Robotic Control of All-Optical Ultrasound Imaging

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INTRODUCTION

Many surgical procedures are performed minimally invasively, with the use of miniaturised devices, such as catheters and endoscopes. One such procedure is fetoscopy for both diagnostic and therapeutic purposes. Miniature imaging probes are essential for procedures performed during pregnancy to avoid surgical complications and improve outcomes. Current instrumentation is based on thin rigid endoscopes comprising working channels that can be used to deliver instrumentation into the workspace.

Recent research has focused on improving intrauterine visualisation; one such way is using all-optical ultrasound (OpUS), where ultrasound is both generated and received using light [1]. OpUS can provide high resolution imaging from small form factor devices. Current devices typically contain a single transducer element and hence provide only A-scans. Combination with robotics shows potential for performing accurate imaging sweeps during surgical procedures [2].

This paper presents the design and operation of a rigid, robot-mounted endoscope that integrates an OpUS sensor. Through a ROS interface, A-scans and kinematic information are acquired simultaneously and in real-time during robotic manipulation. After performing a calibration between the sensor and the robot, a tissue mimicking phantom with anatomically realistic vascular structures was imaged using various scanning trajectories, and the resulting 3D data were collected, processed and displayed in real-time.

MATERIALS AND METHODS

An instrument with a diameter of 5mm and length of 300mm was developed with a stainless-steel shaft. The tip of the endoscope was printed in stainless steel with channels for a stereo CMOS camera (Naneye Stereo, ams AG, Austria), fibre optic lighting channels, and a 1.1mm working channel. The instrument shaft is held in a housing made from PLA using an Ultimaker 3, (Ultimaker BV, Netherlands), this housing provides the interface to mount the instrument to a robot flange.

An all-optical ultrasound probe comprising a fibre optic ultrasound transmitter and a fibre optic ultrasound receiver was fabricated. The two optical fibres were held adjacent, and heat shrink tubing was used to align their distal end surfaces. This pair of optical fibres was housed

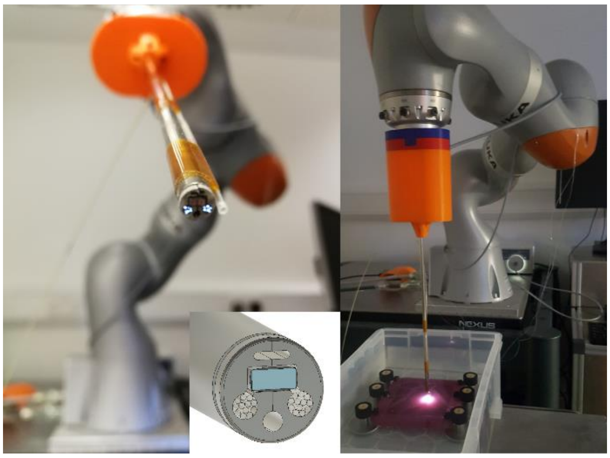

Figure. 1. Left - close-up of assembled endoscope tip showing the Naneye stereo camera, lighting channels, OpUS imaging probe and robotic manipulator. **Inset** - CAD model of endoscope tip. **Right** - Photograph of the rigid endoscope positioned above an acoustic placenta phantom.

within an acoustically transparent polymer tube (TPX, outer diameter: 1.2mm) for robustness. This OpUS imaging probe achieved an axial imaging resolution of 60μm[3]. In this instance, the OpUS sensor could not be placed within the working channel of the endoscope due to the protective TPX sheath around the sensor. It was therefore mounted to the side of the instrument shaft, thus increasing the overall diameter of the endoscope to 6.2mm. The assembled endoscope, which can be seen in Fig. 1, was mounted to a KUKA LBR iiwa 14 R820 robotic manipulator (KUKA AG, Germany), which is a 7 DOF manipulator with a payload of 14kg, a repeatability of ±0.15mm, and a reach of 820mm.The instrument is controlled through a ROS interface, where the robot manipulator is controlled through a high speed joint interface (500hz, Fast Robot Interface, Kuka). The instrument is constrained to a virtual Remote Centre of Motion (RCM) placed at the incision point on the body using a custom written interface based on the motion planning framework MoveIt. A-scans are sent from the OpUS processing cart using the LabVIEW ROS package, where each A-scan is converted to a point cloud message in the RCM coordinate system and published. These A-scans are then cumulatively merged as they are published and processed through a voxel filter to prevent overlapping points.

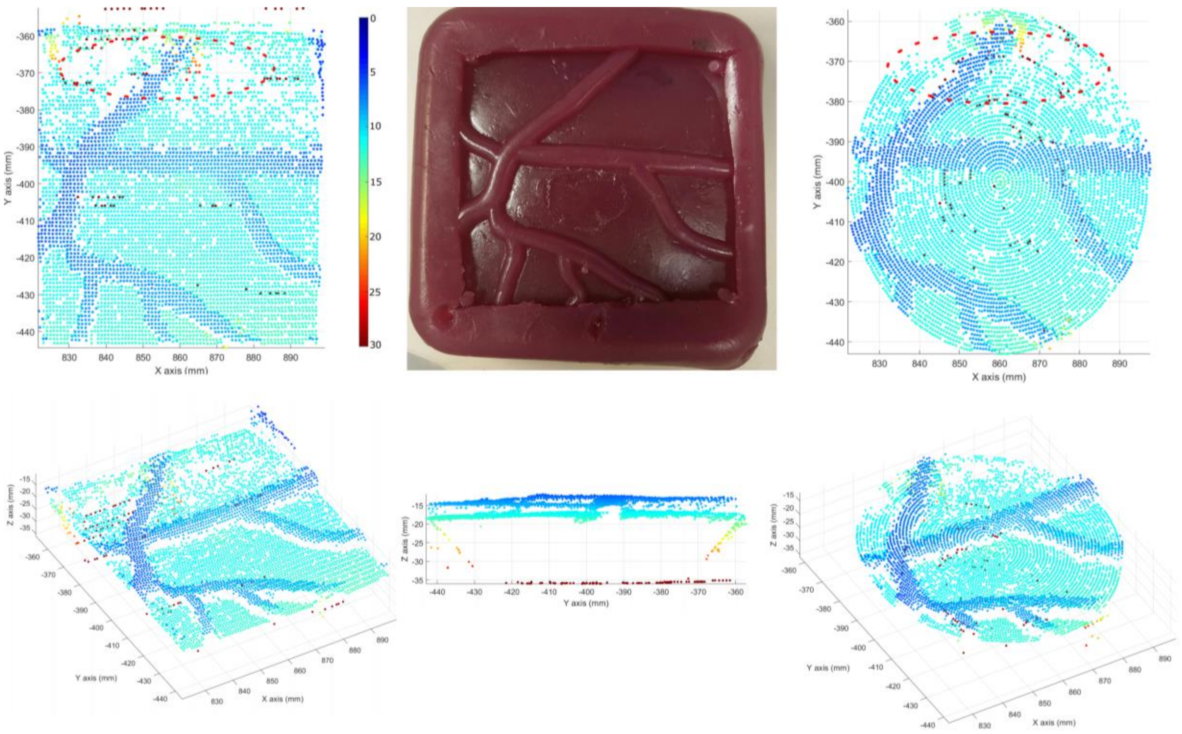

Figure. 2. 3D visualisation of the OpUS images of the placenta phantom acquired through robotic probe manipulation. A photograph of the ultrasound placenta phantom is shown in the centre of the top row **Left column -** 3D OpUS images obtained using a raster scan pattern, in top-down (top) and angled (bottom) view. **Right column -** 3D OpUS images obtained using a spiral scan pattern. **Bottom centre -** side-view of the 3D OpUS image obtained using a spiral scan pattern. In each image the distance of the points from the endoscope tip are colour-encoded using the colourbar (in mm) displayed in the top left panel.

RESULTS

A placenta phantom was fabricated using gel wax as a tissue-mimicking material. The phantom featured clinically realistic acoustic properties such as propagation speed of sound, echogenicity, and speckle pattern [4]. This phantom was placed into a water bath onto an acrylic sheet and clamped down with metal posts along the side of the phantom.

The phantom was scanned using the endoscope with two independent scanning trajectories: a raster and a spiral trajectory. The RCM was placed approximately in the center of the phantom and 160mm above the phantom. The raster scan was generated on a plane over the entire 80mm x 80mm area in 1mm increments at approximately 10mm from the phantom. The spiral scan was limited to a total diameter of 80mm and comprised 40 cycles around the start point to yield a similar scan point density. The resulting 3D OpUS images are shown in Fig. 2.

CONCLUSION AND DISCUSSION

This paper has presented the design, control, and operation of a multimodal robotic endoscope with integrated white light and optical ultrasound imaging. The endoscope consists of a miniature stereo camera, fibre optic light channels and an optical ultrasound sensor within a 6.2mm overall diameter; whilst being manipulated by a robot arm, constrained through software to a RCM.

The endoscope is demonstrated through generating scanning paths over a gel wax placenta phantom. A-scans acquired by the OpUS sensor are processed into 3d surfaces using the kinematics of the endoscope. The vessels can be clearly discriminated from the main body of the placenta. To the authors' knowledge, the OpUS scans presented in Fig. 2 are the largest presented in literature. Future work will focus on minaturisation of the endoscope while introducing an internal channel for the OpUS sensor together with therapeutic laser light delivery. In addition, the integration between the imaging sensors and robot manipulator will be utilised to constrain the robot to the surgical scene and to introduce adaptive scanning and treatment trajectories.

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