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Remote measurement of tilt using fiber optic sensor

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A fiber optic tilt sensor is presented which can remotely sense the changes in tilt by the modulation of the light intensity. Plastic optical fibers (POF) are used in the preparation of the sensor probes. One fiber of the probe transmits the light and the other fiber receives the reflected light from the reflecting surface of the liquid filled in the sensor. The light emitting diode (L.E.D IF-E96) is used as a light source and the reflected light is detected by a simple and economical light dependent resistor (LDR). The performance of the tilt sensor has been tested with different numbers of probes and the experimental results obtained are very close to the theoretical derivations. The sensitivities for one, two and four probes are 0.029 V $mrad^{-1}$, 0.060 V $mrad^{-1}$ and 0.125 V $mrad^{-1}$ respectively.

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1. Introduction

A tilt sensor detects the angle between a sensing axis and a reference vector. It has been used in various industrial areas related to aerospace, automobiles, landslide management and building construction [1]. Different techniques have been used in the measurement of this important quantity. They differ in the principle of operation, reliability, sensitivity, cost and size [2]. The bubble vial played an important role in the surveying instruments like theodolite [3, 4].Electrolytic tilt sensors are precise, inexpensive and can produce accurate pitch and roll measurements in a variety of applications [5]. Angle sensors, based on the principle of auto collimation, can accurately measure small tilt angles of a light-reflecting flat surface [6]. Fiber Bragg gratings (FBGs) sensors have also been developed for the measurement of tilt which has the advantages of simple structure [7]. In another paper an angled-mirror as fiber-optic sensor's reflective modulator is introduced [8]. This paper presents a fiber optic tilt sensor which is low cost, simple in operation and has flexibility with the point of view of sensitivity. It can also be used for the remote measurement of tilt. Prototypes for different sensitivities have been developed and tested.

2. Theory

The operating principle of the presented sensor depends on the position of the liquid surface under the tilted state. With tilt, the surface of the liquid, changes its position. If the liquid is reflecting in nature and one fiber of the probe is connected to the light source and probe is held at a fixed distance from the liquid surface, the intensity of the reflected light from the liquid surface will change with the value of the tilt. For this purpose, mercury is used to reflect a light signal proportional to tilt since it has high reflective index. In this case, the probe has two optical fibers kept at equal and appreciable distance from the wall of the container to avoid the error due to surface tension. One fiber of the probe carry the light from the light source (L.E.D IF-E96) and the other collects the reflected light from the surface of the mercury and carries it to the light detector. The intensity of the reflected light will depend on the gap width between the reflecting surface and the head of the probe [9, 10] as shown in figure 1. It has two operating regions. OA is called the front slope and it is highly linear and sensitive while AB is called back slope. It has negative linear slope, less sensitivity and is operative up to large gap. The designed sensor can work in both the regions. However, proto-type is designed to work in the A`B region to cover large tilts. The performance of the sensor is analyzed by using one, two and four probes.

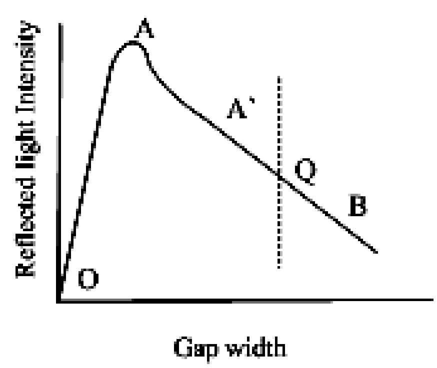

Fig. 1. Reflected light power versus gap width Characteristic of the system.

2.1 One probe Tilt sensor

Fig. 2 describes the working principle of the sensor with one probe only. The mercury surface will respond to the tilting of the base and the gap width between the probe head and the mercury surface, d, will decrease or increase as the tilt is clockwise or anticlockwise.

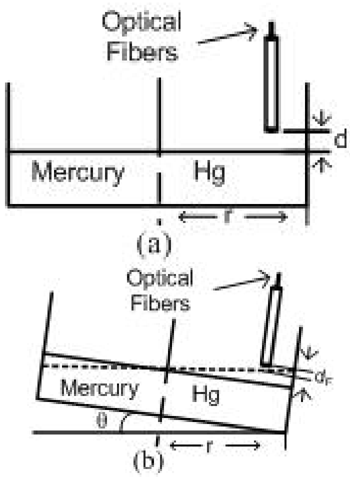

Fig. 2. Variation of gap width, d, with the change in tilt angle θ (a) Zero tilt position (b) Clockwise tilt.

Tilting of the transducer in the clockwise direction moves the mercury surface closer to the head of the probe and far for anticlockwise tilting. For clockwise and anticlockwise tilt respectively, the following equation can be written:

$$d_F = d - \Delta d \quad (1)$$

$$d_F = d + \Delta d \quad (2)$$

Where, d_F ,d represent the gap width between the probe and the surface of the mercury at some value of tilt and at zero tilt position respectively, and Δd is the relative change in the gap width, due to the tilt, which can be written in terms of tilt angle, θ as follows:

$$\tan\theta = \frac{\Delta d}{r} \quad (3)$$

Since θ is too small, equation (3) can be rewritten as:

$$\Delta d = r\theta \quad (4)$$

If the gap width, at zero tilt, chosen in the back slope of the Intensity versus gap width characteristic then the intensity of the light (I) decreases linearly with the gap width [11]. The change in the intensity of light with the gap width, from the zero tilt position, may be written as:

$$\Delta I = -k\Delta d = -kr\theta \quad (5)$$

Where, *k* is the constant of proportionality and *r* represents the distance from the central axis of the transducer to the probe. Tilting of the transducer in both directions will vary the light received by the receiver fiber and this variation will be proportional to the variation in the gap width, hence the detector output can represent the change in the tilt angle *θ*. In this application, light dependent resistor (LDR), having a resistance R at a particular intensity, is used to sense the changes in the intensity of light. Due to the change in intensity of the light, corresponding change in resistance of the LDR may be given by the following expression:

$$\Delta I = -k_1 \Delta R \quad (6)$$

Where, k_1 is the proportional constant. Substituting the value of ΔI from equation (5) in equation (6), the following expression is obtained:

$$\Delta R = k_t r\theta \quad (7)$$

Where, k_t is a constant. Equation (7) shows that change in resistance of LDR is directly proportional to the change in tilt. Hence by measuring the change in the resistance of LDR, tilt can be measured in either direction. Figure 3 shows a simple active circuit for the accurate measurement of the change in resistance [11].
Suppose, in Figure 3, $R`_2$ and R_2 are the resistances of the LDR sensor at a particular value of tilt and at zero tilt conditions respectively. Then, for clockwise tilt:

$$R`_2 = R_2 - \Delta R_2 \quad (8)$$

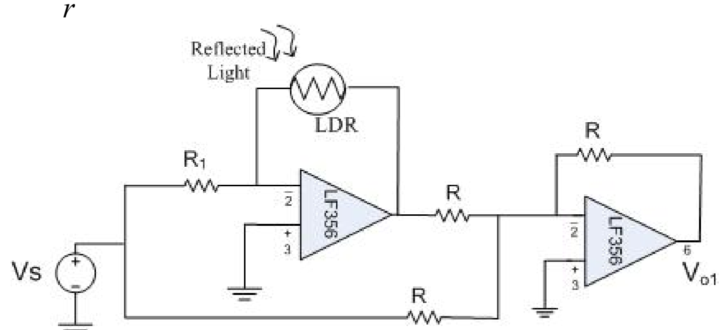

Fig. 3. Schematic Circuit Diagram for the measurement of change in resistance with one probe.

$$V_{o1} = -\frac{\Delta R_2}{R} V_s \qquad (9)$$

Substituting the value of ΔR_2 from equation (7), then equation (9) can be rewritten as:

$$V_{o1} = -\frac{k_t r\theta}{R} V_s \qquad (10)$$

2.2 Two probes tilt sensor

In this case two probes of optical fiber are used. They are installed at equal distance from the central axis of the chamber. It is tried to keep the distances between probes and mercury equal at zero tilt condition as shown in Figure 4(a). Figure 4(b) shows how the distance will change for both of the probes if the transducer is tilted in clockwise direction and Figure 4(c) shows the case of tilting in anti-clockwise direction. The dotted line represents the new positions for the mercury surface. For both directions of tilt, the gap width will decrease for one probe and increase for the other one by the same value.

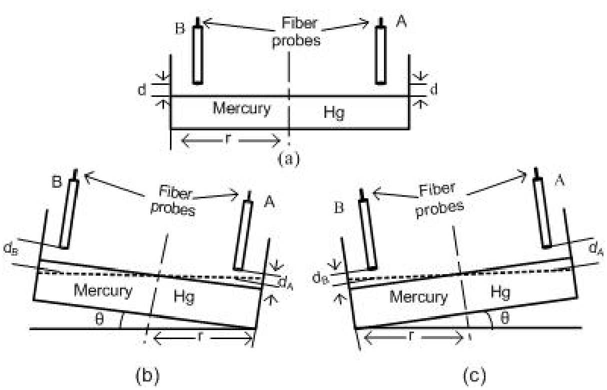

Fig. 4. Tilt meter using two fiber pairs. (a) Zero tilt position (b) Clockwise tilt (c) Anticlockwise tilt.

In the case of the clockwise tilting, the intensity of the reflected light will increase at probe A and will decrease at probe B which can be written as follows:

$$\Delta I_A = -k_2(d - \Delta d) \qquad (11)$$

$$\Delta I_B = -k_2(d + \Delta d) \qquad (12)$$

Where, I_A and I_B are the intensities of the reflected light received at probe A and B respectively. The difference of light intensities (ΔI) will be proportional to the twice of the mercury level change (Δd) and twice of the tilt angle. This can be written as follows:

$$\Delta I_A - \Delta I_B = 2k_2\Delta d = 2k_2 r\theta \qquad (13)$$

Where, k_2 is the proportionality constant. For each probe an LDR is installed to convert the changes in the intensity of the light to resistance value. Due to difference in intensities the changes in the resistances of LDRs will be different and may be given as follows:

$$\Delta I_A = -k_1 \Delta R_A \qquad (14)$$

$$\Delta I_B = -k_1 \Delta R_B \qquad (15)$$

The LDR detectors are connected in the incremental resistance measuring bridge as shown in Figure 5. Since the intensity of the reflected light is increasing in one side and decreasing in the other side, the changes in the resistances of the LDRA and LDRB are of opposite nature where LDRA is attached to the fiber probe A and LDRB is attached to the fiber probe B in figure 4(b). For clockwise tilt, resistance of LDRA will be decreasing while resistance of LDRB will be increasing and the output voltage of the circuit increases proportional to double of the tilt angle. The sensitivity of the two probes system will be just double of the single probe system.

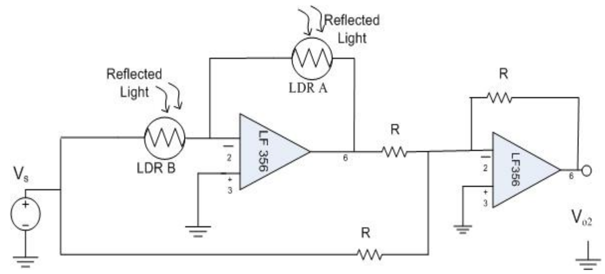

Fig. 5. Schematic Circuit Diagram for the measurement of change in resistance with two probe.

Suppose that R_A and R_B are the resistances of the detectors LDRA and LDRB at zero tilt condition respectively. Then, with change in tilt (clockwise), as explained above, each detector resistance R_A and R_B will take new values $R`_A$ and $R`_B$ respectively.

$$R`_A = R_A - \Delta R_A \qquad (16)$$

$$R`_B = R_B + \Delta R_B \qquad (17)$$

Where, ΔR_A and ΔR_B are the relative resistance changes at LDRA and LDRB respectively. Assume that R_A=R_B=R and ΔR_A=ΔR_B=ΔR, then the output voltage can be written as:

$$V_{o2} = -2\frac{\Delta R}{R + \Delta R} V_s \qquad (18)$$

Since R >> than ΔR (the experiment shows that ΔR is smaller than R by 4×10^{-3}) equation (18) can be rewritten as:

$$V_{o2} \cong -2\frac{k_t}{R} r\theta V_s \qquad (19)$$

Equation (19) shows that the output voltage of the circuit with two probes becomes just double the value obtained for the case of single probe.

2.3 Four probes tilt sensor

In this case, four probes are used; each probe has its peer probe in the opposite side of the sensor as shown in figure 6. The variation of the distances between the head of the probes and the mercury surface will take place with tilting and this will lead to increasing in the intensity of the reflected light in one side and decreasing in the other side. Using equation (13) we can write:

$$\Delta I_A - \Delta I_B = 2k_2 r\theta \text{ and } \Delta I_C - \Delta I_D = 2k_2 r\theta \qquad (20)$$

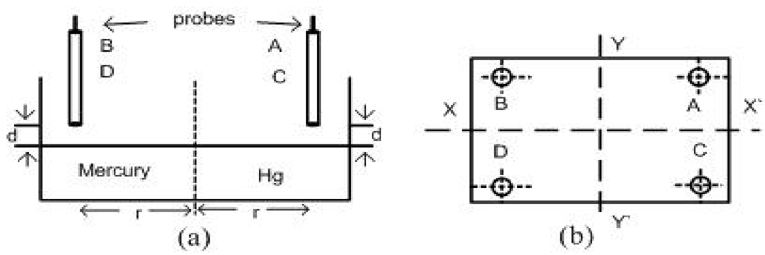

Fig. 6. Tilt meter with four fiber probes. (a) Side view (b) Top view.

For this purpose, a signal processing circuit consists of two incremental resistance measuring circuits connected to a summer is used, as shown in figure 7. In this case, the output voltage of the signal processing circuit may be given as:

$$V_{o4} \cong -4\frac{k_t}{R} r\theta V_s \qquad (21)$$

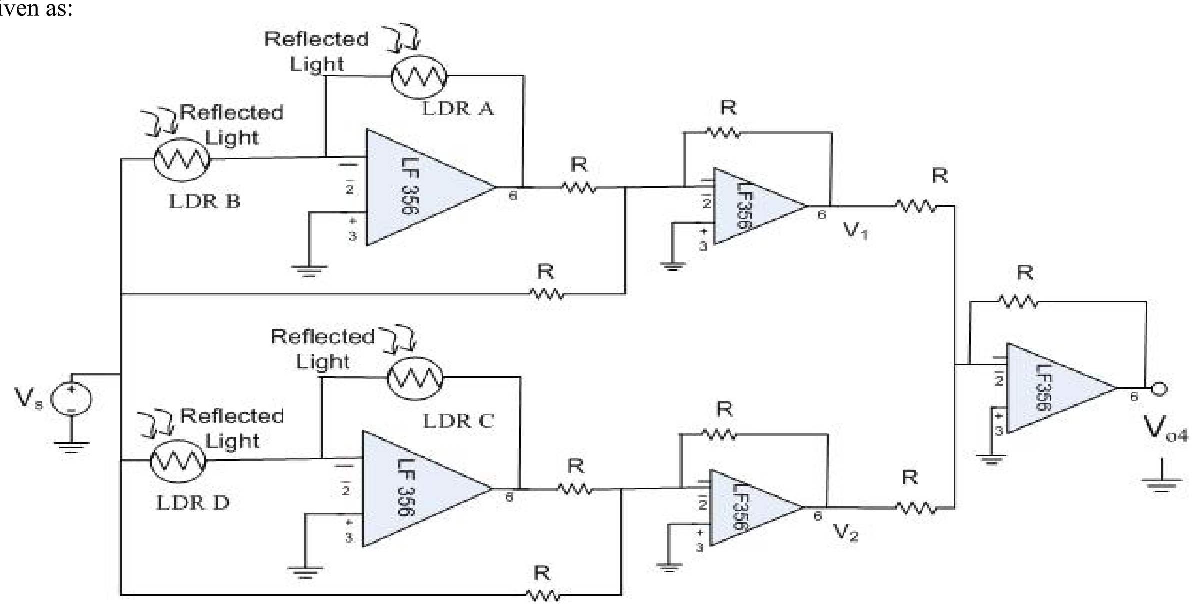

Fig. 7. Schematic circuit diagram for the measurement of changes in the resistances of LDRs with four probes.

3. Experimental method and results

The fabricated sensor consists of a square box made of Perspex (15×15×10 cm) with three screws in the base for tilt adjustment. Inside the box, a probe guiding system is placed at opposite side of the box. Through guider, the position of the probes, with respect to mercury surface, may be adjusted precisely, at the same time. To avoid the depression in the level of mercury, due to surface tension, the guider is designed such that the probes are kept at a distance of 2 mm from the opposite sides of the container wall as shown in figure 8.

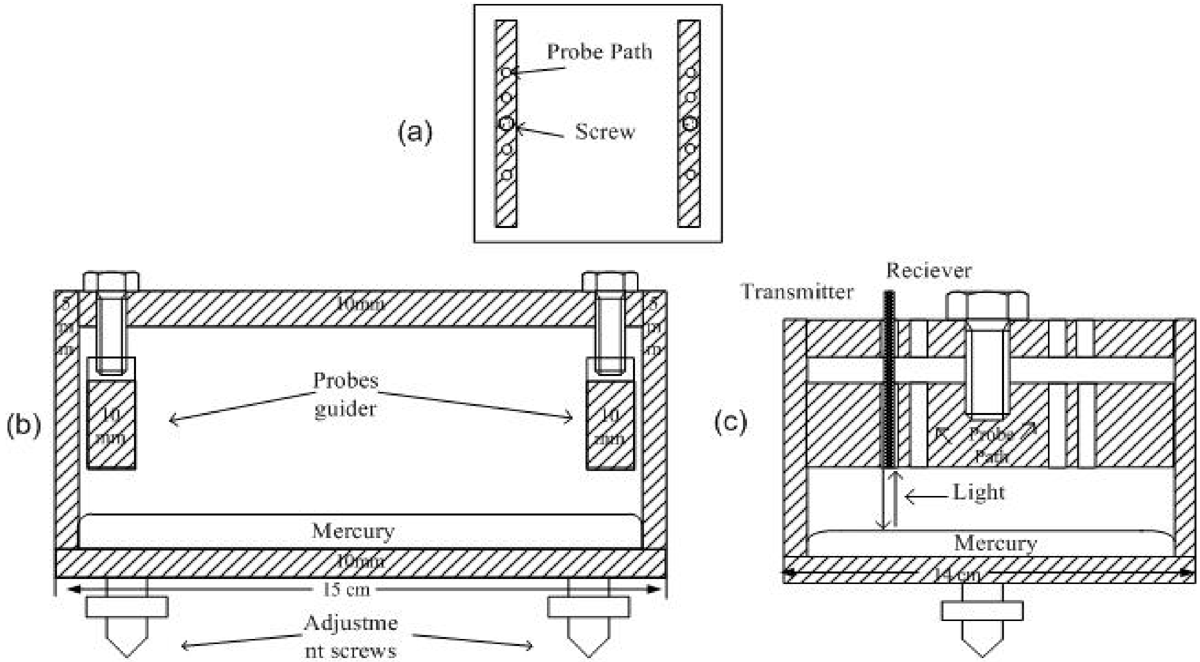

Fig. 8. (a) Proposed sensor_ Top view (b) Front Cross-sectional view (c) Side Cross- Sectional View.

Plastic Optical fibers are used in the fabrication of the probes as they are cheap, robust and easy to handle. Glass fibers can also be used and it has further advantage over the Plastic type such as sensitivity, lower attenuation and compatibility with fiber optic telemetry but they are difficult to handle and fragile. The gap width between the mercury and the probes heads is decided according to the range and desired sensitivity. In the experiments, conducted for the calibration of the tilt sensor in the laboratory, the gap width is kept 6 mm at zero tilt. In this way the back slope of the Reflected light versus gap characteristic will be employed.

Two pairs of the optical fiber, with lengths of 40 cm each are used and one fiber of the probe is connected with the light source and the other fiber is connected to the detector. L.E.D (IF-E96) with 660 nm wavelength excited by 2.5 volts is placed in the transmitter circuit. The light will be reflected from the mercury surface and the receiver fiber will send it to the detector. Light dependent resistor (LDR) is used to detect the light. It is noted that at zero tilt condition the resistances of the detectors are not exactly equal. For this reason, a small variable resistance is connected in series with the detectors to get zero output voltage at zero tilt condition.

The three screws in the base of the proposed sensor are used for the adjustment of initial level. Known value of tilt is provided with the help of a tilt causing system made of two Perspex sheets, one sheet is moved precisely by a distance measured by digital micrometer as shown in figure 9.

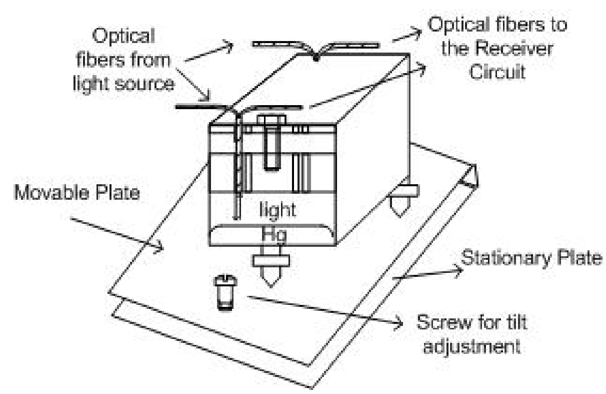

Fig. 9. Calibration system for the tilt sensor.

For every precisely known value of tilt, output of the detecting system, is measured accurately by using one, two and four probes. The obtained results are drawn in figure 10. The first quadrant data has been obtained by giving clockwise tilt while fourth quadrant data is obtained by giving the anti-clockwise tilt. Experiments conducted under controlled conditions yield results which are quite linear and values of R^2 (correlation coefficient) are 0.9993, 0.9995 and 0.9996 for one, two and four probe systems respectively and very small non-linearity may be attributed to the random effects. The sensitivity of the system is 0.029 V mrad-^{1}, 0.060 V mrad-^{1} and 0.125 V mrad-^{1} in the case of using one, two and four probes respectively. However the ratios of the theoretically and practically obtained sensitivities are very close and may be given as 1:2:4 and 1:2.08:4.3 respectively.

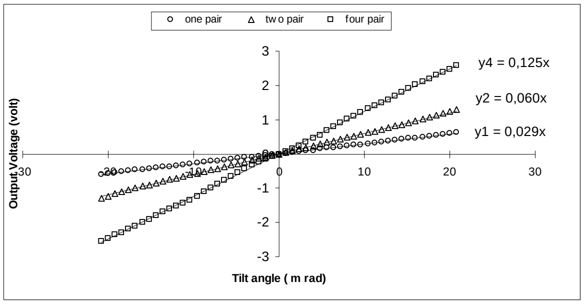

Fig. 10. Calibration curves of one, two and four probes arrangements.

3.1 Source of errors

The misalignments of the probes may introduce different detector responses, which will lead to none zero output voltage at the zero tilt condition. However, this type of error may be taken care off by giving a precise guide for the position of the fiber probe with respect to liquid surface. Further improvement may be obtained by using precision type variable resistances in series with the detectors. These adjustments may lead to zero output voltage at balance condition. The vibrations in the liquid may be the source of noise and my lead to errors when fast responding system is used. It is observed that by increasing the number of probes, the effect of vibrations on the output voltage, is appreciably reduced which may be due to the summation of the outputs of the probes. Hence for stable operation it is necessary to use more than two probes.

4. Conclusion

A highly flexible design of a Fiber optic tilt sensor for remote measurement of tilt is presented. It is low cost, simple to design and utilizes off the shelf components. It has been simulated, designed, fabricated and tested for one, two and four probes and it has been found that the test results agree with the simulated results very closely. Theoretically, the sensitivities of the one probe, two probes and four probes systems should have the ratio of the order of 1:2:4. However, practically determined sensitivities have the ratio of 1:2.08:4.3 which are very close to the derived values. The calibration method was repeated a number of times, under controlled conditions, to verify the linearity of the system. The data obtained show that the relationship between output voltage and tilt is quite linear and values of correlation factor, R^2 are 0.9993, 0.9995 and 0.9996 for one, two and four probe systems respectively and very small non-linearity may be due to the random effects. There is no upper limit for the number of probes and number will be decided by making a compromise between cost and overall sensitivity. To reduce the size and complexity of the system an optical multiplexer may be employed to gather with a microcontroller. The microcontroller will help in increasing the intelligence as well as the flexibility in the system. The contamination of the mercury surface, due to oxidation, may be avoided by taking the purest form of mercury and filling the space with inert gases like nitrogen, argon etc. The fabricated sensor is going to be used in the monitoring of the landslides.

Acknowledgments

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