Sensors and Actuators A 173 (2012) 254–266

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

A micro motion sensing system for micromanipulation tasks

Win Tun Latt [a,*], U-Xuan Tan [b], Andreas Georgiou [a], Ananda Ekaputera Sidarta [b], Cameron N. Riviere [c], Wei Tech Ang [b]

[a] Hamlyn Centre for Robotic Surgery, and Department of Computing, Imperial College London, London SW7 2AZ, UK
[b] School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798, Singapore
[c] Robotics Institute, Carnegie Mellon University, Pittsburgh, PA 15213 USA

ARTICLE INFO

Article history:
Received 12 June 2011
Received in revised form 4 September 2011
Accepted 6 September 2011
Available online 24 October 2011

Keywords:
Position sensitive detectors
Feedforward neural network
Micromanipulation
Microscale sensing

ABSTRACT

An optical-based motion sensing system has been developed for real-time sensing of instrument motion in micromanipulation. The main components of the system consist of a pair of position sensitive detectors (PSDs), lenses, an infrared (IR) diode that illuminates the workspace of the system, a non-reflective intraocular shaft, and a white reflective ball attached at the end of the shaft. The system calculates 3D displacement of the ball inside the workspace using the centroid position of the IR rays that are reflected from the ball and strike the PSDs. In order to eliminate inherent nonlinearity of the system, calibration using a feedforward neural network is proposed and presented. Handling of different ambient light and environment light conditions not to affect the system accuracy is described. Analyses of the whole optical system and effect of instrument orientation on the system accuracy are presented. Sensing resolution, dynamic accuracies at a few different frequencies, and static accuracies at a few different orientations of the instrument are reported. The system and the analyses are useful in assessing performance of hand-held microsurgical instruments and operator performance in micromanipulation tasks.

1. Introduction

Vitreoretinal microsurgery and some cell micromanipulation tasks are fields that require very high tool positioning accuracy. In vitreoretinal microsurgery, there is some degree of consensus among vitreoretinal microsurgeons that instrument-tip positioning accuracy of 10 μm is desired [1] while cell micromanipulation tasks require accuracy ranging from a few tens of micrometers to nanometers depending on the applications.

Many involuntary and inadvertent components are present in normal human hand movement. These include physiological tremor [2], jerk [3] and low frequency drift [4]. These undesirable components have limited manipulation accuracy of surgeons in microsurgery, and cause certain types of procedures to be generally infeasible, such as retinal vein cannulation and arteriovenous sheathotomy [5]. Several types of engineered accuracy enhancement devices have been or are being developed in order to improve manipulation accuracy of microsurgeons, including telerobotic systems [6], the “steady-hand” robotic system [7], and fully hand-held active tremor canceling instruments [8–11]. To better engineer and evaluate performance of such systems, thorough knowledge of these components present in microsurgeons during microsurgical operations is required.

Several one-dimensional (1-D) studies of motion have been reported for microsurgeons [2,12] and medical students [13]. Some studies have examined only physiological tremor [2,13], the roughly sinusoidal component of involuntary motion. Others have examined also the general motion of surgeons [4,12]. Studies of micromanipulation tasks of microsurgeons in 3D are rare in the literature. That is partly due to the fact that commercially available motion tracking systems such as Optotrak, Aurora (Northern Digital, Waterloo, Canada) [14,15], Isotrack II (Polhemus, Colchester, Vt.), miniBIRD (Ascension Technology Corp., Burlington, Vt.) [16], Fastrak (Polhemus, Colchester, Vt.) [17,18], and the HiBall Tracking System [19] are not suitable for such studies since they are bulky or else do not provide adequate accuracy and resolution for micro scale motion.

To address the above issues, motion sensing systems which can sense microsurgical instrument motion in micro scale are developed based on a passive tracking method [20–22], or an active tracking method [23–25]. Although systems based on active tracking method (active tracking systems) can provide high resolution due to high intensity light reception at the sensors, the light sources have to be fixed on the instrument to be tracked, requiring electronics and wires on the instrument. Additional weight and clumsiness

* Corresponding author. Postal address: Imperial College London, Department of Computing, South Kensington Campus, London SW7 2AZ, UK. Tel.: +44 06790 6942; mobile: +44 07542163363.
E-mail addresses: w.tun-latt@imperial.ac.uk, robotics.researcher@gmail.com (W.T. Latt).

0924-4247/$ – see front matter
doi:10.1016/j.sna.2011.09.009

due to the need to have electronics, wires, and the light sources make it non-ideal for studies of micromanipulation tasks since instruments which are heavy or clumsy alter natural hand dynamics [26] and distract the surgeons.

On the other hand, systems based on passive tracking method (passive tracking systems) are best suited for studies of micromanipulation tasks since they require only a reflective marker. Therefore, all the mentioned issues present in systems based on active tracking method are eliminated although they suffer from poor resolution due to relatively lower light intensity received at the sensors. In all these systems, position sensitive detectors (PSDs) and lenses form the main components whereby the accuracy is limited by nonlinearity inherent in PSDs and distortion (i.e., nonlinearity) introduced by the optical system.

It is well known that lens introduces distortion. PSD also introduces distortion effects that vary from sensor to sensor reducing accuracy significantly at micron and submicron levels. The overall nonlinearity is the combination of distortion effects from the lenses and PSDs. Passive tracking systems described in [20,21] do not take care of nonlinearity and ambient light effects. Accuracies of the systems at different tilt orientations of the instrument are not investigated nor described although they can be affected by different tilt orientations due to incomplete absorption of IR light by the non-reflective instrument shaft. Accuracy is poorer without calibration because of the imperfect alignment and assembly of the components. If accuracy and resolution can be improved by eliminating inherent nonlinearity and increasing signal to noise ratio, respectively, the systems can be suitable systems for the assessment and microsurgical trainings of surgeons, and as accurate ground truth systems to evaluate accuracy enhancement devices [6–11].

In this paper, development and analysis of the whole optical system based on the passive tracking method are described. Calibration using a neural network to reduce nonlinearity of the measurement is proposed, and described. Measures to improve sensing resolution of the system so that it has adequate sensing resolution for micromanipulation tasks in spite of the nature of a passive tracking method are presented. Analysis of the effect of microsurgical instrument orientation on the system accuracy is presented. Sensing resolution, dynamic accuracies, and static accuracies at different orientation of the instrument are reported.

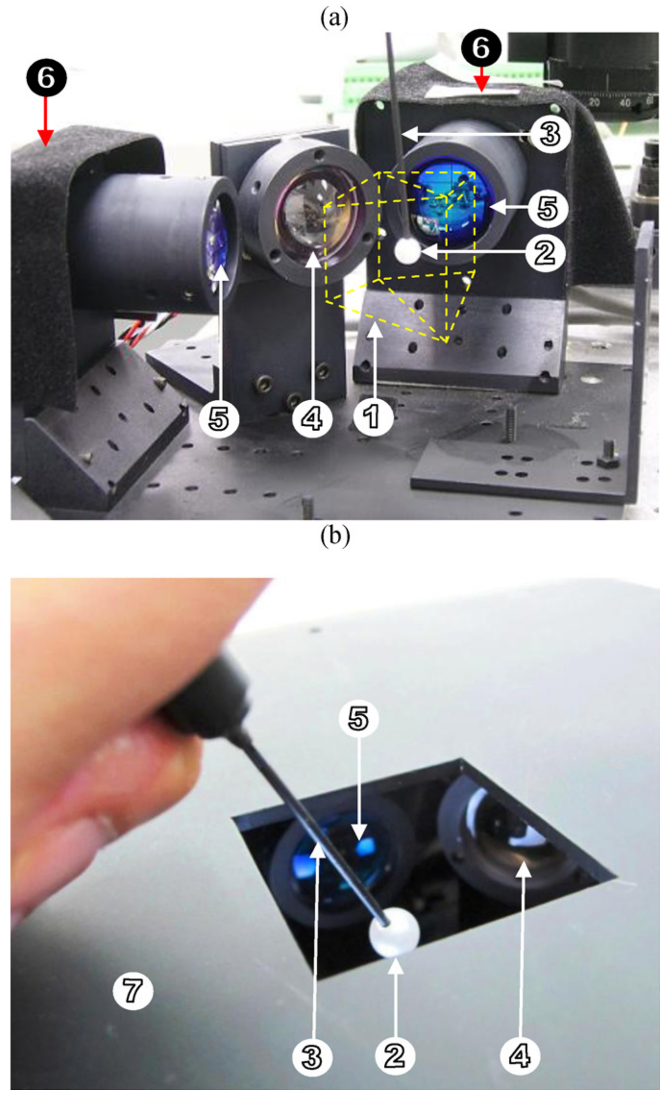

Fig. 1. Pictures of Micro Motion Sensing System (M2S2): (a) without the hand-support cover, and (b) with the hand-support cover, showing (1) the location of the workspace (within the yellow dash line), (2) the reflective ball, (3) non-reflective instrument shaft, (4) the aspheric lens, (5) bi-convex lenses, (6) the PSD modules placed inside light absorption cloths, and (7) the hand-support cover.

2. System description

In this section, design and development of the optical micro motion sensing system (M2S2) is first described. Then, measures to increase signal-to-noise ratio to improve system resolution are presented. The main components of the system are two PSD modules (DL400-7PCBA3, Pacific Silicon Sensor Inc, USA), three lenses, an IR diode with its switching control circuit, a white reflective ball, and a non-reflective shaft as shown in Figs. 1 and 2. The two PSD modules are placed orthogonally to each other. PSDs are chosen among other sensors such as CCD, and CMOS since the PSDs detect the centroids of the IR rays striking their surfaces; thereby they work optimally with out-of-focus sensing/imagery. Another reason is that they offer adequate high position resolution and fast response [27] at an affordable cost.

Each PSD module employs a two-dimensional PSD with a 20 mm square sensing area. There are two pairs of output electrodes in a two-dimensional PSD – *X*-axis electrode pair and *Y*-axis electrode pair. The current produced at an electrode depends on the intensity and position of the centroid of the light striking the PSD [28]. With regard to an electrode pair, the electrode located nearer to the light centroid will produce more current than the other. With this phenomenon, the position of the light centroid can be calculated once the current produced at each electrode is known. The module converts current produced at each electrode into voltage. For each PSD module, two normalized voltage outputs independent of the light intensity – one representing the light centroid position in *X*-axis, and the other representing in *Y*-axis – are obtained by dividing the difference between the two voltages of each electrode pair with their summation.

Bi-convex lenses (LB1761-B (Ø 25.4 mm, f = 25.4 mm), Thorlabs, Inc., USA) are placed at 50.8 mm (two times focal length) in front of each PSD. These lenses are anti-reflection coated to maximize the transmission of IR light. Distance between center of the workspace (shown in green dotted line in Fig. 2) and each of the two lenses is also 50.8 mm.

The white reflective ball (Ø 6 mm) from Gutermann (Art. 773891), whose location is to be sensed, is attached to tip of the instrument shaft which has 1 mm diameter and is painted with a non-reflective black color as can be seen in Fig. 1. The IR diode delivers IR light onto the workspace. Sensing of the three-dimensional motion of the ball, and hence the instrument shaft tip, is achieved by placing the ball in the workspace. IR rays from the IR diode are