A 360 DEGREE SIDE VIEW ENDOSCOPE FOR LOWER GI TRACT MAPPING

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Cancers of the gastrointestinal (GI) tract is the second most common cause of cancer death; however, studies have shown that early diagnosis and intervention can significantly improve their prognosis [1]. Routine GI endoscopy is invaluable for the identification, diagnosis and treatment of inflammatory, pre-cancer and cancerous lesions in the upper and lower GI tract [2,3]. During an endoscopy procedure, it is critical to localize lesions for effective diagnosis and treatment. For example, during colonoscopy, to examine the lower GI tract, it is important to document the location and extent of colonic mucosal neoplastic lesions (e.g., colorectal cancer), pre-neoplastic lesions (e.g., colon polyps) or other inflammatory, potentially pre-neoplastic diseases (e.g., Crohn's disease, ulcerative colitis) [3]. Without accurate, reproducible lesion localization, it is difficult to confirm complete lesion removal, assess treatment effect, or detect lesion recurrence during follow-up surveillance tests. Because the colon is contractile and mobile within the abdomen, localization of colonic mucosal lesions is very imprecise. Therefore, there is a critical need for a new approach to visualization of the colon to permit accurate, reproducible, non-invasive localization of mucosal lesions during repeated procedures.

Most current endoscopes are designed to image a wide field-of-view (FOV) in the forward direction (shown in Fig. 1). This forward viewing model is similar to walking down a dark hallway (or tunnel) with a flash light aiming forward. Although this forward-viewing approach has become 'second nature' to a trained GI endoscopist for navigating the endoscope inside the GI tract, it is difficult for a computer to accurately create a 2-dimension (2D) or 3-dimension (3D) view of the luminal side wall for post-procedure viewing. Illumination of the luminal side wall and light collection efficiency are also not optimal for forward-viewing endoscopes which have not been optimized for viewing the side wall. For alternative, radial-viewing techniques, depth-of-field (DOF) is less critical since the diameter of the GI tract is comparable to the diameter of the endoscope shaft. Consequently, light collection is more uniform across the FOV of a radial viewer and the DOF design criteria for a radial-viewing endoscope can be relaxed compared to forward-viewing endoscopes.

SUMMARY

This paper discusses the design and development of a 360° side view endoscope and its application in imaging the lower gastrointestinal tract.

Since 2008, we have being exploring various techniques targeting the problem of generating a radial view in a confined space such as in an endoscope including optical imaging module design and fabrication, image processing and reconstruction, side-view illumination, as well as the overall electronic system [4,5]. In the optical imaging module, we designed an endoscope optics system that is capable of simultaneously acquiring forward and radial views simultaneously. The forward-view is for navigation as in a conventional endoscope, while the radial-view optical design is optimized for a balance between image quality and light collection. Our design (shown in Fig. 2) essentially separates the forward and side views: (1) a set of lenses and conic mirrors (also known as a *catadioptric* optical design) that captures the radial view; and (2) through a hole in the center of the radial-view components, a conventional wide-angle lens system that captures the forward view. The two imaging modes share a number of lenses and a single imager is used for simultaneous acquisition of both views. The lens design framework allows for the optimization of various trade-off profiles between the desired parameters for both forward and radial views including resolution, FOV and light collection efficiency.

Through collaboration with the Instrument Technology Research Center of the National Applied Research Laboratories (Hsinchu, Taiwan, Republic of China), a 3:1 scale prototype was fabricated with optimized optomechanical barrels (Fig. 3a). The performance of the optical imaging module integrated with a CMOS camera was characterized with a trade-off profile that assigns priorities to having a point-spread function that spans the area of a pixel of the camera, long DOF in the forward view, and large numerical aperture (which is a metric for light collection) for the radial view.

Fig. 1 The forward view of colon taken using a Pentax colonoscope during a routine colonoscopy procedure.

We also unwrapped the cylindrical side-view images (Fig. 3b) to a 2D view of a flat surface (Fig. 3d), which is similar to the algorithms used for Google Street View. This technique combining forward and radial views would be suitable for the acquisition of images and their subsequent display in a standardized, 2D mapping representation of the colonic mucosa. To arrive at this flexible lens design that allows for various trade-off profiles, we started with the class of *single-viewpoint* catadioptric designs, which was developed for computational vision applications [6]. These designs had an "effective view-point" which allows the image to be unwrapped with respect to a perspective projection. Perspective projection is a mathematical tool that is used in computational vision to model image formation. The other popular mathematical tool is the orthographical projection, which is implemented by telecentric lens systems. The single-viewpoint family of catadioptric designs allowed us to hand-tune the curvature of the mirrors of our catadioptric design to coincide with the entrance pupil location of the forward lens design. That gave us a starting ground, and we then hand-tuned the number and the type of refractive elements. The end result was a lens design that was stable enough to allow different trade-off profiles to be implemented as lens design optimization cost functions. We would have not been able to reach a useable design if unconstrained optimization had been used. Fig. 3 shows the results of the unwrapping algorithm and reconstruction of a 3D cylindrical sidewall surface into a 2D view.

Illumination is an important component of an endoscopic imaging system. Conventional endoscopes employ fiber bundles to delivery light from external lamps to the forward direction. For efficient illumination of the radial-view mode, a light emitting diode (LED) array integrated at the tip of the endoscope was designed and optimized to work with the radial-view design. The LED array design is simulated using a non-sequential ray trace tool, which iteratively tested a large number of commercially available LED system designs until find the optimized design for uniformity. As shown in Fig. 4, the LED arrays are mounted on the outer sidewall of an endoscope. Given the close illumination distance to the GI tract sidewall, the wide angle (typically ∼120°) LED dies are sufficient to achieve uniform illumination without the needs for additional optics. The results show that the design achieved illumination over a field-of-view in a cylindrical volume.

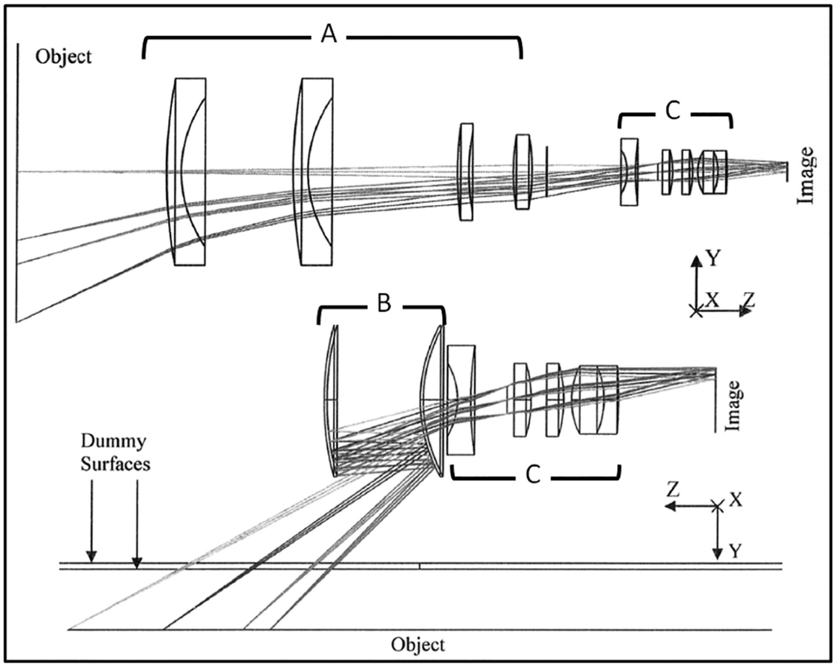

Fig. 2 The dual-view endoscope design. The forward and radial views share lens group C and the camera (indicated as the Image). The forward view is formed by the combination of lens group A and C while the radial view is formed by the combination of Mirror group B and lens group C. The mirror group B has clearance holes in the center allowing forward viewing.

In GI endoscopy screening applications, reconstruction of the images into a map of the GI track sidewall is highly desired, e.g., for documentation of the location of lesions, repeat lesion localization in subsequent procedures and reviewing the images (including automated lesion detection) after the procedures. In a forward-view system, sufficient spatial separation of two viewpoints, e.g., similar to stereoscopic vision, is required to generate an accurate 3D representation of the GI tract. Given the limited physical space in the intended

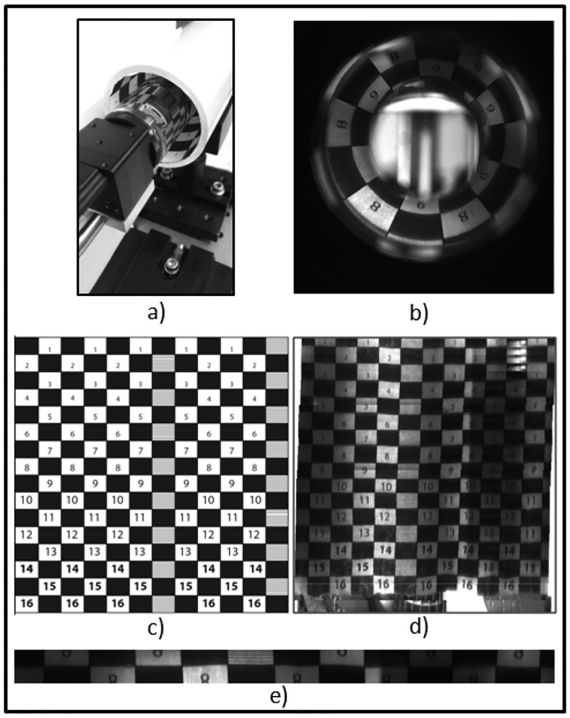

Fig. 3 Dual-view prototype and radial view reconstruction: a) the prototype imager integrated with a CMOS camera; b) the radial view of a cylinder with printed grid patterns; c) original grid pattern; d) reconstructed grid pattern by stitching multiple frames of unwrapped radial-view images; e) unwrapped single frame radial view.

application, this approach is very difficult. We have addressed these challenges by developing a side/radial-view system that directly images the side-wall surface as a 2D image using a single camera. This system enables the subsequent image reconstruction without the need for stereoscopic 3D reconstruction. The imaging system remains a wide-field imaging device, which is simpler and more practical compared to endomicroscopy designs that require raster scanning[7]. In addition to conventional flexible catheter-based endoscopes, such an imager design is intrinsically compatible with capsule endoscopes for which the acquired images are evaluated post-procedure.

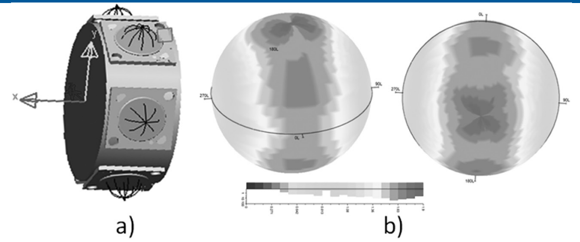

Fig. 4 An LED array based radial illumination design: a) 3D view of the LED array; and b) intensity distribution of the LED array on the radio FOV.

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