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A micro-optical system for endoscopy based on mechanical compensation paradigm using miniature piezo-actuation

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ABSTRACT

The goal of the study was to investigate the feasibility of a novel miniaturized optical system for endoscopy. Fostering the mechanical compensation paradigm, the modeled optical system, composed by 14 lenses, separated in 4 different sets, had a total length of 15.55 mm, an effective focal length ranging from 1.5 to 4.5 mm with a zoom factor of about 2.8×, and an angular field of view up to 56°. Predicted maximum lens travel was less than 3.5 mm. The consistency of the image plane height across the magnification range testified the zoom capability. The maximum predicted achromatic astigmatism, transverse spherical aberration, longitudinal spherical aberration and relative distortion were less than or equal to 25 μm, 15 μm, 35 μm and 12%, respectively. Tests on tolerances showed that the manufacturing and opto-mechanics mounting are critical as little deviations from design dramatically decrease the optical performances. However, recent micro-fabrication technology can guarantee tolerances close to nominal design. A closed-loop actuation unit, devoted to move the zoom and the focus lens sets, was implemented adopting miniaturized squiggle piezo-motors and magnetic position encoders based on Hall effect. Performance results, using a prototypical test board, showed a positioning accuracy of less than 5 μm along a lens travel path of 4.0 mm, which was in agreement with the lens set motion features predicted by the analysis. In conclusion, this study demonstrated the feasibility of the optical design and the viability of the actuation approach while tolerances must be carefully taken into account.

1. Introduction

Recent advances in mini-invasive surgical techniques [1–3], as single port surgery (SPS) and natural orifice trans-luminal endoscopic surgery (NOTES), have been pushing the biomedical research toward the study of a next generation of feasible service tools for intra-corporal vision and tissue manipulation. These tools potentially can overcome the limitations, recognized in such new techniques, of conventional rigid laparoscopic instrumentation [4–7]. Basically, they are mainly passive instruments using optical fibers to deliver the light into the abdominal cavity and rod lenses to transmit the image back to the external camera sensor. Flexible endoscopes, ordinarily adopted in diagnostics, have been endeavored in substitution to rigid laparoscopes. They have a steerable tip to ease navigation, to direct the camera and the instruments. However, only the deflection of the tip can be controlled by means of steel cables, while the rest of the body is passive. Basically, flexible endoscopes are unsuitable for SPS and NOTES, being documented to suffer from both manipulation and vision issues [8]. For example, controlling the stiffness of the flexible endoscope is not trivial with effects on accurate force exertion. The number of tools that can be simultaneously used (number of tool channels) is one or two, and those tools are parallel and at close distance, impairing tool triangulation. Moving the axial position of the endoscope tip, to adapt the field of view of the surgical target, is not facilitated and still requires extra expert assistance. In order to overcome such drawbacks, several research developments of innovative surgical platforms, based on micro-robotic solutions, have been carried out [9–13]. As for the vision facility, there have been R&D efforts in the direction of providing into a single distal device the main functional features such as scene illumination, imaging, target variable magnification (variable focal length) and vision orientation.

As far as the magnification is concerned, conventional zoom imaging systems are composed of several optical lens sets and some of them are variable in position. Mechanical compensation (MC) allows optical zoom with two mobile lens sets [14]. A coordinated motion of the two lens sets makes possible to change the magnification ("variator" lens set) while preserving the image focus ("compensator" lens set). However, moving to miniaturization, the

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accurate control of the lens coordinated motion requires ad-hoc actuators. For example, considering a 10 mm optical system length, such an approach requires micro-metric lens positioning resolution (∼10 μm), which is difficult to achieve with traditional electromechanical motors. In order to overcome the need of moving two lens sets, the combination of a single-moving-optical element and an extended-depth-of-focus method was proposed, which yielded a zoom factor of about 2.5× for an overall optical system length less than 12 mm [15]. Despite technically easier than traditional MC, the extended-depth-of-focus method required a cubic phase mask (spatial phase modulation function in the aperture stop of the lens system) and additional digital image restoration processes to recover the defocus effect [16].

In order to cope with miniaturization and accurate position control issues, shape memory alloys (SMA) and piezo actuation were proposed. SMA actuators were largely investigated as founding technology in miniaturized robotic systems for their significant displacement and force generation [17]. For example, in [18,19], the authors presented an actuation system based on miniaturized SMA wire on silicon (4.5 mm × 1.8 mm) able to generate a displacement of about 600 μm. Similarly in performance and size, piezo-motors have been recently successfully proposed for biomedical applications where the resolution and accuracy of the instrument positioning are demanding [20–23]. In [21], the authors proposed a piezoelectric ultrasonic microactuator (1.5 mm × 1.5 mm × 5 mm) able to generate a force of about 30 mN for driving optics with potential applications in mobiles and micro-cameras. A linear piezo-motor (2.8 mm × 2.8 mm × 6 mm) (Squiggle® SQL-RV-1.8, Newscale Technologies Inc., Victory, NY, USA) was adopted to actuate a mini-robot in cardiac surgery [22] and a distractor in jaw bone surgery [23]. Interestingly, this commercial microactuator is able to exert a force of 300 mN along a travel path of 6 mm with a nominal positioning resolution of 0.5 μm, and overall overcomes (3.3 V) the high voltage power supply requirement typical (∼100 V) of the traditional piezoelectric crystals.

In this paper, we describe the optical design of an innovative miniaturized camera, to be integrated within a robotic endoscope, which provides zoom capability thanks to mechanical compensation. A closed-loop actuation unit, devoted to properly and accurately move the lenses, was implemented and tested in a prototypical setup, by using Squiggle piezo-motors and magnetic position encoders (NSE-5310, AMS, Unterpremstaetten, Austria).

2. Miniaturized optical system design

The main requirements of endoscopic vision in mini-invasive abdominal surgery [8] were mainly taken into consideration for the optical design and then translated into a set of technical specifications (Table 1). A distance range from the vision tool to the surgical target ranging from about 50 to 150 mm and a corresponding depth of field range in between 5 and 20 mm are common vision requirements. Typically a laparoscope as an angular field of view (FOV) of about 70°–80°. At an object distance of 50 mm, an angular field of view (FOV) of about 50°, corresponding to a transversal object size of about 60 mm, is usually considered adequate. Chromatic quality of the resulting image is a significant feature for diagnostic and tissue discrimination purposes as well. As the aperture is essential because it determines the resolution of the optical system, we setup its value by defining the stop surface diameter.

The main environmental constraint was represented by the size of the surgical incision, which typically ranges from 10 to 15 mm. According to such requirements, a maximum external radius of the camera of 10 mm, with maximum length of 30 mm was attempted. Assuming the lens support of at least 1 mm in thickness, a maximum lens diameter of 7 mm, a minimum lens edge of 0.5 mm and an overall optical system length lesser than of 20 mm, were setup, as well. The design of the optical zoom took also into account the maximum travel path of the selected micro-motors (6 mm).

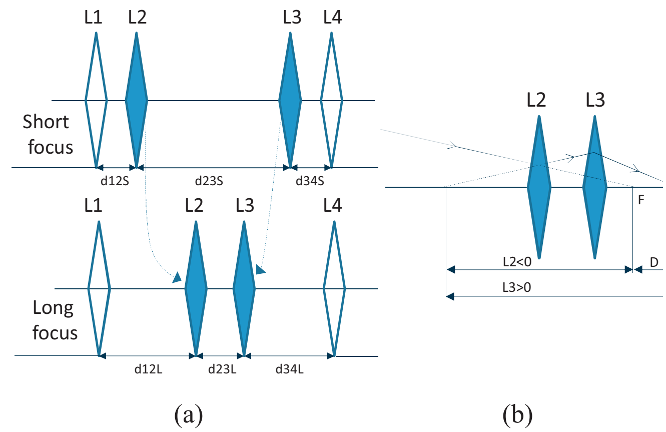

Fig. 1. Schematic diagram of a mechanical compensation system (a). L1 is the front fixed set, L2 is the mobile zoom set, L3 is the mobile compensation set and L4 is the rear fixed set. The set distances at short focus and long focus are d_{12S}, d_{23S}, d_{34S}, and d_{12L}, d_{23L}, d_{34L}, respectively. Zoom and compensation sets (b). F and F' designate object spot of the zoom set and image spot of the compensation set. During mechanical motion D should be held constant.

In this study, the mechanical compensation (Fig. 1) was implemented using four lens sets, two fixed and two mobile, in the positive-negative-positive-positive optical format (see Appendix). The relations among the set distances d_{12}, d_{23}, d_{34} were determined in function of the optical features required to the system.

The initial design was optimized, considering lens radius and inter-component separations, lens distances, even glasses, by using Optalix software (Optenso, CH). A stop surface diameter of 1 mm was defined. Along with the various identified requirements (Table 1), astigmatism, transverse and longitudinal aberrations, and distortion quantities were opportunely included in the optimization for minimization. According to basic manufacturing tolerances, a lens edge less than 500 μm was not allowed. No aspheric surfaces were employed in the design. The best compromise between optical performances and surgical needs leaded to an optical system composed by 14 lenses, with a total length of 15.55 mm, and an overall EFL ranging from about 1.5 to 4.3 mm (zoom factor: 2.8×) (Fig. 2). Set I (distal lenses), featuring a wide aperture angle, consisted of the coupling between a negative doublet (glasses: SF4, SF5) and a convex lens (glass: LAF2), with a resulting positive focal length (36.93 mm). The negative doublet reduced the chromatic aberrations, whereas the convex lens, with high dioptric power, provided focus capability at lower distances. This allowed to get closer to the set II and reduce the overall length of the optical system.

The mobile zoom set II, consisting in a positive meniscus (glass: LAF2) and a negative doublet (glasses: LAF3, SF8) with a negative focal length (−4.96 mm), provided focal length adaptation of the whole optical system varying the aperture angle without affecting the image height. The mobile compensation set III, keeping the image focus without varying the magnification factor, consisted in a negative meniscus (glass: FK5) and a positive doublet (glasses: SF15, BASF64), with a positive focal length (2.53 mm). Set IV, devoted to the final image focus, consisted in a negative doublet (glasses: SF4, SF4), a positive meniscus (glass: LAF2), and a final positive doublet (glasses: LAF2, SF4). This last set was characterized by a positive focal length (17.17 mm) and a high dioptric power. The predicted lens travel (Fig. 3) was almost linear for the compensation