Seismic Surveying with Drone-Mounted Geophones

Srikanth K. V. Sudarshan[1], Li Huang[1], Li Chang[2], Robert Stewart[2], and Aaron T. Becker[1]

1. Department of Electrical and Computer Engineering, 2. Department of Earth and Atmospheric Sciences
University of Houston, 4800 Calhoun Rd, Houston, TX-77004
{skvenkatasudarshan, lhuang21, lchang13, rrstewar, atbecker}@uh.edu

***Abstract*— Seismic imaging is the primary technique for subsurface exploration. Traditional seismic imaging techniques rely heavily on manual labor to plant sensors, lay miles of cabling, and then recover the sensors. Often sites of resource or rescue interest may be difficult or hazardous to access. Thus, there is a substantial need for unmanned sensors that can be deployed by air and potentially in large numbers. This paper presents working prototypes of autonomous drones equipped with geophones (vibration sensors) that can fly to a site, land, listen for echoes and vibrations, store the information onboard, and subsequently return to home base. The design uses four geophone sensors (with spikes) in place of the landing gear. This provides a stable landing attitude, redundancy in sensing, and ensures the geophones are oriented perpendicular to the ground. The paper describes hardware experiments demonstrating the efficacy of this technique and a comparison with traditional manual techniques. The performance of the seismic drone was comparable to a well planted geophone, proving the drone mount system is a feasible alternative to traditional seismic sensors.**

I. Introduction

Hydrocarbons (coal, oil, natural gas) supplied more that 66% of the total energy consumed according to an estimate by IEA (International Energy Agency) in 2014 [2]. Millions of dollars are invested in seismic exploration to find underground hydrocarbons. Avoiding hazards and maintaining safety during exploration is necessary because hydrocarbons are inflammable. Traditional exploration involves planting geophones (sensors) into the soil and detecting seismic disturbances caused by vibrating trucks or dynamite detonations which act as a vibration source. As these vibrations propagate they are reflected and refracted by different layers below the surface. Geophones sense these vibrations and store the data onboard or send it to a data processing unit. The data obtained describes the amplitude of the seismic waves at the geophone locations. Instead of randomly searching for hydrocarbons, explorations are carried out using elaborate technical procedures, equipment, and skilled labor over a large area. This increases the possibility of discovering hydrocarbon-reserves in an optimal fashion, using the data obtained. Cables are used to connect the seismic recorder and the sensors, but cabling cost is proportional to area, and certain terrains are inaccessible, such as jungles or wetlands []. The exploration process involves repeated manual deployment and redeployment of sensors. Applying current advancements in robotics and automation could reduce the cost, decrease time and increase precision in sensing seismic waves. Fig. 1 displays the major drawbacks of traditional seismic exploration and the solution presented in this paper, a flying UAV for geophone placement and recovery.

Fig. 1: Comparing manual and robotic geophone placement. a.) Currently, geophones are planted manually. A well planted geophone is aligned with the gravity vector. b.) Traditional methods require extensive cables to connect geophones to the seismic recorders and batteries. c.) The *Seismic Drone* in this paper is an autonomous unit requiring no external cables. This paper presents an automated process for sensor deployment and retrieval. See video of prototype at [1].

Drones or unmanned aerial vehicles (UAVs) are flying platforms with propulsion, positioning, and independent self-control. As drone technology improves and regulations are adopted, there are major opportunities for their use in scientific measurement, engineering studies, education and agriculture [3]. In particular, measuring mechanical vibrations is a key component of many fields, including earthquake monitoring, geotechnical engineering, and seismic surveying. Seismic imaging is one of the major techniques for subsurface exploration and involves generating a vibration which propagates into the ground, echoes, and is then recorded using motion sensors. There are numerous sites of resource or rescue interest that may be difficult or hazardous to access. In addition, the abundance of survey sites require a great deal

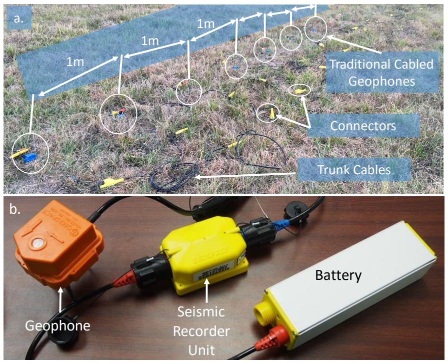

Fig. 2: Comparing state-of-the-art seismic survey sensors a.) Traditional cabled system, the geophones (sensors) are connected in series to the seismic recorder and battery. b.) Autonomous nodal systems, each geophone has a seismic recorder and a battery making each geophone “autonomous" from the other geophones.

of hand labor. Thus, there is a substantial need for unmanned sensors that can be deployed by air and potentially in large numbers. The goal of this paper is to design, build, and demonstrate the use of motion sensing drones for seismic surveys, earthquake monitoring, and remote material testing.

Section II gives an overview of the current state-of-the-art technology available in the industry and why it is useful to complement current technology with the Seismic Drone. Section III describes the hardware experiments and results performed, validating that the seismic drone is a reliable option. Section IV concludes with future work.

II. Overview and Related Work

A. Seismic Exploration Methods

During seismic surveys the source of seismic/vibrational waves is excited to generate waves that propagate under the earth's surface. These waves are sensed by geophone sensors and are recorded for later analysis, to detect the presence of hydrocarbons. Fig. 2 describes the current sensors available and Fig. 1c. shows the proposed solution, the seismic drone.

These sensors are used to sense the vertical external displacement U caused by the vibrational waves that propagate with a velocity c in the positive and negative x-directions and is represented by the 1-D differential equation

$$\frac{\partial^2 U}{\partial^2 t} = c^2 \frac{\partial^2 U}{\partial^2 x} \tag{1}$$

The velocity of a seismic wave approximately ranges from $2-8$ km/s. Its general solution is given by

$$U(x,t) = f(x \pm ct) \tag{2}$$

The equations stated above are a generalized representation of a vibrational wave. For example, a vibrating string would satisfy the equation.

$$c^2 = F/\rho \tag{3}$$

In the above equation, F is the vibration force and ρ is density. This equation is a hyperbolic equation from the theory of linear partial differential equations and is challenging to solve because of sharp features that can reflect off boundaries.

This is a 3-D seismic wave equation that scales in complexity and connects the motion of the moving coil with the relative magnetic flux, for a displacement caused by an external source.

$$m\frac{\partial^2 \xi}{\partial^2 t} + c\frac{\partial \xi}{\partial t} + k\xi = m\frac{\partial^2 U}{\partial^2 x} - Bli \tag{4}$$

Here ξ is the coil displacement, k is the spring constant, m is the moving mass of the coil, c is the friction coefficient, B is the magnetic flux density, l is the length of coil wire, i is the current. These equations can be found in many geophysics textbooks, for example see [4].

Cabled Systems

Traditional *cabled systems* are extensively used for seismic data acquisition in hydrocarbon exploration. A group of sensors (geophones) are connected to each other in series using long cables, and this setup is connected to a seismic recorder and a battery. The seismic recorder consists of a micro-controller which synchronizes the data acquired with a GPS signal and store the data on-board. Generally, four-cell Lithium Polymer (LiPo, 14.8V, 10Ahrs) batteries are used to power this system. This method of data acquisition requires many manual laborers and a substantial expenditure for transporting the cables. The major difficulties faced in using cabled systems for data acquisition are (1.) Conducting a seismic survey in rugged terrains (2.) The manual labor available might be unskilled or expensive depending on the location.

2. Autonomous Nodal systems

Currently, *autonomous nodal systems* [5] are extensively used for conducting seismic data acquisition surveys in USA. Unlike traditional cabled systems, autonomous nodal systems are not connected using cables. The sensor, seismic recorder, and battery are all combined into a single package called a node, that can autonomously record data as shown in Fig. 2. Even in these systems the data is stored in the on-board memory and can only be acquired after the survey is completed. This is disadvantageous since errors cannot be detected and rectified while conducting the survey. Recently, wireless autonomous nodes have been developed. These systems can transmit data wirelessly as a radio frequency in real time [6]. Yet these systems still require manual laborers for planting the autonomous nodes at specific locations and deploying the large antennas necessary for wireless communication.

B. Seismic Drone

The concept of using robots to place seismic sensors dates to the 1980s. Mobile robots have placed seismic sensors on the moon [7]. Postel et al. use mobile robots for geophone placement in, patent application [8]. Plans are underway for a swarm of seismic sensors for Mars exploration [9].

This paper presents a *seismic drone*. It combines the quality of data acquisition present in a traditional exploration method with an autonomous unmanned air vehicle (UAV) which has high maneuverability and the capability of performing precision landing. The primary prototype consisted of a single geophone, Arduino Uno micro-controller, amplifier and a battery. This system is not stable and if planting of the geophone spike failed, it would result damaging the drone. Thus we moved on to the second prototype with

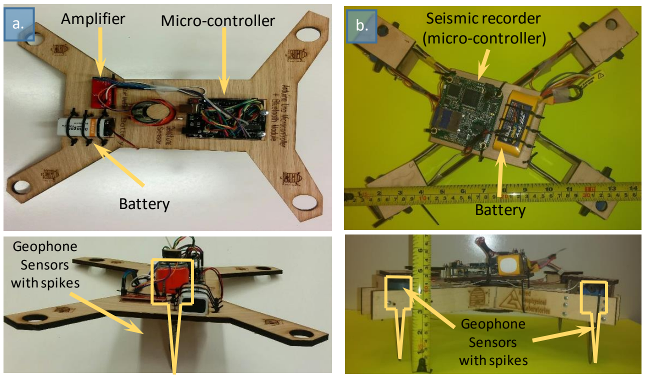

Fig. 3: a.) The first prototype consisted of a single 14Hz geophone with a Arduino Uno micro-controller and a 9V battery. b.) The second prototype consists of four 100Hz geophones, a Seismic Recorder (SR) and a LiPo battery (14.8V, 0.5Ah, 4 cells).

a seismic recorder, battery, and four geophones that are embedded onto a platform and could be attached to an UAV. This sensor platform with 4 geophones provided stability and acted as an extension of the drone's landing gear, there by solving the issue of tipping over during landing. These prototypes are shown in Fig. **??**. By inputting a specific GPS location, the UAV can accurately deploy the seismic data acquisition system. A *geophone* senses ground movement (velocity)and converts it into voltage, which is recorded with a seismic recorder. The deviation of this measured voltage from the base line is called the seismic response and is analyzed for identifying and classifying the type of hydrocarbon present. The geophones obtain data which is processed by the seismic recorder and stored in the on-board memory. The seismic recorder is a micron-controller designed for seismic exploration applications and has a 24-bit accuracy on the ADC conversion, and sampling rates as low as half a millisecond. Using this device helps us obtain quality data compare to the commercially available micro controllers. The drone system could successfully automate the deployment and recovery. By using a robot to perform the above task, costs and errors are reduced.

III. Experiments

The sensor platform of the seismic drone contains four geophones as shown in Fig. 3 and the current seismic drone can only plant (submerge the spikes) in soft soil. Traditionally, planting the geophones is essential to obtain reliable coupling between the ground and sensor. To overcome the issue of satisfactory coupling we use four geophones that are connected in series. The geophones are placed $20-30$ cm apart, but due to the fast propagation of seismic waves can be considered as four geophones being placed at the same location. Hence instead of one *well-planted* geophone at a particular location, we use four *satisfactorily-planted* geophones to obtain comparable results. In particular, the alignment platform ensures sensors are perpendicular to the ground. A video of the prototype performing the experiments is available at [1].

We conducted three experiments to prove the seismic drone is a feasible option that can replace current state-of-the-art technology in the field of seismic exploration. The first experiment compares the sensed seismic vibrational wave output from traditional geophones with the seismic drone. This comparison validates the capability of the proposed system to replace a conventional setup. The second experiment analyzes autonomous flying with and without the sensor platform, to explore the reliability of autonomous flight and the effects of the sensor platform on the command execution capabilities due to signal interference. The third experiment compares soil penetration and the angle of incidence in three different soil types. This is important to ensure quality data despite soil variations and shows that the platform can takeoff, even when the geophones are well planted in soil. Traditional geophone placement requires pushing the geophone spike into the earth to ensure ground-sensor coupling. The quality of a placement is determined by this coupling and the alignment of the spike with gravity vector. Sensitivity decreases with the cosine of the angle from the spike to the gravity vector.

A. Seismic Survey Comparison

The primary experiment presented in this paper compares the proposed *Seismic Drone* performance with a traditional cabled sensing system. We compare the seismic drone with different variations to understand its performance. The comparison is done with a *well-planted* geophone: a completely planted geophone where the spike is completely beneath the surface *satisfactorily-planted* geophone: spike is partially into the ground. The drone is also compared to a geophone mounted on a *round-platform* made of fiber glass and finally to a geophone mounted on a long rectangular *wooden-platform*. The described setups are shown in Fig. 4. Ideally geophones are always well planted into to the ground, the platform setups and satisfactorily planted geophones are tested to test how performance varies with coupling to the ground. Seismic exploration must detect the oscillating seismic wave and sensing quality is a function of coupling.

A sledge hammer was used as a source to create the seismic vibrations that propagate beneath the surface. The seismic drone was flown to its respective survey location next to the well planted, satisfactorily planted, round platform and wooden platform geophones. The geophones from the traditional, and seismic drone setup were connected to the *Strata-Visor*, a special computer designed for plotting the data acquired from exploration. The sledge hammer was used to strike a vibrating plate attached to the ground thereby creating seismic waves for analysis.

From the results obtained we observe that the amplitude peaks of the seismic drone is similar to the setups (*well-planted, satisfactorily-planted, round-platform, wooden-platform*) as shown in Fig. 8. We observe oscillations in the *round platform* and *wooden platform* since these are not fixed to the surface. Instead of detecting the strike, the platform starts oscillating due to the strike and these oscillations eventually dampen out over time. The performance of the *round platform* and *wooden platform* are poor in comparison to the *well planted* geophone, which is the standard for this experiment. The seismic drone setup and the well planted geophone display excellent similarities

Fig. 4: Different geophone configurations and setups compared with the seismic drone for analyzing the seismic wave output obtained after triggering the source: a.) round platform b.) wooden platform c.) well planted geophone d.) satisfactorily planted geophone e.) drone system with sensor platform (Seismic Drone).

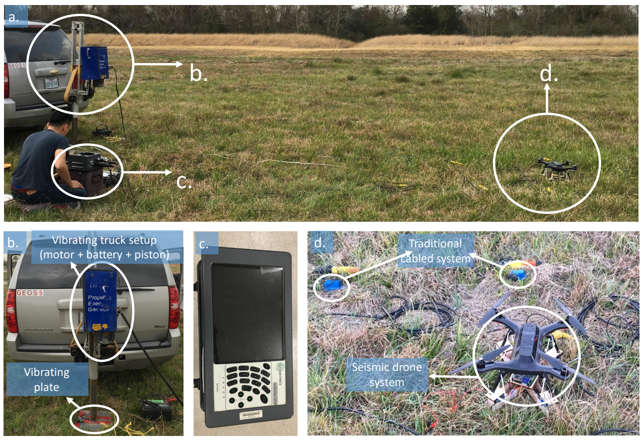

Fig. 5: A survey comparison was performed to obtain the shot gather plots of the traditional cabled system and seismic drone. a.) Overview of the experiment. b.) The vibrating setup strikes the metal plate below and generates vibrational waves. c.) Strata-Visor is a device used to store and process the signals from the cabled system and the seismic drone. d.) The drone system and the cabled system are listening to the vibrational waves and sending their corresponding readings to the Strata-Visor.

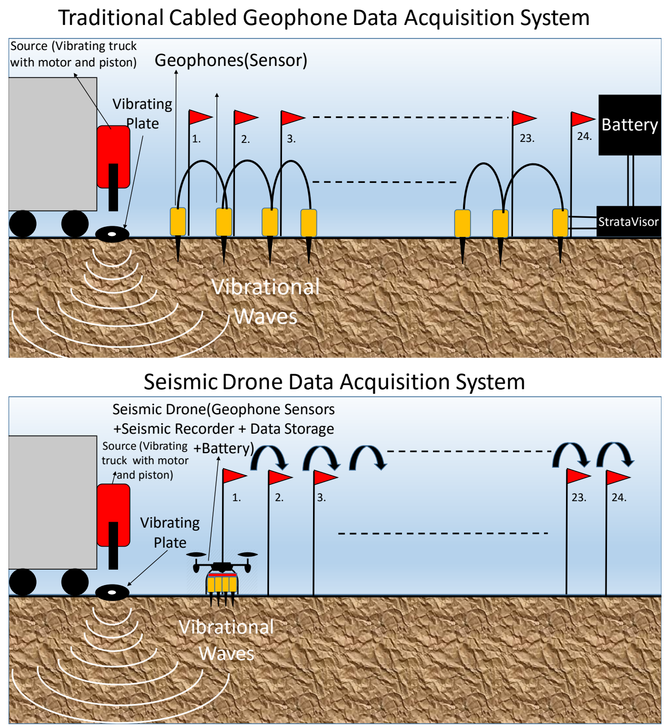

Fig. 7: A schematic of a proposed drone setup which can replace manual laborers during seismic surveys.

in their response. Both the seismic drone and the well planted geophone setup have minimal oscillations, which is an important feature for seismic exploration, this validates the efficiency in coupling with the surface.

Experiment 1 compares the performance of the seismic drone with other setups. The experiment described above was a one-to-one based comparison, however seismic explorations use thousands of geophones to conduct a seismic survey. Thus Experiment 1 was extended to compare the performance of a traditional cabled 24 geophone system connected to a 24 channel seismic recorder and a battery with an autonomous seismic drone. The geophones were planted vertically into the ground, 1 m apart from one another. A schematic of the traditional setup is shown in Fig. 6 and the same experiment was repeated for the seismic drone as shown in Fig. 7. We used a vibrating truck setup to generate the seismic wave. The geophones are well planted, the drone was flown from $1-24$ locations and the readings were taken by generating seismic waves each time. The metal plate was struck 24 times, once for each location.

Fig. 5 describes the important components of the field experiment performed. Results of the seismic survey field test comparison between a 24 channel traditional cabled geophone system and the seismic drone shown in Fig. 9. Both the plots were obtained using a *Strata Visor*, a device that can obtain, store and plot the sensed data. It is extensively used with traditional geophone setups because the geophones can only sense vibrational waves and is dependent on other devices for storage and data processing. To allow a fair comparison, the autonomous setup that *can* store the sensed data present on the seismic drone was not used in this experiment. We observe excellent similarity, thereby proving the seismic drone system can compete with state-of-the-art technology in seismic exploration.

B. Accuracy of autonomous landing with geophone setup

Seismic exploration depends on accurate placement of geophones over a large geographic area. This experiment tested the *accuracy* of autonomous landing of the fully loaded seismic drone system compared to the autonomous landing of the drone system without the sensor base.

The drone system used is a 3DR Solo.The seismic drone was commanded to land at the goal location marked with a 'x' using a blue insulation tape, with and without the sensor platform. The test was repeated ten times to test the accuracy of autonomous landing. The drone uses GPS for landing which is not highly accurate and hence lands at locations close to the goal location. The origin of the coordinate system was marked with a 'x' using a yellow insulation tape. Measuring tapes were used to measure the location at which the drone landed to the origin. The sensor base attached to the drone for seismic sensing has four geophones. A geophone has a strong magnet attached to a spring to measure vibrations. These magnets on the sensor

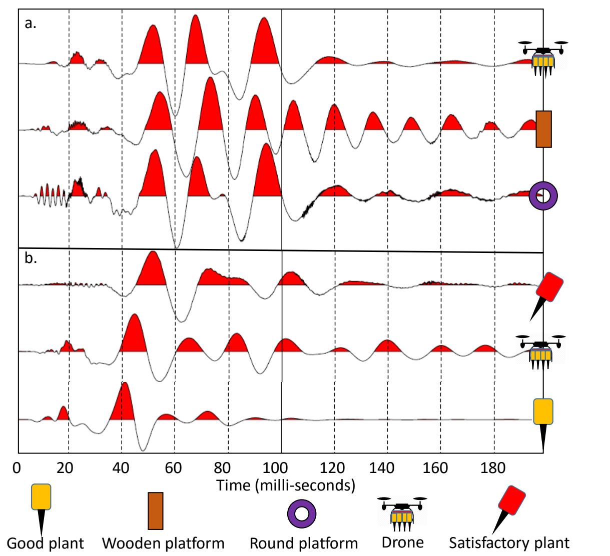

Fig. 8: Displays the seismic wave generated by different geophone setups and the seismic drone. a.) Compares the drone setup with different platforms (round and wooden platforms) oscillations in these platforms are not damped quickly since they are not fixed to the ground, The max amplitude values are similar and appear almost simultaneously indicating these setups were placed very close to each other, so no time shift is observed. b.) Compares the drone setup with planted geophones (well planted and satisfactorily planted), we observe mild oscillations in the drone setup compared to the fixed ones since they are planted into the ground. The max amplitude values are similar but do not appear simultaneously, indicating these setups were placed approximately half meter apart, and hence time a shift occurred.

base influence the internal compass of the drone system with their strong magnetic fields. This effect can be observed in the plots shown in Fig. 10. The 1^{st} and 2^{nd} standard deviation ellipses are much smaller for the drone system without the sensor base than the system with the sensor base. The GPS used by the drone has an accuracy of five meters and we observe the landing locations approximately to be normally distributed. 95% of the landings were within 1 m for the drone system without the sensor base and around 2 m for the drone system with sensor base. The current landing accuracy is sufficient for seismic exploration. A 2 m error in distance from the landing site corresponds to an increase or decrease in travel time for the seismic wave by 25 ms approximately.

The autonomous planning of the drone is done using a mobile application called *Tower*. This app can be used to plan complex autonomous trajectories, and the drone can perform different tasks at different waypoint locations.

C. Penetration and Angle with the Horizontal

This experiment tests the soil penetration capabilities of the seismic drone setup in different soil types. Good coupling with soil is important for obtaining quality data, hence the experiment explores the penetration capability of the setup in common soils. We performed the experiment in grass, sand, and dry clay. The penetration was maximum in sand followed by grass, but the drone could not drive the geophone spike into dry clay, as shown in Fig. 11. Failing to penetrate through dry clay was inevitable even with a manual plant. The seismic sensors are highly sensitive and could collect data without penetrating through a surface, if place vertical to the surface. Since the design considers vertical placement of geophones, a seismic analysis could be achieved by landing on any flat hard surface like dry clay, terrace of a building or a cement road. This system could replace humans who risk lives to sense earthquakes or perform quality checks on a partially completed bridge.

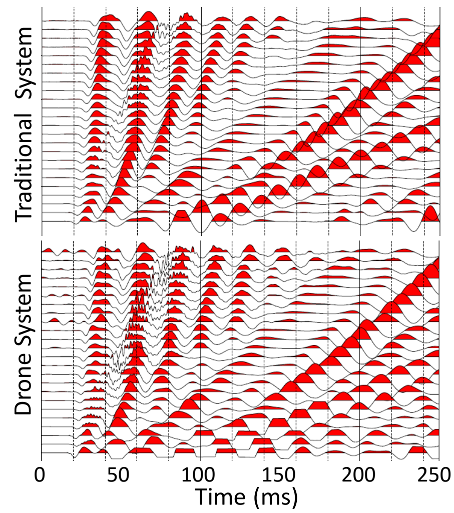

Fig. 9: A *shot gather* plot comparison, the x-axis is time in milliseconds and the y-axis is the channel number on the Strata-Visor, to which both the setups are connected. Each survey location is 1 m apart and the wave generated from the source propagates beneath the surface. The waves are time shifted from the first channel to the end. a.) shot gather for a traditional cabled system. b.) shot gather for the seismic drone system.

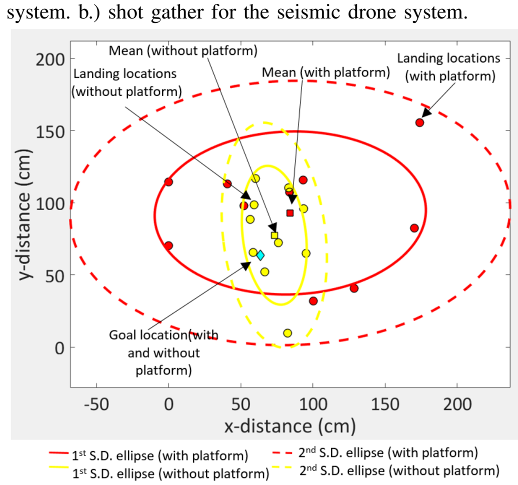

Fig. 10: The plots describe autonomous landing with and without the sensor platform. For 10 landings the landing locations are closer to the goal location for without the sensor platform than with the sensor platform. The mean, 1st std. ellipse and 2nd std. ellipse are shown for both cases.

The final experiment measured the angle of deviation of the geophone from vertical. Ideally the geophones should be perpendicular to the ground. This is necessary to obtain quality data, since the data loses accuracy with the cosine of this angle. A rule of thumb is to have less than $5°$ error for a geophone. It is important to land on a flat surface with less than $10°$ deviation from the horizontal. The drone cannot take off if it is at an angle to the ground. These two constraints complement each other. We collected data of the roll and pitch Euler angles to calculate the deviation from

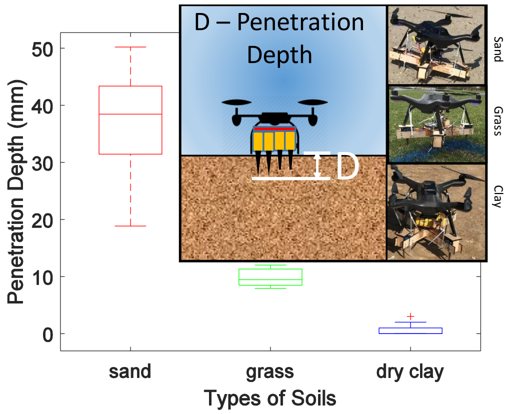

Fig. 11: Box and whisker plots comparing the variations in depth of planted geophones attached to the seismic drone

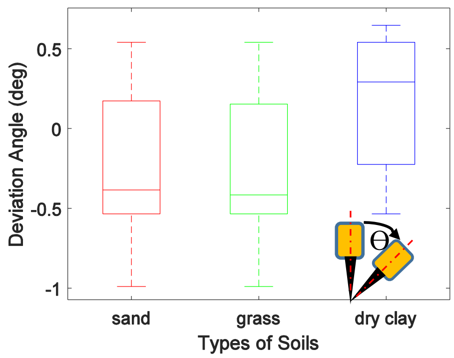

Fig. 12: Box and whisker plots comparing the variations in angle of deviation from horizontal of the seismic drone

the horizontal using the cross-product of rotation vectors $R_x(Roll) \times R_y(Pitch)$, as shown in Fig. 12.

IV. Conclusion

In this paper we present an autonomous technique for geophone placement, recording, and retrieval. The system enables automating a job that currently requires large teams of manual laborers. The paper described hardware experiments demonstrating the efficacy of the seismic drone compared to traditional techniques. The drone-sensing platform's output was comparable to a well planted geophone, suggesting the feasibility of the proposed system. Autonomous landing was displayed using GPS, thus displaying closed loop control. This proved human involvement could be drastically minimized by adopting the proposed technique. Angle of penetration was compared between different soil types resulted in deviations of around 2 deg. This proved the excellency in sensor platform design and reduced errors in sensor data. The system displayed the ability to penetrate soil types like sand and grass and, inability to penetrate hard types like dry clay yet it could perform sensing and obtain sensory data.

In the future drone systems could be designed solely for seismic exploration purposes there by increasing robustness, increasing flight and stationary periods, and be weatherized. A quad rotor system in general has limitations in flight time and in the future we would like to separate the sensing platform from the deployment unit. By creating mechanisms for deployment i.e. drop and pick up of sensing units. Designs could be made to make sensors either immobile passive sensing units that just listen or mobile active units that could create and measure a seismic wave. Given a heterogeneous set of sensing unis, further optimization could give insight on number of each type of sensing unit required. Pre and post signal processing techniques could be adapted to improve the quality of sensing. Data could be transmitted in real time to ease the exploration process and, identify errors and perform corrections. Transmitting high amounts of data is an issue, novel methods to compress, transmit, receive and interpret is an exciting research direction. Creating path planning algorithms for performing deployment retrieval tasks constrained by the availability of resource is an interesting future direction. It may be more beneficial to deploy one or more sensor packages and return the drone to a home base for charging or have a team of drones that divide the task of sensor deployment and retrieval. The precision on the GPS could be improved by upgrading to a RTK (Real Time Kinematic) or a DGPS (Differential GPS) system. Including other sensors like lasers, sonar, or a vision system could improve precision in deployment, can improve robustness to random disturbances and avoid obstacles. There are many opportunities for future work. A mobile app could be created to perform tailor-made tasks focusing on seismic exploration, which could be used by an human/robot operator to plan an exploration strategy. These ideas could be enforced to make the real system accessible and operational by a minimal work force.

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