Microprocessor-Based Noncontact Distance Measuring Control System

JIUNNJYH WANG, J. C. WAMBOLD, and J. J. HENRY

ABSTRACT

A microprocessor-based noncontact ranging system is discussed, which, along with a computer-based videographics system, constitutes a noncontact texture profiling system developed at the Pennsylvania Transportation Institute. Consisting of a 6502-based single board computer and a Polaroid ultrasonic circuit board, the ranging system is used to monitor the displacement between a traveling test vehicle and the road surface. The texture measurement is performed by the videographic system, which is capable of acquiring data only when it is within a range of ± 1.2 mm from the pavement. Because the system is mounted in a moving vehicle, it is continuously moving up and down relative to the pavement and, consequently, a ranging device is needed to trigger the data acquisition only when the system is in range. Because the system is to run at highway speeds, the ranging system needs to operate at a sampling rate of 40 per second with a resolution of 0.3 mm or better. The final system achieved a rate of 60 samples per second with a resolution of 0.17 mm. A high resolution of the videographic system is achieved because the ranging system eliminates the need for a large depth of field. In addition, the ranging system is capable of data processing, self-calibration, and controlling, and thus has the potential for other applications such as road roughness measurement, liquid level sensing, and any general noncontact displacement measurement.

In a noncontact texture measurement system described elsewhere in this Record by Her et al., an optical system consisting of a stroboscopic light source and lens assembly is used to project a strong beam of light (in the shape of a long, thin strip) with a sharp edge down to the road surface. The projected light area on the road surface is then taken as a picture by the TV camera and stored as a digitized picture in the LSI-11 processor. The processor performs an edge detection algorithm of the digitized picture and, after angle correction, stores it as a profile of the texture. Because all of the apparatus is maintained on a vehicle moving at 40 mph, bouncing of the vehicle will result in the whole system, lens assembly and TV, constantly going in and out of focus.

A ranging system is needed to solve the problem. There are three functions provided by this ranging system.

1. The ranging system closely monitors the displacement between the vehicle and the road surface and is able to indicate when the system is in focus and to fire the strobe. Thus, a sharp picture is guaranteed whenever a picture is taken.

2. The ranging system determines when the video signal of texture image is available and when it should be acquired and processed before the image fades. This is done by issuing a command to the LSI-11 processor, which hosts the video-digitizer.

3. The texture image in the picture is always at the same position because the picture is always taken at a fixed position, the focal position. This facilitates the processing of the texture image as the processor is able to search for the image more efficiently.

With some modifications, a ranging system designed for these purposes can also be applied to road roughness measurement.

PRINCIPLE OF SYSTEM OPERATION

The speed of sound in a homogeneous medium is constant for a constant set of environmental conditions. Therefore, with each unknown distance, there is an associated time interval determined by the speed of sound in that particular medium. If the time interval can be measured, it can be converted into distance with respect to sound speed at that set of ambient conditions. However, the correct speed of sound is not always available for time-to-distance conversion, especially when ambient conditions such as temperature, humidity, and windspeed keep changing. A measurement error results unless the correct speed of sound at that ambient condition is used for time-to-distance conversion. Another measurement error comes from the varied vehicle speeds. As shown in Figure 1, the sound path is V-shaped. Different vehicle speeds result in a different sound path and time interval for a fixed distance between the vehicle and the road surface (path A for a slower vehicle, path B for a faster vehicle). The distance D' as measured by the moving vehicle without correction can be found to be (1):

$$D' = DV_c/(V_s^2 - V_v^2)^{1/2} \tag{1}$$

where

D = distance between vehicle and road surface;
V_v = vehicle speed. In the case where wind is present, this represents the magnitude of vector sum of vehicle velocity and sound velocity component in the direction of vehicle motion;

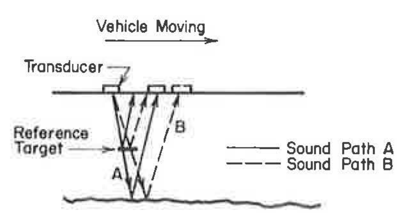

FIGURE 1 Sound path for measurement.

V_C = speed of sound used by computer for time to distance conversion; and

V_S = speed of sound at that set of environmental conditions.

It is shown that D' is a function of the speed of sound and the vehicle speed. Under normal operating conditions with V_V ranging from 0 to 60 mph, D = 40 cm, and V_S = 343 m/s at 20°C, an intolerable error of as much as 1.2 mm, which is equal to the allowed system depth of focus, could occur.

This problem can be overcome in this design by placing a fixed calibration target at a predetermined distance d. Because the distance d measured by the moving vehicle is

$$d' = dV_c/(V_s^2 - V_v^2)^{1/2} \quad (2)$$

the true distance between vehicle and road surface can be obtained by calculating D'/d' x d = D. Therefore, the distance measuring can be free of errors caused by environmental variations and vehicle speed changes.

Both the measurement of time intervals and the time-to-distance conversion were performed by a 6502-based microcomputer. In operation, a certain number of sound pulses are transmitted toward the road surface, and the resulting echoes from the calibration target and the road surface are detected. The elapsed time intervals between initial transmission and echo detection are recorded by a timer under computer control and stored in memory for conversion. The system clock frequency is 1 MHz, and the counting error is no more than 1 μs, which corresponds to a resolution of 0.17 mm, well within the tolerance needed for this project.

SYSTEM DESCRIPTION

Two primary components constitute the Polaroid ultrasonic ranging unit: an acoustical transducer and an ultrasonic circuit board (2). Together, these components are capable of detecting the presence and distance of objects within a range of approximately 0.9 to 35 ft.

The principal component in this device is the transducer, which acts as both loudspeaker and microphone. It has been designed to transmit the outgoing signal and also to function as an electrostatic microphone in order to receive the reflected signal.

The ultrasonic circuit board electronic system controls the operating mode (transmit/receive) of the transducer. It is composed of three major sections that control transducer operation and allow information gathered by it to be used as desired. Among the sections are a digital circuit, an analog circuit, and a power section.

Figure 2 shows a block diagram of the ultrasonic ranging unit. An appropriate drive signal initiates the transmission of an ultrasonic pulse by the transducer. When the unit is activated, the transducer emits a sound pulse, then waits to receive the echo returning from whatever object the sound pulse has struck. The emitted pulse is a high-frequency, inaudible "chirp" lasting for 1 ms and consisting of 56 pulses at 4 carefully chosen, ultrasonic frequencies: 60, 57, 53, and 50 kHz. Occasionally, a single frequency could be cancelled because of certain target topographical characteristics and no echo would be reflected. The use of four frequencies overcomes that possibility.

A crystal-controlled clock in the digital circuit generates the ultrasonic frequencies that comprise the pulses transmitted by the transducer. After generating the chirp, the operating mode of the transducer changes from loudspeaker to microphone to detect the returning echo. Upon receiving the echo, the transducer converts the sound energy to electrical energy, which is amplified by the analog circuit and then detected by the digital circuit to produce the time it takes from transmission to get the echo-received signal.

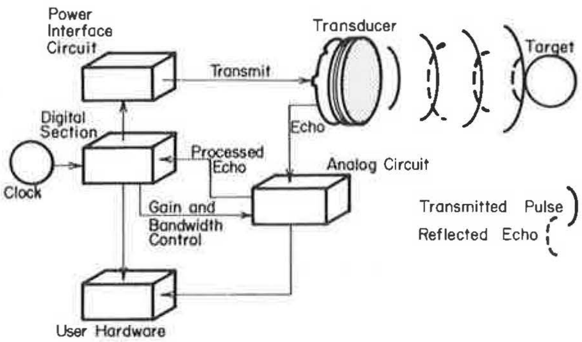

FIGURE 2 Block diagram (transmitting and receiving).

The waveforms presented in Figure 3 illustrate the pertinent timing relationships of the following:

1. Power (VSW) is a drive logic signal that initiates the transmit-receive cycle by supplying the ultrasonic circuit board with the VSW signal. The VSW signal has to reach a low level before a new cycle can be initiated.
2. Transmission (XLG) is the digital logic drive for the transmitted signal. It consists of 8 cycles at 60 kHz, 8 cycles at 57 kHz, 16 cycles at 53 kHz, and 24 cycles at 50 kHz, for a total of 56 cycles, and lasts for a period of about 1 ms. All timing relationships between the transmitted signal and the received echoes are determined from the leading edge of this signal.
3. Amplified echo is useful for observing the reflected echoes.
4. Processed echo is useful if echoes other than the first are of interest.
5. Detected echo (FLG) is the signal that indicates that the echo has been received.

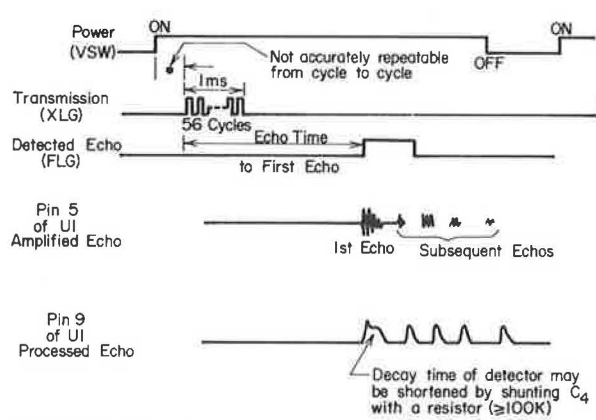

FIGURE 3 Wave-forms.

Because the purpose of the ranging system for the texture project is to closely monitor the displacement between the vehicle and the road surface, sonar response time and the measuring rate of the ranging system have an important effect on the performance of the system. The effects of these two factors are discussed below.

Sonar Response Time

Because of finite sound velocity, there is always a measurement error caused by time delay if the detected object is moving with respect to the transducer, as in the case of the texture project. Assuming the transducer at the height of D is bouncing at f Hz with an amplitude A, it can be found that the maximum error E due to sonar response delay T_d is

$$E = \pm A \sin (\pi f T_d) \qquad \text{where } T_d = 2D/\text{sound speed} \tag{3}$$

This maximum error occurs when the vehicle is passing through the vehicle static equilibrium position, which is also the vehicle system focal position. It is clear that the shorter the distances between transducer and calibration target and road surface are, the smaller the lag effect and error will be. Thus, to reduce the time delay, the transducer and calibration target should be placed as close to the road surface as possible. The only limit on the position of the calibration target is that it should not hit the pavement as the vehicle bounces up and down; 20 cm is taken as a reasonable distance between pavement surface and calibration target. The position of the transducer is limited to the transmitting pulse duration of the ultrasonic circuit board. The leading edge of the reflecting echo can only be detected after the transmission duration period is over and the lasting echo vibrations caused by the transducer holder have been damped out. The ultrasonic circuit provides a pulse duration of 1 ms, which is followed by 3 ms of echo reflecting from the transducer holder. That means the distance between the transducer and the calibration target will be too long (70 cm) to be favorable as far as the response time and space are concerned. Therefore, it was necessary to reduce the pulse duration of the original ultrasonic circuit board in order to place the transducer closer to the calibration target and reduce the measurement error.

Through hardware and software techniques, the ultrasonic circuit board was modified to have an 80-μs pulse duration, which consists of 4 pulse cycles at 50 kHz. This enabled the transducer to be placed 20 cm above the calibration target and resulted in a time delay of 2.4 ms. With the vehicle bouncing at f = 2 Hz with amplitude A = 10 cm, the maximum error is found to be E = ± 1.5 mm. This amount of error is intolerable; however, it will be corrected during the data processing as will be discussed later.

Measuring Rate

The measuring rate or sampling rate affects the accuracy of estimation and the quality of the acquired picture. With the larger sampling rate, the displacement can be monitored more closely, and better estimation and control result.

Because there is a power dissipation problem, the recommended measuring rate for the ultrasonic circuit board is 5 times per second. This is too low to fulfill the performance requirement, because the moving vehicle will bounce at a frequency as high as 20 Hz. This problem also was solved by reducing the transmission pulse duration. It is during the pulse duration that a large current is induced, generating heat that must be dissipated. Therefore, the solution to the sonar response time problem also solved the sampling rate problem without causing further heat dissipation requirements. A measuring rate of 60 times per second was achieved, and the performance of the ranging system was greatly improved.

SYSTEM IMPLEMENTATION

The noncontact texture measurement system comprises the modified ranging unit, an LSI 11/23 processor, television camera, a strobe, and a 6502-based single board computer that coordinates the functions of all the other components. Figure 4 shows the system block diagram. The single board computer provides the drive signal for the ultrasonic circuit board, detects the transmission and echo signal from the ultrasonic circuit board, and records the time interval for data processing. After data processing is completed and a new picture is to be taken, the single board computer will fire the strobe and synchronize the grabbing of the picture with the vertical sync of the television camera by issuing a timely command to the LSI processor.

A 6522 VIA (Versatile Interface Adapter) (3) in the single board computer acts as an interface between the CPU and other system components. The interface block diagram is shown in Figure 5.

The transducer holder and calibration target are attached to a frame, which is placed in line with the television camera and lens assembly. A detailed drawing of the transducer holder is shown in Figure 6. An almost sound-transparent foam is used to prevent dirt and spray from causing damage to the transducer during operation.

One main program and an interrupt request (IRQ) service routine constitute the system software; however, a collection of data processing routines is contained in the IRQ routine. The system software serves two functions. The first function involving measurement data generation and recording is treated first; the second function involving data processing and real-time control is discussed next.

The main program and most of the interrupt request service routine, as shown in Figures 7 and 8,

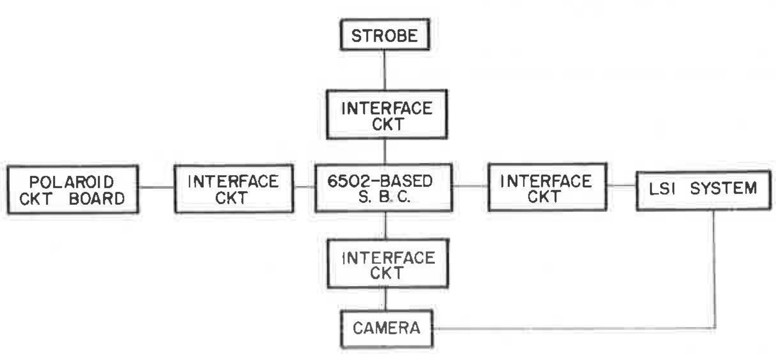

FIGURE 4 System block diagram.

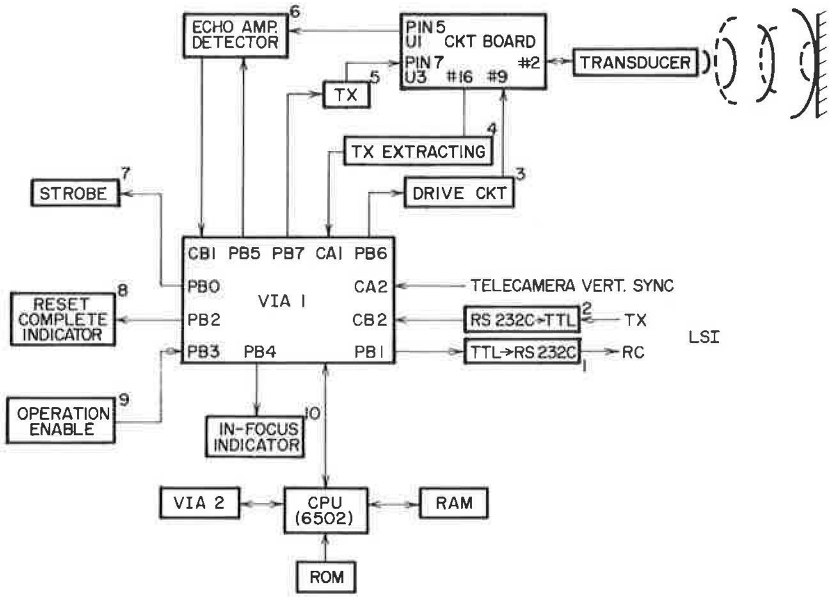

FIGURE 5 Interface block diagram.

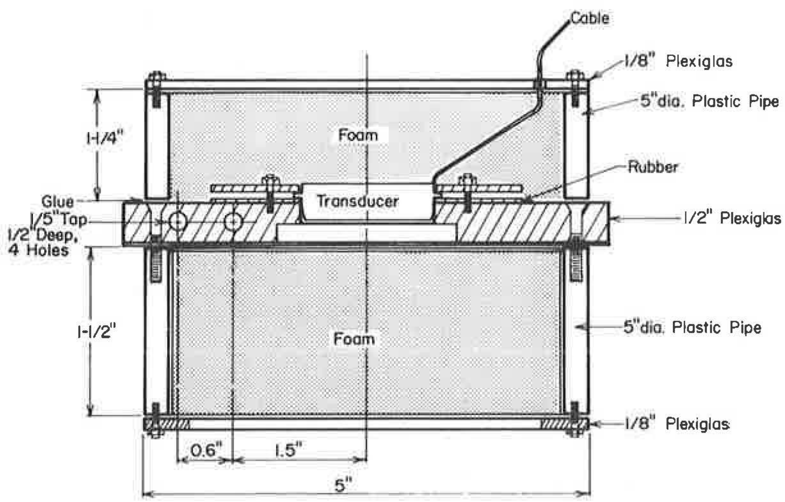

FIGURE 6 Transducer holder.

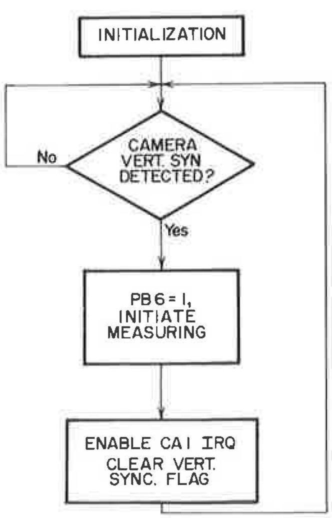

FIGURE 7 Main program flow chart.

perform the measuring and data recording. The description of these two modules is as follows.

Main Program

The main program does the initialization, which assigns program variables with predetermined values and sets up the proper operation mode for the VIA I/O port, timers, and interrupt controls. The measuring cycle is synchronized with the television camera field-scanning cycle (60 Hz). After a vertical synchronization signal is detected, the measuring cycle is initiated by providing a drive signal to the ultrasonic circuit board through pin 36 of the VIA. Then the program clears the vertical synchronization flag and executes a waiting loop until a new vertical synchronization is detected and a new operating cycle starts. During this waiting loop, interrupt requests from the ultrasonic circuit board (due to the transmission signal and the reflection echo signals) will occur and the IRQ routine is called.

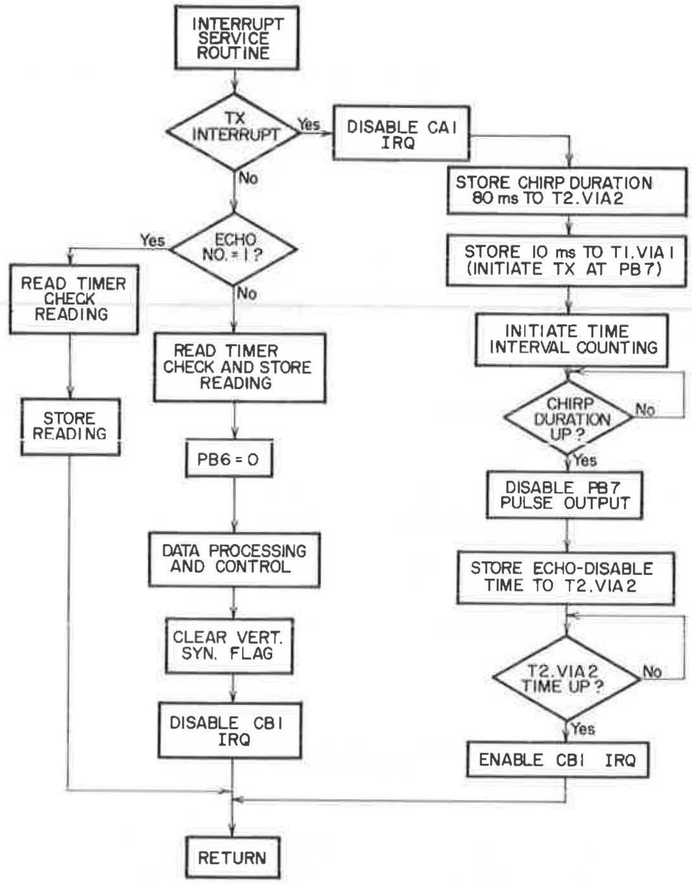

FIGURE 8 IRQ routine flow chart.

IRQ Service Routine

Three interrupt requests will occur during each measuring cycle as follows:

1. Interrupt request from the transmitting signal: the transmitting signal of 1-ms duration from the ultrasonic circuit board is routed to the VIA to generate an interrupt request instead of driving the transmitting power amplifier as originally designed. This service routine is called to generate 4 cycles of the 50-kHz pulse, which is output to the ultrasonic circuit board as the transmitting signal. Counting of the time interval is initiated at this stage.
2. Interrupt request by the reflecting echo from the calibration target: this interrupt service routine will record the timer reading as the basis for calibration. Because the 16-bit timer is composed of two 8-bit/byte timers and each timer is read separately, readings have to be checked for each data point.
3. Interrupt request by the reflected echo from the road surface: in this service routine, the timer reading is recorded and the drive signal at PB6 is cleared in order to initiate the next measuring cycle. Measured data from 2 and 3 are then used in the data processing and control function.

Four routines perform the data processing and control function. The system software flowchart in Figure 9 shows the relationship between these routines. The data generation routine provides the data necessary for these processing routines.

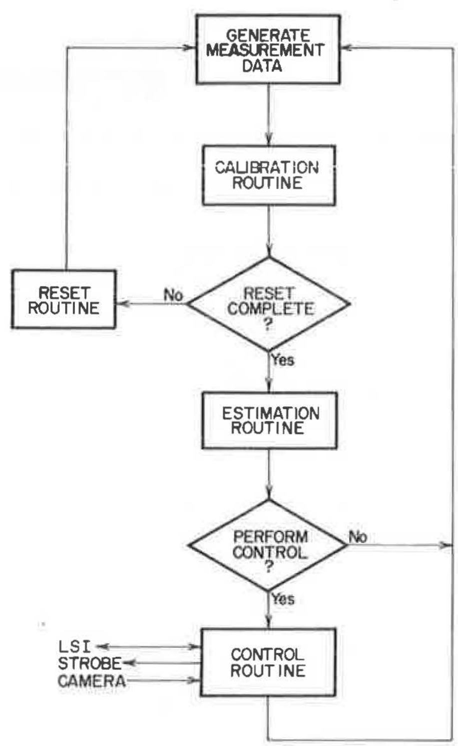

FIGURE 9 Data processing and control flow chart.

Calibration Routine

Because the speed of sound changes due to environmental conditions, and because the vehicle speed may also change during operation, a calibration procedure is necessary for each measurement cycle. This calibration is done by dividing the time interval of the detected echo from the road surface by that from the calibration target, which is placed 20 cm away from the transducer.

Reset Routine

The reset routine is called just after a new operation starts and before the vehicle moves. The function of this routine is to get the best focal length that will yield the best texture image and store it in memory as a standard focal length for use by the data processing routine. Because of the system transient response after power-on, the measurement results are discarded until 30 measurement cycles have been completed. The system is then believed to be stable and 10 measurements are collected. A procedure is applied to delete the maximum and minimum values of these 10 data, and the average of the other 8 measurements is taken as the standard focal length for the system.

Estimation Routine

To obtain the best texture image during the operation with the vehicle bouncing up and down, this routine predicts the time when the system will be in focus so that the control function can be performed at that time. The three most recently measured data points are collected and processed in the following way: (a) If all three measurements are within a 1.2-mm deviation from the standard focal length, the control function is performed immediately without doing an estimation, because the system lies well within the focus range. (b) If these conditions are not met, an estimation is performed, using a first-order Taylor series expansion formula as follows:

$$FL = f(t + \Delta t) = f(t) + f'(t)\Delta t \quad (4)$$

where

$f(t)$ = current vehicle position,
FL = standard focal length,
Δt = time interval predicted, and
$f'(t)$ = rate of change in vehicle position.

The use of a first-order formula is justified by the fact that $f''(t)$, the rate of change of $f'(t)$ as the vehicle passes through the vehicle static equilibrium position, is negligible and so are the higher order terms.

It should be noted that near the vehicle equilibrium position $f(t)$ is actually the vehicle position 1.2 ms before an echo is received because of the sonar response delay discussed earlier. Also, it takes about 0.8 ms to perform the data processing up to this point; therefore, if Δt is smaller than 2 ms, it means that the system already passed the focal position and processing stops. On the other hand, if Δt is larger than 18 ms, it means that one more measurement can be taken and a better estimation might result; therefore, the processing procedure ends here.

If Δt is between 2 and 18 ms, the time interval of t-2 ms is loaded into the computer timer and counting is initiated. When this time interval elapses, the control routine is called.

Control Routine

The control routine first fires the strobe so that an instant image of the texture is burned on the camera vidicon. This image will remain clear for at least one frame period (32 ms) because of exposure to a strong light source. The control routine will then issue a timely command to the LSI processor to freeze the acquired picture for later image processing. Because the strobe may be fired at any time between frame acquiring periods, an undesired picture with partial texture image might be acquired if the freeze command is issued to LSI immediately after the strobe is triggered. Therefore, in order to acquire a picture with a complete texture image, the freeze command is issued only after a camera vertical sync signal is detected, which means a new frame with complete texture image will be acquired.

OPERATIONAL CONSIDERATIONS

Because of the self-calibration function in this ranging system, temperature fluctuations and wind gusts during operation will cause no effect on the accuracy of measurement. However, a temperature difference may exist between the sound path immediately adjacent to the surface and the ambient environment. This problem can be solved if the reset procedure is performed at the proper location so that surface temperature effect is incorporated into the calculation of the standard focal length. If the surface temperature has significantly changed since the reset function was performed, it may be necessary to repeat the reset function, depending on the quality of the picture.

Figure 10 shows an estimation of the worst case of the traffic noise spectrum at the acoustic transducer (4, Ch. 2). Figure 11 shows the free-field receive response for the ultrasonic transducer.

The ultrasonic transducer is designed to operate above 20 kHz, and because traffic noise above 20 kHz is insignificant, the ranging system is not susceptible to traffic noise. The transducer holder also helps shield the transducer from traffic noise.

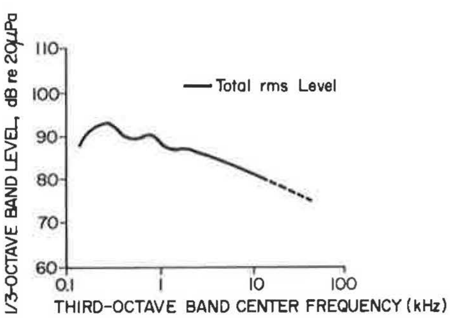

FIGURE 10 Estimated worst case traffic noise spectrum at the ultrasonic transducer.

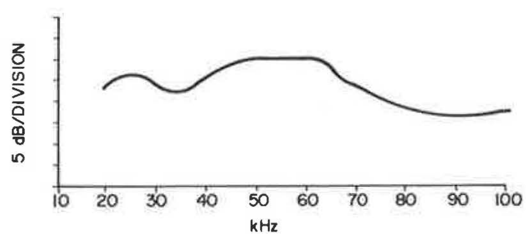

FIGURE 11 Free-field receive response.

Because 2 to 18 ms may elapse between the time a measurement is taken and the time a picture is taken, because of the estimation requirement, the distance between the acoustic footprint and the pavement surface where the picture is taken may range from 3.5-31.5 cm. If there is an abrupt change in pavement surface, such as a pothole or slope changes, which is unpredictable, a poor quality picture might be taken.

CONCLUSIONS

This microprocessor-based ranging system has performed satisfactorily in the texture project. If it is necessary to further improve the resolution and accuracy, the existing 1-MHz processor can be replaced with a higher frequency processor. If a 2-MHz microprocessor were used, the resolution would be improved to 0.08 mm, all data processing and control functions could be done faster, and better control quality could be achieved.

The Polaroid ranging unit is easy to use as an ultrasonic transmitting and receiving device. However, it has two drawbacks as far as this system is concerned. One is the power dissipation problem, and the other is the uncertain time interval between the VSW signal and the leading edge of the transmission signal, XLG (see Figure 3). Six to seven ms are wasted during this period. Adding 3 ms of sonar response time to this time interval, the maximum measuring rate can only reach 100 Hz, even if the power dissipation problem is solved. Thus, if a faster measurement is required, as in the road profilometer application, it would be necessary to design a new ultrasonic transmitting and receiving device.

Other applications include an electronic dipstick for sensing liquid level, machinery control, general noncontact displacement, and focusing instrumentation. An additional application is to sense approaching objects in safety areas. Most of these uses can be applied in the field of robotics.

ACKNOWLEDGMENTS

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