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Pico Lantern: Surface reconstruction and augmented reality in laparoscopic surgery using a pick-up laser projector

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ABSTRACT

The Pico Lantern is a miniature projector developed for structured light surface reconstruction, augmented reality and guidance in laparoscopic surgery. During surgery it will be dropped into the patient and picked up by a laparoscopic tool. While inside the patient it projects a known coded pattern and images onto the surface of the tissue. The Pico Lantern is visually tracked in the laparoscope's field of view for the purpose of stereo triangulation between it and the laparoscope. In this paper, the first application is surface reconstruction. Using a stereo laparoscope and an untracked Pico Lantern, the absolute error for surface reconstruction for a plane, cylinder and ex vivo kidney, is 2.0 mm, 3.0 mm and 5.6 mm, respectively. Using a mono laparoscope and a tracked Pico Lantern for the same plane, cylinder and kidney the absolute error is 1.4 mm, 1.5 mm and 1.5 mm, respectively. These results confirm the benefit of the wider baseline produced by tracking the Pico Lantern. Virtual viewpoint images are generated from the kidney surface data and an in vivo proof-of-concept porcine trial is reported. Surface reconstruction of the neck of a volunteer shows that the pulsatile motion of the tissue overlying a major blood vessel can be detected and displayed in vivo. Future work will integrate the Pico Lantern into standard and robot-assisted laparoscopic surgery.

1. Introduction

Laparoscopic surgery is minimally invasive and has several advantages over open surgery. However, laparoscopic surgery poses its own set of challenges associated with surgical navigation. These include surface depth recovery, instrument tracking and haptic feedback. This paper presents the Pico Lantern, a device built primarily to address the challenge of surface depth recovery by mapping the shape of internal organs.

The Pico Lantern is a projector that is small enough to be dropped into the abdominal cavity (via a cannula or incision) and picked up therein, by the surgeon. It is a source of structured light and, simultaneously, a projector for augmented reality in surgery. In addition to doing surface depth recovery, or surface reconstruction, it detects and highlights subtle surface movements associated with the pulsatile motion of underlying blood vessels. The Pico Lantern is designed for enhancing laparoscopic surgeries in general. Partial nephrectomy (kidney cancer resection) has been chosen as the first application for the Pico Lantern. A video of a Pico Lantern prototype scanning an ex vivo kidney is in the supplementary material.

1.1. Motivation

One of the main motivations for developing the Pico Lantern is to overcome the reduced depth perception and limited viewpoints in laparoscopic surgery. Further challenges that need to be overcome are to make it easier to register pre-operative and intra-operative images, to identify important subsurface anatomy such as blood vessels and to provide a tool for visualizing surgical guidance information. In this paper, the Pico Lantern data is used for surface reconstruction of objects and organs, detecting blood vessels and creating virtual viewpoints of the surgical scene. Further, the Pico Lantern's augmented reality feature is used to project surgical guidance information onto the surgical scene.

1.2. Background

A laparoscope is an instrument that is inserted through a small surgical incision and used for looking at the inside of the abdomen

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and pelvis. The majority of laparoscopic surgery is done using monocular laparoscopes making it difficult to perceive spatial relationships between objects in the surgical scenes. Several companies have improved visual perception for surgery by developing stereo laparoscopes. Examples are the 3DHD Vision System (ConMed, NY, USA), the Endoeye Flex 3D (Olympus, Shinjuku, Tokyo, Japan) and the da Vinci Surgical System for minimally invasive surgery (Intuitive Surgical, Sunnyvale, CA). The da Vinci system offers both stereo vision and dexterous tele-manipulation of the surgical tools and laparoscope. For these reasons and more, 85% of radical prostatectomies in the USA are performed as robotic-assisted laparoscopic radical prostatectomies with the da Vinci surgical system (Barry et al., 2012) and robotic-assisted laparoscopic partial nephrectomy is a standard of care for renal cancer (Janetschek, 2007). The da Vinci system is an ideal testing platform because it can hold the Pico Lantern steady. Also, because it has a stereo laparoscope, the Pico Lantern surface reconstruction can be compared to conventional stereo laparoscopic surface reconstruction.

1.3. Related work

1.3.1. Surface reconstruction

Within the research community, there has been sustained interest in developing guidance tools for minimally invasive surgery. An important criteria for many of these guidance tools is that they perform 3D surface reconstruction of the tissue quickly and accurately for registering pre-operative images to the live surgical view (Benincasa et al., 2008; Pratt et al., 2010). The challenge is to perform such registration in real-time in the presence of displaced and possibly deformed soft tissue surfaces.

A detailed review of the five main approaches for 3D surface reconstruction in laparoscopic surgery has recently been published (Maier-Hein et al., 2013). The five approaches are stereo endoscopy (requiring a stereo endoscope), monocular shape-from-X, Simultaneous Localization and Mapping (SLAM) from a moving camera, time-of-flight from a specialized illumination unit, and structured light. Each approach offers benefits and trade-offs.

The structured light approach replaces a camera in the conventional stereovision system with an active device which projects a known coded pattern onto the scene. The known pattern is then identified in the captured image. Several research groups have made important contributions to the field of structured light in laparoscopic surgery. They have all demonstrated mapping smooth featureless organ surfaces quickly and accurately. Hayashibe et al. (2006) developed a laser-scan endoscope for real-time 3D shape intraoperative measurement and visualization. They solved the correspondence problem between the laser-scan endoscope and endoscope by using an optical galvano scanner and high-speed camera to create and detect a laser-beam strip that scanned the tissue surface (Hayashibe et al., 2006). Maurice et al. (2012) built a structured light vision system in a 10 mm diameter two-channel laparoscope and achieved satisfactory 3D reconstruction results at 25 images/s in an in vivo pig experiment. They designed a monochromatic subperfect map-based pattern and sped up the pattern decoding process by utilizing the known epipolar geometry of the laparoscope. Reiter et al. (2014) presented the Surgical Structured Light (SSL) system which projects a pattern that is invisible to the surgeon. This is possible because the SSL system includes two off-the-shelf 10 mm laparoscopes, a narrow-band blue LED projector and a dichroic beam splitter (Reiter et al., 2014). Two other groups have used flexible probes for delivery of the structured light. One flexible probe used Single Shot Structured Light that was delivered via a sensor head with a diameter of 3.6 mm which contained a catadioptric camera and pattern projection unit (Schmalz et al., 2012). The second flexible probe was a 1.7 mm multi-spectral fiber-based structured light probe (Clancy et al., 2011) that can fit in the biopsy channel of an endoscope and project a constant pattern of 127 identifiable colored spots. The Pico Lantern differs from all of the devices in the papers listed above because the structured light source is inside the abdomen, it is free to move relative to the laparoscope and no external tracking tool is required. This means that there are fewer calibration and registration steps and a reduced lever arm effect so the surface reconstruction and augmented reality projections are potentially more accurate.

1.3.2. Augmented reality

Another related research area for surgical guidance is augmented reality. This topic has a history of more than three decades of work. A pioneering contribution to the field in augmented reality and laparoscopic surgery was the display of computer-generated subsurface anatomy to the surgeon with a combination of a camera, projector and helmet-mounted display (Fuchs et al., 1998). Challenges in augmented reality surgical guidance include the transformation of images into the laparoscope view and the natural depiction and spatial perception of structures (Hansen et al., 2010).

More recently, a large projector for interventional radiology (Nicolau et al., 2008) and a handheld projector for open surgery (Gavaghan et al., 2012) have been used as sources of structured light and augmented reality. The projectors used in those experiments were placed outside of the patient. Recently, the multi-billion dollar cell phone industry has shown significant interest in miniaturizing projectors so that they can be built into consumer electronics. We have leveraged the miniaturization of laser-based Pico projectors to develop a low cost (<$ 500US) pick-up projector for laparoscopic surgery. The projector uses laser diodes and a raster scanning laser (micro electro mechanical system scanner mirror: $2.9 \times 2.2 \times 1$ mm^3) from the Microvision ShowWX + Pico projector (Redmond, WA, USA). The proposed system is called a Pico Lantern because it illuminates the area of interest after it is dropped into the abdominal cavity and picked up therein. It projects high fidelity images that are in focus at almost all depths because it has a single-pixel beam expansion that matches the rate of expansion of the projected image size.

Further, the surgical scene is shown from virtual viewpoints. In the future, surgeons may use these virtual viewpoints to visualize complex intra-operative surgical scenes. For example, virtual viewpoints would be helpful in determining the distance from the surgical instrument to the tissue or how far the kidney tumor protrudes from the kidney surface.

Many types of augmented reality can be implemented with the Pico Lantern by projecting computer-generated images onto tissue surfaces. For augmented reality the same coordinate system transformations that are already used to calculate the 3D surface reconstruction are used. A projection of the frequency filtered displacement of the tissue back onto the tissue surface is demonstrated in this paper. Solutions to the challenges of projecting on non-white curved surfaces exist (Park et al., 2006). It is also possible to adjust projected images so that they appear undistorted on curved surfaces (Tardif et al., 2003). Like a real lantern, the Pico Lantern can be used as a supplementary light source which can be automatically adjusted to reduce bright specular reflections. It can also be used to illuminate surfaces from a shallow angle to detect small protruding features by their long shadows.

1.4. Scope of work

Preliminary work on the Pico Lantern concept was previously published (Edgcumbe et al., 2014). This paper is an extension over the previously published work because of the following new additions:

1. A 28 mm diameter working Pico Lantern prototype, shown in Fig. 1 and in the supplementary video, which can be picked up by a laparoscopic tool and moved freely to project patterns and images (the previous publication proposed a design for a Pico Lantern prototype but it was not fully functional).