Optical sensor systems based on determining angular displacements

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Abstract

A renaissance for optical sensors can be foreseen in the wake of the arrival of new optical components such as low- cost diffractive optical elements, Vertical Cavity Surface Emitting Lasers (VCSELs) and pixel arrays based on the CMOS technique. This article will depict the basics for optical systems for measuring angular deflections followed by a more detailed description of two such systems one showing a high-cost but precise system for measuring angular positions, the other illustrating a commercial low-cost and low-accuracy system for measuring 2-D rotations of a reflective surface, both of which rely on probing the speckle pattern arising from scattering of coherent light from the surface of the test object.

Introduction

When coherent light – usually from a laser source – is reflected off a rough or a semi-rough surface, the scattered wavelets will interfere as they propagate, and a usually strong variation in the intensity will be perceived in the observation plane.[1] The strength of the intensity variations in this speckle pattern will rely on the coherence properties of the light source, the scattering properties of the scattering surface and the optical system between the surface and the detector plane, while the dynamic properties will depend on the dynamics of the object as well as of the optical system connecting the object with the detector(s). Needless to say, this speckle pattern provides a unique "fingerprint" of the surface area under investigation, as the pattern is determined by minute surface height variations of the object.

Optical measurement schemes taking advantage of speckle motion for determination of surface displacements have been around for decades. In the field of common holography, the "image" of the object will merely consist of recording the interference pattern between a reference wave and a speckled field scattered from the object on a high-resolution photographic plate. The intensity will contain information on the phase of the object field and thus information on the position of the object. Two exposures on the same holographic plate will reveal the deformation experienced by the object between the two recordings.[2] The impediment of exposure of a photographic film has now been overcome by recording the speckle pattern with a CCD-camera, which has revitalized the field of whole-field displacement measurements.[3]

Simple systems based on dynamic speckles for real-time velocity and displacement determination have been present for a period of time. Systems for velocity determination fall in two distinct classes; either they operate by cross correlating the signals from two spatially separated detectors and thereby finding the transit time of the speckle pattern, which gives the velocity.[4] Alternatively, they employ the Doppler shift as a measure for the instantaneous velocity.[5] Common for both of these systems is that they probe the speckles in the near-field by imaging the surface onto the detector(s).

In this article, we will show two systems where we probe the angular deflection rather than the linear displacement. The first system is a very precise angular encoder and is presently being scrutinized for industrial implementation.[6] The second system is used to supplement the well-known mouse as an input device for a PC.[7] This system is optically simple but may reveal new possibilities that compact optical systems could have in the future.

Theory

The basic set-up for the two systems to be dealt with later is shown in Fig. 1. A collimated laser beam illuminates the object through a beamsplitter. A lens with a focal length, f, collects the diffusely scattered light which here illuminates a linear photo detector array. Of particular importance here is the relation between the speckle displacement in the detector plane, Δp, as a function of the rotation of the object, θ. Based on the *ABCD*-matrix method, explained elsewhere in this special section, this relation can be shown to be

$$\Delta p = -2\theta \left\{ f + \frac{z_2}{f}\left(\frac{R}{2} - z_1 \right) \right\}, \qquad (1)$$

where z_1, z_2 and R are defined in Fig. 1. It can be seen from the above equation that the linear surface displacement, $R\theta$, is probed in case the detector array is placed in the image plane with respect to the object, i.e. $z_1 \cdot z_2 = f^2$. Of primary interest here is the case where the detector array is placed in the Fourier plane of the lens, i.e. $z_2 = 0$. Here the speckle displacement will only be given by the angular rotation alone independent of the radius of rotation, R. Alternative positions of the detector array will make the speckle displacement depend on both the surface displacement and the rotation of the object. A natural question occurs when the detector(s) are placed in the Fourier plane. What will happen if

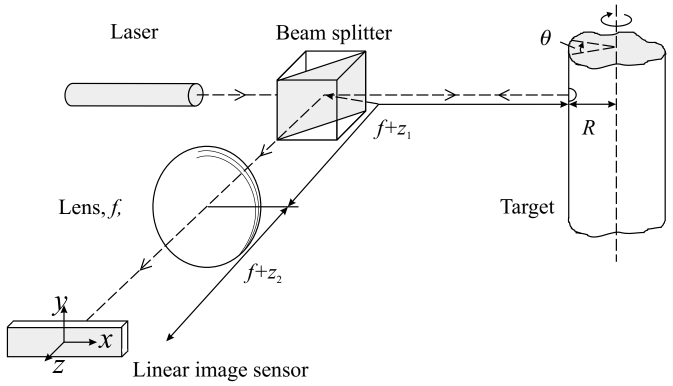

Fig. 1. Basic set-up for determining linear and angular displacements of a target.

the object is linearly translated? A closer examination reveals that such a motion will merely cause the speckles to decorrelate or "boil" as it is usually phrased, without giving rise to any bulk speckle displacement.

So, in conclusion it can be said that the speckles in the Fourier plane will move according to the angular displacement of the object, and any superimposed linear motion will cause no bias effect, but will slightly decrease the measurement accuracy by lowering the correlation between the observed speckle patterns.

The angular encoder

A system has been built very similar to the one shown in Fig. 1, except that the beamsplitter was left out and the illuminating laser was angularly displaced from the optical axis of the detector, thus eliminating the loss introduced by the beamsplitter. When the CCD detector array is properly positioned, the relation between speckle displacement and rotation is given by $\Delta p = -2 f \theta$. This means that this type of measurement of a rotating object is independent of the wavelength, both the distance and radius of rotation of the object, and any corresponding linear displacement of the rotating stage.[8]

To be used as an angular encoder, the operation is as follows. A speckle pattern is recorded at the zero angular position. Next, the object is rotated slightly (approx. 0.3 degrees, depending on the radius of curvature of the shaft and the illuminating spot size) and a new speckle pattern is recorded and compared with the previous one. The speckle displacement, and thereby the exact angle of rotation, is obtained after finding the peak for the cross covariance between the two speckle patterns. This can be done with a precision close to 1/50'th of the pixel size for the CCD-array. This gives the exact angular displacement incurred by the object between the two exposures. Both recorded speckle patterns are stored in a computer together with the corresponding angular positions of the stage. This procedure is repeated around the complete circumference of the shaft, and the corresponding speckle patterns are "stitched together", as described above.

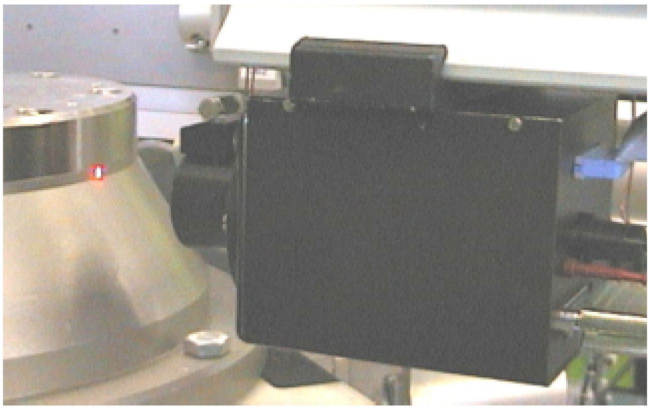

Fig. 2. The angular encoder.

After a rotation of 360°, the initial speckle pattern reappears, and any accumulated error can be eliminated. The set of recorded speckle patterns, labelled with their corresponding angular positions, forms a set of maps covering the entire circumference. This set can now be used as a look-up table to find the angular position of the rotary table with a relative precision of 3 10^{-3} rad and a global precision of approximately 75 10^{-6} rad. Figure 3 shows a comparison between the rotary table used for small-angle neutron scattering and the readings made by the encoder. The rather large difference between the two readings (approx. 150 mdeg, peak-to-peak) is believed to be primarily due to the tolerance of the built-in encoder in the rotary stage. Duplication of the experiment at a different position and thus with a different set of speckle patterns has shown the same behaviour, sustaining the statement that the major contribution to the difference stems from the built-in encoder. In addition, an experiment performed by recording the speckle pattern at a reference position, and comparing it with the speckle pattern after the rotary stage returned after a small deflection, has shown that the stage will overshoot by as much as 10 mdegs. Therefore, it is reasonable to believe that a major part of the deviation stems from the encoder itself placed inside the rotary stage.

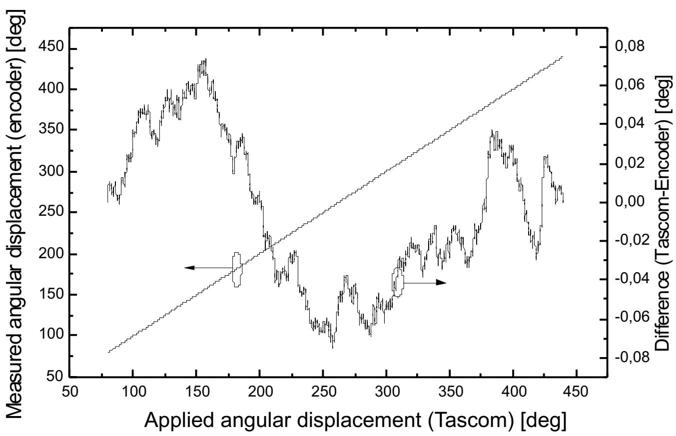

Fig. 3. Relation between applied and measured values of angular position, to the left, and the difference between measured and applied readings, to the right.

Pen Mouse

A pen-like mouse complementing the ordinary mouse as an input device for a PC has been developed.[7] The aim here was to design an optical system that could fit within a pen-like structure

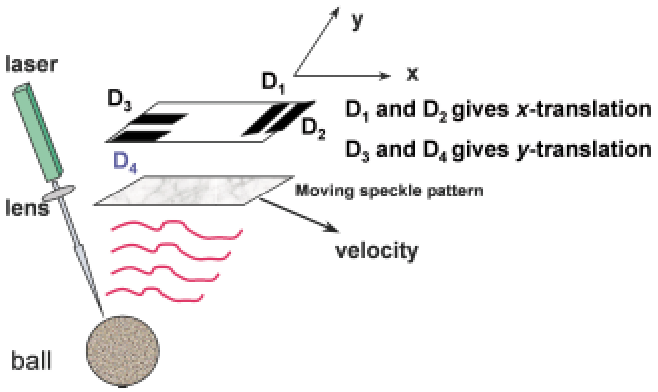

Fig. 4. Simple system for measuring rotations in two dimensions. Speckles from diffusely scattered light off the rotating ball sweeps across the two pairs of detectors.

and probe the rotation in two directions of a reflective surface, here a four millimeter steel ball. The product addressed the consumer market, and therefore the system should meet some rather restrictive economic criteria. In addition, as the system was intended for battery operation, the power consumption should be minimized. On the other hand, the high accuracy offered by the system above was not required.

A schematic drawing of the optical set-up is shown in Fig. 4. Due to the size and cost restrictions inherent in the project, a tiny Vertical Surface Emitting Laser (VCSEL) was chosen as the illuminating coherent source of light. Although the VCSEL was believed to be a spatially incoherent source, the measured speckle pattern had a modulation depth close to unity, and thus this source showed up to be a good choice. In addition, the total electrical power consumption was as low as 20 mW for cw-operation giving 1 mW of optical power ($\lambda = 850$ nm), a figure that here was further reduced by chopping the VCSEL with a frequency of 700 KHz and a duty cycle of 30%. Moreover, a new single mode

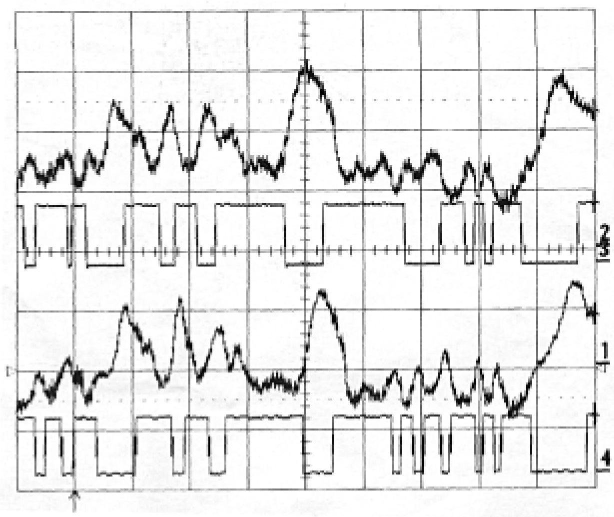

Fig. 5. Analogue detector signals from two adjacent detectors, the upper trace showing the leading detector. The digitised versions are shown below each of the signals.

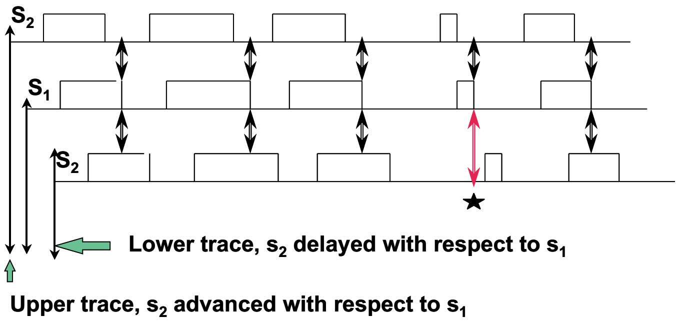

Fig. 6. Digital processing scheme for determining speckle movement and direction.

VCSEL with even lower power consumptions has now been released and might be used in the future.

The VCSEL was placed on a printed circuit board at a distance of 15 mm from the reflective, rotating ball. Two pairs of detectors, placed on the same board next to the VCSEL, collected the dynamic speckle pattern reflected off the ball. Two adjacent detectors provided two electrical signals of which one was delayed with respect to the other, the relative time of arrival being given by the direction of rotation. A representative trace of the signals is shown in Fig. 5, together with the digitised corresponding version of the signals.

An algorithm, like the one schematically shown in Fig. 6, processes the digitized detector signals. One digital channel is used as the reference, and the value of the digital signal from the adjacent detector is probed at the down-slope of the reference detector. The value of this signal will determine the direction of the speckle movement and the number of down-slopes will give the corresponding distance travelled by the pattern. Because speckles are structures with stochastic properties, some speckles will give erroneous counts that have to be eliminated during subsequent processing. This is the case for the lower trace, where a "small" speckle depicts an erroneous direction of movement.

The opto-unit is shown in Fig. 7 together with the flex print, which is placed inside the pen. The signals from the four detectors are processed in one of the two integrated circuits (ASICs) mounted on the flex print, which also includes a second ASIC

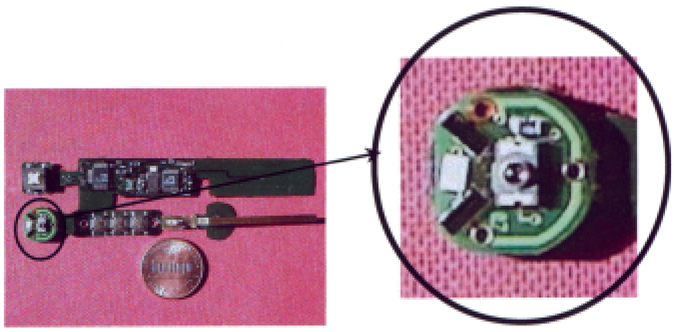

Fig. 7. Flex print including analogue ASIC for speckle demodulation and ASIC for transmitting data to the PC. Right panel shows the opto-unit with centrally placed VCSEL and two double detectors placed at an angle of 90° with respect to each other.

that transmits data from the pen to the PC. The ASIC processing the detector signals is dedicated to this project and combines analogue as well as digital processing.

Data is transmitted from the radio in the pen to the PC with an update rate of 40 Hz. These telegrams contain information on the four types of counts, both up- and down counts for the x- and y-channel, respectively. In addition, the status of the push buttons is transmitted in each telegram as well as the code for the pen. Based on this and the personal profile for the user, i.e. speed and acceleration, the driver software decides what the cursor movement should be.

Conclusion

The future of optical sensor systems for industrial applications depends heavily on criteria that previously have been difficult to cope with. Accuracy has usually been a trademark for optical sensors at the expense of price, size and robustness. Penetration of the industrial scene calls for addressing these issues. It is our belief that the arrival of new elements such as VCSELs, CMOS-cameras and diffractive optical elements will pave the way for further use of optics in industry. Here, we have shown two of our ongoing projects, which take advantage of some of these optical devices. In this way, we hope to attract attention to the possibility for a larger industrial dissemination of optics.

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About the authors

Steen G. Hanson received his Ph.D. degree from the Technical University of Denmark in the field of dynamic laser light scattering. He is currently Head of Research Programme on Optical Diagnostics and Information Processing at Risø National Laboratory. The current work is focused on the development of optical measurement systems for probing displacements of solid objects as well as further developments on the complex *ABCD*-fomalism for treating light scattering from solid and diffuse objects being described by their stochastic properties only.

René Skov Hansen recieved his Bs in Electrical Eng. from the Engineering College of Odense and his M.Sc. in Optical Eng. from the University of Aalborg. The subject was the generation of spatial subharmonic gratings in $Bi_{12}SiO_{20}$ crystals. René recieved his Ph.D. degree in 1998 from the University of Odense, Denmark. The title of his thesis was “Holographic and Speckle Interferometry: Theoretical and experimental aspects of displacement measurements on diffusely and specularly reflecting surfaces”. Afterwards he was employed at The Danish Meteorological Institute, working with measurements of the Ozone layer by using optical methods. Now René is employed as a scientist at Risø National Laboratory, Department of Optics and Fluid Dynamics, Denmark. His main interest is in the field of optical metrology especially focused on statistical optics and electro optics. He is currently working on a Laser Doppler Anemometer (LDA) to remotely measure the wind speed in front of a wind turbine.

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Bjarke Rose received his Ph.D. degree in electrical engineering in 1998 from the Technical University of Denmark. His Ph.D. work was carried out at IBSEN Micro Structures A/S in collaboration with Risø National Laboratory and the Technical University of Denmark. During this work, he studied the physics of dynamic laser speckle and utilized this knowledge in the construction of compact optical sensors. He is currently employed at ADC Denmark (the former IBSEN Micro Structures), where he works as an engineer, R&D, in the field of dense wavelength division multiplexing (DWDM).