A Heterogeneous Robotics Team for Large-Scale Seismic Sensing

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***Abstract*— Seismic surveying requires placing a large number of sensors (geophones) in a grid pattern, triggering a seismic event, and recording accelerometer readings at each sensor. The location of hydrocarbons is inferred from these readings. Traditional seismic surveying employs human laborers for sensor placement and retrieval. The major drawbacks of surveying with human deployment are the high costs and time, and risks to humans due to explosives and harsh climatic conditions. We propose an autonomous heterogeneous sensor deployment system using drones to plant immobile sensors and deploy mobile 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 hydrocarbons reservoirs of coal, petrol, and natural gas. Traditional seismic surveying involves manual laborers repeatedly placing geophone sensors at specific locations connected by cables. Cables are bulky and the length required is proportional to the area surveyed. Surveys routinely cover hundreds of square kilometers, requiring 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. Nodal sensors are becoming popular due to reduced costs in seismic sensing. However, these sensors are still planted and recovered by hand.

We propose a heterogeneous robotic system for obtaining seismic data, shown in Fig. 1. The system consists of two sensors, the SmartDart and the SeismicSpider. The SmartDart is a dart-shaped wireless sensor that is planted in the ground by dropping from a UAV. The SeismicSpider is a mobile hexapod with three of legs replaced by geophones. This system is designed to automate sensor deployment, minimizing cost and time while maximizing accuracy, repeatability, and efficiency. The technology presented may have wide applicability where quickly deploying sensor assets is essential, including geo-science, earthquake monitoring, defense, and wildlife monitoring. add citations for each

Fig. 1: The heterogeneous sensor system presented in this paper: wireless SmartDarts and a SeismicSpider, both designed for deployment from a UAV.

II. Overview and Related Work

This paper presents a *heterogeneous sensor system* for automatic sensor deployment. The goal is to overcome the drawbacks of deploying seismic sensors manually. In previous work [1], we demonstrated a UAV equipped with four geophone sensors as landing gear. This UAV automated sensor deployment by flying to GPS waypoints to obtain seismic data. This solution had several limitations. Magnet-coil geophones contain a permanent magnet on a spring inside a coil. Voltage across the coil is proportional to velocity. Beneath the coil housing is a metal spike. Geophones are *planted* by pushing this metal spike into the group, which improves coupling with the ground to increase sensitivity.

The magnet-coil must be aligned with the gravity vector. Mialignment reduces the signal proportional to the cosine of the error.

The geophones in [1] were connected to the UAV, causing four problems (1) one UAV was required for each additional sensor, (2) the force for planting the geophone was limited by the weight of the UAV, (3) the platform required a level landing site, (4) the magnets in the geophones distort compass readings, causing landing inaccuracy when autonomous.

The proposed heterogeneous sensor system separates the sensing units from the UAV. This reduces the cost per sensor. Dropping the geophones enables increasing geophone penetration by increasing drop height and eliminates the necessity for a level landing site. The new design also increases separation between geophones and the UAV.

A. Related Work

Seismic surveying is a The patent [2] proposed using robots for geophone deployment. Their idea is to have a propulsion module that either be a wheels, tracks, turbines, helicopter blades etc. This robot is used to deploy sensors at specified locations. The system consists of modules for ensuring the sensor is well planted and placed perpendicular to the ground. The modular approach to a deployment system is innovative but might not be practically feasible. While servicing a large area ability to deploy multiple sensors in limited time is a key factor. The approach seems to be well suited for short surveys. The system proposed in our paper consists a multi-agent system approach. In patent [3] an unmanned flying vehicle is used to harvest data from multiple sensors and there by easing the data collection process. The main focus is on data collection rather than automatic sensor deployment. Some works relate to surveying an earth quake prone region to collect data as in [4]. The goals of these papers is to perform a survey rather than sensor deployment. Other works like [5] relate to marine seismic surveying with autonomous vehicles. An interesting proposal was to perform a seismic survey using augmented reality [6].

B. Overview of Seismic Sensing Theory

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.

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

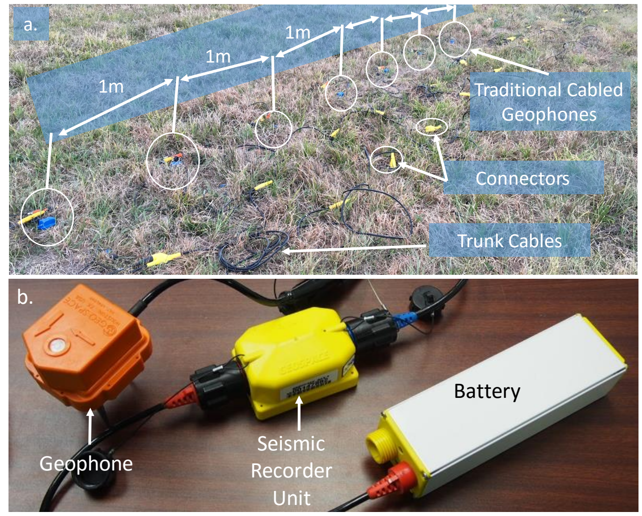

Fig. 2: Comparing state-of-the-art seismic survey sensors a.) Traditional cabled system, the geophones (sensors) are connected in series to the seismic recorder and battery. b.) Autonomous nodal systems, each geophone has a seismic recorder and a battery making each geophone “autonomous" from the other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

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 [7].

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* [8] 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 [9]. 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) Heterogeneous Sensing System

The concept of using robots to place seismic sensors dates to the 1980s. Mobile robots have placed seismic sensors on the moon [10]. Postel et al. proposed mobile robots for geophone placement [11]. Plans are underway for a swarm of seismic sensors for Mars exploration [12].

C. Sensor networks

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

The Smart Dart combines a geophone(GS-100) with the fins and body of a lawn Jart^{TM}, using a 3D-printed chamber that encloses a WiFi-enabled micro-controller (link) called Photon as shown in Fig. 3. The center of the chamber is slotted to fit a wooden card holding an accelerometer that transmits data back to the user through the Photon. This design was selected because the centered accelerometer card allows for the microcontroller and it's battery to be placed on opposite sides of each other, keeping the center of mass of the object in the center. The Smart Dart deployment mechanism was designed to allow the seismic drone to carry four Smart Darts in a circular array, and release them when it reaches the desired GPS location, one at a time. The circular Dart tip allows the Darts to be locked into the geometry of the mechanism, resting on top of a rectangular slot-path. A Servomotor rotates the Dart tips through the rectangular slot-path, ending at a large circular slot, allowing the Darts to release from the mechanism.

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

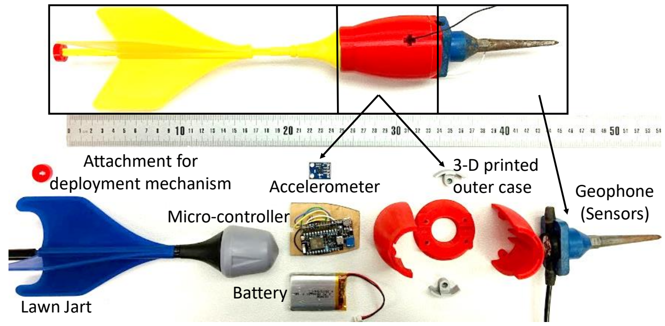

Fig. 3: Cross-section of the smart dart sensor. It consists of a lawn jart fin, electron micro-controller, 3D printed protective casing and a geophone

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 smart darts perform in different soils, this experiment measured penetration into 4 soil types. Each trial was performed by holding the darts at the tip 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 penetration depth, the buried darts were marked where the spike met the soil, the dart was then pulled from the soil, 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, measured using a pocket penetrometer. Measurements for compression strength vary drastically with small deviation in measurement location, so we took this measurement 10 times at 10 different locations in each soil type and took the average. A graph displaying these varying heights vs. their penetration depth can be seen in Fig. 4 and a graph displaying the penetration angle at the varying heights can be seen in Fig. 5

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. 6.

To determine the difference in performance between straight-finned darts and twisted-finned darts, we ran a drop test with 10 trials for both types of dart at a constant height in one soil type. Each trial was initialized by holding the dart horizontally at a height of 10.5 meters, dropping it into

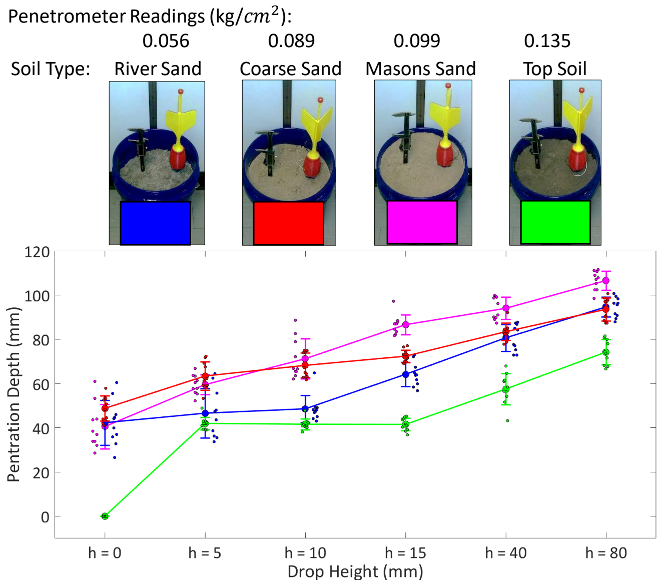

Fig. 4: Drop height vs. penetration depth in four soil types.

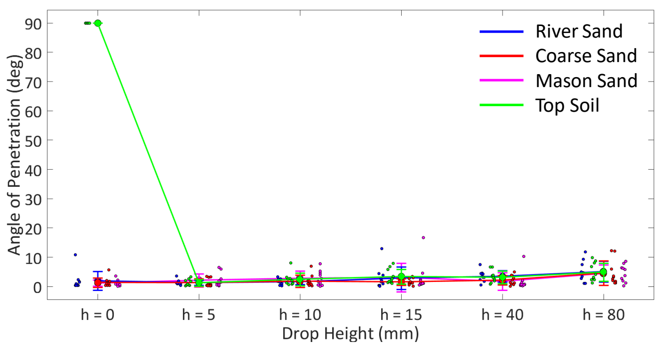

Fig. 5: Drop height vs. angle of deviation in four soil types.

the soil, and recording the penetration depth and penetration angle. Holding the darts horizontally emphasized the angle-correcting behavior of the fins. The angle of penetration and penetration depth were recorded as in the other drop test experiments. A graph showing the values recorded for penetration depth and angle in Fig. reveals that twisted-finned darts had greater variation in angle and less penetration.

3) Shot gather comparison

Exp 3: Dart sensing accuracy vs ground setup

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

Fig. 6: Outdoor Drop test comparing Straight vs Bent fins performance. a.) smart dart dropping b.) measuring drop height

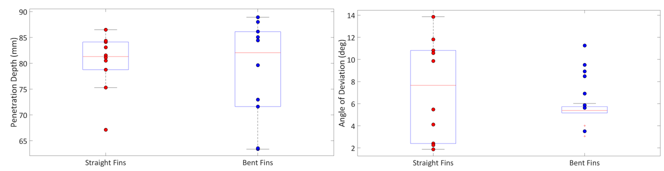

Fig. 7: Straight vs Bent fins comparing a.) penetration depth b.) angle of deviation. Experiment used a fixed drop height of 9.8 m.

3) Exp 3: Deploying and Retrieving Hexapod

Exp 5: Retrieving 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.

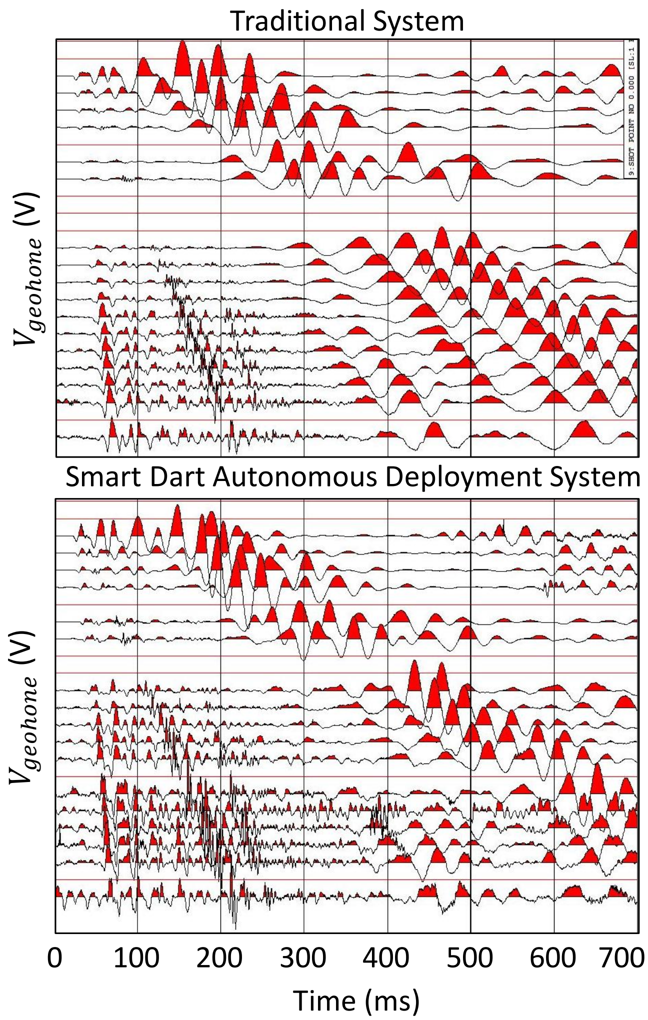

Fig. 8: Shot gather comparision of traditional geophones vs autonomously dropped smart dart sensors a.) Traditional b.) Smart darts

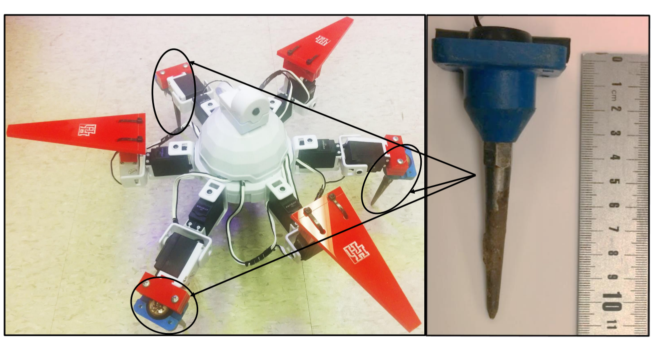

Fig. 9: The SeismicSpider is a six-legged mobile robot where three legs are replaced by geophones. It has the ability to sense seismic waves and store the data obtained.

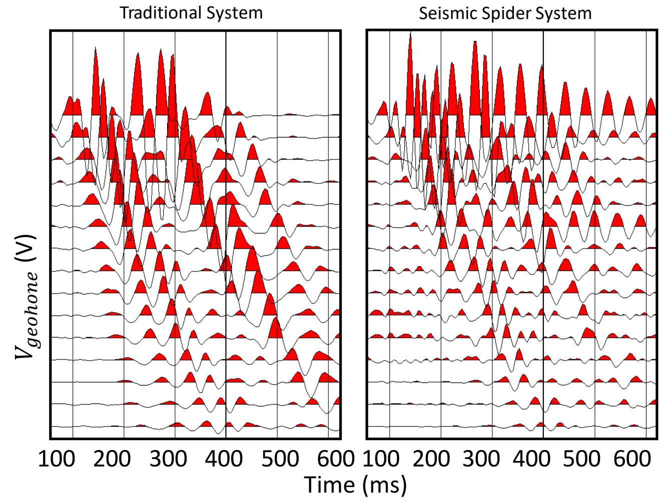

Fig. 10: Shot gather comparison of traditional geophones vs. hexapod sensor.

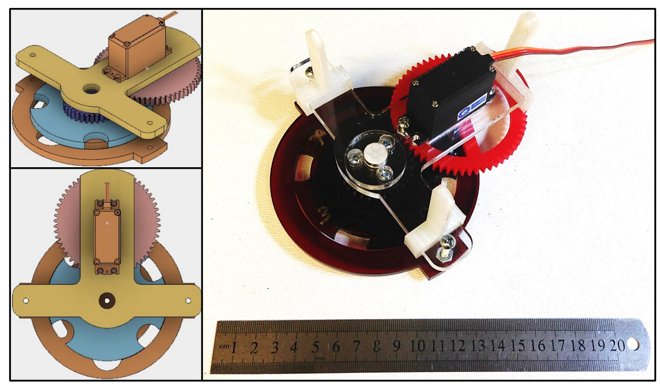

Fig. 11: Deployment system for dropping SmartDarts from the UAV. Pictured design holds 4 darts, but can be scaled according to the UAV's carrying capacity.

Exp 4: Automatic drop from drone, accuracy in placement

The UAS is a 177 cm wing span hexacopter, controlled by the Pixhawk flight controller running ArduPilot Mega flight software. The UAS has a 3DR GPS module using the UBlox NEO-7 chipset.

For the accuracy test, 6 sets of dart, 4 darts in each set, were dropped on the same GPS waypoint. Between each drop, the UAS travel to another GPS waypoint close by to cancel out the flight controller's stable hover as shown in Fig. 12a. UAS return to launch platform to be reloaded and data is recorded after each set.

To record data, one dart was picked from the first set as the reference point (the lower left in Fig. 12b), hence the first data point will be 0,0. A lager dry-wall square is placed with the origin at the dart's drop point to establish axes.

After the first set of data has been recorded, the darts are collected and reloaded on to the UAS for next set of deployment. A rod is placed in the position of the first dart to keep reference as shown in Fig. 12c. The dry-wall square is kept in place, strings were tied on the ground to lengthen the reference axes. Future deployment will be compared against the reference point and axes.

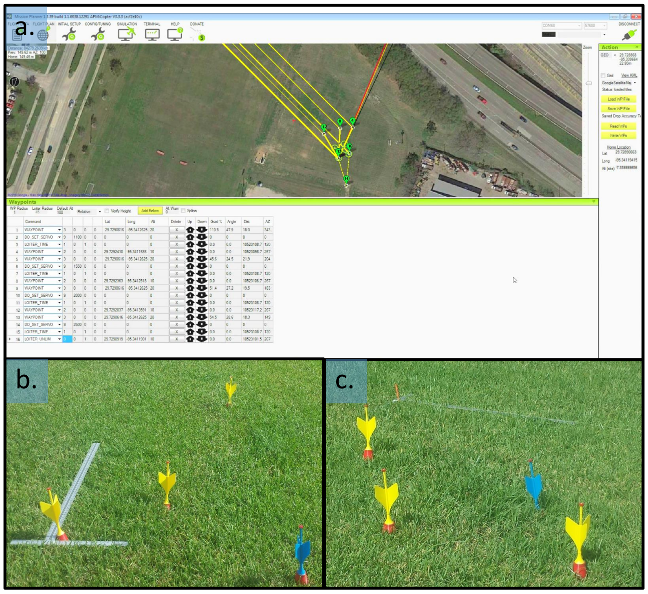

Fig. 12: a.) Flight plan of accuracy test b.)First set of dart with reference axes c.)Later Dart Sets

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AN: Need figure for accuracy of
placement for drone drop
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2) Height vs. penetration depth

Exp 5: Height vs. penetration depth

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AN: Need figure for accuracy of
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VI. Comparision

A. Ballistic Deployment

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 [13].

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

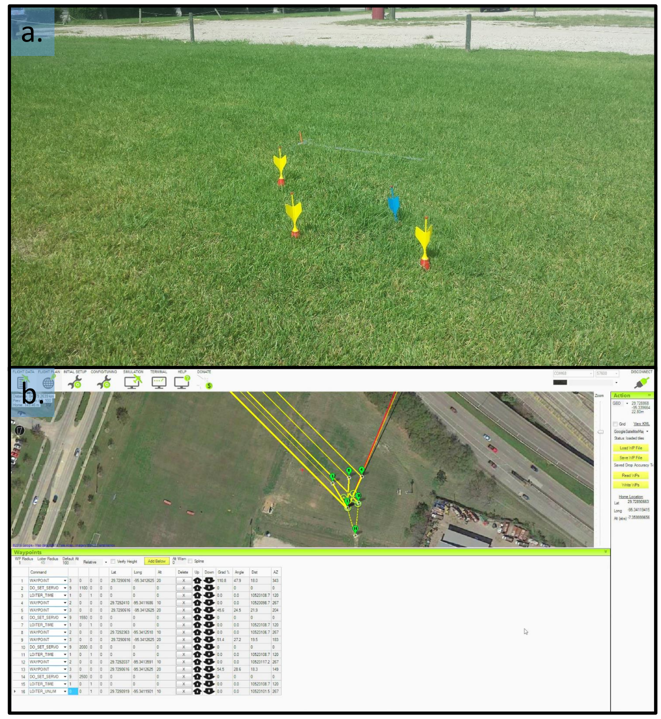

Fig. 13: a.) Smart darts deployed autonomously by the deployment unit (hexacopter) b.) Screen shot of flight plan for autonomous deployment

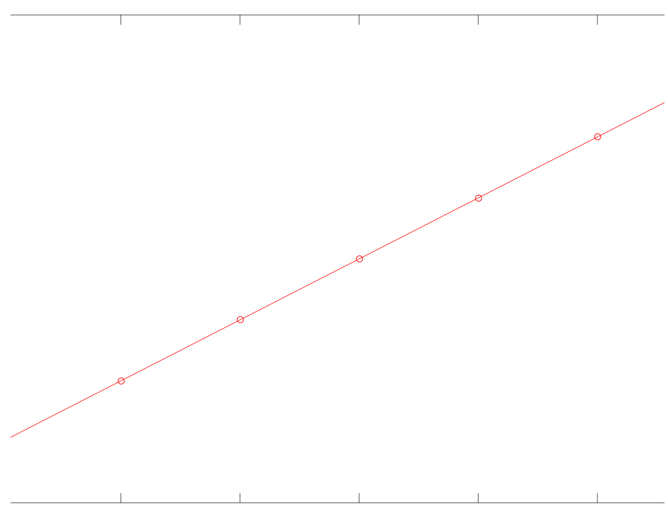

Fig. 14: Plot of pneumatic cannon firing angle vs ending angle

Fig. 15: Seismic dart pneumatic launcher with air compressor

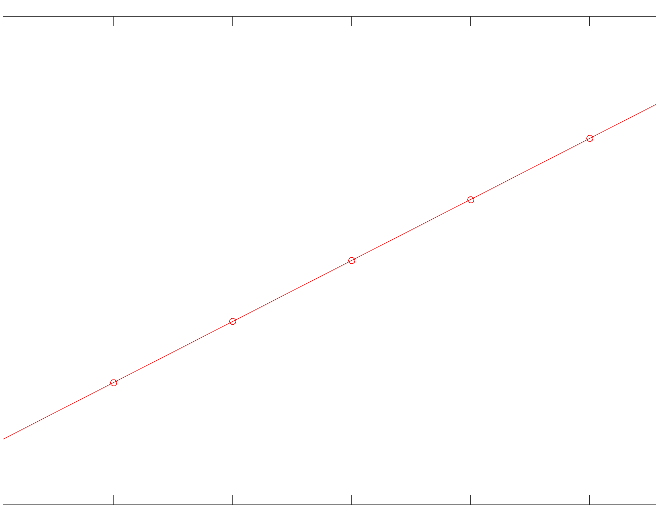

Fig. 16: Plot of pneumatic cannon firing angle vs ending angle

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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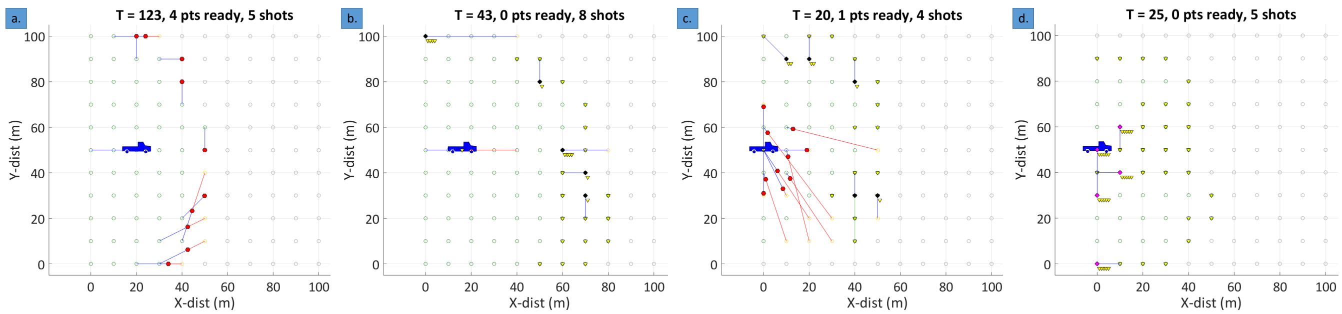

Fig. 17: Simulations were performed to estimate time take by different sensors a.) Only seismic spiders b.) Smart darts and deployment system c.) Heterogeneous System d.) Human workers

S. No.	Type	Numbers of Units	Time Taken for Survey (s)	Velocity (m/s)
1.	Hexapods	10 Hexapods	471	1
2.	Quadcopters, Smart Darts	4 Quadcopters, 20 Smart Darts	86	20
3.	Quadcopters, Hexapods, Smart Darts	4 Quadcopters, 10 Hexapods, 20 Smart Darts	75	Quad – 20 Hex - 1
4.	Workers	5 Workers, 75 Darts	467	1.38

Fig. 18: Simulations were performed to estimate time take by different sensors a.) Only seismic spiders b.) Smart darts and deployment system c.) Heterogeneous System d.) Human workers