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 (and industries) for subsurface exploration. It involves generating a vibration which propagates into the ground, echoes, and is recorded using motion sensors. Often sites of resource or rescue interest may be difficult or hazardous to access. In addition, traditional seismic imaging techniques rely heavily on manual labor to plant sensors, lay miles of cabling, and then collect the sensors. Thus, there is a substantial need for unmanned sensors that can be deployed by air and potentially in large numbers. This paper presents a working prototype of autonomous drones equipped with geophone vibration sensors that can fly to a site, land, listen for echoes and vibrations, store the information on-board, 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 on earth during the past accordng to an estimate by IEA (International Energy Agency) [1]. Millions of dollars are invested in exploration. Avoiding hazards and maintaining safety during exploration is necessary because hydrocarbons are highly-inflammable. Traditional exploration involves planting geophones (sensors) into the soil and detecting seismic disturbances caused from vibrating trucks or dynamite detonations which act as a source of vibration. As these vibrations propagate to the surface they are detected by the geophones and the data is stored. The data obtained describes the amplitude of the plastic waves generated by the source over a period of time. This data is used to reconstruct the 3-D layers beneath the surface and the presence of hydrocarbons. Instead of randomly searching for hydrocarbons, explorations are carried out using elaborate technical procedures, equipment, and skilled labor over a large area, thereby increasing the possibility of discovering hydrocarbon-reserves in an optimal fashion. 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

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.

wetlands. The exploration process involves repeated manual deployment and redeployment of sensors. Applying current advancements in automation would reduce the costs, decrease time and increase precision. Fig. 1 displays the major drawbacks of traditional seismic exploration and the solution presented in this paper, a flying robot for geophone placement and recovery.

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, and education. 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 of hand labor. 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 an seismic drone that can fly to a site, land, then listen for echoes and vibrations, transmit the information, and subsequently return to its home base. 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 a source is excited to generate seismic/vibrational waves that propagate under the earth's surface and are sensed by geophone sensors and recorded for later analysis to detect the presence of resources. Fig. 2 describes the current sensors available and the proposed solution, the seismic drone. These sensors are used to sense the vibrational wave that propagates with a velocity c in the positive and negative x-directions and is represented by the (1-dimensional) 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 generalized equations that represent a vibrational wave in physics, and can be used

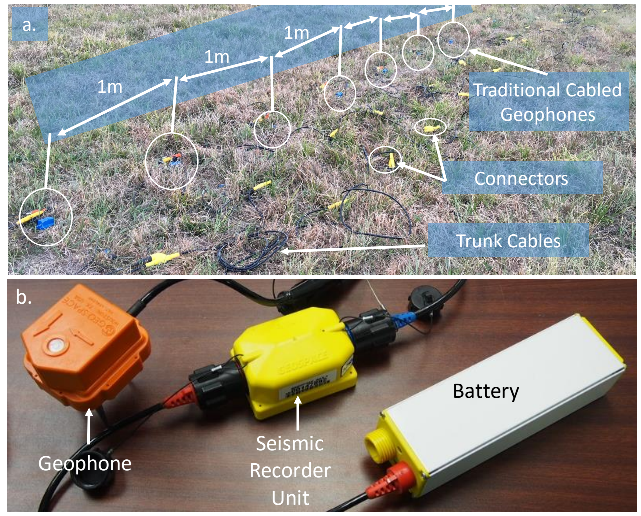

Fig. 2: Comparing the state-of-the-art seismic survey sensors a.) In traditional cabled system, the three geophones(sensors) are connected in series to the seismic recorder and battery. b.) In autonomous nodal systems, each geophone has a seismic recorder and a battery making the system "autonomous"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

to describe a string that is vibrating. Hence we obtain the equation where F is vibration force and ρ is density.

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

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.

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

The above equation is a 3-dimensional seismic wave equation that scales in complexity and links the motion of the moving coil relative to the magnetic flux for a given displacement caused by an external source where ξ is coil displacement, k is the spring constant, m moving mass of the coil, c is friction coefficient, g is gravitational acceleration, B is magnetic flux density, l is length of coil wire, i is the current and U is the external displacement. These equations can be found in many geophysics textbooks, for example see [2].

a) Cabled Systems

Traditional *cabled systems* are extensively used for seismic data acquisition in hydrocarbon explorations. 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 microcontroller which synchronizes the data acquired with a GPS signal and store it in the onboard memory. 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 system 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.

b) Autonomous Nodal systems

Currently *autonomous nodal systems* [3] 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, and this node can autonomously record data. 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 [4]. 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 [6]. Postel et al. describe using mobile robots for geophone placement in patent application [5]. Plans are underway for a swarm of seismic sensors for Mars exploration [7].

This paper presents a *flying 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. A seismic recorder, battery, and four geophones are embedded onto a platform which can be attached to an UAV. This setup is shown in Fig. 2. By inputting a specific GPS location, the UAV can accurately deploy the seismic data acquisition system. A *geophone* is a device that converts ground movement (velocity) into voltage, which may be recorded with a seismic recorder. The deviation of this measured voltage from the base line is called the seismic response and is analyzed for structure of the earth. The geophones obtain data which is processed by the seismic recorder and stored in the on-board memory. The major advantage of the drone is automating the deployment process and recovery. By using a robot to perform the above task, costs and errors are reduced. Because we use the same micro-controller as in the traditional cabled systems, we obtain the same 24-bit accuracy on the ADC conversion and sampled rates as low as half a millisecond. Future work on the seismic drone should enable it to transmit data wirelessly and hence obtain seismic plots in real-time. Because the deployment is autonomous, it is precise and the system has the ability to re-deploy or return home from the current deployment site.

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.

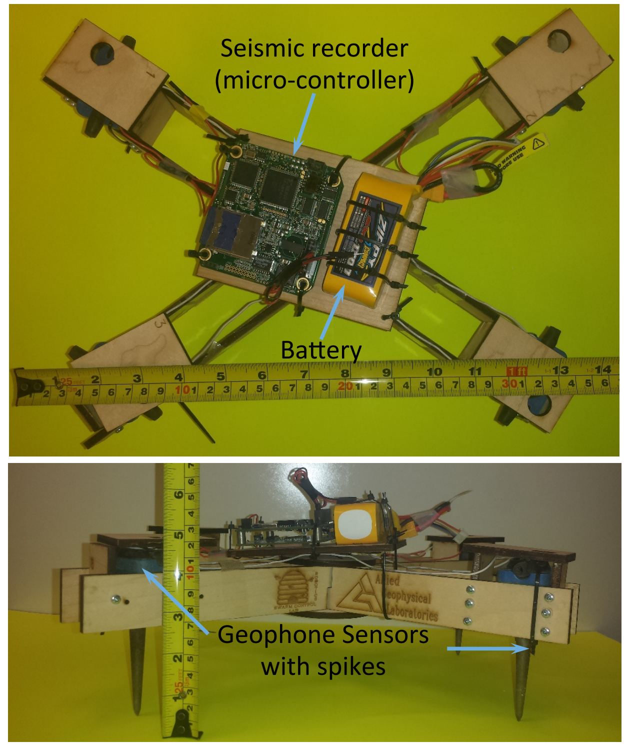

Fig. 3: The seismic drone's sensor base consists of four geophones, a Seismic Recorder (SR) and a LiPo battery (14.8V, 0.5Ah, 4 cells).

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

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).

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*. 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 above mentioned setups and in the drone were connected to *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 there by creating seismic waves for analysis.

The results are shown in Fig. 8, we observe the amplitude peak of the seismic drone is similar to the setups (*well-planted, satisfactorily-planted, round-platform, wooden-platform*) placed next to the drone. 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 in their response. Both the seismic drone and the well planted geophone setup have minimal oscillations, which is an important feature for seismic exploration, validating the seismic drone has good coupling with the surface.

Experiment 1 compares the performance of the seismic

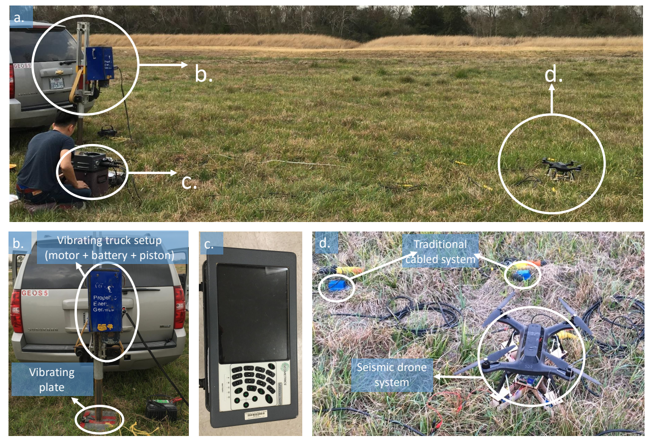

Fig. 5: A survey comparison was performed to obtain the shot gather plots of the traditional cabled system and seismic drone. a.) Overview of the experiment. b.) The vibrating setup strikes the metal plate below and generates vibrational waves. c.) Strata-Visor is a device used to store and process the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

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 as 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

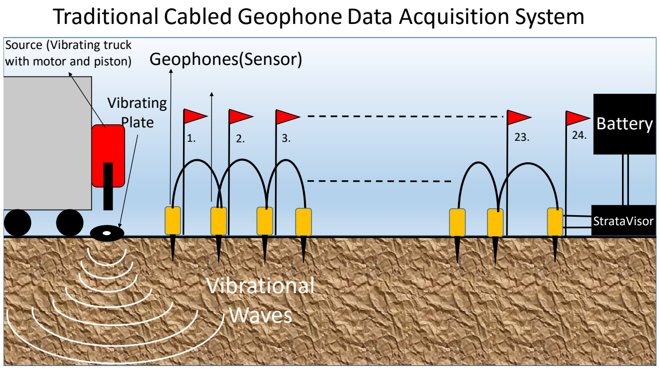

Fig. 6: A schematic of a traditional 24 geophone system, used extensively for seismic data acquisition.

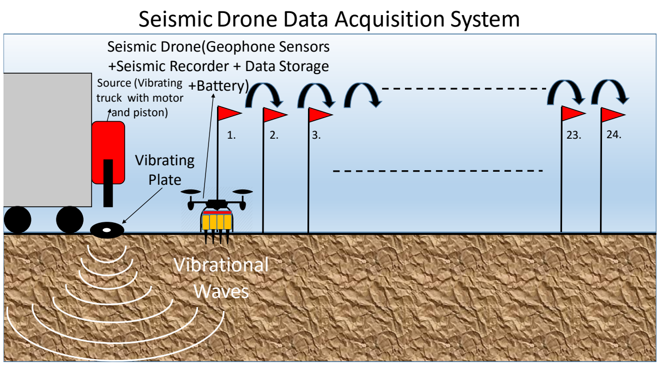

Fig. 7: A schematic of a proposed drone setup which can replace manual laborers during seismic surveys.

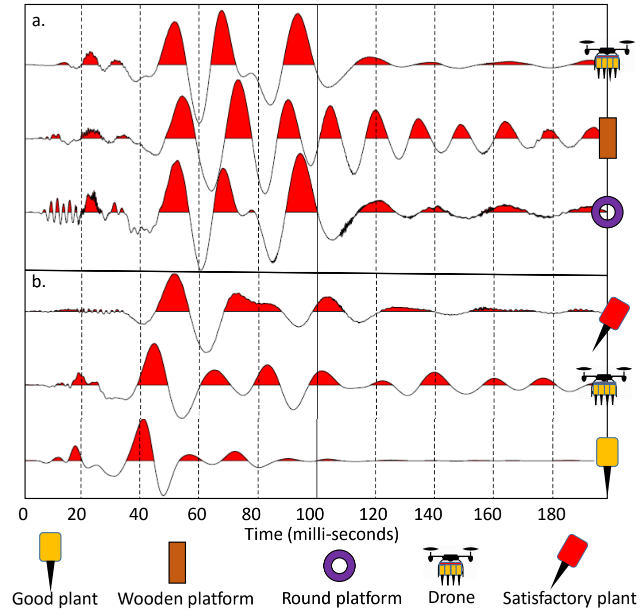

Fig. 8: Displays the seismic wave generated by different geophone setups and the seismic drone. a.) Compares the drone setup with different platforms (round and wooden platforms) oscillations in these platforms are not damped quickly since they are not fixed to the ground, The max amplitude values are 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.

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 is a 3DR Solo. It uses GPS for autonomous navigation and three compasses to measure its orientation. The landing location with an 'x' using blue insulating tape and the origin of the coordinate system was marked with a 'x' using a yellow insulating tape as shown in Fig. 11. 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 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. 12. 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 hence the landing locations accuracy are approximately 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, as indicated by of the target 95% standard deviation ellipse. The current landing accuracy is sufficient for seismic exploration. A 2 m error corresponds to a time shift of 25 ms approximately.

The autonomous planning of the drone is done using a mobile application called *Tower* shown in Fig. 10. This app can be used to plan complex autonomous trajectories, and the drone can perform different tasks at different waypoint locations. Future work will modify the app to perform tailor-made tasks focusing on seismic exploration.

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. 13.

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

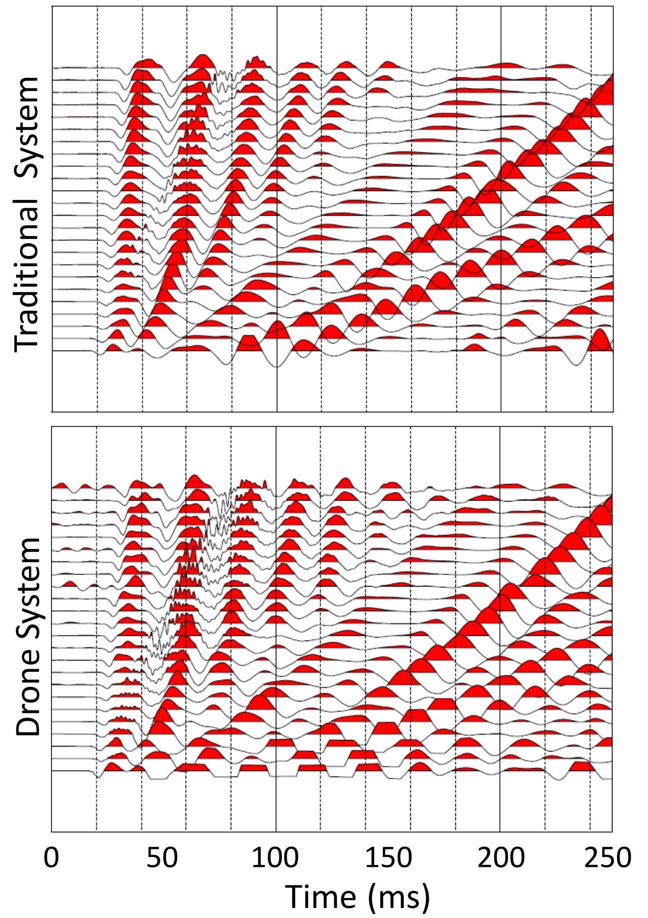

Fig. 9: A *shot gather* plot comparison, the x-axis is time in milliseconds and the y-axis is the channel number on the Strata-Visor, to which both the setups are connected. Each survey location is 1 m apart and the wave generated from the source propagates beneath the surface. The waves are time shifted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

for a geophone. It is important to land on a flat surface with less than $10°$ deviation from the horizontal, otherwise the drone will not fly due to difficulties it faces in take off while inclined at an angle. These two constraints complement each other. We collected data of the roll and pitch Euler angles to calculate the deviation from the horizontal using the cross-product of rotation vectors $R_x(Roll) \times R_y(Pitch)$, as shown in Fig. 14.

IV. Conclusion

This paper presented an autonomous technique for geophone placement, recording, and retrieval. This robot can enable automating a job that currently requires large teams of manual laborers. The paper described hardware experiments demonstrating the efficacy of this technique and comparing it with traditional manual techniques. There are many opportunities for future work. In particular, the current drones are not designed for long stationary periods and must be weatherized. It may be more beneficial to deploy one or more sensor packages and return the drone to a home base. Finally, there are many opportunities for teams of drones to divide

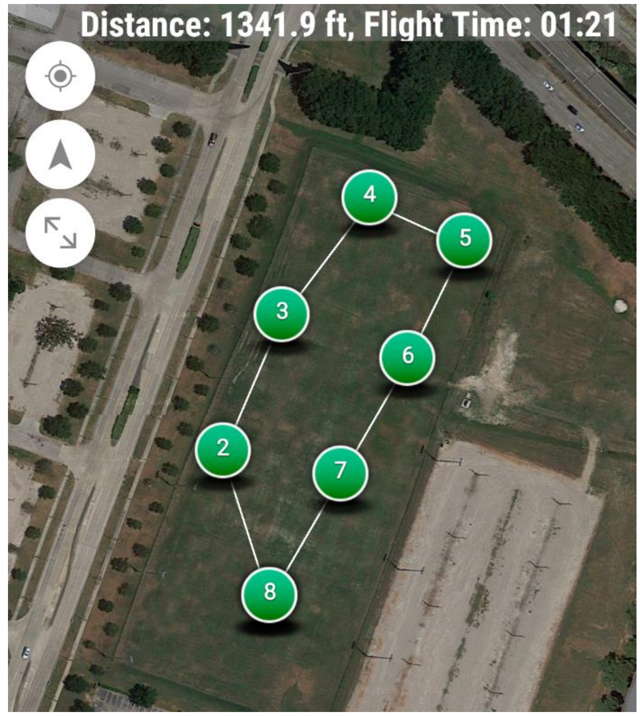

Fig. 10: Screenshot from the Tower App, that can be used for autonomous waypoint control. The app can be edited and programmed for performing specific tasks.

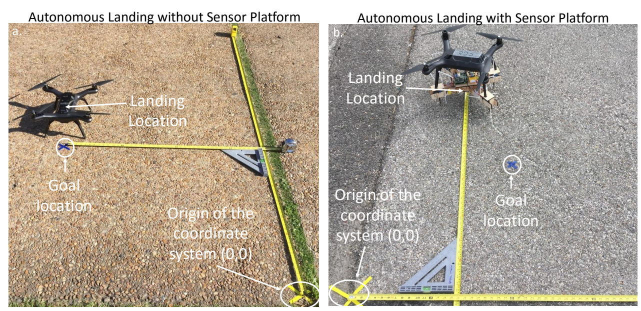

Fig. 11: The seismic drone was commanded to land at the goal location marked with a blue 'x', with and without the sensor platform. The test was repeated ten times to test the accuracy of autonomous landing. The drone uses GPS for landing which is not highly accurate lands at locations close to the goal location as shown. The origin of the coordinate system was marked with the yellow 'x', measuring tapes were used to measure the location at which the drone landed to the origin. a.) without the sensor platform. b.) with the geophones and sensor platform.

the task of sensor placement.

References

[1] International Energy Agency, "IEA Energy Atlas." [Online]. Available: http://energyatlas.iea.org

[2] P. M. Shearer, *Introduction to seismology*. Cambridge University Press, 2009.

[3] G. W. Wood, R. L. Workman, and M. W. Norris, "Distributed seismic data-gathering system," Mar. 3 1998, uS Patent 5,724,241.

[4] J. Jiang, A. A. Aziz, Y. Liu, and K.-M. Strack, "Geophysical data acquisition system," Jun. 16 2015, uS Patent 9,057,801.

[5] Jean-Jacques Postel, Thomas Bianchi, Jonathan Grimsdale, "Patent us20140307525: Drone seismic sensing method and apparatus," October 2014. [Online]. Available: https://www.google.com/patents/US20140307525

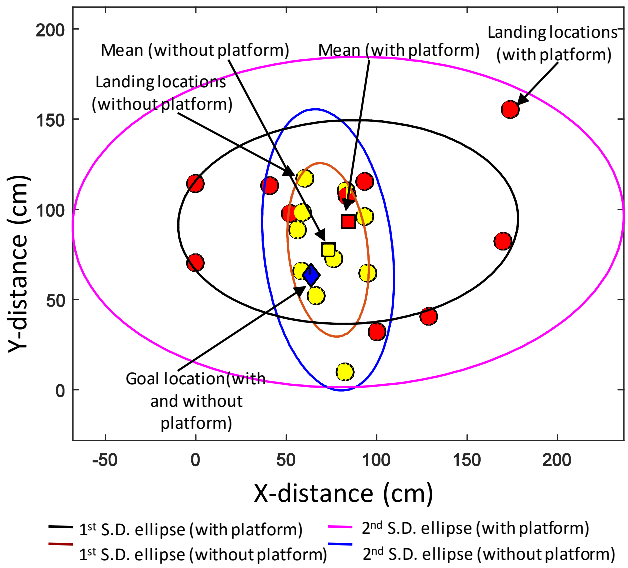

Fig. 12: The plots describe autonomous landing with and without the sensor platform. For 10 landings the landing locations are closer to the goal location for without the sensor platform than with the sensor platform. The mean, 1st std. ellipse and 2nd std. ellipse are shown for both cases.

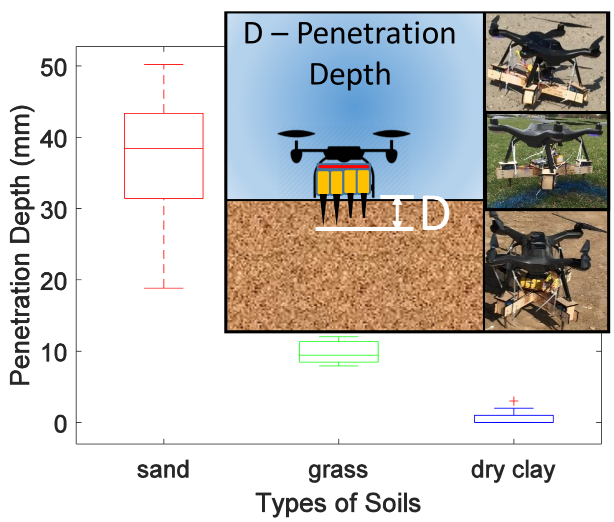

Fig. 13: Box and whisker plots comparing the variations in depth of planted geophones attached to the seismic drone

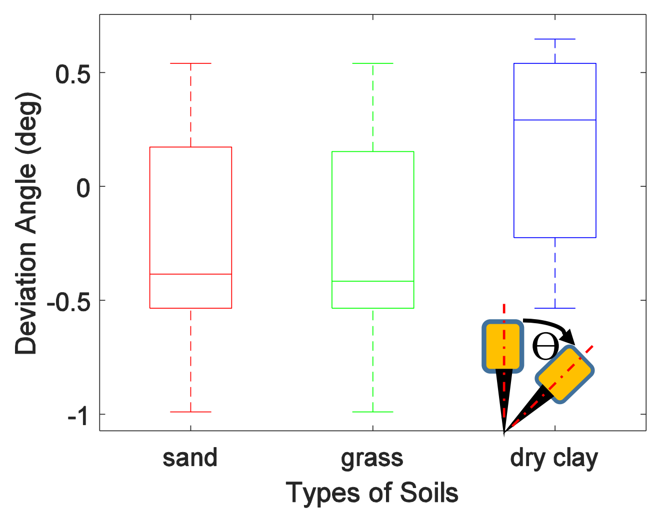

Fig. 14: Box and whisker plots comparing the variations in angle of deviation from horizontal of the seismic drone

[6] Goins, Neal Rodney, A. M. Dainty, and M. N. Toksöz, "Lunar seismology: The internal structure of the Moon." in *Journal of Geophysical Research: Solid Earth 86.B6*, 1981, pp. 5061–5074.

[7] M. A. P. G. 2006, "Robotic mars exploration strategy 2007–2016," March 2006. [Online]. Available: http://mepag.jpl.nasa.gov/reports/3715_Mars_Expl_Strat_GPO.pdf