Large-Scale Seismic Sensing by a Heterogeneous Robotic Team

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***Abstract*— Seismic surveying requires placing a large number of sensors (geophones) in a large grid pattern, triggering a seismic event, and recording accelerometer readings at each sensor. These readings are inverted to infer the location of hydrocarbons. Traditional seismic surveying employs human laborers for sensor placement and retrieval. Use of explosives, harsh climatic conditions, high costs and time associated with human deployment are the major drawbacks of traditional surveying. We propose an autonomous heterogeneous sensor deployment system using drones to plant and recover sensors. Detailed analysis and comparison with tradition surveying were conducted. Hardware experiments and simulations prove the effectiveness of automation in terms of cost and time. The proposed system overcomes the drawbacks and displayed higher efficiency.**

I. Introduction

Seismic surveying is a geophysical technique involving sensor data collection and signal processing. It aims at identifying and retrieving hydrocarbons like coal, petrol, natural gas. Traditional seismic surveying involves manual laborers placing geophone sensors at specific locations connected by cables. Cables are bulky and the amount required is directly proportional to the area surveyed. On average hundreds of square kilometers must be surveyed, requiring many kilometers of cabling. Remote locations often require seismic surveying, with concomitant problems of inaccessibility, harsh conditions, and transportation of bulky cables and sensors. These factors increases the cost.

Nodal sensors are a relatively new development to the seismic sensing. Nodal sensors are autonomous units that do not require bulky cabling. They have an internal seismic recorder, a micro-controller that records seismic readings from a high-precision accelerometer. Because this technology does not require cabling, the overall cost is reduced. Currently nodal sensors are becoming popular in the USA due to reduced costs in seismic sensing. However, these sensors are still planted and recovered by hand. This paper introduces an automated technology for planting and recovering wireless sensors. The technology presented may have wide applicability for quickly deploying sensor assets for geoscience, earthquake monitoring, defense, and wildlife monitoring. add citations for each

II. Overview and Related Work

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, an Arduino Uno micro-controller, an amplifier, and a battery. This system was not stable and if the plant of the geophone spike failed, the drone fell on its side. The second prototype has a seismic recorder, a battery, and four geophones all embedded onto a platform that is attached to an UAV. This sensor platform with 4 geophones provided stability and acted as an extension of the drone's landing gear, solving the issue of tipping over during landing. These prototypes are shown in Fig. 1. 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 micro-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. This device helps us obtains data comparable to 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.

A. Seismic Sensing

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. **??**. shows the proposed solution, the deployment unit and siesmic sensors.

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

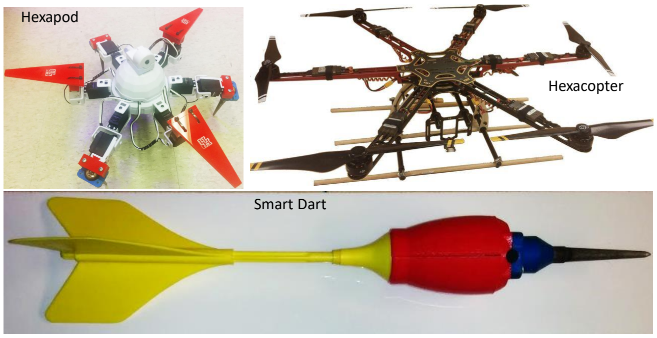

Fig. 1: This figure depicts the heterogeneous sensor system used for seismic data acquisition. It consists of two sensors the hexapod and the smart dart. These sensors have complementing features. The hexacopter shown is used as a deployment unit.

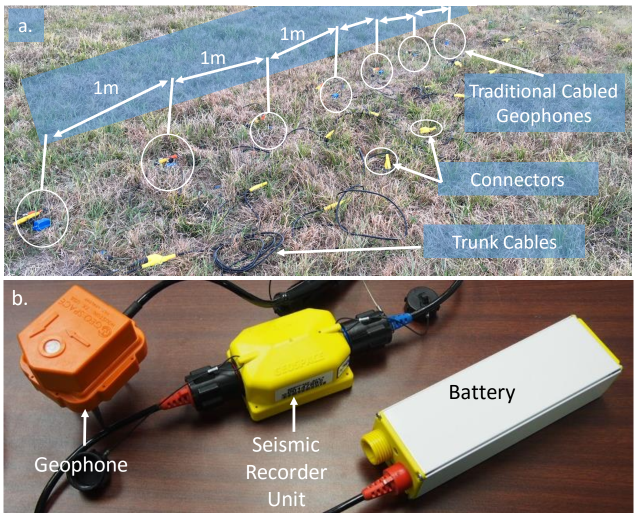

Fig. 2: Comparing state-of-the-art seismic survey sensors a.) Traditional cabled system, the geophones (sensors) are connected in series to the seismic recorder and battery. b.) Autonomous nodal systems, each geophone has a seismic recorder and a battery making each geophone "autonomous" from the other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

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 [1].

1) 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* [2] 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 [3]. Yet these systems still require manual laborers for planting the autonomous nodes at specific locations and deploying the large antennas necessary for wireless communication.

3) Seismic Drone

The concept of using robots to place seismic sensors dates to the 1980s. Mobile robots have placed seismic sensors on the moon [4]. Postel et al. proposed mobile robots for geophone placement [5]. Plans are underway for a swarm of seismic sensors for Mars exploration [6].

B. Sensor networks

C. Multi-Robot Assignment

III. Smart Darts

A. Design

The Smart dart combines a geophone(GS-100) with the fins and body of a lawn Jart (TM), using a 3D-printed cham-

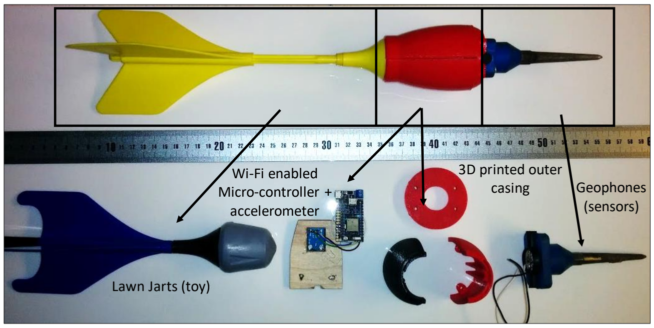

Fig. 3: This is the cross-section of the smart dart sensor. It consists of a lawn jart fin, electron micro-controller, 3D printed protective casing and a geophone

ber that encloses a photo cellular-enabled micro-controller (link) called *Photon* as shown in 3.

This design was selected because of (blah blah)

The following sections compare the performance of the Smart Darts in different soils,

B. Experiments

1) Drop tests in different soils

This experiment varied the drop height and measured the penetration depth in four types of soil. Proper planting of a geophone requres godd contact by ensuring the geophone is pushed deep into the soil, and the sensors should be close to vertical because accelerometers deviation from to determine the minimum height for Each trial measured the penetration depth and the angular error from vertical. This experiment compared drop tests as function of soil type. Results are summarized in Fig. 4, which shows penetration depth, and Fig. 5, which shows angle of defication.

Soil types are calibrated using a hand-held penetrometer(E-280)

To determine how the smart darts would perform in different soils, we ran an experiment on their penetration into 4 different soil types. Each experiment was carried out by holding the darts at their tips opposite to the spike in a vertical position and releasing them at varying heights into the buckets of soil and measuring their penetration depth, and angle of penetration. To measure their penetration depth, the buried darts were marked at a point on it's spike where it met the soil, the dart was then pulled out of the ground, and the distance from the spike tip to the marking was measured with calipers. The angle of penetration was recorded from the accelerometer inside the dart. The soil types were categorized by their compression strength, which was measured using a pocket penetrometer. Since measurements for compression strength vary drastically with small deviation in measurement location, we took this measurement 10 times at 10 different locations in the same soil type and took the average. A graph displaying these varying heights vs. their penetration depth can be seen in figure.... and a graph displaying the penetration angle at the varying heights can be seen in figure...

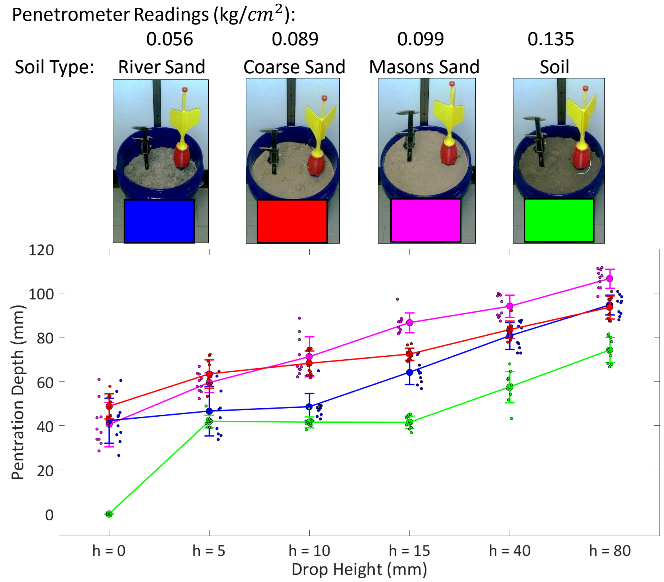

Fig. 4: Drop height vs. penetration depth in four soil types.

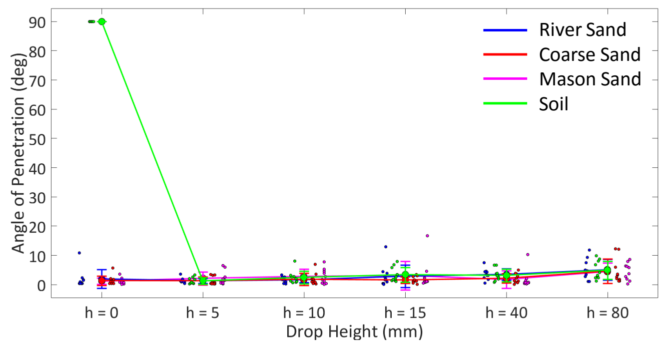

Fig. 5: Drop height vs. angle of deviation in four soil types.

2) Straight vs Bent Fins

Drop tests as function of height. Compares depth and angle for twisted vs. straight tail. Results are summarized in Fig. 7.

To determine the difference in performance between straight-finned darts and twisted-finned darts, we ran a drop test experiment on each type of dart 10 times at a constant height in only one soil type. Each experiment was carried out by holding the darts horizontally at a height of 10.5 meters, dropping it into the soil, and recording it's penetration depth and penetration angle. The purpose of holding the darts horizontally in this experiment was to study the angle-correcting behavior of the fins. The angle of penetration and penetration depth were recorded in the same way as in the other drop test experiments. A graph showing the values recorded for penetration depth and angle can be seen in figure...

3) Shot gather comparison

Exp 3: Dart sensing accuracy vs ground setup

Srikanth: Need figure for accuracy of placement for drone drop

Fig. 6: Difference in design between straight and bent fins.

Fig. 7: Outdoor Drop test comparing Straight vs Bent fins performance. a.) smart dart dropping b.) measuring drop height

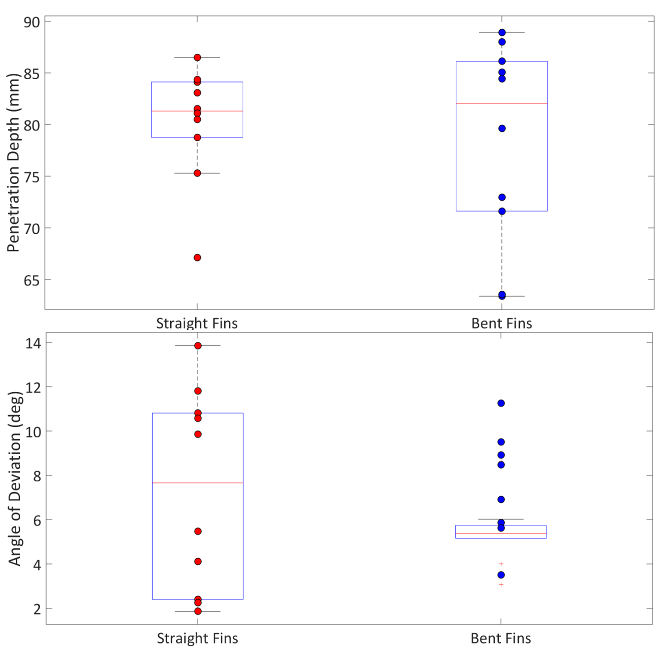

Fig. 8: Straight vs Bent fins comparing a.)penetration depth b.)angle of deviation. Experiment used a fixed drop height of 9.8 m.

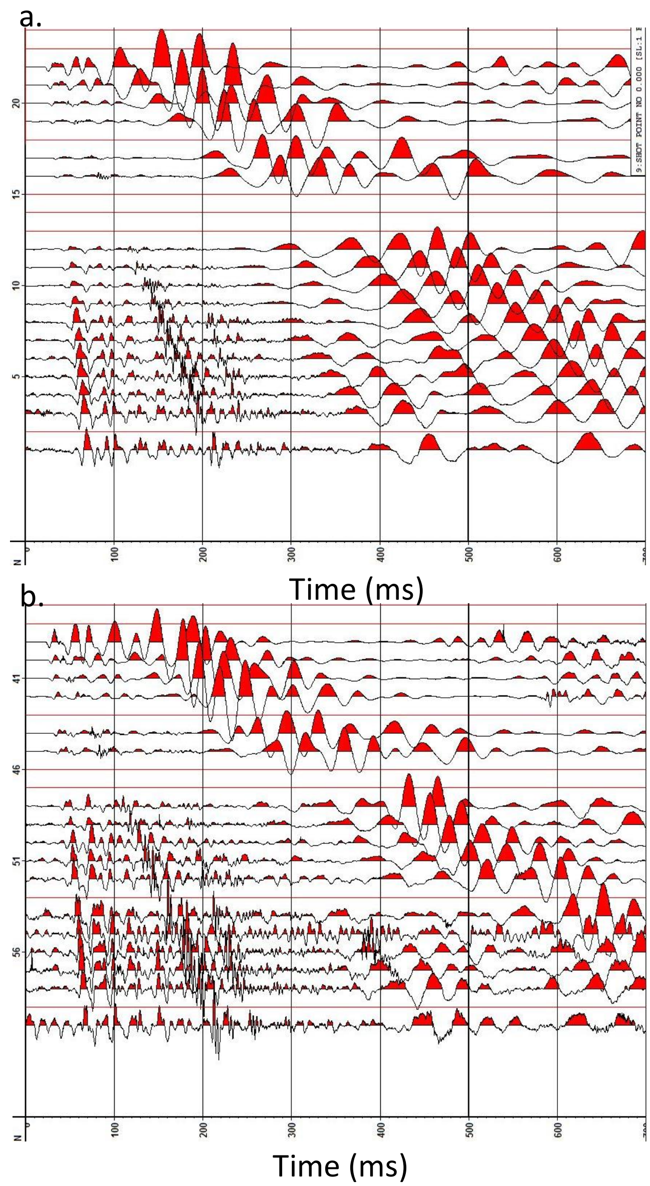

Fig. 9: Shot gather comparision of traditional geophones vs autonomously dropped smart dart sensors a.) Traditional b.) Smart darts

IV. SeismicSpider

A. Design

B. Experiments

1) Exp 1: Accuracy plot

Hexapod move to desired GPS location (plot accuracy)

2) Exp 2: Shot gather comparison

Hexapod sensing accuracy vs ground setup

3) Exp 3: Deploying and Retrieving Hexapod

Exp 5: Retrieving Hexapod

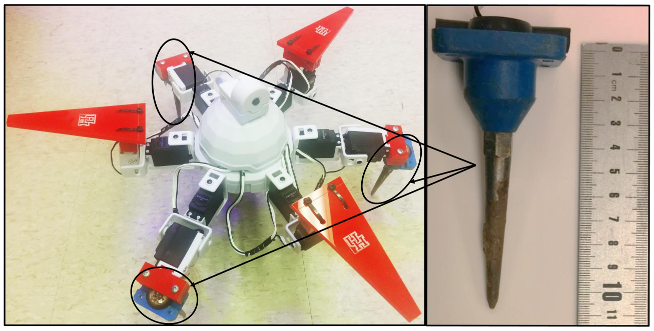

Fig. 10: The hexapod sensor is a mobile unit with three of it's legs replaced by geophones. It has the ability to sense seismic waves and store the data obtained.

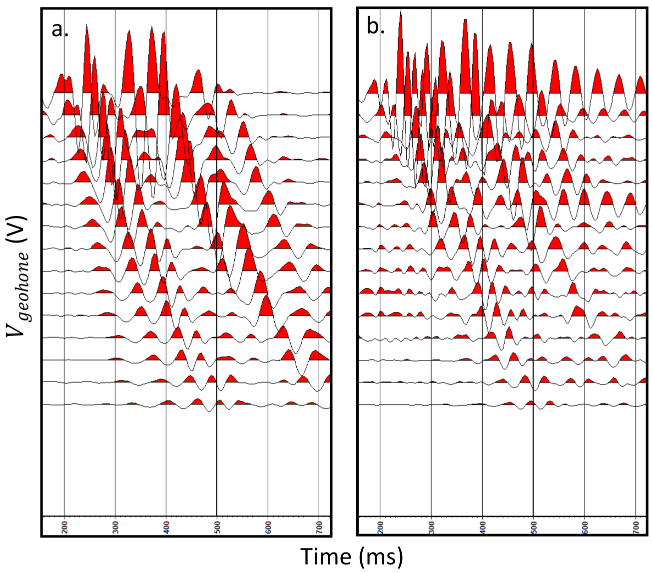

Fig. 11: Shot gather comparison of traditional geophones vs hexapod sensor a.) Traditional b.) Hexapod

V. DeploymentUnit(UAV)

A. Design

Victor: image of the deployment system.

An: I want to know about the deployment unit.

B. Experiment

1) Autonomous drop demonstration and accuracy

The current drone can place the SmartDart within ± 1 m of the desired location. This inaccuracy is 1) There are often features (rocks, water, etc.) that require this amount of error from theoretically assigned locations, 2) some survey designs include a random placement component to improve noise cancellation, 3) this error minimally perturbs the data since seismic waves travel at 600 m/s in near surface, so a one-meter inaccuracy equates to $\approx$1.6 ms delay, 4) the response of a receiver to seismic vibrations is an average over a number of meters.

The critical factor is to know exactly (within 10 cm accuracy) the geophone location. Knowledge of this exact location allows corrections for the possible jitter in arrival times of the signal due to inaccuracy of placement.

Exp 4: Automatic drop from drone, accuracy in placement

AN: Need figure for accuracy of placement for drone drop

2) Height vs. penetration depth

Exp 5: Height vs. penetration depth

AN: Need figure for accuracy of placement for drone drop

VI. Comparision

A. Ballistic Deployment

add figure of pneumatic cannon

add figure of plot of pneumatic cannon firing angle vs ending angle

B. Simulation Studies

A scheduling system to compare time and costs for seismic surveys with varying numbers of Deployment Units, Seismic-Spiders, SmartDarts, and Human manual laborers was coded in MATLAB, available at [7].

add showing simulation (maybe the 3 options from Srikanth's talk)

add plot or table showing results of simulation

VII. Conclusion and Future Work

This paper presented an autonomous technique for geophone placement, recording, and retrieval. The system enables automating a job that currently requires large teams of manual laborers. Three components were introduced, SmartDarts, a mobile SeismicSpider, and a deployment unit. Field and laboratory hardware experiments demonstrated the efficacy of the seismic drone compared to traditional techniques. The SmartDart's output were comparable to well-planted geophones, suggesting the feasibility of the proposed system. For hard surfaces where the SmartDart could not penetrate, an autonomous alternative was presented, the SeismicSpider. The SeismicSpider is mobile, can actively adjust its sensors to ensure ground contact and vertical placement, and can be deployed and retrieved by drone.

Autonomous deployment was conducted using GPS, proving human involvement could be drastically minimized by adopting the proposed technique. Hardware experiments compared the autonomous system to manual planting and ballistic deployment. Simulation studies show time and cost savings over traditional manual techniques.

Future systems should be weatherized and be designed solely for seismic exploration purposes to increase robustness, range, and speed.

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