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# Comparison of an ultrasonic distance sensing system and a wire draw distance encoder in motion monitoring of coupled structures

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**Abstract.** Coupled structures are widely seen in civil and mechanical engineering. In coupled structures, monitoring the translational motion of its key components is of great importance. For instance, some coupled arms are equipped with a hydraulic piston to provide the stiffness along the piston axial direction. The piston moves back and forth and a distance sensing system is necessary to make sure that the piston is within its stroke limit. The measured motion data also give us insight into how the coupled structure works and provides information for the design optimization. This paper develops two distance sensing systems for coupled structures. The first system measures distance with ultrasonic sensor. It consists of an ultrasonic sensing module, an Arduino interface board and a control computer. The system is then further upgraded to a three-sensor version, which can measure three different sets of distance data at the same time. The three modules are synchronized by the Arduino interface board as well as the self-developed software. Each ultrasonic sensor transmits high frequency ultrasonic waves from its transmitting unit and evaluates the echo received back by the receiving unit. From the measured time interval between sending the signal and receiving the echo, the distance to an object is determined. The second distance sensing system consists of a wire draw encoder, a data collection board and the control computer. Wire draw encoder is an electromechanical device to monitor linear motion by converting a central shaft rotation into electronic pulses of the encoder. Encoder can measure displacement, velocity and acceleration simultaneously and send the measured data to the control computer via the data acquisition board. From experimental results, it is concluded that both the ultrasonic and the wire draw encoder systems can obtain the linear motion of structures in real-time.

**Keywords**: translational motion monitoring; ultrasonic distance sensor; wire draw sensor; coupled-structure dynamics

## 1. Introduction

Structures including coupled structures are subject to harsh environments in their life cycles from extreme and cyclical loading conditions, and possibly from internal and external corrosion

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(Zhu *et al.* 2016). These present significant challenges to the structure systems, which are used to serve for years and endure risk of failure (Frangopol *et al.* 2015). The structural failures such as overload, jamming and parts damage will result in serious losses of properties, ecocatastrophes and even deaths (Brownjohn *et al.* 2011). All these are difficult to be identified by periodical inspections or routine safety operations. New sensors or sensing systems with high sensitivity and reliability are in great demand for large-scale industrial deployment.

In this paper, two measurement systems are developed to detect the translational motion of coupled structures. The measured motion data give us insight into how the coupled structures absorb the movement between two host structures. The data also provide information for the design optimization of the coupling arm.

Ultrasonic-based distance measurement is now recognized as a simple and inexpensive answer to many demands of industrial manufacturing (Carullo *et al.* 1996, Marioli *et al.* 1988). For instance, ultrasonic distance sensor is used to monitor the pedestrian traffic by measuring distance based on the round trip time of the ultrasonic waves (Marioli *et al.* 1988). Ultrasonic sensor makes it possible to construct small and privacy free measurement environment. The use of such a technique in an industrial environment is sometimes prevented by its drawbacks, such as poor sensitivity to temperature (Găşpăresc *et al.* 2014). Recently, the temperature effect can be satisfactorily compensated by adding a small circuit to the sensor (Mariani *et al.* 2016, Minomi *et al.* 2013).

Encoder is another commonly used device to monitor position (Lee *et al.* 2016). Incremental encoder plays an important role in automation, drilling excavator system, machinery construction, medical technology and many other industries. For instance, Ogitsu *et al.* developed a vehicle following device that uses a wire draw encoder for guiding elderly people in residential streets in urban areas (Ogitsu *et al.* 2014). The encoder measures the vehicle-to-vehicle distance when attached to metallic parts on the rear of the preceding vehicle.

A wire draw encoder has a rotary encoder in its rewind mechanism and can measure the length of the drawn wire. It provides the number of pulses in proportion to the amount of movement, and its pulses are accumulated by a counter to determine the position. This facilitates positioning on linear measuring paths (Lee *et al.* 2016).

## 2. Ultrasonic sensing system

Ultrasonic sensor transmits ultrasonic waves from its transmitting unit and again receives the ultrasonic waves reflected from an object via its receiving unit. From the measured time interval between sending the signal and receiving the echo, the distance to an object is determined. The transmitting unit and the receiving unit in some ultrasonic distance sensors are integrated as one unit to save space. While, most ultrasonic distance sensors have separate transmitting unit and receiving units as in this paper.

For distance sensing, first a high level electrical signal is supplied as IO trigger for at least 10us. After receiving the IO trigger, the ultrasonic module automatically sends eight 40 kHz square waves and detect whether there are returning pulse signals. If there are signals returning, the time of the high output IO duration is recorded to calculate distance as:

$$d = t * v_s / 2 \tag{1}$$

where $d$ is the distance, $t$ is the measured time and $V_s$ is the velocity of sound.

Table 1 Electrical parameters of US-100 module

| Working voltage | DC 5.0V |
|---|---|
| Working current | 15mA |
| Working frequency | 40KHz |
| Max range | 300mm |
| Min range | 3mm |
| Measuring angle | 30 degree |
| Trigger input signal | 10us TTL pulse |
| Echo output signal | TTL pulse |
| Dimension | 435mm×20mm×15mm |

As sound velocity increases by 0.607 m/s when the temperature rises for 1℃, the velocity of sound is temperature dependent

$$v_s = /2331.45 + 0.607 * T \tag{2}$$

where *T* is the temperature.

### *2.1 Single ultrasonic sensor system*

In this session, an ultrasonic sensing system with US-100 module is set up and tested (Fig. 1). As shown in Fig. 2, the distance measurement system consists of the sensing module, an Arduino Uno R3 data acquisition board, a cable to connect the Arduino board to the control computer and necessary connecting jumpers. US-100 provides 3mm to 300mm non-contact measurement and the ranging accuracy is 5mm. It has a temperature compensation module. To ensure accuracy, the target object is better within +/-15 degree range. The modules functions by its ultrasonic transmitters, receiver and control circuit. Table 1 lists its main electrical parameters.

Arduino is an open-source physical computing platform based on a microcontroller board and a development environment for writing software for the board. In this sense, Arduino makes computers have functions to sense and control the physical world more easily. Arduino projects can be stand-alone, or they can communicate with software running on the control computer.

The open-source Arduino Software makes it easy to write code and upload it to a control board. It runs on Windows, Mac OS X or Linux. The environment is written in Java and based on Processing and other open-source software. In this research, programming codes are specifically developed for ultrasonic distance sensing.

The Arduino Uno R3 interface board is a microcontroller board which features Atmega16U2 programmed as a USB-to-serial converter. It has 14 digital input/output pins, 6 analogue inputs, a 16 MHz ceramic resonator, a USB connection, a power jack and a reset button. It can be simply connected to a computer with a USB cable. The four screw holes on the board allow the board to be attached to a surface or case.

The Arduino Uno can be powered via USB connection or with an external power supply of 6 to 20 volts. Each of the 14 digital pins on the Uno board can be used as an input or output. They operate at 5 volts. Each pin can provide or receive a maximum of 40 mA. The Uno has 6 analogue inputs, each of which provides 10 bits of resolution. By default they measure from ground to 5

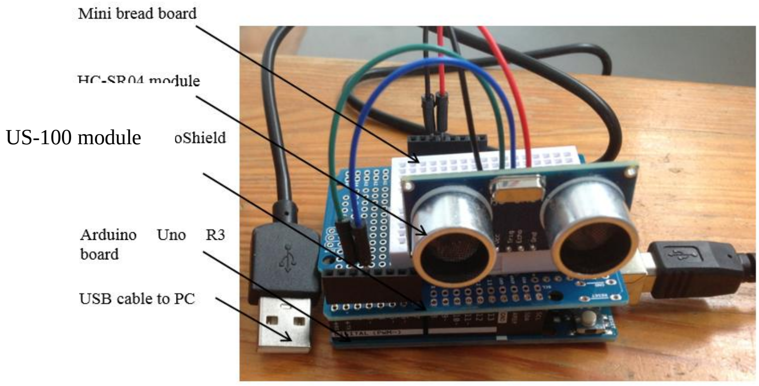


Fig. 1 An Ultrasonic sensing system with US-100 module

volts.

To assemble the ultrasonic distance sensing system, the four pins of the US-100 module are connected to the corresponding pins on Arduino Uno R3 board. Via a USB cable, Arduino Uno board is connected to the control computer. The control codes were specially developed for the from the serial port and saved with time stamps by the computer.

In this approach, the measurement system consists of the compact ultrasonic sensing module, the Arduino interface board and the control computer. No expensive and cumbersome oscilloscope or signal amplifiers are included in the setup. In addition, both the US-100 module and the Arduino board are powered by the control computer so no extra power supply is needed. The elimination of oscilloscope, amplifiers and power unit greatly simplifies the measurement system. As a result, the system is convenient and portable, especially suitable for onsite measurement where the available space is limited.

Ultrasonic distance sensors have other unique advantages. The measurement is non-contact and the response is linear with distance. They can work in any light condition and is independent upon the surface color or the optical reflectivity of the object. Ultrasonic sensors also have disadvantages which need to pay attention. They better view a hard and flat surface perpendicularly to receive ample sound echo. Changes in the environment, such as temperature, pressure, humidity, and airborne particles affect ultrasonic response.

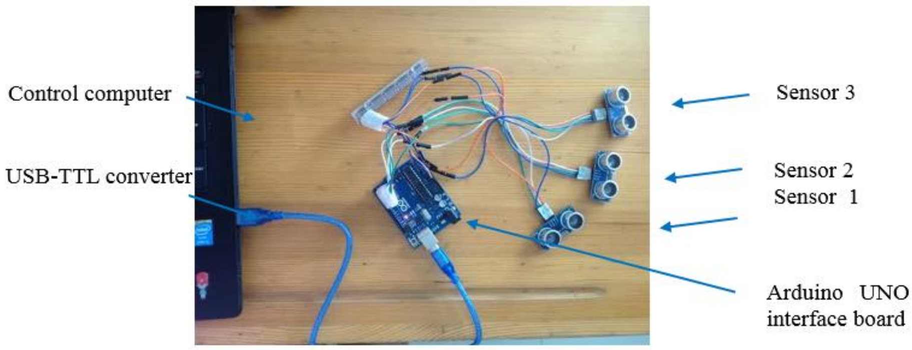


Fig. 2 Ultrasonic distance sensing system with three distance sensors

### *2.2 Three ultrasonic sensors system*

To monitor the translational motion of complex coupled structures, a multi-sensor system is developed and tested. The ultrasonic distance sensing system consists of three ultrasonic sensing modules which can measure three different sets of distance data at the same time. The three modules are synchronized by the Arduino interface board and the self-written software. A control computer is used to communicate with the modules.

Each ultrasonic sensor transmits high frequency ultrasonic waves from its transmitting unit and evaluates the echo received back by the sensing unit. From the measured time interval from sending the signal to receiving the echo, the distance to an object is determined. Fig. 2 illustrates the ultrasonic distance sensing system. The collected data are sent to the Arduino UNO R3 interface board then transferred to the control computer. The power for the sensing modules is provided by the computer through USB port. The motion data can be real-time displayed and saved by the computer.

## 3. Wire draw distance sensing system

Encoders are electromechanical devices to monitor linear or rotational motion by converting a central shaft rotation into electronic pulses of an encoder. The encoder’s output pulses are then counted and evaluated by a control unit to determine displacement, velocity and acceleration. The measured data are transmitted to the control PC via a data acquisition board, which is capable of collecting data from three sensors at the same time. Encoders are typically used in industrial automation, medical devices, structural and automotive testing, injection molding, hydraulic cylinder control, etc.

An encoder is usually composed of four main parts: measuring cable, spool, spring and rotational sensor (potentiometer). When the cable extends along with the movable object, it causes the spool and sensor shafts to rotate. The rotating shaft creates an electrical signal proportional to the cable's linear extension or velocity.

W38S6 Wire Draw Encoder has a measurement range of 1000mm with a resolution of 1mm. W38S6 has a cost-effective and space-saving design with dimensions of 50mm*50mm*76mm. The small size to measurement range ratio makes it suitable for tight installation spaces. Owing to the integration of the spring in the measuring drum, the encoder has great vibration resistance. It also has light yet temperature-resistant plastic housing. The draw wire is maintenance-free and no strictly parallel alignment is required during measurement. The life of the wire draw mechanism reaches one million cycles. The measurement cable (moving part) is so thin that can be easily deployed for onsite measurement. The working temperature range is from -30℃ to +70℃, suitable for harsh environment.

Before measurement, simply mount the encoder to a fixed surface and attach the stainless steel cable to the movable object. As the object moves, the encoder produces an electrical signal proportional to the cable's linear extension or velocity. This signal is then sent to a PC via a suitable interface such as a data acquisition board. The encoder is powered via the Data Acquisition Board from the control PC. Fig. 3 shows a setup with W38S6 Encoder, data acquisition board and control PC. The wire draw distance sensing system has advantages of high resolution, fast response, rugged, inexpensive, light-weight, etc. The measurement is linear in the whole range.

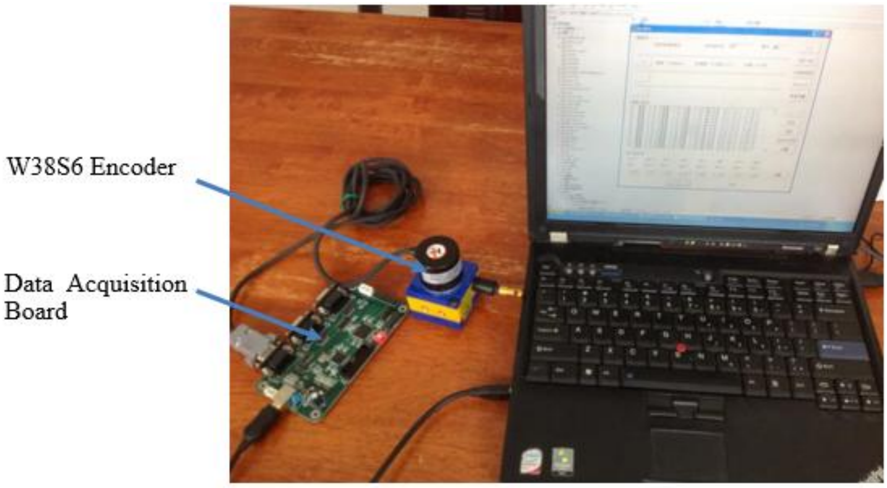


Fig. 3 W38S6 Wire draw Encoder system

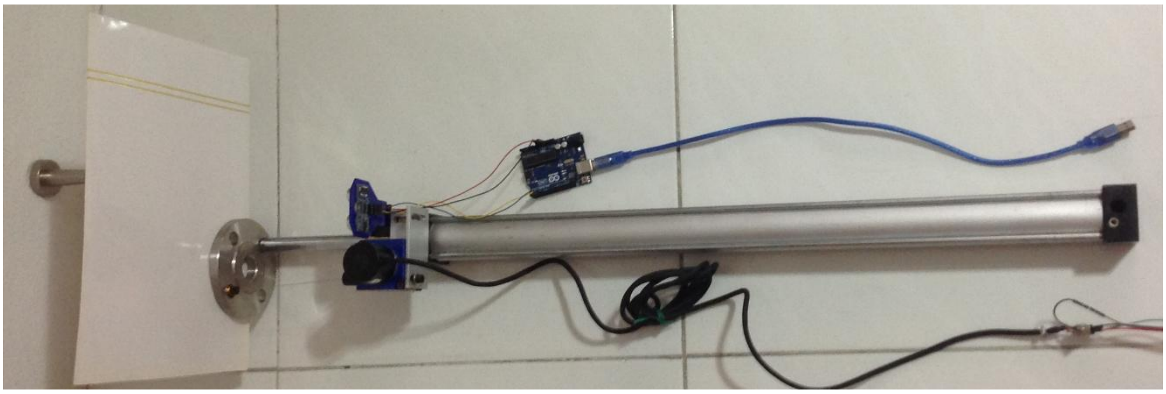

Fig. 4 Experimental setup to measure the translational motion of a cylinder using ultrasonic and wire draw sensing systems

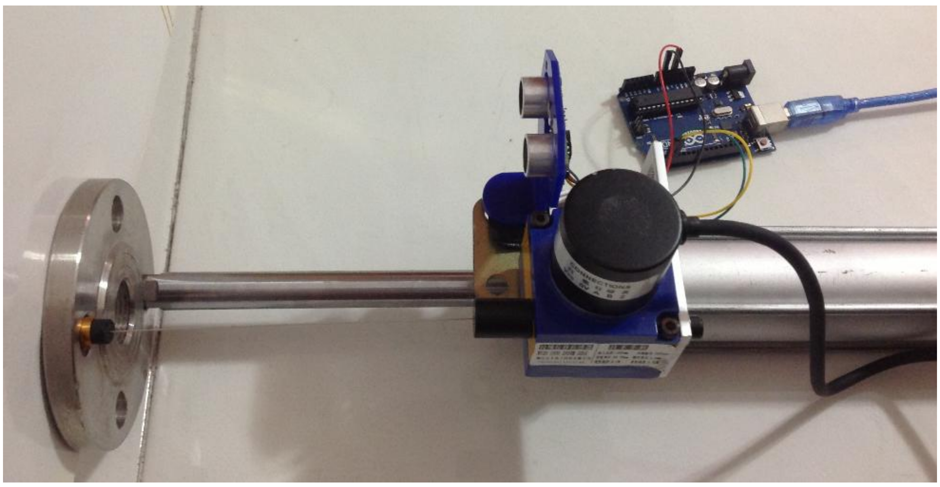

Fig. 5 Experimental setup of ultrasonic and wire draw sensing systems

As the encoder and the data acquisition board are powered by the computer, the elimination of the oscilloscope and the power units greatly reduce the complexity of the measurement system, making measurement convenient and easy. As the measurement system is simplified, the deployment fee and the electrical insulation cost in harsh on-site environment are also reduced.

## 4. Experimental comparison

In this section, experiments are carried out to monitor the linear motion of structures. The performance of the ultrasonic distance sensing system and the wire draw encoder system is experimentally investigated. Figs. 4 & 5 depict the first experimental setup.

Hydraulic pistons are commonly used in coupled structures to absorb the relative motions between two host objects and to secure a minimum and maximum standoff between the objects. In this paper, SC40-600 Standard Cylinder is employed as the first test structure to simulate a piston mechanism. The cylinder body is made of aluminum alloy, while its pull-rod is made of stainless steel with a diameter of 16mm. The maximum stoke is 600mm. The working medium of the cylinder is air to provide stiffness along the cylinder axial direction. As the cylinder is equipped with self-lubricating bearings, the piston rod does not require extra lubrication. The operating noise is quite low.

In experiments, the SC40-600 cylinder body is fixed to the ground by glue. As shown in Fig. 4, the ultrasonic sensor is clamped to an L-shape frame, whose other side is fixed to one end of the cylinder by screws. While, the W38S6 Wire Draw Encoder is mechanically clamped to the same end of the cylinder by screws via two metal frames. A flange is clamped with the movable pull-rod of the cylinder. The measuring cable of the encoder is attached to the flange to measure the distance between the cylinder body and its moving pull-rod. The stretching force applied to the cable is negligible. In such setup, the displacement input is the same for both sensing systems.

The pull-rod of the cylinder is moved back and forth. At the same time, upon the trigger from the same control computer, the ultrasonic sensing system and the wire draw encoder start to catch the linear motion of the pull-rod. The sampling rate of the ultrasonic sensor can be set by self-developed programme and is set to be 10 Hz here. The wire draw encoder measures displacement,

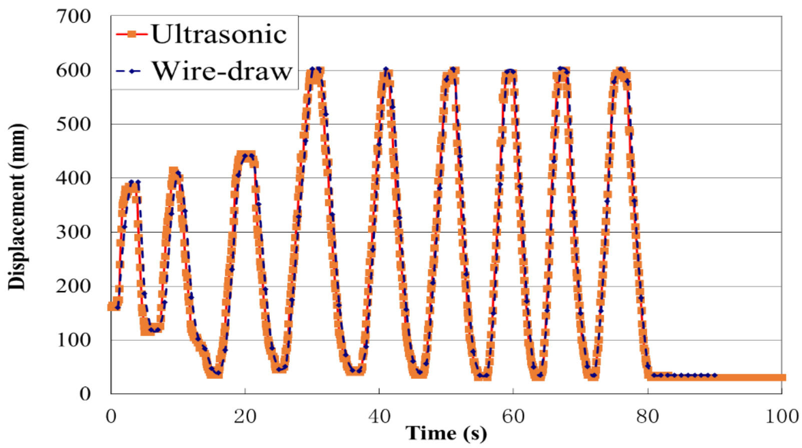


Fig. 6 Displacement measured by the ultrasonic and the wire draw sensing systems

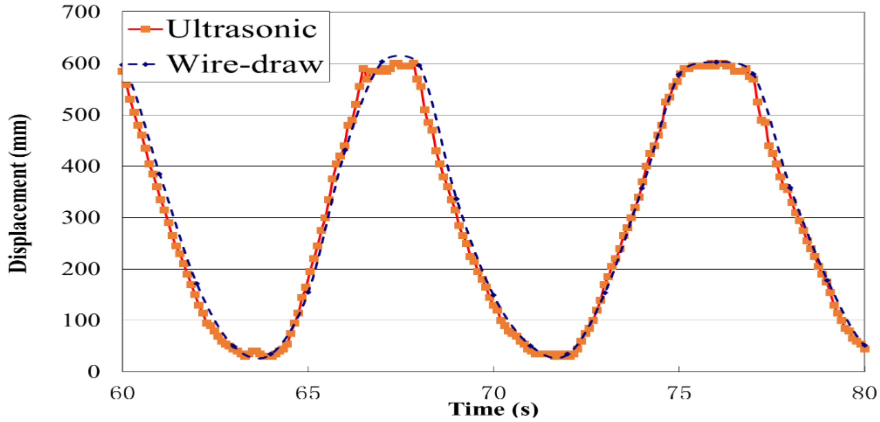


Fig. 7 Displacement measured by the ultrasonic and the wire draw sensing systems (60s to 80s)

velocity and acceleration simultaneously and send the measured data to the control PC via the data acquisition board.

Fig. 6 plots the measured translational displacement data from the ultrasonic and the wire draw encoder. Fig. 7 shows the displacement curves from 60s to 80s to give a closer look. Examination of the curves illustrates that the two sets of results have good agreement with each other. They demonstrate matching cycles of signals, describing the input displacement with peaks and troughs at the same time instants. The displacement difference between two sets of curves is within 0.2%, well within the range normally expected in experimental analysis.

To further verify the applicability of the two sensing systems, experiments using a mini-car as the second test structure are carried out (Figs. 8-9). The car is subjected to a manual force and moves back and forth. The distance between the wall and the moving mini-car is to be measured by the sensors. The US-100 ultrasonic sensor is glued to the car via an L-shape frame. The sampling rate of the ultrasonic sensing module is set to be 10 Hz. The W38S6 wiredraw encoder is glued side by side to the ultrasonic sensor.

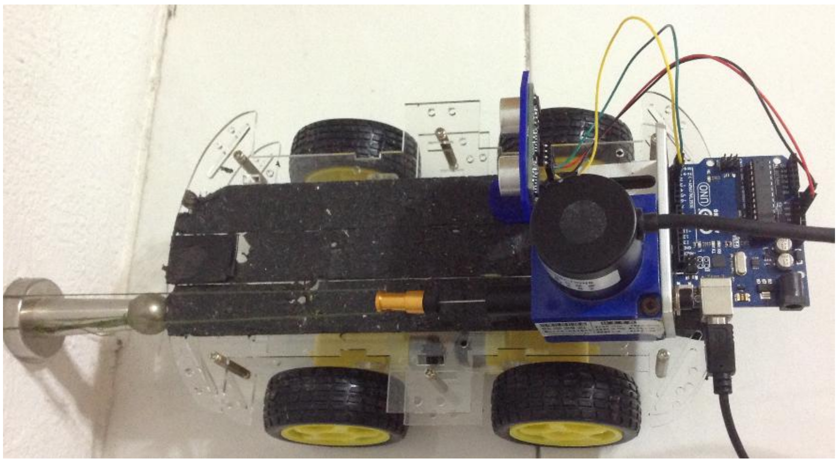

Fig. 8 Experimental setup using a mini-car as the test structure

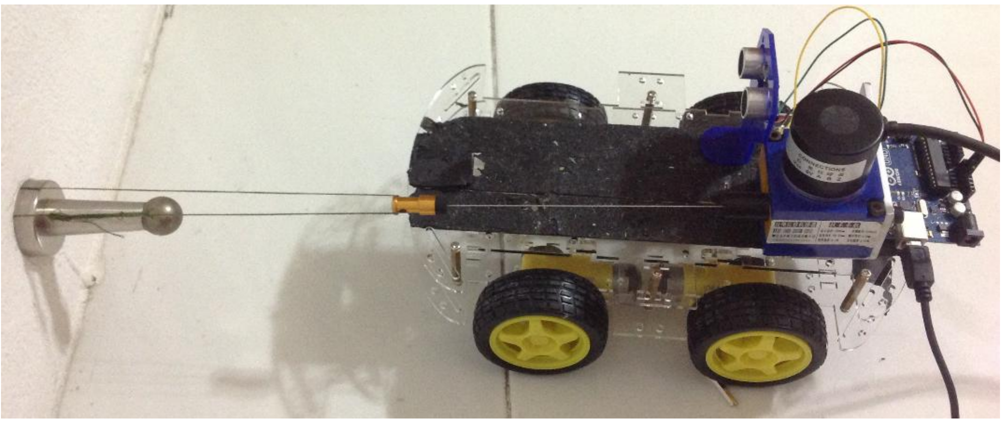

Fig. 9 Experimental setup when the mini-car moves back and forth

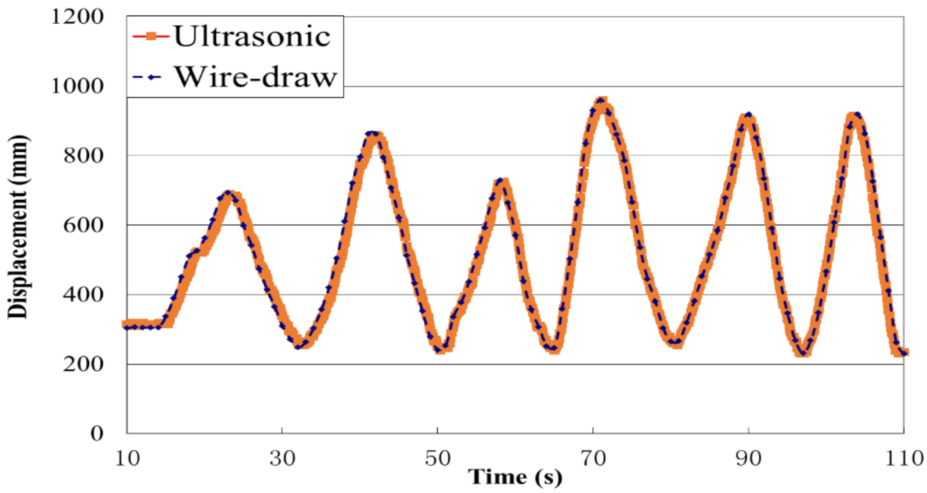


Fig. 10 Displacement measured by the ultrasonic and the wire draw sensing systems (mini-car)

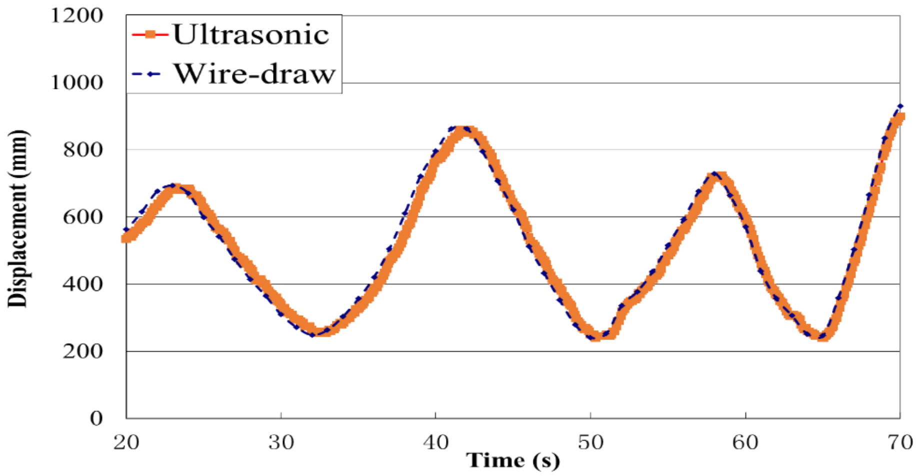


Fig. 11 Displacement measured by the ultrasonic and the wire draw sensing systems (20s to 70s)

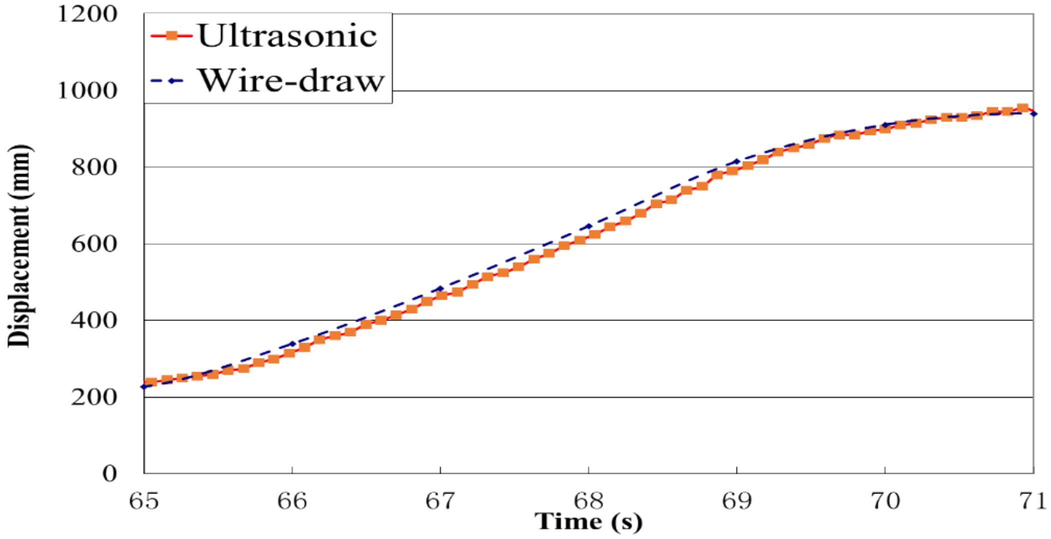


Fig. 12 Displacement measured by the ultrasonic and the wire draw sensing systems (65s to 71s)

Fig. 10 to Fig. 12 show the time history of two sets of distance signals. As can be observed, for the same input motion, the displacement measured by the two sensing systems match very well. Both systems can accurately track the moving object with a high enough sampling rate. While, the accuracy of the US-100 ultrasonic sensor is 5mm which the accuracy of the W38S6 wire draw encoder is 1mm.

## 5. Conclusions

In this paper, to monitor the translational motion of coupled-structures, two efficient sensing techniques are explored and the prototype sensor systems are built and tested. Ultrasonic sensing module detects the position of the object by measuring the length of time from the transmission to reception of the ultrasonic wave. Wire draw encoder monitors linear motion by converting a central shaft rotation into the electronic pulses. Experiment results demonstrate that both sensing systems can accurately track the moving objects with good agreement. The ultrasonic system can realize a high sampling rate by self-developed software with an accuracy of 5mm. While, the encoder has higher accuracy of 1mm. To monitor the translational motion of complex coupled structures, a multi-sensor system is also developed. The system consists of three ultrasonic sensing modules and can measure three different sets of distance data at the same time.

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