XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

HOW TO USE REFLECTIVE OPTOCOUPLERS AS POSITION SENSORS

V. Naydenov, P. Sente and C. Eugène
Research Center in Mechatronics, Catholic University of Louvain
Louvain-la-Neuve, Belgium

Abstract: Due to its numerous qualities, namely their low cost, infrared reflective optocouplers are of large use in the industry to detect an object passing in their field of view. They nevertheless are mainly limited to deliver a pure dichotomic information. The purpose of the paper is to propose several solutions for using this component as an accurate position sensor at the industrial level. Linear and angular displacements are both considered with emphasis on a linear response. A global linearity of about 1% is achieved for a few centimeters and a few tens of degrees ranges.
Keywords: displacement sensors, reflective optocouplers, sensors for robotics

1 INTRODUCTION

How to use a low-cost reflective optocoupler as an accurate position sensor for industrial purpose ? This is the topic addressed by this paper. Infrared reflective optocouplers are very popular sensors utilized in the industry to detect an object passing in their field of view. They are characterized by their compactness, speed, simplicity and low cost ; they are furthermore without contact with the moving object and insensitive to electric perturbations for what concerns their front-end part as it lays on an optical principle. They are nevertheless generally limited to a raw dichotomic information on the presence or the absence of the object to be detected without to give any quantitative measurement of its position.

We propose in this paper different ways to use this sensor on a quantitative manner and mainly according to a linear law, for the accurate measurement of a distance or an angle, the linearity being typically 1% for ranges corresponding to a few centimeters or a few tens of degrees.

The linearity error will be defined in this paper as the maximum deviation between the true sensor output and the "best" straight line (i.e. the least squares fit) expressed in percent of the output dynamic for the choosen distance range.

The specific application for which this study was carried out is key positions measurements of an industrial keyboard controlling diverse displacements of teleoperated moving objects. The scope of our study is nevertheless larger and can cope with numerous industrial situations namely in robotics and mechatronics and, more generally, wherever a large amount of low-cost dynamic position sensors are needed.

The requirement of our sensor for our application is to measure the instantaneous position of the key during its depression course in order to control a remote actuator accordingly. The acquisition time of the key position must not be higher than 1 ms which qualifies the family of optical position sensors as good candidates. A linear position-to-voltage transmittance of our sensor is furthermore highly desirable as it makes the control of the actuator easier.

2 INFRARED REFLECTIVE OPTOCOUPLERS

To recall, a reflective object sensor consists of an emitting diode and a photoreceiver mounted side by side on parallel or converging optical axes. Usually the diode emits in the near infrared (IRED) and the receiver is a phototransistor (PT) (figure 1). The size of this component is often small, typically 2 cm^2. The phototransistor responds to the diode radiation only when a reflective object passes within its field of view. An IR transmissive filter at the receiver window is often used to minimize the effects of ambient light. A more radical solution, complementary to the former one, should be to use a synchronous modulation-demodulation principle to drive the IRED and to detect the signal at the PT output. Generally, a micro lens is mounted on both IRED and PT parts in order to transmit a narrow beam to the target and to focalize the intercepted spot at the receiver input.

The way to determine quantitatively the distance of an object to the optocoupler is to measure the amplitude (i.e. the light flux) of the reflected signal reaching the receiver. This quantity is not only depending on the distance of the object but also on the nature of its reflective surface, i.e. its spectral and spatial reflectivity. The response depends as well on the type of the reflective optocoupler used, especially on the emission and reception apertures of the optocoupler components (optical aspect). In any case, an initial calibration is thus needed. This calibration is to be repeated periodically in function of the surface alteration of the reflective object (dust deposition). The ambient temperature must also eventually be taken into consideration.

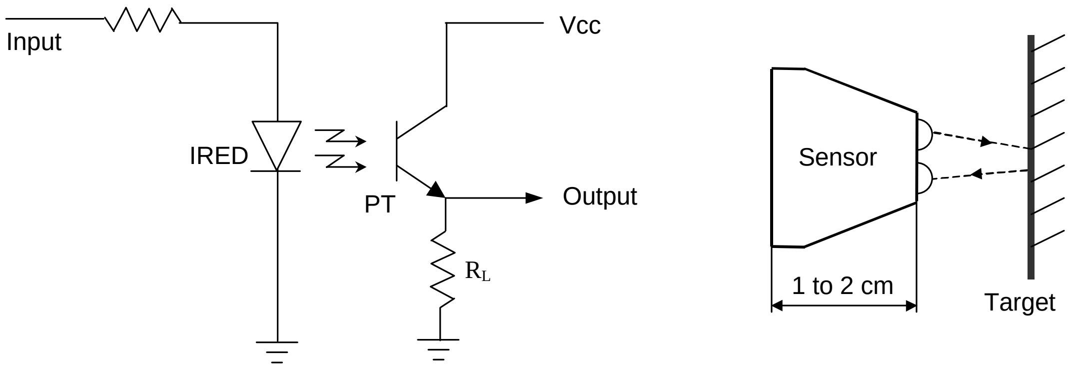


Figure 1. Infrared reflective optocoupler

3 LINEAR DISPLACEMENT SENSORS

3.1 Direct position measurement of an object through its distance to the sensor

A first way to use the sensor is to measure the displacement of the target in its direction, from or towards it. As said above, the sensor response is dependent on the target reflective surface which can be alterated by dust and which thus requires a periodic calibration. The optic of the optocoupler plays also a major role. Experiences show, and this is confirmed by manufacturer data sheets, that the target displacement range for a linear response is very limited, typically a few millimeters. For larger displacements (a few centimeters), an "optical" amplification is possible f.i. by placing on the target end a diffuse cone-shaped tip and by presenting the sensor facing the cone surface, out of the target displacement axis. Figure 2 gives a typical result obtained with the sensor QRB1134 from QT. A 1% linearity was obtained for target displacements of about 10 mm.

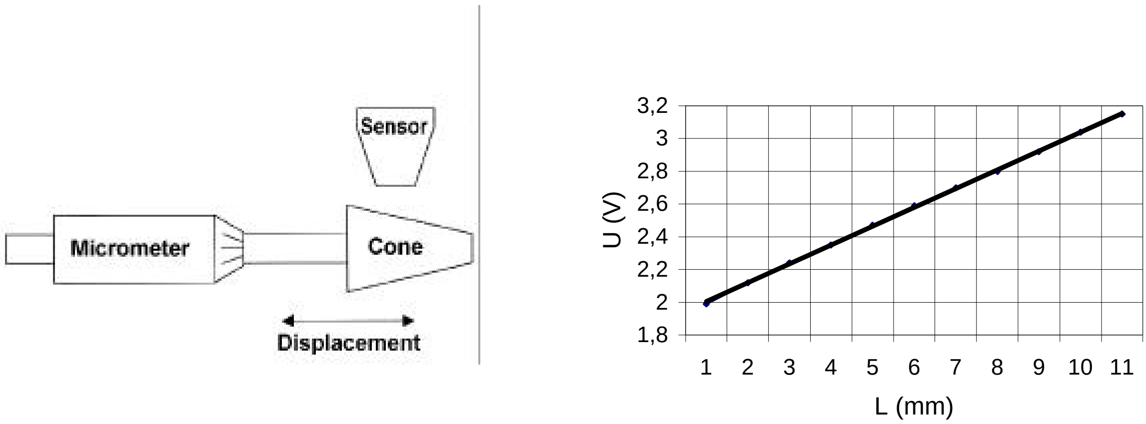


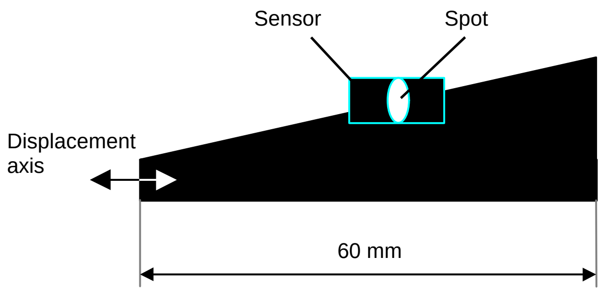
Figure 2. Optical amplification of the displacement range by sighting on a conic surface

3.2 Moving object with modulated reflective surface properties

An alternative way to use a reflective optocoupler as a position or displacement measuring system is to place it in a configuration where the movement of the object can be materialized by the displacement of a shaft or a rigid tape transversally to the sensor and at constant distance from it. The displacement will be measured through an adequate modulation of the reflectivity of the tape surface, covered by a PC-generated pattern printed on a strip. The progress versus the former solutions is that the sensor response is this time entirely under the control of the reflective pattern.

A simple idea is to fix on the shaft a strip of a gray gradation (from white of maximum reflectivity to black of minimum reflectivity) in linear dependence to the longitudinal position. This idea is similar as the "optical corner" used in optics. Different variants were tested but without full satisfactory results concerning the linearity.

An alternative way is to act no more on the gradation profile of a gray strip but on the shape of the edge of a black profile on a white background. We use here the property that the IRED spot, impinging on this edge, covers a black and white zone of variable proportion and that the receiver spatially integrates the reflected spot modulated in such a way. A ramp profile of the edge is a priori obvious (figure 3) but the linearity is still rather poor. We actually obtain a S-shaped curve. The reason of it comes from the shape of the spot area which is circular or elliptic. We can fit a polynomial equation on this curve but such an equation is not easy to be used in real time control. Of course, it is always possible to restrict the range to a span for which the linear approximation is acceptable, but this range should be too short to be useful.



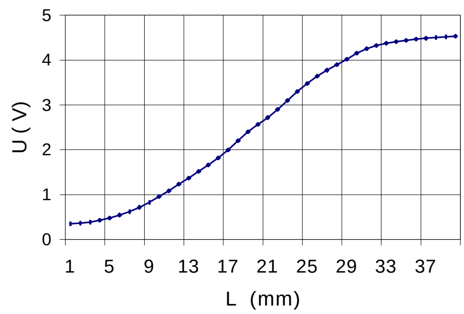
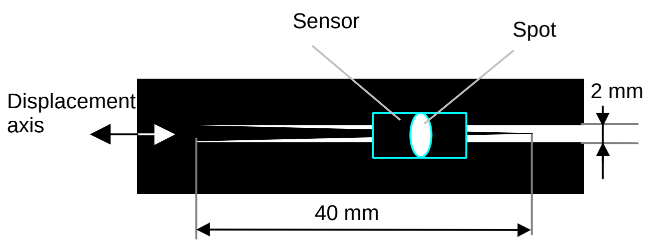


Figure 3. Reflectivity modulation by ramp profile edging

A solution to this problem is to cut the edges of the circular or elliptic spot in order to reduce it in an essentially rectangular area and to expose it to a black-and white triangular pattern. An elegant solution is the specific geometrical profile proposed in figure 4. We obtain this time an excellent linear response : a whole linearity of 1% has been obtained for a few centimeters displacements.



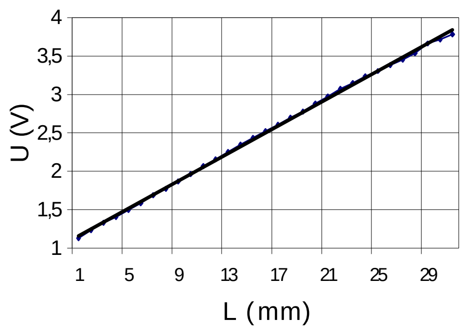


Figure 4. Ramp profile edging with linear response

4 ANGULAR DISPLACEMENT SENSORS

4.1 Introduction

In robotics and mechatronics, simple and low-cost measurements of angular displacements are as important as of linear ones. Here again, reflective optocouplers can offer a satisfactory solution. All the ideas proposed under the heading 3.2 (PC-generated strip patterns) for lineary moving objects can be transposed on rotational moving targets in order to measure their angular displacements. We propose nevertheless a radically different way hereafter developed.

We indeed observe that, for an adequate position and orientation of the sensor facing the reflecting target, a near-linear response of the sensor is obtained in function of the angular displacement of the target,even for large rotations. This observation has been made for diffuse reflective targets which is the common situation. A theoretical explanation of it is hereafter proposed under the hypothesis of a perfect diffuser (responding to the law of Lambert i.e. exhibiting a radiance independent of the direction of observation).

4.2 Response of a reflective optocoupler to the rotation of a perfect diffuser

Consider the figure 5. The IRED source is supposed punctual and delivering from point S an intensity I in a narrow beam of solid angle Ù towards a plane target perpendicular to the plane of incidence. P is the impact point of the beam on the target ; this one is angulary orientable around point A (á is the angular deviation of the target from its position normal to the beam, its value being positive for the removal direction of the target from the sensor). The distance d between S and P is :

$$d = d_0 + D\tan a \tag{1}$$

where D is the distance between A and the beam line. The irradiance E_P received in P follows the classical law :

$$E_P = \frac{I\cos a}{d^2} \tag{2}$$

As the target is a perfect diffuser, the beam reflected by it exhibits a constant radiance L in all directions. Applying the law of Lambert, we have :

$$L = (r/p)E_P \tag{3}$$

where ñ is the reflexion coefficient of the target for the incident light spectral content.

We suppose now that the receiver part (PT) of the sensor is at the same position S as the transmitter and has its sensitive area normal to the direction SP. The quantity measured is the irradiance received in point S irradiated by the reflected beam :

$$E_S = \frac{I_{refl}}{d^2} = \frac{Ls}{d^2} \tag{4}$$

where ó = Ùd^2 is the apparent area of the incident beam normal to its direction (Ù is small). The quantity collected at the receiver output is thus the measure of the radiance L reflected by the target. It is :

$$E_S = \frac{rI\Omega}{p\,d_0^2}\;\frac{\cos a}{(1+k\tan a)^2} \qquad \text{with} \quad k = D/d_0 \tag{5}$$

We thus observe that the measured quantity E_S is proportional to the function f :

$$f(a,k) = \frac{\cos a}{(1+k\tan a)^2} \tag{6}$$

with k = D/d_0 as an adjustable parameter.

Remark : In order for the output signal to be the image of the function f, it is in fact not required that the receiver is at the same position S as the transmitter. As L is constant, this position is arbitrary, at the condition that the flux received by the receiver covers the total area of the photosensitive detector. Similarly, transmitter and receiver can be equipped by lenses without to impair the proportionality of the output signal to the function f.

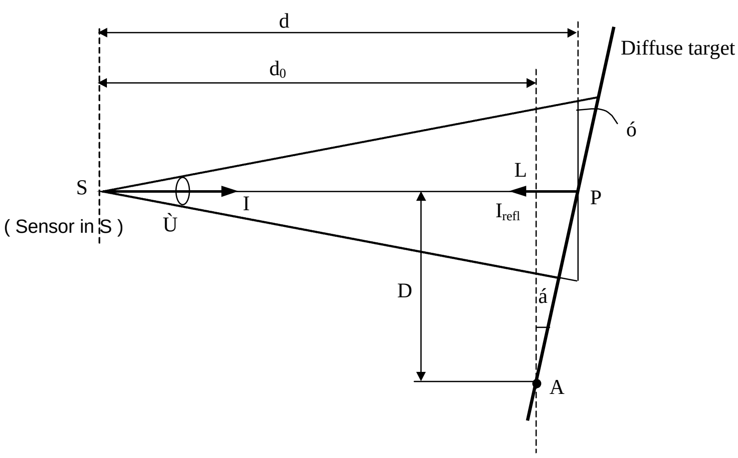


Figure 5. Response of a reflective optocoupler to the angular displacement of a perfect diffuser

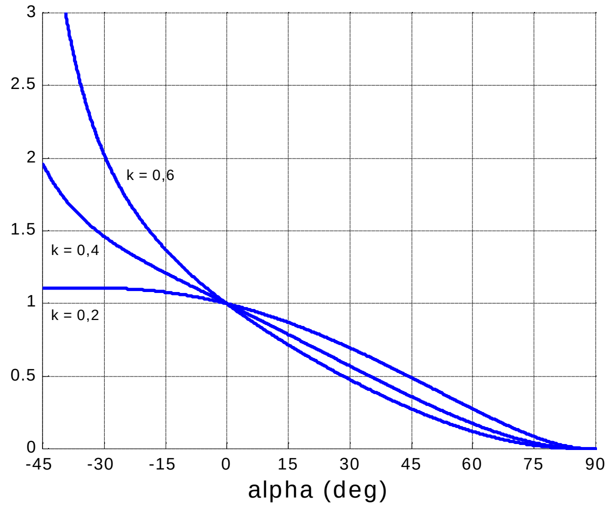


Figure 6. Function f = cosá/(1 + ktaná)^2 for different values of k

Figure 6 gives the curves f in function of á for three values of parameter k. It is seen that at á=0, the curvature is inversed between k=0.2 and k=0.6 with a curvature quasi null for k=0.4, warranting for this value a linear dependence of f versus á around á=0. By computing the null condition for the second derivative of f around á = 0 (inflexion condition at this point), we obtain exactly :

$$k = 1/\sqrt{6} = 0.408 \qquad (7)$$

Figure 7 shows the function f for this particular value of k. This curve is in fact remarkable. We indeed observe a long straight line for positive á. This is due to a slight negative curvature for small á's followed by an inversion of the curvature for higher á's. The exact curve intersects the straight line tangent at the origin (doted line) at the angle á = 47E3. If, for instance, we limit the á span between -15E and +50E, the linearity error is not higher than 0.5% of the total ordinate excursion.

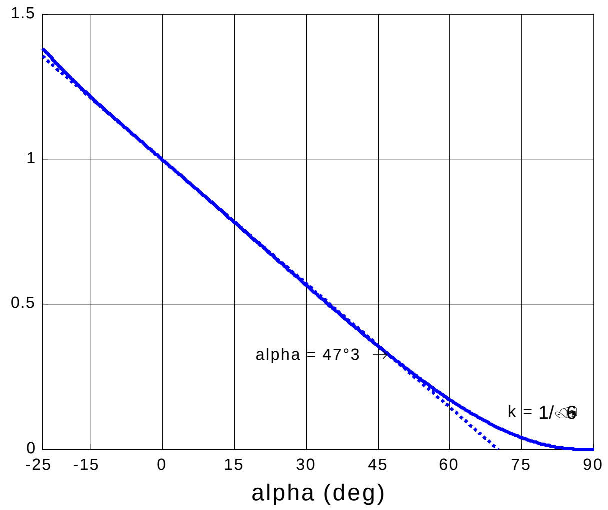


Figure 7. Function f for k=1//6 giving an inflexion point at á=0

Figure 8 confirms this behaviour by experiments performed with the sensor Lite-On LTH 1155 located at a distance d_0 = 10 mm from the target. The target is a diffuse white reflector. Among the curves showed, the best straight line is obtained for a transverse distance D=0.4 mm which confirms the optimal value of k of about 0.4. A linearity of about 1% was obtained for angular displacements between -30E and +30E ! It is worthwile to point out that the sensor position for this best straight line is very critical needing thus a careful fixing of the sensor at the right position.

Let us still mention that a linear displacement can be transposed into an angular one through an appropriate kinematic link; it is actually what we did with our industrial keyboard (See figure 9).

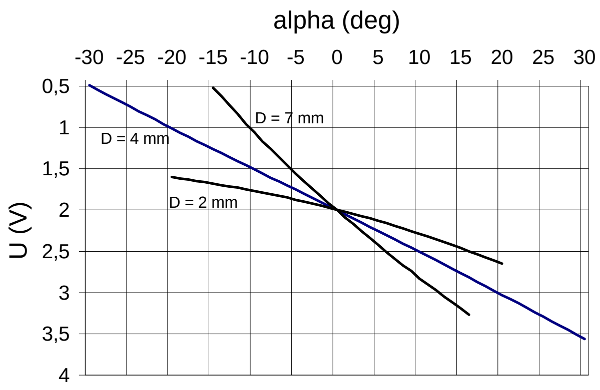
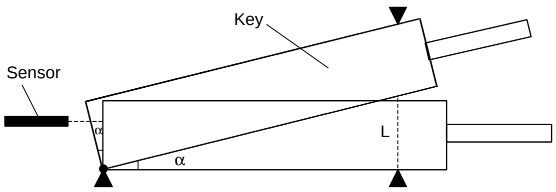


Figure 8. Experimental confirmation of figure 7



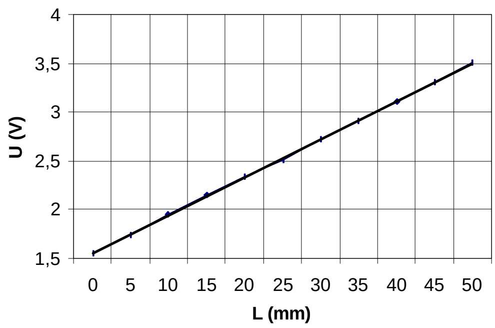


Figure 9. Determination of the linear displacement of a key through angular measurement

5 CONCLUSION

We proposed several solutions to use a low-cost reflective optocoupler, normally limited to a pure dichotomic observation, in order to measure the linear or angular displacement of a moving object according to a linear response. A linearity of about 1% was achieved for linear and angular ranges of a few centimeters and a few tens of degrees. As the response is depending on the surface property of the target and often also on the position of the sensor, a periodic calibration is nevertheless required to maintain these performances.

ACKNOWLEDGMENTS

This work is presented in the frame of a research programme partially supported by the Walloon Region of Belgium that we thank.

AUTHORS: C. EUGÈNE (corresponding author), V. NAYDENOV and P. SENTE, Catholic University of Louvain, Department of Electrical Engineering, Maxwell Building, B-1348 Louvain-la-Neuve, Belgium
phone +32-10472268, fax +32-10-478667, e-mail: eugene@lei.ucl.ac.be