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Sensor Applications

An Acoustic 3D Positioning System for Robots Operating Underground

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Abstract—Underground robots are potentially helpful in many application domains, including geotechnical engineering, agriculture, and archaeology. One of the critical challenges in developing underground robotics is the accurate estimation of the positions of the robots. Acoustic-based positioning systems have been explored for developing an underground 3D positioning system. However, the positioning range is limited due to attenuation in the medium. This letter proposes an underground positioning system that utilizes a novel and easy-to-implement electronic approach for measuring the acoustic propagation times between multiple transmitters and a receiver. We demonstrate a prototype using four transmitters at the surface and a single buried acoustic sensor as a proof-of-concept. The times of arrival for signals emitted by the different sources are measured by correlating the transmitted and received signals. The distances between the multiple transmitters and a receiver are estimated, and a tri-linearization algorithm is used to estimate the position of the buried sensor in 3D with respect to reference coordinates. The system is tested in a soil tank. The experimental results show that the proposed system is able to estimate the 3D position of buried sensors with an error of less than ±2.5 cm within a measurement field of size 50 cm × 50 cm × 35 cm in X, Y, and Z (width × length × depth). The proposed electronic synchronization approach allows increasing the positioning range of the system by increasing the number of transmitters at the surface. This paves the way for the development of a positioning system for robots operating underground.

Index Terms—Sensors, instrumentation, underground sensing, buried robotics, geotechnical engineering.

I. INTRODUCTION

Buried robots with integrated sensing systems have potential applications in areas such as soil science, structural health monitoring, and site characterization for geotechnical engineering applications. Such robots may be equipped with embedded sensors to measure various soil properties such as soil moisture, stress, chemical properties, and so on [1].

Localization of robotic systems has attracted much attention from researchers in recent years; however, most of the developed localization systems are focused on the space above ground. Localization of objects underground is still an open challenge, primarily because techniques based on ultra-high frequency (UHF) signals, very-high frequency (VHF) signals, or the Global Positioning System (GPS) are not suitable for the underground environment. This is because UHF and VHF signals attenuate very heavily underground. The conventional indoor localization techniques based on ultrawideband signals, WiFi, ZigBee have been adapted to underground scenarios [2], [3]. However, the RF-based techniques face serious challenges such as extreme path-loss, non-line-of-sight (NLOS) propagation, ambient noise, and waveguide effect [4].

Magnetic-induction (MI) based 3D positioning system for the indoor environment is reported in [5]. The MI-based approach offers high accuracy with reduced secondary effects such as multipath fading and path-loss. MI-based systems for underground 3D positioning are reported in [6], [7]. The systems utilize three orthogonal transmitters and receivers. The transmitted signal establishes a quasistatic field and does not rely on the propagating wave. As the relative magnetic permeability of most materials in an underground environment is close to unity, low-frequency (up to a few kilohertz) fields are relatively unaffected by losses and multipath fading effects. Systems based on MI provide a reliable and accurate solution for the 3D position estimation. However, the electronics of any MI-based system are bulky due to the inductive coils, and this limits their applications for subsurface robot position estimation.

Another promising approach for underground exploration is to use acoustic waves. Acoustic-based positioning systems are widely used for indoor applications due to their simplicity and low cost [8], [9]. However, the physical behavior of acoustic signals in soil is different from that in air. In particular the attenuation of an acoustic signal is significant in the underground environment. In addition, the velocity of acoustic signal is dependent on the state of the soil, including stress level and density [10]. Therefore, the system needs to be designed considering the medium and depth of the robot underground. In comparison with the MI-based techniques, the acoustic-based technique has the potential to enable a miniaturized and high-resolution position estimation system for buried robots. However, considering the attenuation in the medium, the positioning range is limited. The measurement range can be extended by adding more transducers, but this increases the complexity of the system.

In this paper, we present an acoustic-based 3D positioning technique for underground robots. A simple time-division-multiplexing scheme is used to route a periodically generated chirped pulse to each transmitter in turn. The system requires only one set of hardware for pulse generation and propagation time measurement and so is readily scalable to larger numbers of transmitters. The developed system is tested in soil medium for subsurface positioning of the buried robots over a region with dimensions 50 cm, 50 cm and 35 cm in X, Y, and Z respectively with an error of less than ± 2.5 cm. To the best of our knowledge, this is the first time a 3D positioning system for underground buried robotics using acoustic signals has been reported.

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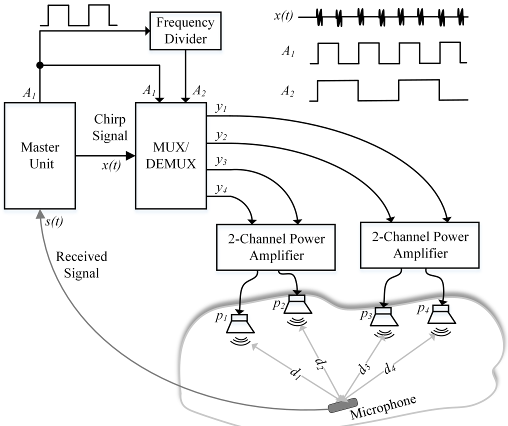

Figure 1. Block diagram of the proposed acoustic based 3D positioning system for underground buried robots.

II. ACOUSTIC SYSTEM DESIGN

A block diagram of the proposed acoustic-based 3D positioning system is shown in Fig. 1. The system uses time of flight to measure the distances between several transmitters (loudspeakers) and a single receiver (microphone). In a typical deployment the transmitters will be at or near the soil surface while the microphone will be mounted on the buried robot. This configuration was chosen over the alternative one, with a single transmitter on the robot and multiple receivers, because it is compatible with small robots that cannot accommodate a bulky loudspeaker. The position of the microphone may be determined from the measured distances by means of appropriate signal processing techniques based on tri-linearization or triangulation.

A. Acoustic Signal Propagation in Soil

The behavior of sound waves propagating in porous media was first described by Biot in 1956 [11]. Biot predicted the propagation of both compressional and shear waves in a porous medium. The shear wave is slow and attenuates faster than the compressional wave [12]. Unlike indoor applications where sound propagation speed is almost constant for a fixed temperature, the amplitude and phase shift of the acoustic signal are affected by various factors in a porous medium [10], [13]. Moreover, the amplitude attenuation and path arrival time also depends on the frequency of acoustic signal [13]. The frequency-dependent nature of acoustic signal attenuation in soil is described in [14]. The attenuation increases with frequency which makes the accurate detection of buried sensors more difficult, while the wavelength decreases which is preferred for better resolution. Therefore, based on this trade-off, an appropriate frequency selection is important to obtain sufficient depth and resolution in the 3D position of the buried robots. The attenuation of the soil is high at a frequency above several kHz. Soil and other granular materials effectively filter high frequency acoustic signals. Seismic waves of frequency less than 100 Hz are used for deep underground exploration. An acoustic signal frequency between 1 kHz and 5 kHz is preferred for an underground positioning system for sub-meter depth with a resolution in the mm range [14].

B. System Architecture

The block diagram of the proposed 3D position system is shown in Fig. 1. A master unit is used for the generation and coordination of the transmitted acoustic signals via multiple transmitters. The master unit generates a chirp signal ($x(t)$) synchronized with a square-wave signal (A_1). Time-division multiplexing is used for the sequential transmission of acoustic signals via four acoustic transmitters. The acoustic signal received by the microphone is transferred via a wired link to the master unit for further processing.

The frequency of signal A_1 is divided into half using a frequency divider. The signals A_1 and A_2 are used as the select inputs for the multiplexer/demultiplexer (MUX/DEMUX). The chirp signal repeats at each rising and falling edge of signal A_1. Only one loudspeaker will be active at a given time based on the signals A_1 and A_2, as shown in the waveform of Fig. 1. The transmitted signal and the received signals are cross-correlated to obtain the time delay between the transmitted and received pulses at the master unit. This delay is taken as the acoustic propagation time between the relevant transmitter and the robot; no correction is needed for the electrical signal propagation times because these will be negligible in comparison.

C. Acoustic Signal Processing

Considering the buried robot will be in the soil, the 3D positioning system must be robust against disturbing noise in the medium. The chirp signal is widely used in radar applications to achieve a maximum signal-to-noise ratio (SNR). The expression for the chirp signal can be written as follows.

$$X(t) = A\ cos\left[2\pi\left(f_o + \frac{f_1 - f_0}{T}t\right)t + \phi_0\right], \qquad (0 \leqslant t < T) \qquad (1)$$

where A is the amplitude of the chirp signal, f_o is the initial frequency, f_1 is the final frequency of the chirp signal, T is the signal duration, and Φ_o is the initial phase of the transmitted signal.

In the absence of multipath interference, the received signal at the buried robot can be modeled as the sum of time variants of expression (1) as follows.

$$x^r(t) = \sum_{p=1}^{4} k_p x(t - \tau_p) \qquad (2)$$

where k_p is the free-space attenuation loss, and τ_p is the time-of-arrival of the transmitted signal from P_{th} (P_1 to P_4) loudspeaker to the receiver, as shown in Fig. 1.

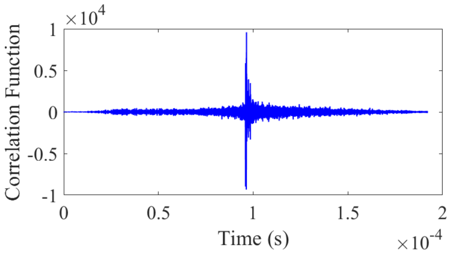

Figure 2. Signal obtained by cross-correlating the transmitted and received signal with respect to the time delay.

The transmitted and received signals are digitized to obtain the time of arrival (ToA) of the received signal with respect to the transmitted signal. The ToA of the received signal can be obtained by performing a cross-correlation between the digitized transmitted and received signals. Cross-correlation measures the similarity between the digitized transmitted and the received signal as a function of the

TABLE 1. Hardware Components of the Prototype System

Details of the hardware of electronics and acoustic modules (\ref)	
Module	Details
Master Unit	Digilent Analog Discovery Board
Power Amplifier	TPA3251EVM (Texas Instruments)
Loudspeakers	WOOFER 150W
Microphone	ADMP401 MEMS Microphone

lag between two signals. The lag is proportional to the ToA of the received signal. An example of a signal obtained by cross-correlating the digitized transmitted and received signals in the soil is shown in Fig. 2. The time at which the correlated signal has the maximum value is the ToA.

D. *Positioning Algorithm*

The times of arrival from the different loudspeakers were used to measure the distances between the transmitters and receiver. A simple tri-linearization algorithm was used to estimate the 3D position of the buried robot with respect to a reference position. For the proposed system, a minimum of four transmitters is needed for 3D position estimation. Assume x, y, z are the unknown coordinates of the receiver. The coordinates of the loudspeakers are x_i, y_i, and z_i, where $i = 1 : 4$. The expression for the localization problem based on lateration can be written as follows.

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = d_i^2 \tag{3}$$

where d_i denotes the distance between the i^{th} transmitter and receiver. The coordinates of one of the loudspeakers need to be chosen as a reference for linearizing Eq. (3). The other equations are subtracted from the expression of the reference loudspeaker, and the unknown position of the receiver with respect to the reference loudspeaker can be obtained. Full details of the algorithm can be found in [8], [9].

III. EXPERIMENTAL PROOF OF CONCEPT

A prototype system was built to test the feasibility of the proposed approach. The components of the prototype are listed in Table 1. The sampling frequency of the master unit for the chirp signal is 60 kHz. The chirp signal has a frequency range between 500 Hz to 4 kHz and duration of 100 ms. The resolution of the analog-to-digital converter for acquiring the analog output of the acoustic sensor is 14-bits. The efficacy of the system was first tested in air. Afterwards, the system was tested in a tank filled with soil.

A. *Indoor Test*

The performance of the prototype system was first tested in air in an indoor environment. The speed of the propagation of sound in air was assumed to be 343 m/s at a temperature of 20 °C. The total volume of the measurement region was 100×100×50 cm^3. A grid was drawn at the base of the measurement region to mark the dimensions accurately. The acoustic sensor was placed in different reference locations on the grid, and the distances between the loudspeakers and the acoustic sensor were estimated. The system was able to measure the 3D coordinates with an error of less than 1.5 cm. This provided initial confirmation of the efficacy of the proposed system. The accuracy of the developed system is comparable with the magnetic-induction based 3D position estimation system [5].

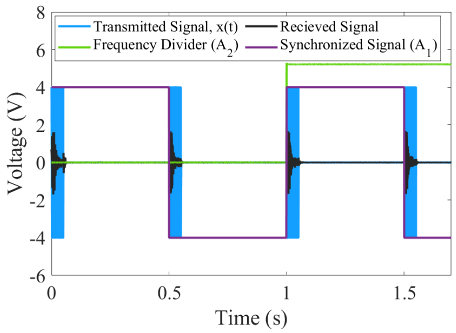

Figure 3. Transmitted and received acoustic signals with associated synchronization signals

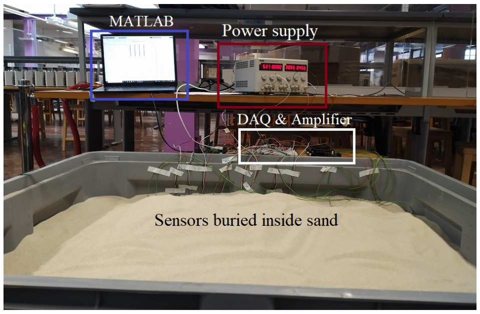

Figure 4. Experimental setup for testing the developed 3D positioning system inside a soil tank

B. *Test in Soil Medium*

A soil tank 1 × 1× 0.45 m^3 in size was set up for the underground position estimation of the buried acoustic sensor. The tank was filled by manually pluviating fuse sand [15]. A funnel was used for sand pluviation. A number of acoustic sensors were buried in the sand in known positions so that the accuracy of the measurements could be carefully obtained. A photograph of the experimental setup is shown in Fig. 4.

The propagation speed of the acoustic signal in the sand was first calibrated by recording the times of arrival at different known distances. A total of 10 samples of the ToA at multiple distances between the transmitter and receiver were recorded and averaged. The experimentally obtained averaged data with a linear best-fit line are shown in Fig. 5. The propagation speed of the acoustic signal in the sand based on the best-fit line is 128 m/s.

The distances between the transmitters and the buried sensors were obtained using the calibrated propagation speed of the acoustic signal and the measured times of arrival. The receiver positions were then estimated using the algorithm described in Section II.D. The

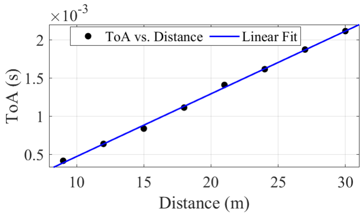

Figure 5. ToA of the received signal with respect to distance between the transmitter and receiver inside the soil.

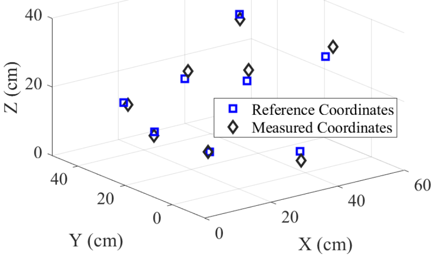

Figure 6. True and experimentally measured coordinates for 3D position estimation inside the sand tank.

TABLE 2. PERFORMANCE MEASURES

Parameters	Expression	Estimated Value
SD (σ)	$\sqrt{\sum_{n=1}^{M} \frac{(S(n)-\overline{S})^2}{M-1}}$	5.2 mm
SNR	$10\log \frac{\sum_{n=1}^{M} (S(n))^2}{\sum_{n=1}^{M} (S(n)-\overline{S})^2}$	39 dB

$S(n)$ is the n^{th} measured ToA value
$\overline{S}$ is the average value of measured ToA

experimental results are shown in Fig. 6. The results show that the system is able to estimate the unknown coordinates of the buried sensors with an error of less than ±2.5 cm with respect to the reference true coordinates.

C. Performance Measures

The standard deviation and signal-to-noise ratio were measured for the prototype system. A total of 100 samples of the ToA were measured, and the performance parameters of the system were estimated as reported in Table 2. The results show that the proposed system is able to provide position measurement with an SNR of around 39 dB and a standard deviation of around 5 mm for a transmitter & receiver distance of 22 cm. Moreover, the proposed system is able to provide a resolution of around 2.5 mm. The developed system consumes a power of around 20W during each transmitted chirp signal for a duration of 100 ms.

The range of the prototype system is limited by attenuation in the soil. The range in all axes could be enhanced by increasing the transmitted power or lowering the acoustic frequency, although in the latter case there would be a corresponding loss of resolution. The range in XY coodinates could be extended either by increasing the number of fixed transmitters or by mounting the transmitters on a rover at the surface and having the rover track the buried robot.

IV. CONCLUSION

An acoustic-based 3D positioning system for buried robots is presented in this letter. The proposed system utilizes a simple electronic system for driving multiple transmitters in time-multiplexed fashion and measuring the times of flight to a single received on the robot. We developed and presented a proof-of-concept prototype and tested it in a soil tank. The experimental results show that the developed system is able to successfully estimate the positions of the buried acoustic sensor with an error of less than ±2.5 cm at ranges up to around 50 cm.

The proposed positioning system requires knowledge of the local acoustic propagation speed in the measurement region. It is envisaged that, in general, this information will be provided by sensors mounted onboard the robot, although in some application scenarios it may be available from independent measurements made, for example, by seismic cone penetration testing.

In real applications the acoustic signals will be subject to scattering and attenuation due to inhomogeneities in the soil. In future work we will explore methods for mitigating this problem by including redundant transmitters so that corrupted signals can be excluded.

V. ACKNOWLEDGEMENT

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