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Development of an Optical Displacement Transducer for the Measurement of Soil Surface Profiles

B. B. Harral*; C. A. Cove*

The transducer is a fast response opto-electronic displacement monitor with a working range of ± 150 mm about a point 600 mm from the sensing head. Although developed for the measurement of soil surface profiles, the transducer will operate on any diffusely reflecting surface. The device collects light from an illuminated spot on the target surface and focuses this on to a position-sensing photodiode, giving an output related to the position of the target. The signal-conditioning circuitry discriminates against the effects of ambient light and compensates for changes in surface reflectivity; a simple technique is included to give an output directly linear with distance. The frequency response is flat up to 40 Hz.

1. Introduction

The study of off-road vehicle dynamics and the behaviour of some agricultural machines often requires the measurement of the soil surface roughness or surface profile. Development of the device described in this paper arose from the requirement for a transducer to measure soil surface profiles in a study of seeding depth control on cereal drills. The need was for a non-contact device with a frequency range from 0 to 40 Hz and capable of measuring variations in height of up to 300 mm. It had to be capable of making measurements without the priorpreparation of the surface and confining its sampling to a sufficiently small area to give accurate profile co-ordinates. If an optical reflectance technique is used it must cope with variations of reflectivity over a range of4: 1.

Simple measurement techniques, such as surveying or a trailed wheel fitted with some means of recording displacement, are either very slow or cause significant deformation of soft surfaces. A device developed by Henry, Sciarini and Van Doren[1] capable of 80 readings/min overcomes some of the problems and automatically records soil profile co-ordinates using a probe to "feel" the soil surface. Unfortunately after 100 readings the equipment must be moved and relevelled. In contrast, Still and Winnett[2] have developed a very sophisticated contactless opto-electronic transducer. Although their device is only suitable for road use in its present form, and is limited to height variations of 72 mm, it has an accuracy of ±0·25 mm and a recording rate of 5000 samples/s.

2. Principle of operation

The optical principle adopted for the device is shown schematically in *Fig. I*, and is similar to the principle used in the transducer developed by Still and Winnett.[2]

Operation of the system relies on the fact that when light shines on a diffusing surface the light is reflected in all directions. A collecting lens is able to gather some of the reflected light and form an image of the illuminated surface spot on a photodetector (see the Appendix). The optical axes of the beam and collecting lens are arranged to be in the same plane and inclined at a small angle to each other. Hence, as the surface level alters, the focused image moves along the detector surface. Theoretically, the image will remain in focus on the detector surface if the detector is inclined at a suitable angle to the optical axis of the collecting lens.

*National Institute of Agricultural Engineering, Wrest Park, Silsoe, Bedford

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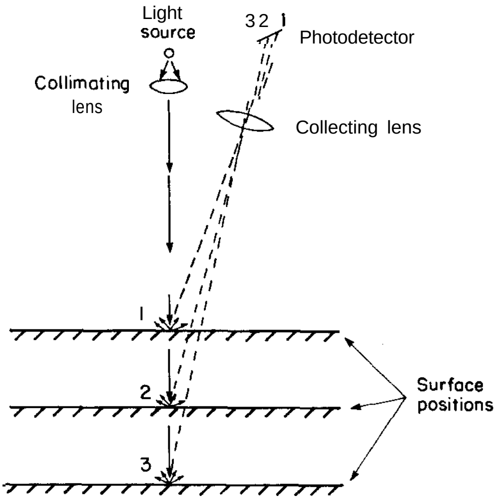

Fig 1. Principle of contactless displacement transducer

3. Design

3.1. *General design*

In designing the layout of the device several factors had to be considered. The most important of these was the noise level, and hence the signal-to-noise ratio (s.n.r.), arising from the position sensing photodiode. This was unfortunately also the factor on which the least information was available. The need for a low s.n.r. dictated the amount of light to be gathered by the collecting lens which was a function of the lens diameter, its distance from the illuminated spot, the reflectivity of the ground surface and the power in the light beam. The distance of the collecting lens from the illuminated spot was in turn dictated by the need to "squeeze" ± 150 mm of working range at a reasonable mean distance on to a detector only 30 mm in length, using cheap readily-available lenses.

A small computer program was written to calculate the positions of light beam, collecting lens and detector, giving 1 % s.n.r. using commercially-available light sources and lenses. The final layout was chosen on the basis of convenient physical size. The final version of the device is shown in *Fig. 2.* Its working range is ± 150 mm about a point 600 mm from the light source and receiver.

3.2. *Light source*

The light source is a semiconductor laser diode, type LB1-O2, manufactured by International Telephone and Telegraph Corporation, operating at a wavelength of 850 mm. These laser diodes are a pulsed type, and in this application the frequency is 7·86 kHz and the duty factor 15 %. Under these conditions the peak output power is 180 mW. Due to its construction, this type of laser does not produce a single parallel beam of coherent light. However, apart from its high output, its other useful feature is its very small emitting area (0·2 x 100 μm), which makes a narrow beam possible over long distances using simple optics.

The light source is shown as a complete unit in *Fig 2.* Driven by a 12 V d.c. supply, the unit contains the electronic pulse circuits, the laser diode and the optical system to produce a suitable light beam. The beam is rectangular in section because of the source shape and is collimated to produce a spot 4 x 20 mm at the maximum range of the device. These dimensions ensure that the spot on the ground is not completely hidden from the collecting lens by very-small scale irregularities in the ground surface. The short dimension of the beam is in line with the photodetector major axis to maximize the resolution.

3.3. *Receiver*

The receiver is also shown in *Fig 2*. Its optical axis is set at 15” to the light beam axis. It consists of a 100 mm diameter *f*/1, Fresnel lens as the collector, and the position sensing photodetector mounted on a printed circuit board. This is a type SD-1166-21-1 1-391 photodetector, manufactured by Silicon Detector Corporation. The position of the mounting board can be adjusted to bring the collected light to a focus on the detector surface throughout the working range of the transducer. Also mounted on the circuit board are amplifiers and filtering circuits. These are mounted as near to the detector as possible to avoid noise pick-up. Power is supplied from an external source and the filtered signals are also taken to an external unit for further processing.

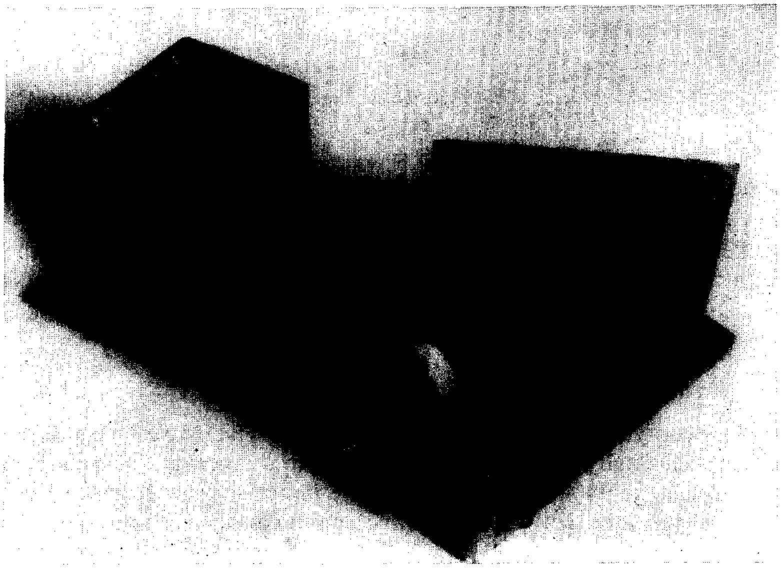

Fig. 2. Transducer with receiver cover removed; (left) light source, (right) receiver circuit board containing detector, amplifiers and filters, (bottom centre) receiver collecting lens

4. Signal processing

The photodetector is sensitive to all wavelengths between 500 and 1100 nm. Since daylight is included in this band, steps must be taken to discriminate between reflected light from the projected beam and reflected daylight which would bias the output. The pulsed operation of the laser diode lends itself to a simple filtering method of separating the beam induced signals from the daylight-induced signals. After filtering, the signals are processed to compensate for variations in signal strength due to changes in ground surface reflectivity. The method of compensation is described in the Appendix.

An important part of the signal processing section is the detection of “out-of-range” and low light conditions. If the ground surface displacement exceeded the set range of the device, an ambiguous output signal would result if the condition was undetected. An erroneous output could also result from too little or no reflected light being received by the collector. This can occur

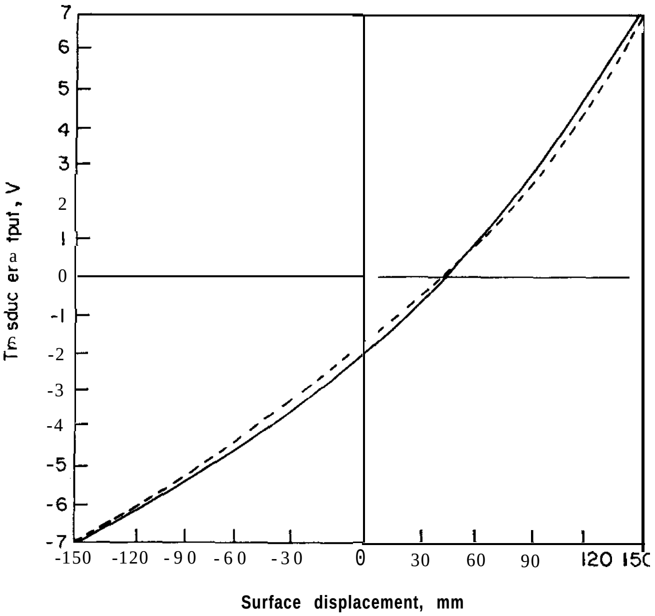

Fig. 3. Transducer output against surface displacement for high (- - -) and low (——) surface reflectivities

through poor reflectivity or the spot being shielded from the collector by an abrupt change in surface profile. In these circumstances the output is tripped to a known level outside the normal range.

5. Calibration

5.1. *Static performance*

Static tests simply consisted of measuring the output at a given target displacement for several surfaces of different reflectivity. As soil is inconvenient to use because of its tendency to crumble and dry out, and so change its reflectivity, alternative materials were found which approximated to the least and most reflective soil surfaces. Fine emery cloth was found to match a dark, wet, and poorly reflecting soil surface while white paper lightly sprayed with "optically black" paint corresponded to a dry and reflective soil surface. ***Fig 3*** shows the results for the 2 different surfaces. The same sample of the substitute material was used in all tests to make the results comparable. As expected, the output is highly non-linear due to the geometrical arrangement of light beam, collecting lens and detector.

5.2. *Dynamic performance*

A dynamic test was made on the device to check the frequency response range. The method used was to present a rotating disc to the device to simulate a known ground surface profile. The plane of the disc was in the plane of the beam and collector axes and the periphery was cut out to form 2 cycles of a sinusoid in polar co-ordinates. The equipment is shown diagramatically in ***Fig. 4.*** A strip of emery cloth was glued to the profiled edge to simulate a poorly reflecting ground surface. The rotor was driven hydraulically and the input frequency was simply varied by altering the rotational speed. ***Fig 5*** shows the output from the device corresponding to an input frequency of 24.7 Hz. The signal has been linearized before display by the technique described in the Appendix.

A frequency response curve, ***Fig. 6,*** was obtained by measuring the amplitude of the transducer output for a range of input frequencies between 7 and 50 Hz.

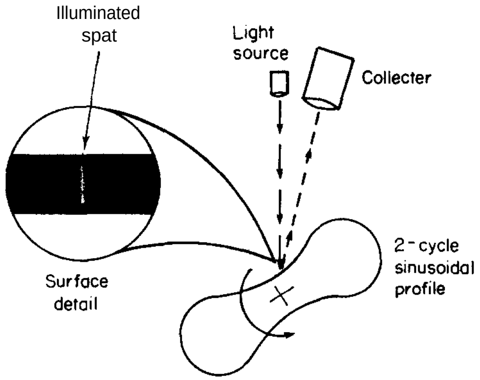

Fig. 4. Sketch of sinusoidal calibration rig

Fig. 5. Transducer output (linearized) from sinusoidal calibration rig, input frequency 24.7 Hz, input amplitude 190 mm peak-to-peak

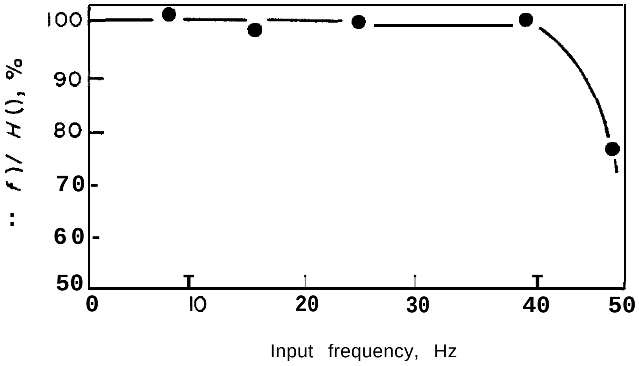

Fig. 6. Frequency response curve showing dynamic output H(f) expressed as a percentage of the static output H(0)

6. Discussion

6.1. *Accuracy*

The accuracy with which the transducer will measure a vertical co-ordinate of the ground profile under dynamic conditions, assuming the device itself is moving horizontally, depends on 3 factors. First, the noise on the output signal causes a maximum error of ±1·5 mm. Second, the width of the spot on the ground (4 mm) causes an average figure to be obtained over an area which depends on the slope of the surface. Laboratory measurements suggest this error will be ±1·0 mm on average. The third factor, which causes the largest error, is the reflectivity of the surface relative to the calibration surface. *Fig. 3* shows the variation in output between 2 surfaces when the reflectivity was changed by a factor of 4. The device does not work in an ideal manner and a possible change in reflectivity of 4 :1 will cause a maximum error of ±3·5 mm. Maximum error is therefore ± 6 mm. Linearization of the output using the simple technique described in the Appendix slightly increases the error due to reflectivity changes, from ±3·5 to ±4·0 mm.

6.2. *Dynamic performance*

The output from the transducer, shown in *Fig. 5,* is a good approximation to the sinusoidal input. The maximum error is 4% of the peak-to-peak signal and, as expected, occurs where the beam strikes the surface at the most oblique angle.

Fig 6. shows a frequency response curve for the device. Over the required frequency range the response is perfectly flat, but about 40 Hz the response falls rapidly. The limit is presently set by components in the processing circuitry but modifications would enable the upper limit to be raised to 250 Hz.

In field use, the device measures ground surface displacement when fitted to a rig which is travelling over the same rough surface. The displacement recorded by the transducer is therefore a combination of the surface profile and the motion of the rig relative to the ground. To obtain the ground profile alone, the rig displacement must be measured and subtracted from the transducer signals.

A feature of the transducer that only becomes important in field use is the operation of the "traps" for out-of-range and low light conditions. These produce a momentary spike or "dropout" in the output as the voltage jumps to an extreme value. Although these dropouts can be recognized during later analysis and eliminated, it is nevertheless important that they do not occur too often. When eliminated, they must be replaced by interpolated data which may be a poor approxmation to the rear profile. Still and Winnett[2] found on average 25 % of their readings were dropouts, the chief causes being low ground reflectivity and shielding of the light spot by abrupt profile changes. Increasing the light source power will compensate for low ground reflectivity but the problem of shieding can only be avoided by having as small an angle as possible between the beam and collector axes. In this respect our device with only 15" between the axes should be better than Still and Winnett's device with 90" between the axes (45" either side of the vertical).

6.3. *Noise*

The significant feature of the noise which appears at the output of the device is that it is low frequency noise, i.e. below 100 Hz. The components within the frequency range of the device are in fact indistinguishable from the signal produced by the ground profile. It is for this reason that it has been necessary to reduce the noise to its present ±0·5% level. As the source of the noise appears to be the position sensing photodiode, it was found that the s.n.r. could only be improved by increasing light source power and hence the light induced signals in the detector.

6.4. *Linearization*

The non-linear relationship between transducer output and ground surface displacement is mentioned in section 5.1. In applications where the output is analysed by a computer, a calibration curve can easily be applied and linearization is unnecessary. However, there will be instances where an immediate indication of the displacement is required, and in these cases a linear output is more convenient.

There are 2 methods of linearizing the output. The first method (the more accurate but also the more expensive) is to use an integrated-circuit function generator. This, in effect, automatically applies a calibration curve. The second method, which is extremely simple but less accurate, is to alter the gain on one of the photodetector outputs relative to the other. The technique is described in the Appendix. The output from the device linearized in this way is shown in ***Fig. 7.*** Maximum deviation from a straight line is 3 % at the extremes of displacement. It must be noted, however, that the surface reflectivity changes now cause a larger error of ± 4 mm. This method of linearization would be ideal where surface reflectivity is almost constant and the full range of the device is not required.

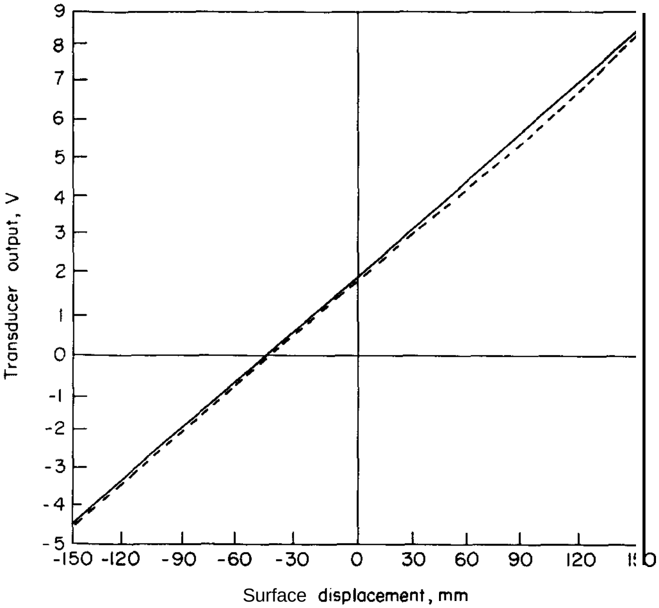

Fig. 7. Linearized transducer output for high (- – -) and low (——) surface reflectivities

6.5. Surface reflectivity effects

Laboratory measurements have shown that the ratio between the best and worst reflectivities of agricultural soils is about 4 :1. This is also the conclusion drawn from other work.[3] In section 6.1 it was shown that it is this change which causes the greatest error in the transducer output.

The source of the problem lies in the fact that the polar distribution of the reflected energy is not the same for different surfaces. Because the light spot on the ground, and hence the image on the detector, are of finite size, the centroid of intensity of the image will vary, depending on the reflected energy distribution, for the same target position. As the detector senses the centroid of intensity, the output will inevitably vary from surface to surface. The situation could be improved by reducing the beam dimensions and hence the size of the illuminated spot on the ground. Reducing the spot size increases the likelihood of the spot being shielded by small-scale irregularities in the ground surface. However, a reduction to one-sixteenth (1 x 5 mm) of the present area would probably give acceptable results. This would require a more elaborate collimating system than is presently being used.

The error due to changes in surface slope relative to the beam and collector is probably due to the same energy distribution effect. Reducing the beam size should help this problem and also define the surface profile more accurately.

7. Conclusions

A transducer based on a simple optical system has been developed which enables displacements to be measured satisfactorily without physical contact with the target. The transducer has a maximum error of ± 6 mm and measures over a range of ± 150 mm about a point of 600 mm from the sensing head.

The device is suitable for diffusely reflecting surfaces and compensates for variations in reflectivity of 4 : 1, while remaining within the stated accuracy.

The frequency response range is from 0 to 40 Hz. This could be increased to 250 Hz by a modification to the processing circuitry.

Accuracy could be increased by improvements to the light beam collimating system.

Dropouts (failures to record) are inherent in the contactless system when used on surfaces with macro-texture. Computer analysis and interpolation are necessary to fill the missing sections.

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Appendix

The detector is a single axis silicon photodiode which gives an output proportional to the position of a spot of light on its surface. It differs from detector types consisting of a linear array of discrete photodiodes in that it gives an analogue, rather than a stepped, output and therefore its resolution is not limited by the spacing of the photodiodes. The form of the photodiode is shown in *Fig. Al.*

The fundamental physics underlying the behaviour of the device has been described by Connors.” For a light spot positioned as shown in *Fig. Al,* and with the terminating impedance approaching zero, the steady state current I_S is given by

$$I_S = P_d R_\lambda \left[\frac{\sinh \alpha (L-S)}{\sinh\ (\alpha L)}\right],$$

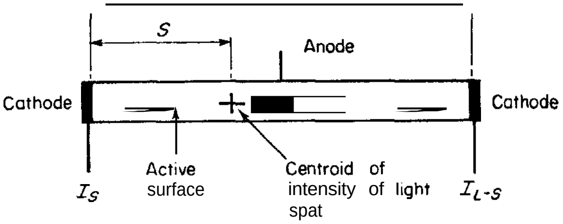

Fig. AI. Photodiode parameters

where P_d is the monochromatic incident power, R_λ is the detector responsivity at wavelength λ and α is a function of temperature and the physical and electrical characteristics of the device.

In practice α is made as small as possible. In the limit as α approaches zero,

$$I, = P_d R_\lambda (1-S/L)$$

and also

$$I_{L-S} = P_d R_\lambda \ (S/L).$$

It should be noted that the output from either terminal depends both on position and light intensity. To obtain an output which is independent of light intensity one signal must be divided by the other.

It is, however, more instructive to consider the general case in which the current outputs are converted to voltages amplified, and then added and subtracted before the division is performed. We can write

$$V_S = K_1 P_d R_\lambda \ (1\text{-}S/L),$$

where V_S is an output voltage and K_1 is an amplification factor. Similarly,

$$V_{L-S} = K_2 P_d R_\lambda \ (S/L).$$

The general expression for an output voltage V_0, which is independent of light intensity, is

$$V_0 = \frac{K_1[1-(S/L)] - K_2\,(S/L)}{K_1[1-(S/L)] + K_2(S/L)} \ .$$

The object is now to find the relationship between K_1 and K_2 which gives the maximum position sensitivity, $(\mathrm{d}\,V_0/\mathrm{d}S)_{\mathrm{max}}$. By differentiation it is found that $(\mathrm{d}V_0/\mathrm{d}S)_{\mathrm{max}}$ occurs when $K_1 = K_2$. In this case

$$V_0 = 1 - 2S/L$$

and the output is linearly dependent on the position of the light spot on the detector.

It is interesting to note that, although the position sensitivity is reduced if $K_1 \neq K_2$, a non-linear function of varying shape can be produced by varying the ratio K_1/K_2. This has a useful application in linearizing the output of the transducer.

A feature of this type of sensor is that the output is independent of the light spot size provided the spot remains within the active surface. In fact, what is actually being sensed is the location of the centroid of intensity of the spot.