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Relative position measurement system for vehicles using diffuse light from LEDs[1]

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ABSTRACT

For the purpose of saving labor and improving safety in farm operations conducted with a pair of vehicles, automatic driving systems of the following or preceding vehicle have been studied. These systems require real-time and precise measurement of the relative position of vehicles. The authors propose a relative position detection system using diffuse light from LEDs. In the first stage of this study, a range-finder was developed and tested, consisting of two stations which emit high-frequency modulated light at each other. The range between the stations is obtained from the phase difference between the two low-frequency beat signals generated in both stations. Performance tests were conducted under direct sunshine, and the maximum and standard errors from the regression values were about 5 and 3 cm respectively in the range from 1 to 10 m.

KEYWORDS. Position detection, Infrared, Diffuse light, Transponder, Light emitting diodes

INTRODUCTION

Some farm operations are conducted with a pair of vehicles. For instance, a forage harvester is followed by a forage wagon while at work. For the purpose of saving labor and improving safety in such operations, automatic driving systems of the following or preceding vehicle have been studied (Iida et al., 1999). These systems require real-time and precise measurements of the relative position and the traveling speed of each vehicle (Imou et al., 2001) to keep the proper positional relationship between the two vehicles.

Although some systems could be considered to measure the relative position, most of them have a weak point. For instance, a pair of RTK-GPS receivers mounted on preceding and following vehicles could provide the relative position, but RTK-GPS's are very expensive. A laser range finder with an auto tracking or scanning device is also available. An auto tracking laser range finder mounted on a vehicle could follow a reflector on the other vehicle and measure the range and direction accurately. However, auto tracking systems are also very costly. Although a scanning range finder is cheaper than an auto tracking system, it can not detect the precise position of the target. Ultrasonic sensors are available at lower cost, but they are susceptible to the effects of wind or sound noises from the vehicles.

The optimum solution would be a real-time, precise and low-cost method of relative position measurement, for which we propose a relative position detection system using diffuse light as shown in Figure 1. An optical transmitter and two receivers are mounted on each vehicle. Each transmitter emits diffuse light in all horizontal directions. Therefore, the system requires neither a tracking nor scanning device. The transmitters are placed at points S_A and S_B, and receivers are

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placed at S_A, $S_{A'}$, S_B and $S_{B'}$. The light signal emitted from S_A is received at points S_B and $S_{B'}$, and the signal from S_B is received at S_A and $S_{A'}$.

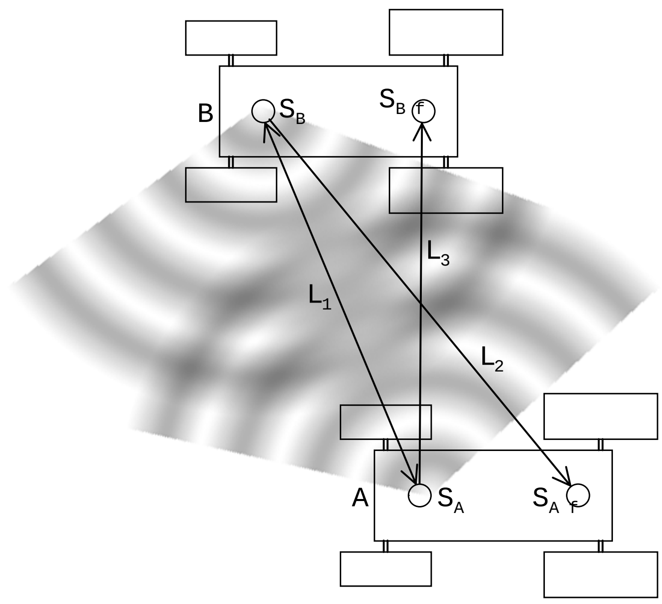

Figure 1. Schematic diagram of the proposed relative position detection system using diffuse light

The relative position and heading angle between vehicles A and B are obtained by detecting distances L_1, L_2 and L_3. The distance L_1 is measured by the method of range finding described in this paper. L_2 and L_3 are not directly measured but obtained from the range differences. L_2-L_1 is obtained by measuring the phase difference between two modulation signals which are emitted at the same point S_B and received at points S_A and $S_{A'}$. L_3-L_1 is measured in the same way. In such systems, range differences can be easily and accurately measured compared to absolute ranges. Therefore, the measurement of L_1 is a key technology in this system. Changes in attitude of the vehicles would cause the error of the measurement, but it could be easily compensated using tilt angle sensors.

In the first stage of the study, we developed a range-finder using diffuse light from LEDs to investigate the feasibility of the proposed system. The target accuracy of the system developed in this study was within 5 cm over the range of 1 to 10 m, which will be acceptable for most farm operations conducted with a pair of vehicles.

MEASUREMENT PRINCIPLE

Figure 2 shows the principle of the developed range-finder. The principle is similar to that of electromagnetic distance measurement instruments (Suda, 1976). The range-finder consists of two stations, referred to here as stations A and B. Each station has an oscillator to generate a high-frequency (HF) signal, of frequencies f_1 and f_2 respectively. These frequencies are different, but close to each other. Although either frequency may be higher than the other, we suppose $f_1 > f_2$. The time functions of the signals are given by the following equations:

$$\begin{aligned} y_1 &= \sin(\omega_1 t - \phi_1) \\ y_2 &= \sin(\omega_2 t - \phi_2) \end{aligned} \quad (1)$$

where, ω_1 and ω_2 are the circular frequencies. These are given by:

$$\begin{aligned} \omega_1 &= 2\pi f_1 \\ \omega_2 &= 2\pi f_2 \end{aligned} \quad (2)$$

ϕ_1 and ϕ_2 are the phases of the signals, which are unknown quantities. The amplitude of every signal can be assumed to be unity because the amplitude is not relevant in principle. The optical radiations from stations A and B are intensity-modulated by the electric signals of y_1 and y_2

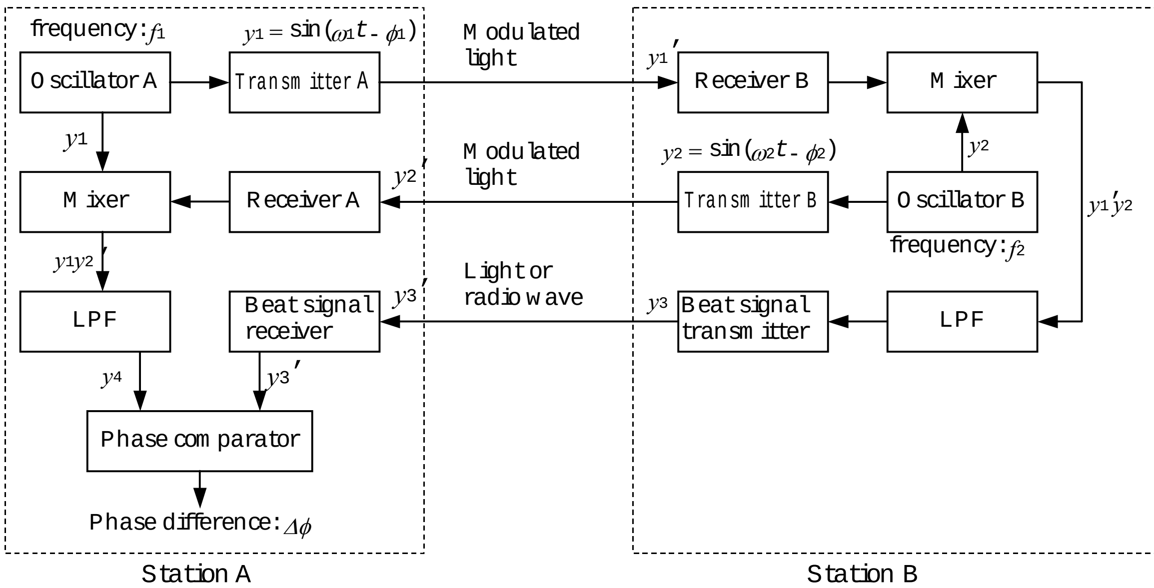

Figure 2. Principle of the developed range-finder

respectively. Each light is received by the receiver of the other station, and the demodulation signal is obtained. If C denotes the speed of light and the distance between two stations is D, the time of the transmission of light will be D/C, and so the demodulation signals are expressed as follows:

$$\begin{aligned} y_1' &= \sin\{\omega_1(t - D/C) - \phi_1\} \\ y_2' &= \sin\{\omega_2(t - D/C) - \phi_2\} \end{aligned} \qquad (3)$$

The amplitude is assumed to be unity also in the equations. In station B, the received signal y_1' and the generated signal y_2 are mixed by a mixer. The mixer is a kind of analog multiplier which outputs the product of two signals as expressed by the following equation:

$$\begin{aligned} y_1'y_2 &= \sin\{\omega_1(t - D/C) - \phi_1\}\sin(\omega_2 t - \phi_2) \\ &= -\frac{1}{2}\cos\{(\omega_1+\omega_2)t - (\phi_1+\phi_2) - \omega_1 D/C\} + \frac{1}{2}\cos\{(\omega_1-\omega_2)t - (\phi_1-\phi_2) - \omega_1 D/C\} \end{aligned} \quad (4$$

We can see from Eq. (4) that the signal has the components of HF of f_1+f_2 and low-frequency (LF) of f_1-f_2. From the signal, only the LF wave is extracted through a low pass filter (LPF). If y_3 denotes the LF beat, y_3 is expressed as follows:

$$y_3 = \cos\{(\omega_1-\omega_2)t - (\phi_1-\phi_2) - \omega_1 D/C\} \qquad (5)$$

In the same way, signal y_1 generated in station A is mixed with the received signal y_2', from which the LF beat y_4 is generated, given by:

$$\begin{aligned} y_1y_2' &= \sin(\omega_1 t - \phi_1)\sin\{\omega_2(t - D/C) - \phi_2\} \\ &= -\frac{1}{2}\cos\{(\omega_1+\omega_2)t - (\phi_1+\phi_2) - \omega_2 D/C\} + \frac{1}{2}\cos\{(\omega_1-\omega_2)t - (\phi_1-\phi_2) + \omega_2 D/C\} \end{aligned} \quad (6$$

$$y_4 = \cos\{(\omega_1-\omega_2)t - (\phi_1-\phi_2) + \omega_2 D/C\} \qquad (7)$$

To compare the phases of the LF beat signals y_3 and y_4, signal y_3 is transmitted from station B to station A by light or radio wave. When the signal arrives at station A, the time function of the signal is obtained from Eq. (5) by replacing t with t-D/C because the time of D/C has passed during the transmission. This is expressed as:

$$y_3' = \cos\{(\omega_1 - \omega_2)(t - D/C) - (\phi_1 - \phi_2) - \omega_1 D/C\}$$
$$= \cos\{(\omega_1 - \omega_2)t - (\phi_1 - \phi_2) - 2\omega_1 D/C + \omega_2 D/C\} \qquad (8)$$

A phase comparator in station A compares the phases of y_4 and y_3', and outputs the phase difference $\Delta\phi$. From Eqs. (7) and (8), $\Delta\phi$ is obtained as follows:

$$\Delta\phi = 2\omega_1 D/C \qquad (9)$$

from which distance D is given by:

$$D = \Delta\phi C/2\omega_1 \qquad (10)$$

Range to the target D is obtained from the phase difference $\Delta\phi$, the speed of light C, and the circular frequency of modulation ω_1.

EQUIPMENT AND METHODS

Range-finder

Optical transmitter and receiver

The authors manufactured a prototype range-finder for tests to determine the feasibility of position detection using diffuse light. Figure 3 shows the optical transmitter and the receiver used for the prototype. The same transmitters and same receivers are used for both stations A and B. The transmitter has 25 high-speed infrared light emitting diodes (LEDs), all of which were attached facing the same direction. The LED was made for optical communication, the specifications of which are shown in Table 1 (Stanley Electric Co., Ltd., 1998).

Figure 3. Optical transmitter and receiver

Table 1. Specifications of the infrared LED

Infrared LED: Stanley, DNF318U	
Shape	•5 mm Epoxy
Peak wavelength	850 nm
Maximum current	100 mA
Radiant intensity	60 mw/sr

Cut-off frequency	30 MHz
Directivity (cone half angle)	20°

Table 2. Specifications of the photo sensor

APD Module: Hamamatsu, C5331-03	
Active area	•1.0 mm
Spectral response range	400 to 1000 nm
Peak sensitivity wavelength	800 nm
Frequency bandwidth (-3db)	4 kHz to 100 MHz
Photo sensitivity (800 nm)	6.75×10^4 V/W
Supply voltage	5 V

An avalanche photodiode (APD) module is used for the optical receiver, the specifications of which are shown in Table 2 (Hamamatsu Co., Ltd., 1998). The sensor module is placed in an aluminum box and the sensor is covered with an IR bandpass filter (Edmund Scientific, Model RT-830) to eliminate the effects of visible light. The center wavelength of the filter is 830nm.

Signal processing

The most important factor of the system is the modulation frequency of the light signal emitted from station A. If the resolution of phase detection is constant, the resolution of range measurement is in inverse proportion to frequency f_1, which can be seen in Eq. (10). Therefore, frequency f_1 should be sufficiently high. In the prototype, the frequency was set at 12.801 MHz. If the resolution of phase detection is 1/10,000, the resolution of range measurement is about 1.2 mm in the case. The frequency was determined also so as to avoid the phase integer ambiguity. In this case, one-full cycle (2π radian) of the phase difference corresponds to the distance of about 11.7 m that is calculated from Eq. (10). Therefore the value is sufficiently long, the phase integer ambiguity will not be a serious problem in the proposed position detection system.

From Eq. (9), it seems that we can set frequency f_2 at any value. However, in practical systems, f_2 should be so close to f_1 as to sufficiently reduce the beat frequency. It enables the system to preciously detect the phase difference of beat signals. In the prototype, frequency f_2 was set at 12.8 MHz, and so the beat frequency was 1 kHz.

In the case that independent oscillators are used to generate the HF signals of f_1 and f_2, the beat frequency f_1-f_2 may change at a considerable rate, even if f_1 and f_2 are almost constant. For instance, a change of 1 ppm in frequency f_1 or f_2 causes a change of 1.28% in the beat frequency, which may change the phases of beat signals in the circuits. Therefore, we used a frequency synthesizer to generate the signal of frequency f_1 in station A. The synthesizer controls frequency f_1 to keep the beat frequency exactly constant at 1 kHz.

Figure 4 is a block diagram of the signal processing circuits of the prototype range-finder. In station B, a temperature compensated crystal oscillator (TCXO) generates the HF signal of 12.8 MHz. The frequency variation of the TCXO is less than 1 ppm. The signal is mixed with the signal of 12.801 MHz transferred from station A. A balanced modulator is used as the mixer. A beat of two signals is output from the mixer and extracted through a LPF. The beat signal having a frequency of 1 kHz is fed into a voltage controlled oscillator (VCO) to generate an intermediate-frequency (IF) signal that is frequency-modulated (FM) by the beat signal. The center frequency of the IF signal was set at 450 kHz. The HF signal of 12.8 MHz and the IF signal are added (i.e. the HF signal is offset-modulated (OM) by the IF signal). The emitted light from station B is intensity-modulated by the HF signal. Thus, the HF signal and the LF beat are transmitted by the same light to station A.

In station A, the received signal is distributed to be fed into an IF band-pass filter (BPF) and a mixer. The IF signal passes the BPF and is demodulated using a phase lock loop (PLL) based FM demodulator. Thus, the beat signal of 1 kHz transferred from station B is reproduced in station A. At the same time, one more beat signal is produced by mixing the 12.8 MHz signal from station

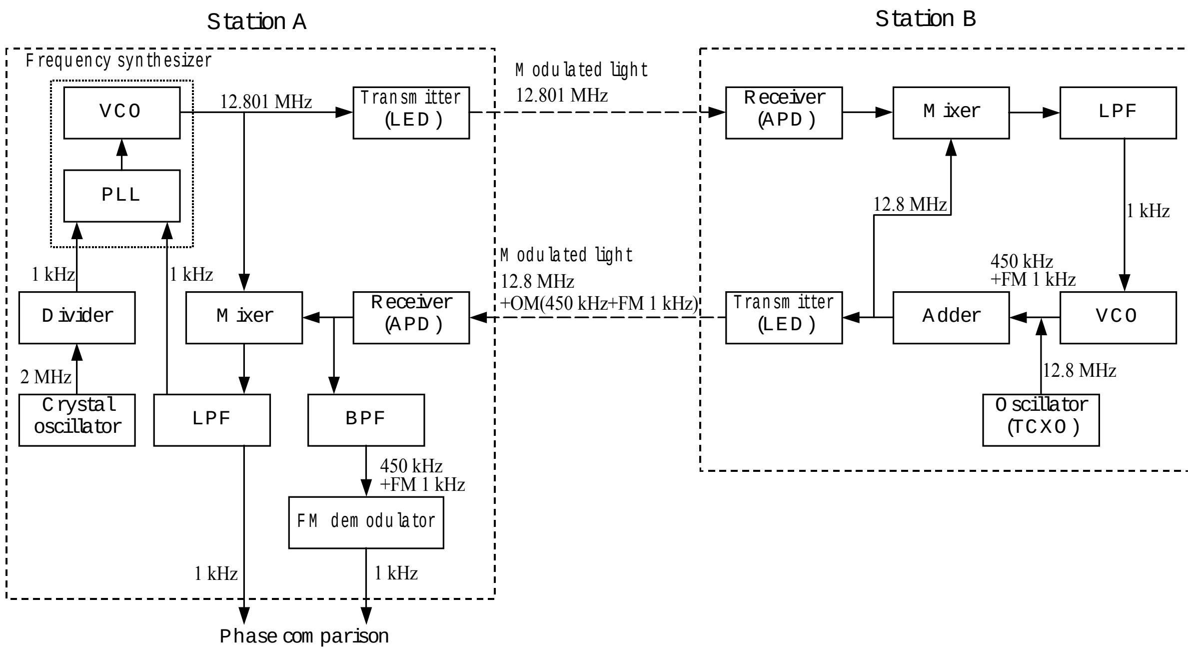

Figure 4. Block diagram of the developed range finder

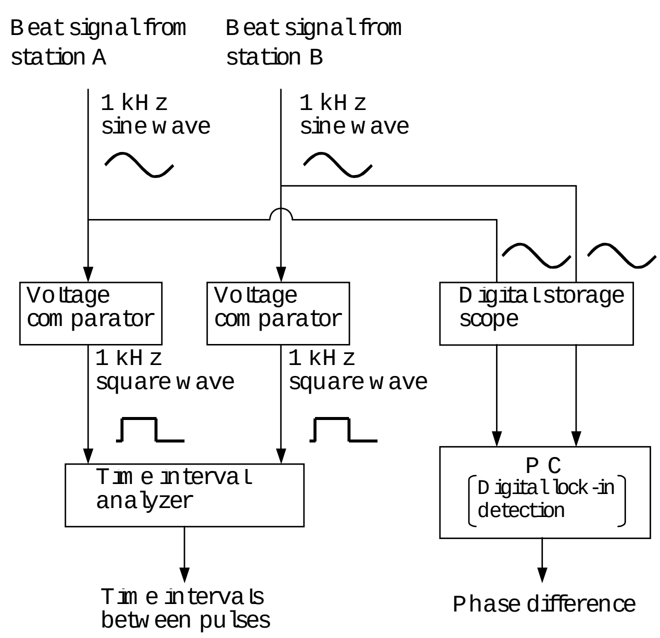

Figure 5. Schematic diagram of the phase difference measurements

B with the 12.801 MHz signal generated in station A. The 12.801 MHz signal is generated by a frequency synthesizer that consists of a PLL and a VCO. The two beat signals are output and the phase difference is measured, from which the distance between the stations is obtained using Eq. (10).

Test methods

Only static tests were conducted in this study to evaluate the basic performance of the developed range-finder. Stations A and B were placed face to face at a given distance and the phase difference was measured. The distance between the stations was increased from 1 m in 1 m steps.

The tests were conducted under direct sunshine, which is a difficult condition for the sensor because the scattered light from the sun enters the sensor and decreases the S/N ratio. The optical receivers were thermally insulated with expanded polystyrene board to suppress the effects of changes in ambient air temperature, and a sunshade was attached to each receiver to prevent direct sunlight striking the photo sensor.

The phase difference was measured as shown in Figure. 5. The authors made an analogue phase comparator in a previous study (Imou et al., 1999). However, in these tests we used commercially available instruments to detect the phase difference, which enabled us to obtain detailed information on the error characteristics of the developed system.

The phase difference was measured in two ways at the same time. One is the digital lock-in method, in which the sine waves of beat signals were stored in a digital storage scope (Yokogawa Electric, Model DL7100) for 10 ms with a sampling frequency of 1 MHz, and the data was fed into a PC. The PC calculated the Fourier coefficients of the 1 kHz harmonic a_1, b_1 for each signal using the following equations:

$$a_1 = \frac{1}{N}\sum_{k=0}^{N-1} g(k)\cos\frac{2\pi k}{n}$$
$$b_1 = \frac{1}{N}\sum_{k=0}^{N-1} g(k)\sin\frac{2\pi k}{n} \qquad (11)$$

where, k is the time sample index, $g(k)$ is the sample value of the signal, N (=10,000) is the number of samples and n (=1,000) is the number of samples in one period of 1 kHz. The phase of each signal ϕ was calculated by:

$$\phi = \tan^{-1}\frac{a_1}{b_1} \qquad (12)$$

from which the phase difference of the signals was obtained.

The second way is time interval measurement, in which the beat signals were converted to square waves by voltage comparators, and the time intervals between the pulses were measured for 100 ms by a time interval analyzer (Yokogawa Electric, Model TA520). The phase difference was obtained from the average value of the time intervals.

RESULTS AND DISCUSSION

While the performance test was carried out, the ambient air temperature was about 29• and the intensity of solar radiation onto a horizontal surface ranged from 0.45 to 0.87 kW/m^2. The test results are shown in Figure 6. The circles and squares represent the data obtained from the time intervals and by the digital lock-in method respectively. The target accuracy of the system developed in this study was within 5 cm over the range of 1 to 10 m, therefore, the performance characteristics in the range of 1 to 10 m were mainly discussed. Lines in the graph are the regression lines of the plots in the range. The regression coefficients and the coefficients of determination are shown in Table 3.

Both results showed good linearity in the range. Thus, the coefficients of determination R^2 were close to one. The theoretical ratio of the changes in phase difference to the changes in distance is calculated from Eq. (10) to be 0.537 rad/m. The gradients of regression lines from the test results were slightly larger than the theoretical value. Although the reason is not clear, an effect of signal intensity on the phase shifts in electronic circuits is considered to be one of the reasons. The intercepts of regression lines were not zero, the reason for which was phase shifts of the signals in the electronic circuits and the cables. There was a difference of about π radian between the results obtained in the two ways because the voltage comparator shown in Figure 5 reversed the signal from station B.

The maximum and the standard errors are also shown in Table 3, which are the maximum and the standard deviations of the measured phase differences from the regression values. The numbers in brackets indicate equivalent distances to the errors, and show that the degrees of

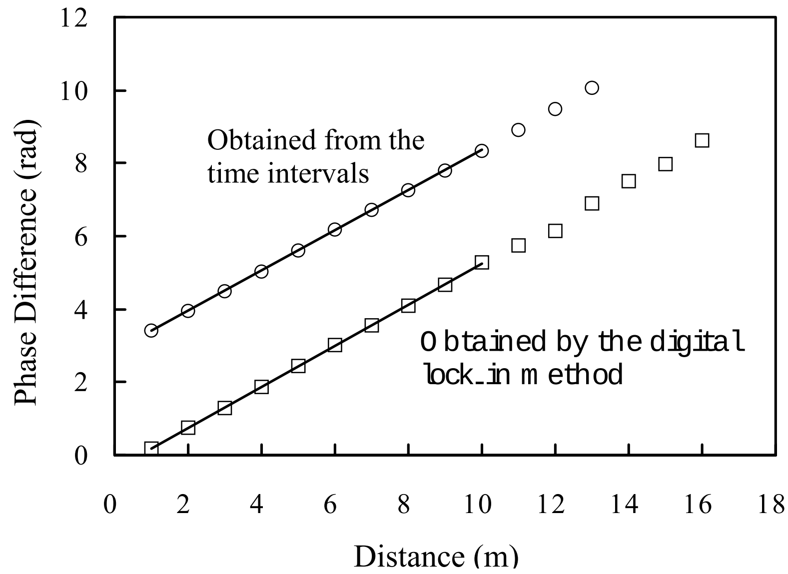

Figure 6. Experimental results of the performance test

Table 3. Regression line parameters from the test results in the range of 1 to 10 m

	Time interval	Digital lock-in method
Gradient [rad/m]	0.5504	0.5649
Intercept [rad]	2.8494	-0.3917
R^2	0.9999	0.9999
Maximum error	0.0271 rad (4.91 cm)	0.0314 rad (5.56 cm)
Standard error	0.0149 rad (2.71 cm)	0.0173 rad (3.06 cm)

errors were on the same level for both methods of phase difference measurement. The maximum and standard errors were about 5 and 3 cm respectively in the range from 1 to 10 m. If both methods provided almost the same accuracies, the time interval method would be advantageous because the device could easily be implemented with electronic circuits for a practical system. The results almost achieved the target accuracy of the development. However, in the tests, temperature effects were not considered. Changes in ambient temperature would affect the phase shifts in electronic circuits, and should be investigated in the next stage of the study.

At the distance of 11 m, the errors were on the same level as those for the distances within 10 m in both methods. At distances above 11 m, the errors were larger. The maximum error was 47 cm observed in the results of digital lock-in method at 12 m. The results obtained from the time intervals were unstable at the distance above 13 m. In the digital lock-in method, measurement was possible within 16 m.

The test results demonstrated the feasibility of the relative position detection system using diffuse light. However, weather conditions (temperature change, rain and fog) were not considered in the experiments. There are some possibilities of performance decrement due to the weather conditions. Change in ambient temperature may cause a drift in the circuit, and rain or fog may reduce the measurable range. Those effects should be investigated in the next stage of the study.

Based on the results in the experiments, we will make a prototype system for field tests. It will have transmitters and receivers, which can transfer the light signal in all horizontal directions.

CONCLUSIONS

The results of this study may be summarized as follows:

1. A relative position detection system using diffuse light was proposed for automatic driving of the following or preceding vehicle used for farm operations.
2. A prototype range-finder was manufactured and tested to investigate the feasibility of the proposed system. It consisted of optical transmitters and receivers to transfer intensity modulated light to each other. Each transmitter had 25 high-speed infrared LEDs, and an avalanche photodiode module was used for each receiver.
3. Performance tests of the range-finder were conducted under direct sunshine. The maximum and standard errors from the regression values were about 5 and 3 cm respectively in the range from 1 to 10 m.
4. The test results almost achieved the target accuracy of the development. However, the effects of temperature change, rain or fog were not considered and should be investigated in the next stage of the study.

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