



Proof of principle of a novel angular sensor concept for tracking systems

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ARTICLE INFO

Article history:

Received 7 February 2018

Received in revised form 31 July 2018

Accepted 9 August 2018

Available online 10 August 2018

Keywords:

ASTRAS

Angular sensor

Rotary encoder

Medical tracking device

ABSTRACT

Robot-assisted and computer-guided minimally-invasive procedures represent a turning point in Minimally-Invasive Surgery (MIS) because they overcome significant limitations found in current state-of-the-art manual MIS procedures (e.g. imprecise motion, hand tremor, fatigue of the surgeon, limited workspace/maneuverability, etc.). Importantly, robotic systems can only reach the required high accuracy and precision when a tracking system with the corresponding accuracy and precision level for the surgical tool's end-effector enables closed-loop feedback control. Herein, we present a tracking system meeting the above required high accuracy and precision called ASTRAS (Angular Sensor for TRacking Systems). In this paper, the working principle and performance of ASTRAS are presented and characterized respectively.

ASTRAS is arranged in a way that a tilt of a mirror produces a shift of a shadow cast on an image sensor. Since the mechanical constraints between the light source, mirrors, shadow mask, and image sensor are known, the angle can be derived from the measured shadow shift. The working principle of ASTRAS allows the measurement of 2 degrees of freedom at once. Additionally, the commercial availability of small image sensors ($\sim 1 \times 1 \times 0.5 \text{ mm}^3$) allows implementing ASTRAS in the future as a down-scaled version in surgical tools such endoscopes.

The characterization of ASTRAS was performed with an experimental setup evaluating the angular measurement performance in one degree of freedom. The results revealed a precision of $\sim 3 \cdot 10^{-6} \text{ rad}$, a thermal stability of $1.9 \cdot 10^{-5} \text{ rad/}^\circ\text{C}$, a long term drift 10^{-5} rad/day , and a linearity error of $\sim 10^{-4} \text{ rad}$.

Future developments will focus on implementing a miniaturized prototype and making a chain of sensors to use in articulated devices.

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1. Introduction

In the past years, robot-assisted and computer-guided surgeries have become more and more important in the medical field. These technological developments enhance the capabilities of surgeons in MIS procedures, which is directly beneficial for patients. The MIRACLE¹ project (Minimally Invasive Robot Assisted Computer-guided Laserosteotomy) is devoted to the development of a robotic

endoscope able to perform osteotomies (bone cuts) with a laser in a minimally invasive way. Such osteotomies have several advantages compared to conventional cuts, for example faster healing or the freedom in cut geometry [1–5]. One fundamental requirement for the MIRACLE project is to perform minimally invasive accurate laser cuts with a precision of $\sim 0.2 \text{ mm}$. For this reason, it is required to know the pose (position and orientation) of the end-effector of the robotic MIRACLE endoscope, or other surgical systems, with high accuracy and precision in order to close the feedback control loop. In the case of a robotic endoscope with many degrees of freedom, such as it is planned for in the MIRACLE project, it is important not only to know the pose of the end-effector but also the entire shape of the endoscope.

General purpose tracking systems (some of which have been adapted for medical applications) based on different technologies

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¹ MIRACLE project is funded by the Werner Siemens-Foundation (Zug, Switzerland).

are available on the market and the most significant will briefly be outlined here [6,7]: optical/infrared tracking systems, electromagnetic trackers, IMU (Inertial Measurement Units), FBG (Fiber Bragg Grating) shape sensors, rotary encoders, and shadow sensors.

Today, optical trackers (e.g. Polaris/Certus NDI [8] and Axios 3D [9]) are the state-of-the-art tracking systems for robotic applications in surgery. Their main components are cameras and retro-reflective markers attached to the device/patient for tracking. Optical trackers are based on the triangulation principle [6–9]. The most attractive features of optical trackers are their high accuracy (e.g. Polaris NDI [8] ~ 0.3 mm (RMS) over ~ 4 m³ working volume) and their reliability (they have been developed and commercialized since the 90 s). However, such optical trackers are strongly limited by the required line of sight, which precludes applications where the instrument is hidden inside the human body (as is the case in endoscopic applications).

EMTS (Electromagnetic tracking systems) are based on the generation of a known electromagnetic field which is then detected by the target sensors to determine their own positions [6–8]. These systems have no line-of-sight requirement and are able to track instruments such as catheters, endoscopes, and the tip of needles within a body. Furthermore, this technology has been developed and commercialized for more than twenty years and have good accuracy (e.g. AURORA NDI [8] accuracy is ~ 0.5 mm and $\sim 0.3^\circ = 5 \cdot 10^{-3}$ rad over 2 m³, ~ 40 Hz update frequency and can track up to eight targets). However, EMTS are limited by the interference produced by other electromagnetic sources (e.g. the robot itself, ferromagnetic tools, etc.), low update frequency, and the maximum number of trackable target sensors. In fact, the latter two features are essential for the precise determination of the pose and shape of the endoscope.

IMU tracking systems are based on MEMS (Micro Electro-Mechanical Sensors) that combines accelerometers, magnetometers and gyroscopes to measure accelerations and angular velocity. As the pose of the tip is determined by integrating these three quantities, small measurement errors accumulate with time, and, therefore, IMUs are not always suitable in medical applications [6]. Despite this intrinsic limitation, IMUs can be small (less than 5 mm side) and have no line-of-sight issue, and so further developments may have interesting applications.

FBG sensors are embedded in optical fibers and can measure their strain at several points. Three FBGs or more (usually four to compensate temperature effects) are attached to a bending support (e.g. a tiny flexible tube). Based on the combined measurement of strain at discrete points along all fibers, it is possible to reconstruct the tube's three-dimensional shape. Though this technology is very promising because of its miniaturized feature, it still requires further developments to be used in applications requiring high accuracy [10].

Another tracking technology is given by rotary encoders, which are suited to measure angles in the joints of articulated devices (e.g. an articulated endoscope). Rotary encoders [11–14] with various working principles exist, whereas Hall Effect Sensors and optical rotational encoders are the most popular because of their high accuracy and reduced size. However, the accuracy of rotary encoders depends inverse proportionately to their size: e.g. rotary encoders from Hengstler with $\sim 10^{-6}$ rad resolution have diameters of about 60 mm [13] and others with 8 mm diameter from RLS have an accuracy of 10^{-2} rad [14]. Medical applications in endoscopes or instruments would require encoders to be much smaller than 10 mm with a much higher accuracy than 10^{-2} rad. Moreover, rotary encoders only work for joints with one degree of freedom (DOF).

The last group of tracking systems outlined here are shadow sensors. These sensors measure the position of a light source or the direction of the impinging light by detecting a shadow image. All

shadow sensors are composed of the following key elements: an image sensor, a shadow mask, and one or more point-light sources (e.g. LED). The first tracking system based on this concept was used to measure the direction of light coming from distant light sources like stars in astronomy [15]. More recently, other sensors have been implemented to measure not only the position of a point light source (e.g. LED) [16,17], but also the position and the orientation of a rigid body on which three or more LEDs are mounted [18,19], or the displacement of a concave mirror with respect to a fixed frame [20]. Some sensors have also been adapted to medical applications and other fields [21]. The development of these sensors has been done in the past few years and there is still some room for improvement. One drawback of the current sensors is that no profound studies on the characterization of these sensors are available to the public. This complicates the interpretation of their performance.

This paper proposes an Angular Sensor for TRACKing Systems (ASTRAS) which belongs to the latter described group of shadow sensors. In addition to the key elements of a shadow sensor, ASTRAS also contains a mirror and a mechanical constraint to limit the DOFs of the system.

In contrast to all other described tracking systems, ASTRAS is ideally suited to be integrated into articulated devices such as a robotic endoscope because of its technical design and intrinsic properties. ASTRAS combines the following advantages: immunity to electromagnetic noise, no line-of-sight requirement, potential for miniaturization (image sensors are available as small as $1 \times 1 \times 0.5$ mm³ [22] and there are several techniques to miniaturize the shadow mask [23,24]), and possibility to track one or two DOFs.

The technical design and the working principle of ASTRAS is discussed in detail in Section 2. A physical setup, described in Section 3, has been developed to characterize the properties of the sensor. The experimental validation and characterization of ASTRAS are described in Section 4. This characterization quantified the key parameters of the mechanical implementation, along with the main sources of error and noise. All parameters and performance measurements are used together to validate the working principle and advantages of ASTRAS over other sensors. Finally, the conclusions from the experimental evaluations are drawn in Section 5.

2. Technical design and working principle

2.1. Technical description of ASTRAS

A technical drawing of ASTRAS is shown in side view in Fig. 1. The purpose of this sensor is to measure the tilt angle β between plane 1 and plane 2 ($2'$ when $\beta = 0$) about the axis x' . In principle, the system can also measure the tilt angle (α) about y' as each value of α corresponds to a unique shadow recorded by the image sensor. Though the theoretical extension to two DOFs seems to be straightforward, the experimental results that are valid for one DOF case cannot be extended directly to two DOFs without any experimental proof. In this work, only the case with one DOF is studied.

Plane 1 has the following elements: an image sensor, a shadow mask separated from the sensor by a transparent layer (or a simple support), and an LED mounted in such a way that it cannot directly illuminate the sensor. In Fig. 1 the shadow mask is indicated by three simple bars but can also have a more complicated shape (e.g. in Fig. 2).

Plane 1 is connected to plane 2 by a mechanical constraint (indicated in Fig. 1 with a simple arrow). This constraint restricts the movement of the planes to one DOF: plane 1 can only tilt with respect to plane 2 (by the angle β). A mirror is attached to plane

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