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 [1], 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 [2], 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.

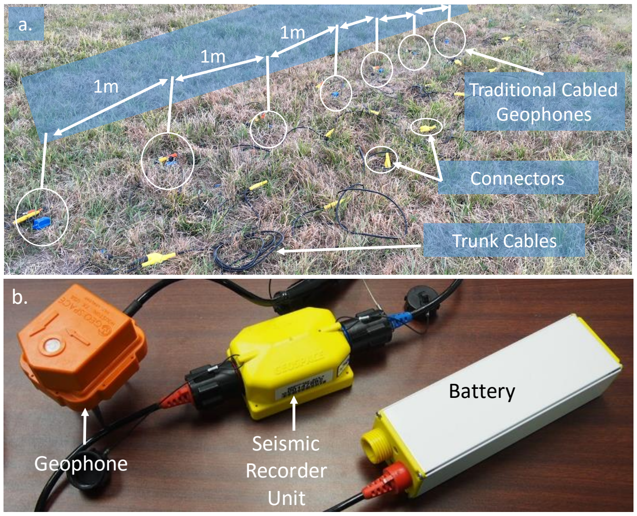

Fig. 2: Comparing state-of-the-art seismic survey sensors a.) Traditional cabled system, the geophones (sensors) are connected in series to the seismic recorder and battery. b.) Autonomous nodal systems, each geophone has a seismic recorder and a battery making each geophone "autonomous" from the other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

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

The geophones in [2] 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. Overview of Seismic Sensing Theory

During seismic surveys a source generates seismic 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 illustrates the components of current sensors.

For clarity, the following section discusses 1D waves. The full 3D equations can be found in many geophysics textbooks, for example [3]. Geophone sensors sense the vertical external displacement U caused by vibrational waves that propagate with a velocity c in the positive and negative x-directions. Typical seismic wave velocities are in the range $2-8$ km/s. These waves are represented by the 1D differential equation

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

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.

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

here F is the vibration force and ρ is density. This hyperbolic equation is challenging to solve because sharp features can reflect off boundaries. `Why do we have any of the previous equations? They would only be useful if we showed an equation on how they are inverted...`

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. Rugged terrain makes carrying and placing cable labor intensive and the local manual labor pool may be unskilled or expensive.

2) Autonomous Nodal Systems

Currently, *autonomous nodal systems* [4] 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 [5]. 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. Related Work

Seismic surveying is a large industry. The concept of using robots to place seismic sensors dates to the 1980s, when mobile robots placed seismic sensors on the moon [6]. Postel et al. proposed a mobile robot for terrestrial geophone placement [7]. Plans are underway for a swarm of seismic sensors for Mars exploration [8]. Additionally, [9] and [10] proposed marine robots for geophone deployment underwater. Other work focuses on data collection, using a UAV to wirelessly collect data from multiple sensors [11]. Our system consists of a multi-agent system approach designed to quickly and efficiently perform a survey.

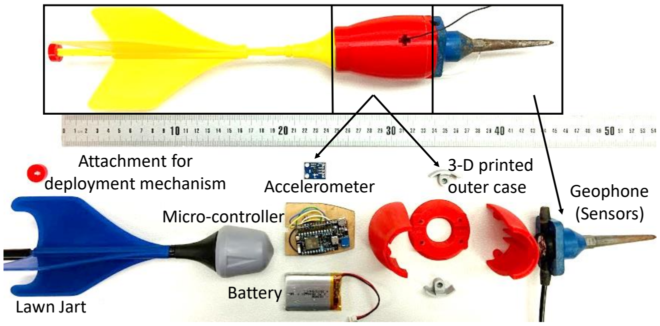

Fig. 3: Cross-section of the SmartDart sensor. It consists of a lawn Jart^{TM} fin, electron micro-controller, 3D printed protective casing and a geophone

C. Sensor networks

D. Multi-Robot Assignment

III. Smart Darts

A. Design

The SmartDart 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 (Electron 2G, particle.io) as shown in Fig. 3. The center of the chamber is slotted to fit a wooden plate holding an accelerometer that transmits data back to the user through the Photon. The centered accelerometer card allows placing the microcontroller and battery on opposite sides, centering the center of mass.

B. Experiments

The following sections compare SmartDart performance.

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 requires (1) pushing the spike deep into the soil to ensure good contact, and (2) aligning the sensors with the gravity vector. Each trial measured penetration depth and the angular error from vertical.

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 four soil types. Each trial was performed by holding the darts at the tip opposite to the spike in a vertical position, releasing them at varying heights into the buckets of soil. 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

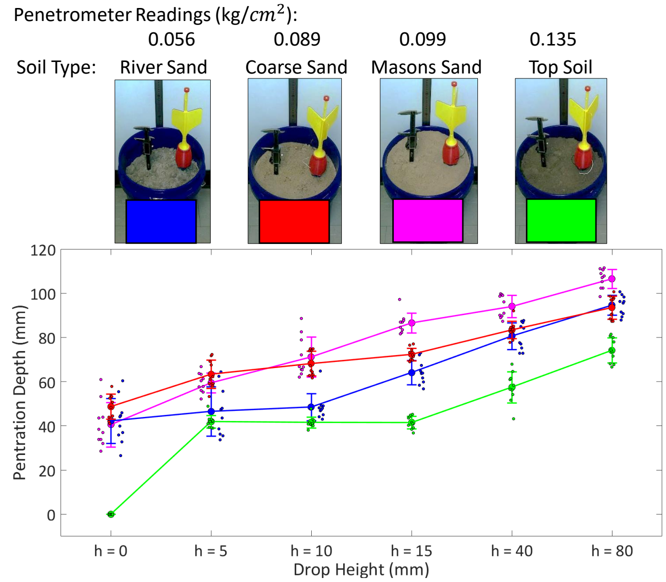

Fig. 4: Drop height vs. penetration depth in four soil types.

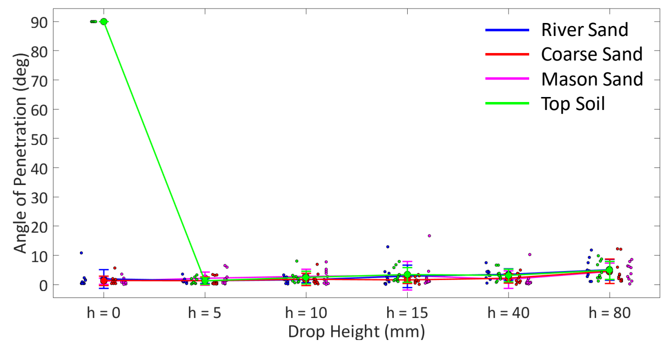

Fig. 5: Drop height vs. angle of deviation in four soil types.

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

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. 6 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

Traditional geophones are mounted in an insulated shock resistive enclosure on a spike. The spikes, varying in length, are inserted into the ground to ensure a firm coupling with

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

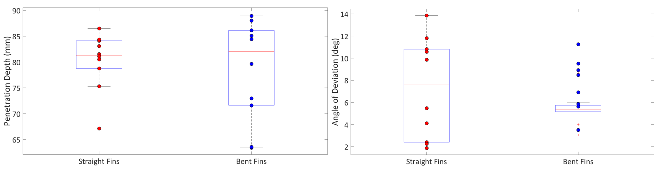

Fig. 7: Straight vs Bent fins comparing a.) penetration depth b.) angle of deviation. Experiment used a fixed drop height of 9.8 m.

the environment. The design of our Seismic Spider prevents full depth insertion of the three inch spikes.

To overcome the coupling issue we are using three geophones per station compared to the typical one. Our immediate goals are to compare amplitude and phase response to that of a standard single station.

A. Design

The Seismic Spider is built from the Six Hexapod kit designed by EZ Robots. Each of the six legs are powered by two 15 kg/cm lever servos. The peg legs were replace by three GS-20DM 14 Hz geophones from Geospace Technologies. The remaining three were designed to match the geophone dimensions and reflect UH school spirit.

Our initial plan to use three geophones require the spider to raise the three inactive legs while acquiring data. This lack of support caused excessive strain on the three servo motors responsible for holding the spider upright introducing unwanted vibration into the system. We found positioning the geophone legs at 20o to normal enhanced the stability and relieved the excessive stress on the servos. With each planted geophone angled inward superposition creates one vertical geophone. The three geophones were in series.

B. Experiments

1) Exp 1: Accuracy plot

Hexapod move to desired GPS location (plot accuracy)

2) Exp 2: Shot gather comparison

A line of twenty four geophones, GS-20DM 14 Hz, were laid out at one meter intervals with our inline source seven meters from the nearest geophone. Beginning from

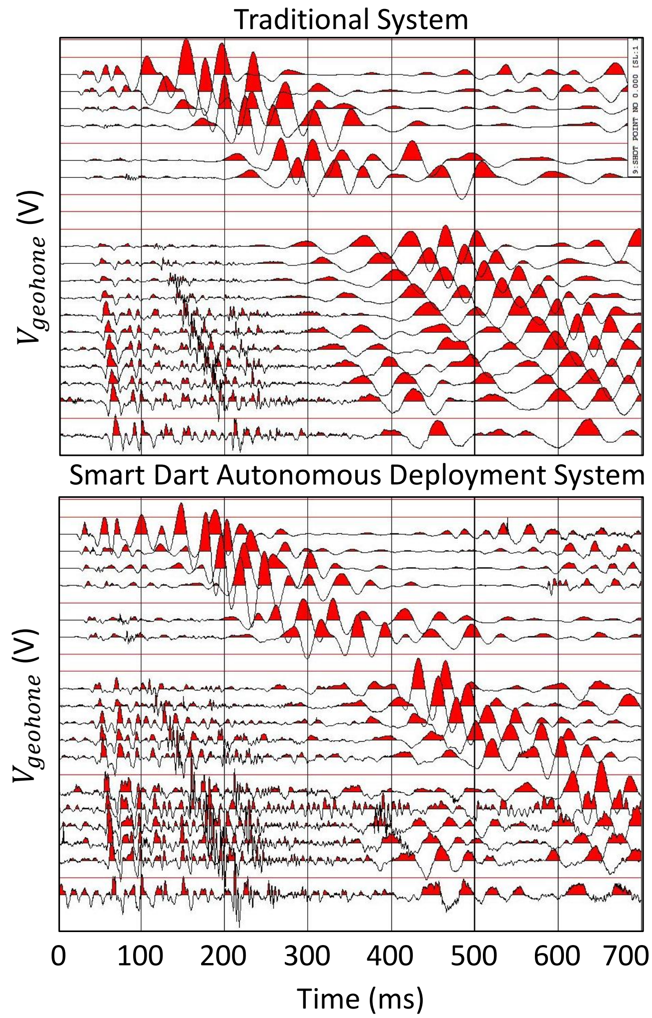

Fig. 8: Shot gather comparision of traditional geophones vs autonomously dropped smart dart sensors a.) Traditional b.) Smart darts

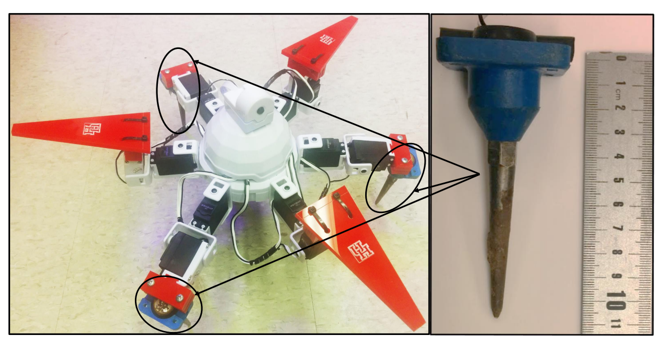

Fig. 9: The SeismicSpider is a six-legged mobile robot where three legs are replaced by geophones. It senses and records seismic data.

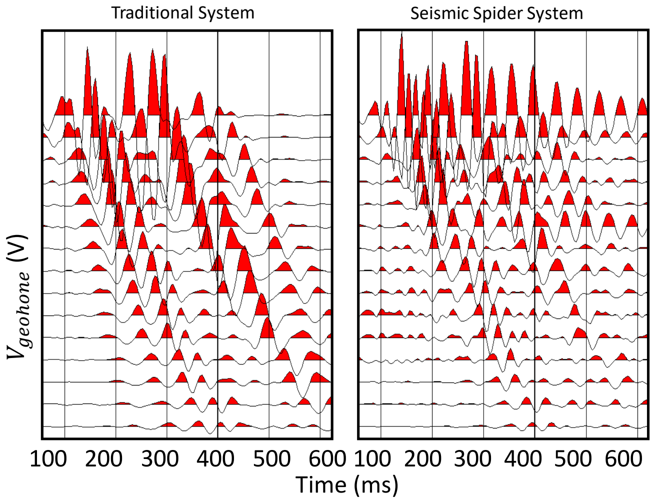

Fig. 10: Shot gather comparison of traditional geophones vs. hexapod sensor.

the farthest offset of 31 meters we manually aligned the Spider with the corresponding geophone, fired the source, then moved one meter ahead.

a) Results

Data from the shot gather comparison is shown in Fig. 10. We found a correlation, unmeasured, with the standard geophones and we more than compensated for loss of amplitude with three geophones, the response was 5 dB greater that the single geophone. The geophone wires proved insufficient to insulate against 60 Hz. Due to the small amount of usable data we were not able to gain meaningful results for phase analysis.

b) Future work

we must filter 60 Hz noise, compare adding geophones to all six legs, and design a larger seismic survey to ensure adequate data for phase analysis.

3) Exp 3: Deploying and Retrieving Hexapod

describe piloting the drone for retrieval. Need image

V. UAV and deployment unit

A. Design

The UAV is a custom-built

An: I want to know about the UAV.

The SmartDart deployment mechanism allows the UAV to carry four Smart Darts in a circular array, and release them when it reaches the desired GPS location, one at a time. The rear of the dart has a circular tip that locks into the deployment mechanism, and rests on a rectangular slot-path.

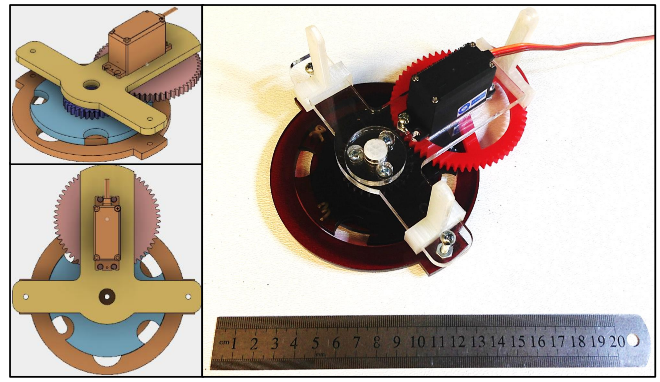

Fig. 11: Deployment system for dropping SmartDarts from the UAV. Pictured design holds 4 darts, but can be scaled according to the UAV's carrying capacity.

A servomotor rotates the dart tips through the rectangular slot-path, allowing darts to release from a circular opening.

B. Experiment

1) Autonomous drop demonstration and accuracy

The current drone can place the SmartDart within ± 1 m of the desired location. This range is within tolerances for seismic surveys because (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 within 10 cm accuracy the geophone location. Such accuracy can be obtained thorugh Real Time Kinematic GPS systems. Knowledge of the exact location allows corrections for jitter in signal arrival times due to placement inaccuracy.

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 darts, 4 darts in each set, were dropped on the same GPS waypoint. Between each drop, the UAV travelled to a nearby GPS waypoint to cancel out the flight controller's stable hover. This path is shown in Fig. 12a. The UAV returned to the launch platform to be reloaded and data was 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 1-m T-square was placed with the origin at the dart's drop point to establish the axes.

After the first set of data was been recorded, the darts were collected and reloaded on the UAV for the next deployment set. A rod was placed in the position of the first dart to keep reference as shown in Fig. 12c. The T-square was kept

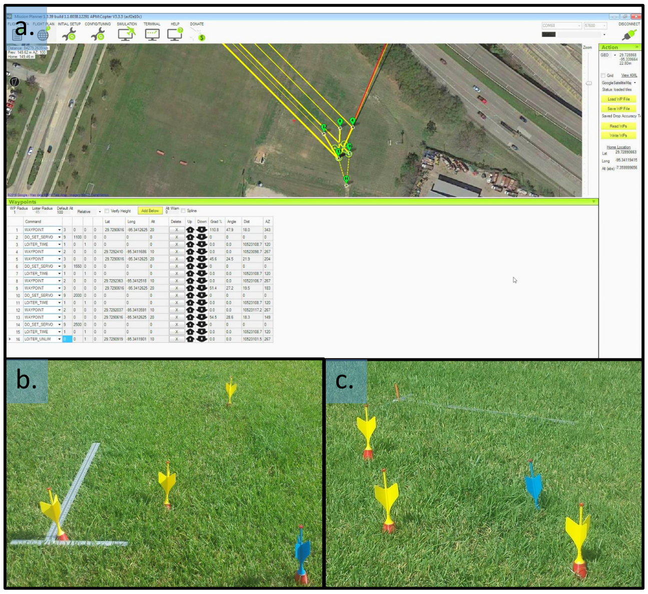

Fig. 12: a.) Flight plan of accuracy test b.) First set of dart with reference axes c.) Later Dart Sets

in place and mason twine was suspended to lengthen the reference axes. Future deployment were measured using the reference point and axes.

2) Height vs. penetration depth

Exp 5: Height vs. penetration depth

FAA rules require that UAVs fly below 400 feet (122 m). Our highest drop tests were from 20 m, and resulted in well-planted geophones on a grass field with density ???? insert penetrometer reading. Harder soils may require faster impact velocity, so this section examines possible impact velocities as a function of drop height. For ease of analysis we will assume the SmartDart has a constant coefficient of drag C_d and that the drag force is proportional to velocity squared and equal to $\frac{1}{2}v^2\rho A C_d$, where v is the velocity, A the cross-sectional area and ρ the density of air. The tests were performed near sea level, so $\rho \approx 1.225\text{kg/m}^3$ and the dart body is 0.06 m in diameter so $A = 0.028$ m^2. We will assume the dart C_d is between that of a streamlined body $C_d = 0.04$ and that of an arrow $C_d = 1.5$ [12], and choose that of a sphere $C_d = 0.47$. The terminal velocity is

$$v_T = \sqrt{\frac{2mg}{\rho A C_d}} \approx 59\text{m/s} \tag{4}$$

The velocity at impact is a function of the drop height h.

$$v_{impact} = v_T\sqrt{1 - e^{-\frac{\rho A C_d}{m}h}} \approx 59\sqrt{1 - e^{-0.008h}}\text{m/s} \tag{5}$$

With $C_d = 0.47$, our drop from 20m achieves only 38% the terminal velocity (19.0 m/s), and for $C_d = 0.04$ only 12% terminal velocity (19.7 m/s). This implies the SmartDart is suitable even for much harder soils than tested this far.

VI. Comparision

A. Ballistic Deployment

See Fig. 14.

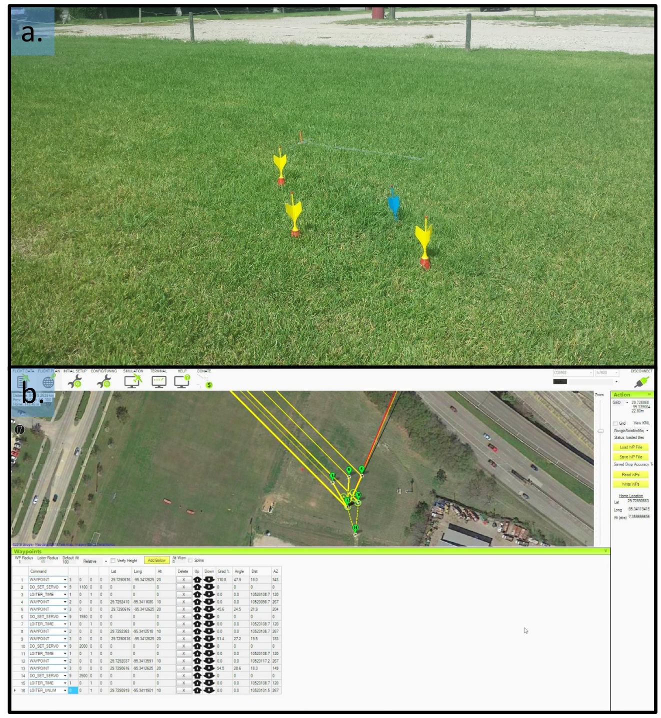

Fig. 13: a.) Smart darts deployed autonomously by the UAV b.) Screen shot of flight plan for autonomous deployment

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B. Simulation Studies

A scheduling system to compare time and costs for seismic surveys with varying numbers of UAVs, SeismicSpiders, SmartDarts, and Human manual laborers was coded in MATLAB, available at [13].

This tool allows us to examine engineering and logistic trade-offs quickly in simulation. For example, Fig. 17 assumes a fixed number of darts, and examines the finishing time with 5 to 500 UAVs. The time required decays asymptotically, but 140 drones requires only twice the amount of time required for 500 drones, indicating that 140 are sufficient for the task. Lines are also plotted for $5000, 1000 and 500$ total darts. In each case, substantial cost savings can be obtained by selecting the number of UAVs required to complete within 5% of the optimal time. The tool is useful for comparing the effectiveness of heterogeneous teams. Table Fig. 16 compares surveying a 1 km x 10 km strip of land with team (a) 5000 seismic spiders(hexapods), (b) 500 UAVs and 5000 smart darts, (c) 500 humans and 5000 sensors(geophones). Team (b) completed 6 times faster than team (c). In Fig. 18 we vary the percentage of individual type of sensor by keeping the total number of sensors a constant. The goal is to analyze ratios of different sensors to optimize cost and time. The number of drones employed for deploying smart darts is considered to be 10% of number of smart darts available. We observe that employing UAVs brings down the deployment time. This is obvious since

Fig. 14: A pneumatic launcher for SeismicDarts. Ballistic dart deployment has limited usefulness because the incident angle is equal to the firing angle.

S. No.	Type	Numbers of Units	Time Taken for Survey (s)	Velocity (m/s)
1.	Hexapods	5000 Hexapods	471	0.2
2.	UAVs, Smart Darts	500 UAVs, 5000 Smart Darts	1216	20
4.	Workers	500 Workers, 5000 Sensors	7371	1.38

Fig. 16: Comparison between different modes of deployment clearly indicate UAV deployment is highly efficient

UAVs move at 20 m/s whereas SeismicSpiders move at 0.2 m/s. The drastic difference in velocities makes the UAV deployment time efficient. The SeimicSpiders are a special type of sensor that could be used for special cases like hard surface sensing or regions where it is difficult for UAVs to access like forests.

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

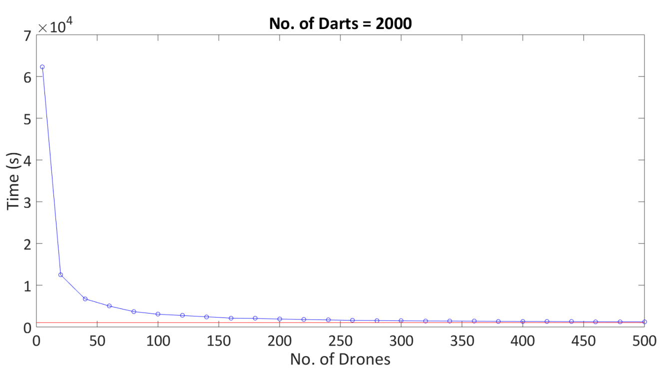

Fig. 17: This plot captures no. of drones vs time taken.

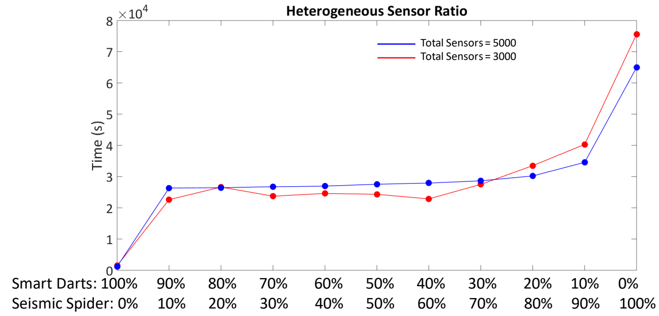

Fig. 18: This plot captures time with respect to different sensor ratios. The total number of sensors {5000,3000} were kept constant. UAVs were taken to be 10% of darts for this experiment.

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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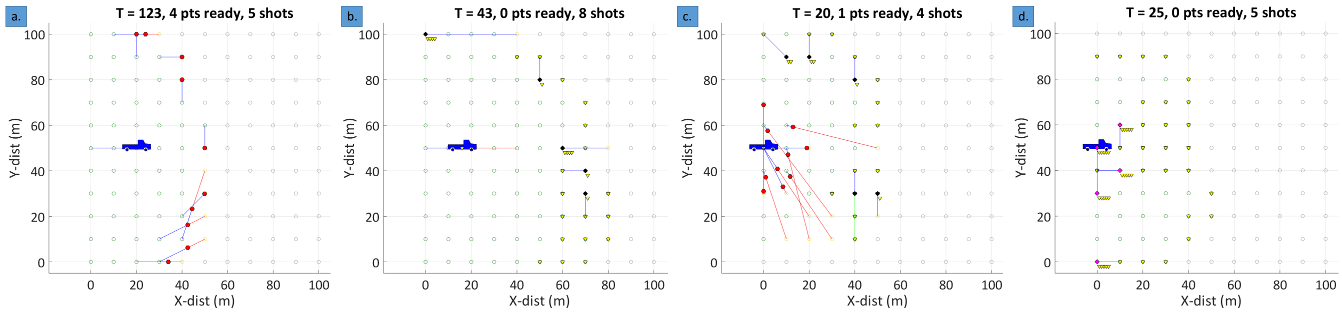

Fig. 15: Simulations were performed to estimate time take by different sensors a.) Only seismic spiders b.) Smart darts and deployment system c.) Heterogeneous System d.) Human workers

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