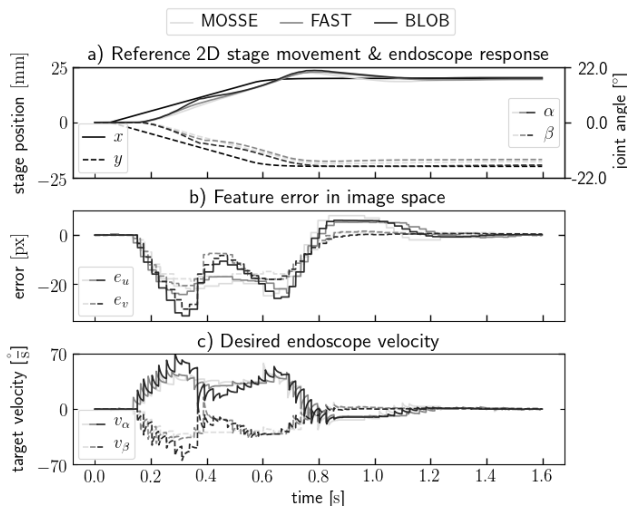


Figure 2: Representative results of one data set per tracker

All three repetitions of the experiment with each tracker resulted in similar performance (Table 1).

Table 1: Results in performance metrics (values: min-max of the three repetitions per tracker)

	MOSSE	BLOB	FAST
Latency [ms]	93-101	91-98	83-96
α -Overshoot [%]	13.8-16.9	15.6-16.9	15.9-16.8
β -Overshoot [%]	0.1-5.6	2.7-4.6	3.2-4.9
Settling time [ms]	344-595	414-553	314-421

IV. Discussion

All three tracking algorithms showed a comparable performance in terms of latency, settling time and overshoot. The marker-less trackers did not fall short of the blob tracker, which we had expected to represent a performance limit of our setup. The comparable results indicate that the main limitations of our visual servoing system might not be accuracy and speed of the tracking algorithm, but rather arise from the mechanical setup or the camera frame rate, which was the main contributor of control latency (40 fps $\hat{=}$ 25 ms/frame). Some adverse effects of the mechanical system can be observed in the results: the first peak of the feature error might originate in an initial stick-slip effect of the actuation, causing the feature error to rise rapidly in the beginning. The greater overshoot in α - than β -direction might be caused by slightly misaligned coordinate frames of the camera and the endoscope. For future work, we plan to improve the mechanics and analyze the visual servoing algorithms with respect to stability and robustness, e.g. for different reference movements, occlusion, or varying lighting conditions. In conclusion, we were able to show feasibility of tracking cartilage tissue with an articulated endoscope using visual servoing algorithms based on low resolution images of a miniature camera.

AUTHOR'S STATEMENT

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