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 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 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 geo-science, earthquake monitoring, defense, and wildlife monitoring. `add citations for each`

We propose a heterogeneous sensor system for obtaining seismic data. The system consists of two sensors 1.) Seismic spider 2.) Smart dart. The seismic spider is a mobile robot(hexapod)with three of it's legs being replaced by geophones. The smart dart is a dart like sensor that is dropped from the deployment unit. The goal is to automate the process of sensor deployment and thus minimizing factors like cost, time and maximizing accuracy, repeatably and efficiency.

Fig. 1: Heterogeneous sensor system(smart dart and seismic spider) being carried by the deployment unit.

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 our previous work [1], we proposed a working prototype of a seismic drone that could fly to GPS waypoints and obtain seismic data. Even though we were able to automate sensor deployment and obtain seismic data there were certain drawbacks like accuracy in placement, improving penetration of the geophone, placing geophones perpendicular to the ground and reducing the cost of sensing unit. The cost of the system proposed was expensive because the deployment system(quadcopter) was attached to the sensing platform. The proposed heterogeneous sensor system separates the sensing units(Seismic spider, Smart darts) from the deployment system(hexacopter), thus reducing the cost of a single sensor. The problems with accuracy were overcome by upgrading the deployment unit from an off the shelf quadcopter to a customizable hexacopter. We had the freedom to place the GPS unit far away from the geopohone sensors to reduce the interference of the magnets. The deployment techniques adapted make sure the geophone sensor lands perpendicular to the ground with ± 10 deg of error.

[2] closely relates to our work, here the authors proposed a novel vehicle 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].

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.

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.

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

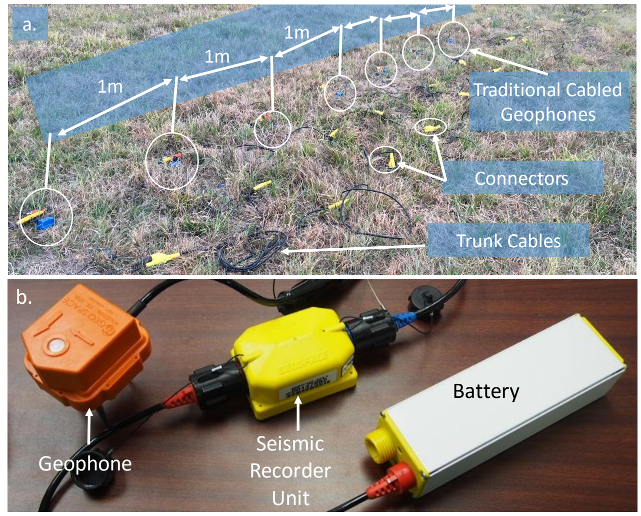

Fig. 2: Comparing state-of-the-art seismic survey sensors a.) Traditional cabled system, the geophones (sensors) are connected in series to the seismic recorder and battery. b.) Autonomous nodal systems, each geophone has a seismic recorder and a battery making each geophone “autonomous" from the other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

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].

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 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$^{\text{TM}}$, 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,

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

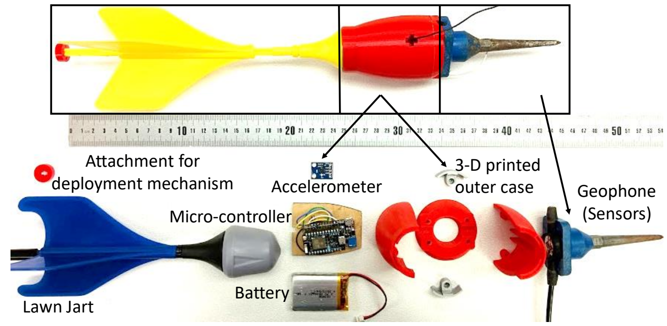

Fig. 3: Cross-section of the smart dart sensor. It consists of a lawn jart fin, electron micro-controller, 3D printed protective casing and a geophone

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 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.

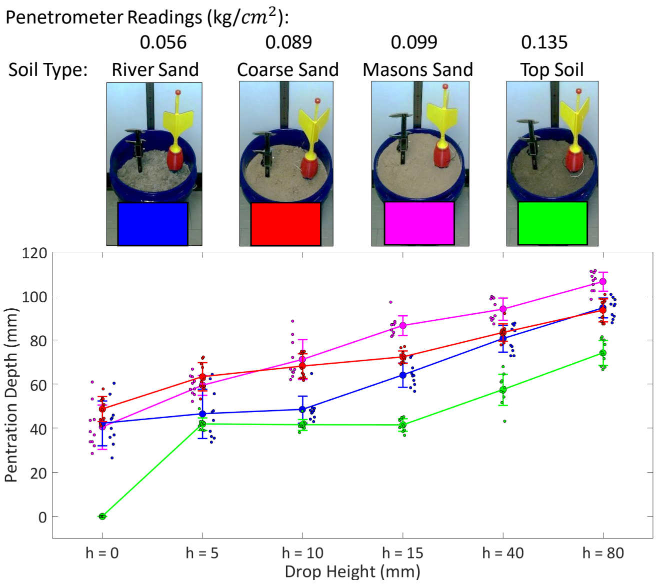

Fig. 4: Drop height vs. penetration depth in four soil types.

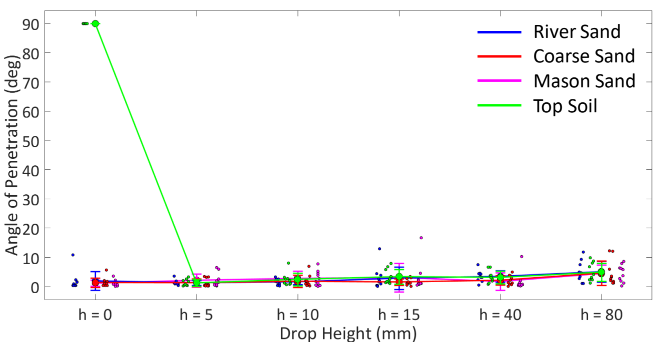

Fig. 5: Drop height vs. angle of deviation in four soil types.

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

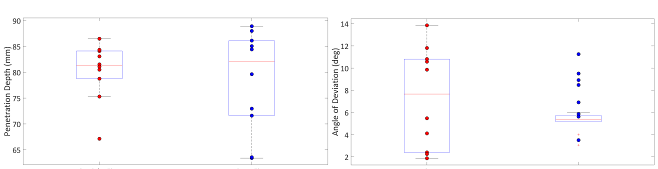

Fig. 7: Straight vs Bent fins comparing a.) penetration depth b.) angle of deviation. Experiment used a fixed drop height of 9.8 m.

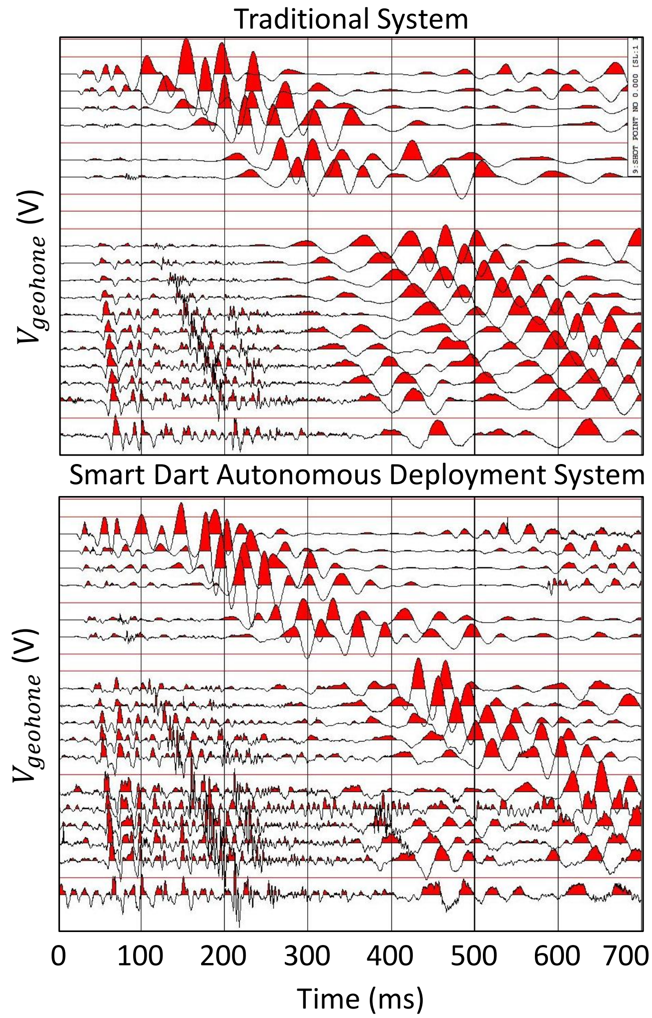

Fig. 8: Shot gather comparision of traditional geophones vs autonomously dropped smart dart sensors a.) Traditional b.) Smart darts

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

3) Exp 3: Deploying and Retrieving Hexapod

Exp 5: Retrieving Hexapod

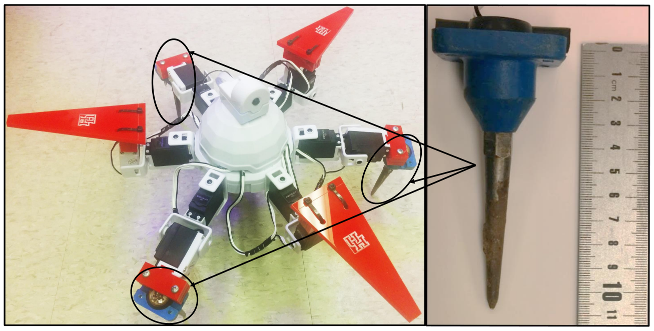

Fig. 9: The hexapod sensor is a six-legged mobile unit where three legs are replaced by geophones. It has the ability to sense seismic waves and store the data obtained.

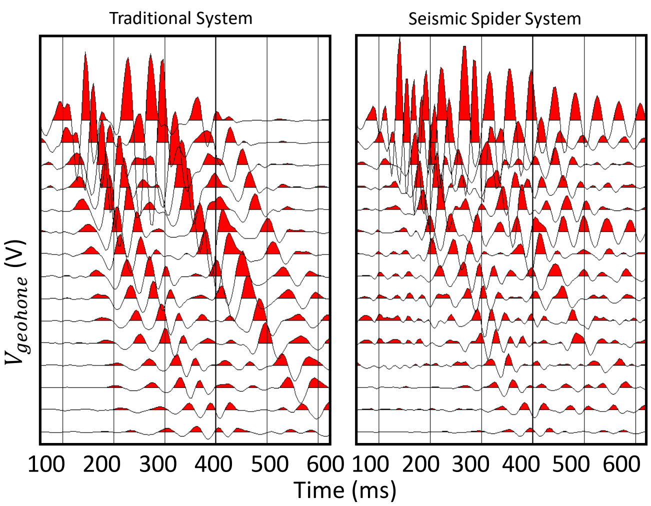

Fig. 10: Shot gather comparison of traditional geophones vs. hexapod sensor.

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

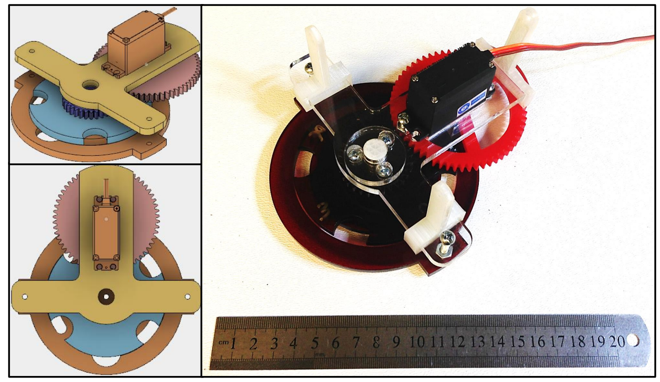

Fig. 11: Deployment system for dropping smart darts from the UAV. Max capacity 4.

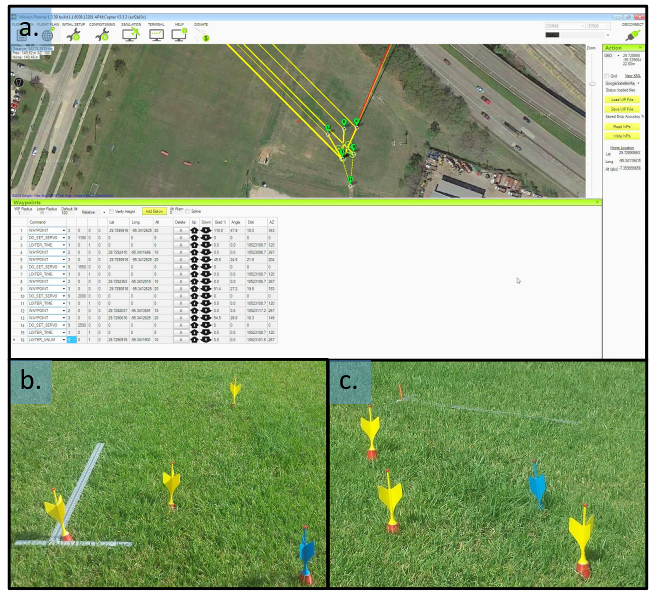

Fig. 12: a.) Flight plan of accuracy test b.)First set of dart with reference axes c.)Later Dart Sets

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 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

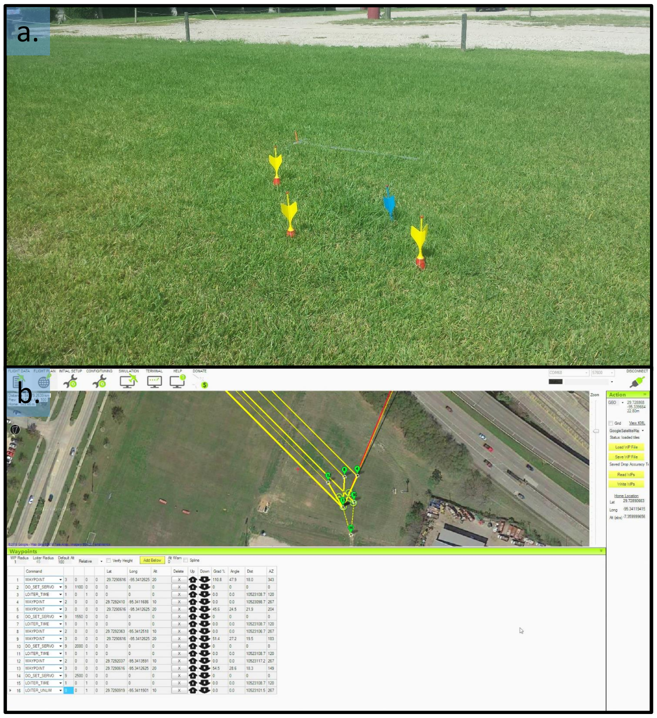

Fig. 13: a.) Smart darts deployed autonomously by the deployment unit (hexacopter) b.) Screen shot of flight plan for autonomous deployment

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.

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

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].

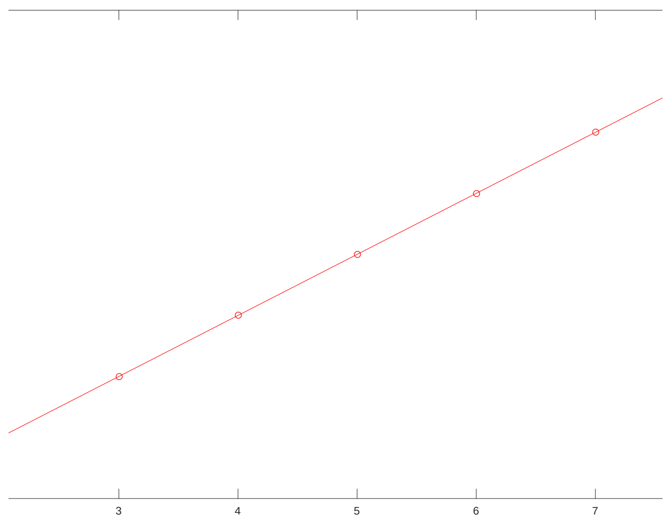

Fig. 14: Plot of pneumatic cannon firing angle vs ending angle

Fig. 15: Seismic dart pneumatic launcher with air compressor

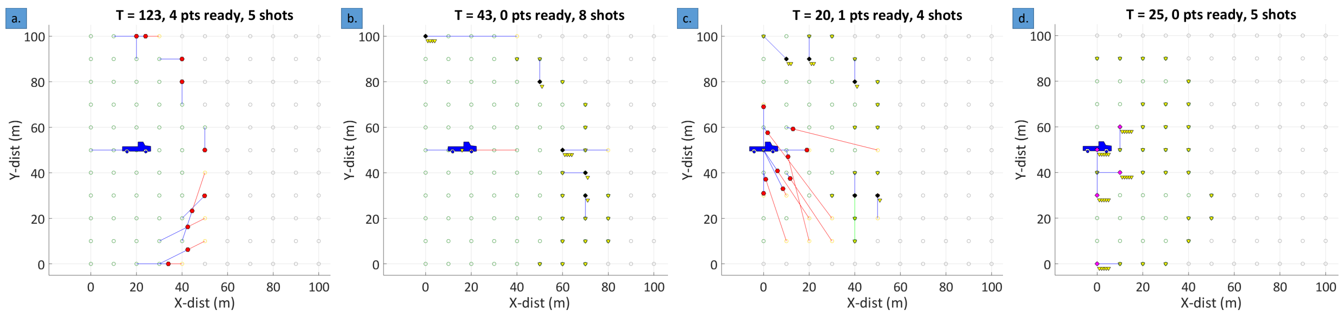

Fig. 17: Simulations were performed to estimate time take by different sensors a.) Only seismic spiders b.) Smart darts and deployment system c.) Heterogeneous System d.) Human workers

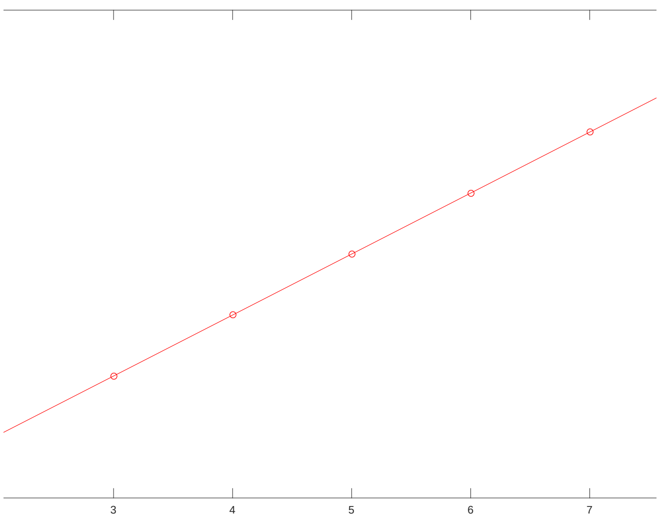

Fig. 16: Plot of pneumatic cannon firing angle vs ending angle

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

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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