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Design and development of linear optical fiber array based remote position sensor

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ABSTRACT

In this paper, we describe the development of linear optical fiber array based remote position sensor that uses the oblique laser triangulation technique. The developed sensor is compliant for non-contact and precise measurement of the position of the desired target. The configuration of sensor head comprises of a diode laser producing a laser beam striking the target at an oblique angle to the surface, an aspheric lens for capturing the scattered light and transmitting it to the linear optical fiber array and finally to the CCD camera. Contrary to conventional methods, the proposed technique has the potential to be applied in hazardous environments containing radioactivity or electromagnetic noise since the camera is placed remotely from the sensor head. The position change information is inferred from the center of laser spot at CCD camera using the Fourier series method. A position resolution of 1 mm (or ~1%) at a standoff distance of ~100 mm between target and light collecting lens was achieved for our selected linear fiber array. Effect of roughness on the accuracy of the measurement was tested by using standard targets of known roughness values. It is seen that the uncertainty in the measured position due to variation in roughness was less than the resolution of our setup for all targets. The error in measurement was high when the roughness of target is comparable to the laser wavelength used due to the diffraction effects at the target surface that ultimately alters the intensity pattern on the optical fiber array.

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1. Introduction

Measurement of distance between objects and position measurement of specific targets pose significant challenges in many industrial and technological applications such as robotics, nuclear fields, military applications, etc [1–3]. Positioning accuracy in alignment is important in many industrial applications such as positioning of cutter in CNC machine, positioning of fuel rod in nuclear reactors etc. In these applications, non-contact sensors are needed, as they do not intervene the ongoing process. With the rapid development of industries, demands of non-contact sensors with high accuracy that are capable of operating in hazardous environment are gaining importance. Among the non-contact position sensors, capacitive, eddy current, ultrasonic and optical sensors are important [1]. Capacitive sensors are simple in construction, provide high resolution over small ranges, but are mainly applicable in clean industrial environments due to their sensitiveness towards dust/oil contamination and humidity. Eddy-Current linear displacement sensors do not have resolution as high as capacitive

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sensors, but are unaffected by debris in the measurement area. Output and linearity of eddy current sensors depend on the electric and magnetic features of the target material. Therefore, individual linearization and calibration is necessary. However, both the above two types of sensors require conductive targets for position measurement. Ultrasonic sensors need large solid angle of the target from the source to have sufficient signal to noise ratio, which may not be required in many applications. They are highly dependent on the target material density, shape and size. With the development of laser, electronics and optical technology, high precision measurement of position using laser-based sensors is now possible. Optical sensors are useful in number of applications as they are relatively immune to various factors like electromagnetic effect, capacitive effects, electromagnetic radiations etc. Advantages of using lasers in optical sensors are that they can be pointed to the target irrespective of its size and distance due to its directional property.

Optical position measurement methods can be divided into the categories as intensity based optical fiber sensors, laser interferometers, time-of-flight sensors, confocal sensors and triangulation sensors [2,3]. The intensity based optical fiber sensors use the light power transmitted between the head of the optical fiber and the target surface. The reflected light from the target is collected by single or multiple fibers based on the requirement. As the target changes its position, the intensity changes at receiving fiber that corresponds to the change in position. Although the light intensity based optical fiber sensors is the simplest method and is relatively inexpensive, the main disadvantage is that it is used for very small range based on the diameter of optical fiber used [3–7]. In time-of-flight pulsed laser range finders, a laser pulse is emitted to the target, and range is measured as the time delay between the emitted pulse and the reflected pulse from the target. It is more appropriate for measurement of large distances and accuracy becomes poorer in small distances (for example, 1 mm displacement shifts the signal by ~3 picoseconds which needs to be detected by electronics circuit) [2,3]. Another technique is laser interferometry, in which fringes are counted to obtain the displacement. Although, high resolution is achievable, number of components in this method makes the sensor bulky [3]. Confocal sensors work on the principle of focusing monochromatic or polychromatic light on the target surface using a multi-lens optical system. In confocal sensor using monochromatic light source, sensor is positioned in a way to receive the maximum signal from the target, as the target changes its position, the output intensity changes at the detector. Common applications for such a sensor are minute displacement measurements and surface profiling. In polychromatic confocal sensors, the lenses are arranged in such a way that the white light is dispersed into a monochromatic light by controlled chromatic deviation. A certain deviation is assigned to each wavelength by a factory calibration. Only the wavelength that is exactly focused on the target surface or material is used for the measurement. Limitation of these types of sensors is the small distance between the sensor and target [3,8–11]. In triangulation technique, a laser projects a spot of light on a diffuse or specular surface, and a lens collects a part of the light scattered or reflected from this surface to image the spot on a position sensor. If the object is displaced from its original position by a small amount, the center of the image spot will also be displaced by an amount from its original position. Therefore, the displacement of this object can be determined by measuring the displacement of the image spot center on the position sensor [12–22]. Various image detectors such as position sensing detector (PSD), charge coupled device (CCD) and split photodiodes can be used depending on the application. Most of the configurations reported in literature [12–22] have used triangulation techniques for position measurement combining them directly with PSD's and CCD's.

In this paper, we describe development of a linear step-index optical fiber array based non-contact and remote position sensor that uses oblique laser triangulation technique. Initially comparison of resolution of both the direct and oblique triangulation method is done analytically and based on the comparison oblique triangulation method was selected as it has better resolution. In all the optical triangulation techniques reported in literature [12–22], scattered or reflected light from the target is collected by the lens and is directly focused onto the CCD or PSD without use of optical fibers, and so these methods are not meant for remote measurement. However, in our technique, instead of imaging directly on CCD camera position information is achieved using linear optical fiber array. This helps in placing the CCD camera remotely at the other end of linear optical fiber array. Determination of target position is done by finding the centroid of laser spot on camera using Fourier series method. Of course, due to oblique incidence of laser, the point of incidence on the target surface gradually changes its location with distance of separation and local surface property can change the intensity pattern on lens ultimately introducing errors in the estimated position. To assess this effect, we have experimentally measured the position of standard surfaces with known roughness using our developed sensor and compared it with the true position measured by micrometer. Factors contributing to the errors are discussed in the paper.

2. Selection of laser triangulation technique for sensor head development

This section gives the comparative assessment of resolution of direct and oblique configuration of triangulation sensors. Based on the evaluation, selection among the mentioned laser triangulation configurations were done for the sensor head development.

The schematic of both configurations of optical triangulation is shown in Figs. 1 and 2. In direct configuration laser is vertically incident on surface and in oblique configuration the laser is incident at an angle to the surface.

In direct type (Fig. 1), do is object distance, di is image distance, Δ is displacement of the object surface from A to B, θ is angle between the incident light axis and imaging optical axis, φ is the angle between photo detector sensitive surfaces

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