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 vibration readings. The goal of the surveying is often to locate subsurface resources. 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 UAVs to deploy mobile and immobile sensors. Detailed analysis and comparison with traditional surveying were conducted. The proposed system overcomes these drawbacks of traditional systems. Hardware experiments and simulations show promise for the effectiveness of automation in terms of cost and time. Autonomous aerial systems will have a substantial contribution to make in future seismic surveys.**

I. Introduction

Seismic surveying is a geophysical technique involving sensor data collection and signal processing. A major application of the method is in the search for subsurface resources. 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. Seismic surveying in remote locations has concomitant problems of inaccessibility, harsh conditions, and transportation of bulky cables and sensors. These factors increase the cost.

Nodal sensors, a relatively new development to seismic sensing, are autonomous units that do not require bulky cabling. They have an internal *seismic recorder*, a microcontroller that records seismic readings from a high-precision accelerometer. Because this technology does not require cabling, downtime and overall cost can be reduced. 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 SeismicDart and the SeismicSpider. The SeismicDart is a dart-shaped wireless sensor that is planted in the ground when dropped from a UAV. The SeismicSpider is a mobile hexapod with three 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 geoscience research [1], earthquake monitoring [2], defense operations [3], and wildlife monitoring [4], [5].

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

II. Overview and Related Work

This paper presents a *heterogeneous sensor system* for automatic sensor deployment. The goal is to overcome the drawbacks of manually deploying seismic sensors. In previous work [6], 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.

The geophones in [6] 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

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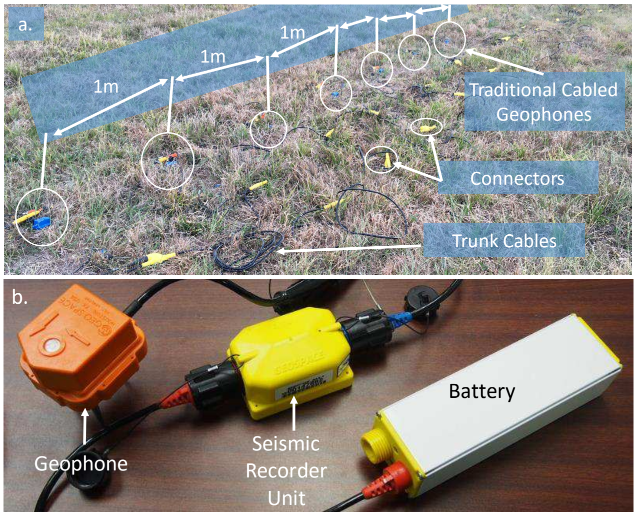

Fig. 2: Comparing state-of-the-art seismic survey sensors. a.) In traditional cabled system, the geophones are connected in series to the seismic recorder and battery. b.) In autonomous nodal systems, each geophone has its own seismic recorder and battery.

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.

1) Geophones

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 vertical. Misalignment reduces the signal proportional to the cosine of the error.

2) 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 stores the data on-board. This method of data acquisition requires many manual laborers and a substantial expenditure for transporting the cables. Rugged terrain makes carrying and placing cables labor intensive, and the local manual labor pool may be unskilled or expensive.

3) Autonomous Nodal Systems

Currently, *autonomous nodal systems* [7] are extensively used for conducting seismic data acquisition surveys. 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 in real time [8]. However, these systems still require manual laborers for planting the autonomous nodes at specific locations and deploying the large antennas necessary for wireless communication.

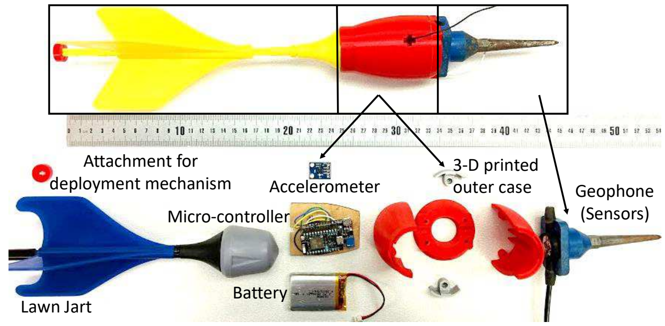

Fig. 3: Components of the SeismicDart sensor: a lawn Jart^{TM} fin, particle.io Photon^{TM} micro-controller, 3D printed protective casing, and a geophone

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 [9]. [10] proposed using a mobile robot for terrestrial geophone placement. Plans are underway for a swarm of seismic sensors for Mars exploration [11]. Additionally, [12] and [13] proposed marine robots for hydrophone deployment underwater. Other work focuses on data collection, using a UAV to wirelessly collect data from multiple sensors [14]. Autonomous sensor deployment and mobile wireless sensor networks have been extensively studied in [15], [16], [17]. Heterogeneous mobile robotic teams were used for mapping and tracking in [18]. Our multi-agent system approach is designed to quickly and efficiently perform a survey.

III. SeismicDarts

The SeismicDart 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 microcontroller (particle.io Photon^{TM}) as shown in Fig. 3. The center of the chamber is slotted to fit a wooden plate holding an accelerometer that transmits data wirelessly through the microcontroller. The centered accelerometer card allows placing the micro-controller and battery on opposite sides, balancing the dart. Designs and instructions to build a SeismicDart are available at [19].

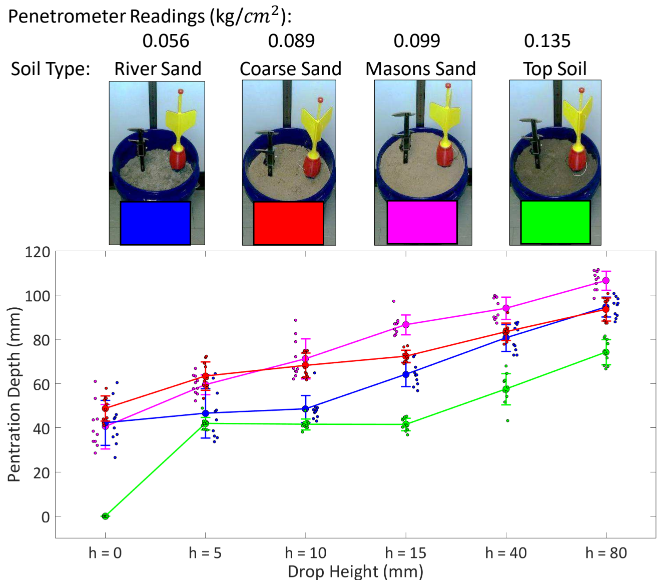

Fig. 4: Drop height vs. penetration depth in four soil types.

A. Experiments

The following sections compare SeismicDart 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 good contact with the soil, in a vertical position. To determine the minimum deployment height for good planting, each trial measured the penetration depth and angular deviation from vertical. This experiment compared drop tests as a function of soil type.

To determine how SeismicDarts 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 and releasing them at varying heights into 19 liter (5 gal.) buckets of soil. Penetration depth and angular deviation were measured. 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 angular deviation was recorded using the accelerometer inside the dart. The soil types were categorized by their compression strength, in kg/cm^3, measured using a soil pocket penetrometer (CertifiedMTP). Measurements for compression strength vary with small deviation in measurement location, so we repeated this measurement 10 times at 10 different locations in each soil type and took the average. These values for soil compression strength and a graph displaying heights vs. penetration depth are displayed in Fig. 4, and a graph of angular deviation is in Fig. 5. The experiment shows that increasing drop height increases penetration on all soils tested. Also, darts dropped in quiescent air remain vertical if they penetrate the soil.

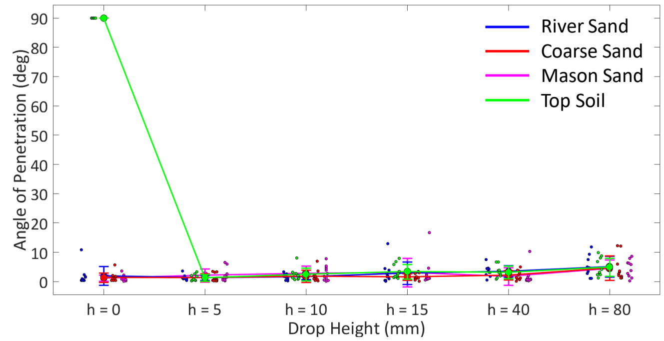

Fig. 5: Drop height vs. angle of deviation in four soil types.

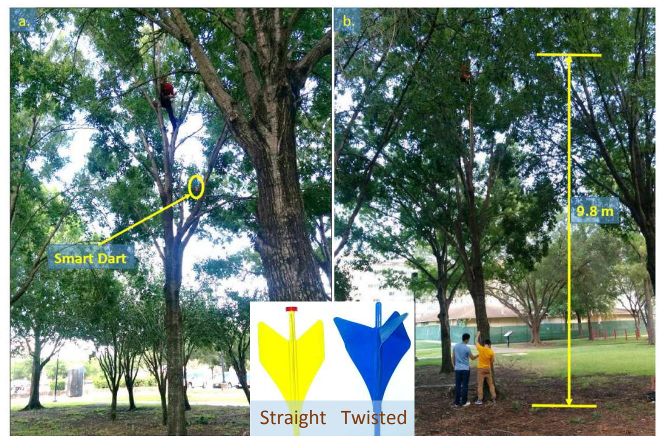

Fig. 6: Outdoor drop test comparing straight vs. twisted fins performance: a.) dropping a SeismicDart, b.) measuring drop height.

2) Straight vs. Twisted Fins

To determine the difference in performance between SeismicDarts with straight fins and twisted fins, 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 9.8 meters, dropping it into the soil, and recording the penetration depth and angular deviation. Holding the darts horizontally emphasized the angle-correcting behavior of the fins. The penetration depth and angular penetration were measured and recorded as in the previous experiment. A graph showing the values recorded for penetration depth and angular deviation in Fig. 7 reveals that SeismicDarts with twisted fins had less angular deviation, but also less penetration depth.

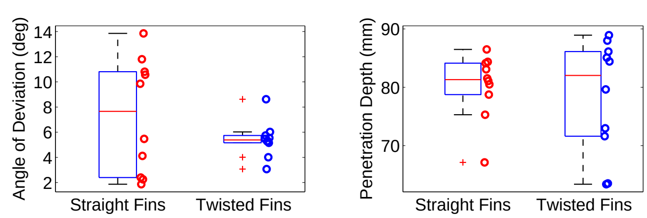

Fig. 7: Straight vs. twisted fins comparing a.) penetration depth b.) angle of deviation. Experiment used a fixed drop height of 9.8 m.

3) Shot gather comparison

Seismic explorations use thousands of geophones to conduct a seismic survey. This experiment compared the performance of a traditional cabled 24 geophone system with readings from SeismicDarts. The geophones were planted vertically into the ground, three meters apart from one another. We used a vibrating truck setup to generate the seismic wave. Only four functional SeismicDarts were built, so these four were dropped from the UAV, a seismic wave was generated and recorded, and the darts were redeployed to obtain all 24 readings.

Results of the seismic survey field test comparison between a 24 channel traditional cabled geophone system and the SeismicDarts are shown in Fig. 8. Both 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 are dependent on other devices for storage and data processing. To allow a fair comparison, the SeismicDart's ability to store sensed data was not used in this experiment. With the exception of SeismicDart reading #19, which may be due to poor terminal connections, the SeismicDart data corresponds well to data from a traditional setup.

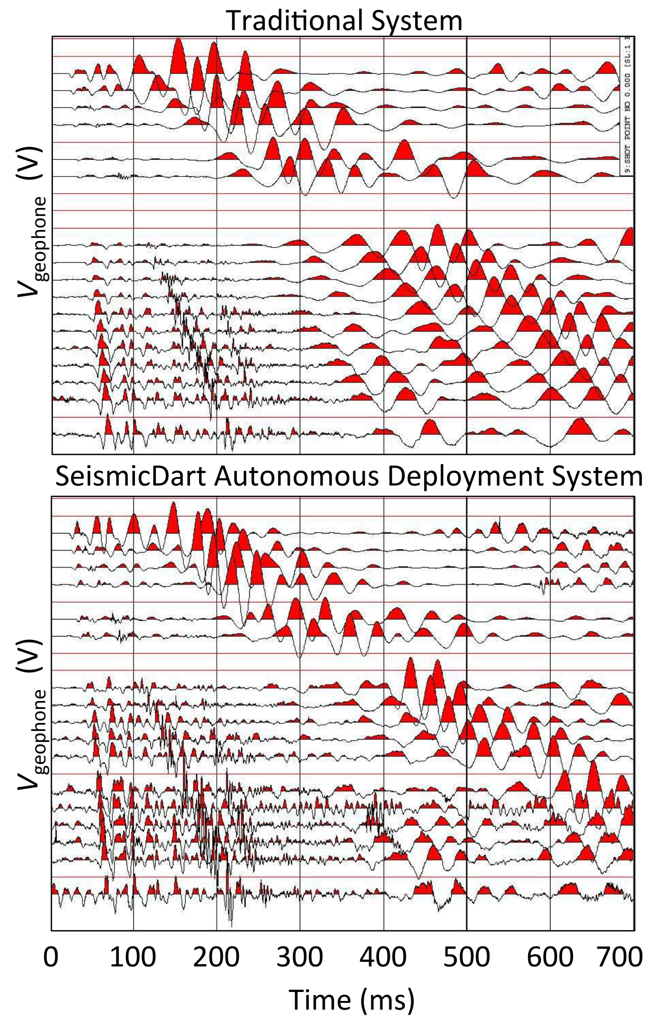

Fig. 8: Shot gather comparison of traditional geophones vs. autonomously dropped SeismicDart sensors.

B. Deploying and Retrieving SeismicDart

First the SeismicDarts are loaded onto to a UAV. Currently a maximum of four sensors can be dropped in a single flight. The flight plan communicated to the UAV provides a GPS waypoint for each SmartDart. The UAV flies to and drops a SmartDart at each waypoint, then returns home.

However, deployment is only part of the problem. Large surveys require moving and reusing sensors. Moreover, SmartDarts are more expensive than standard geophones. Currently retrieval is performed by manually piloting the UAV. Automating this process is left for future work. Fig. 9 shows a SeismicDart being retrieved and redeployed.

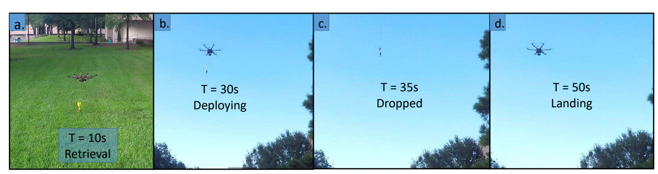

Fig. 9: SmartDart retrieval and redeployment See video attachment.

IV. SeismicSpider

The SeismicSpider 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. Three legs were replaced by three GS-20DM 14 Hz geophones from Geospace Technologies. The remaining three legs were designed to match the geophone dimensions.

Our initial plan to use three geophones required 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. Positioning the geophone legs at 20° to normal enhances stability and relieves the excessive stress on the servos. The three geophones were in series, so with each geophone leg angled inward, superposition replicates the signal from one vertical geophone.

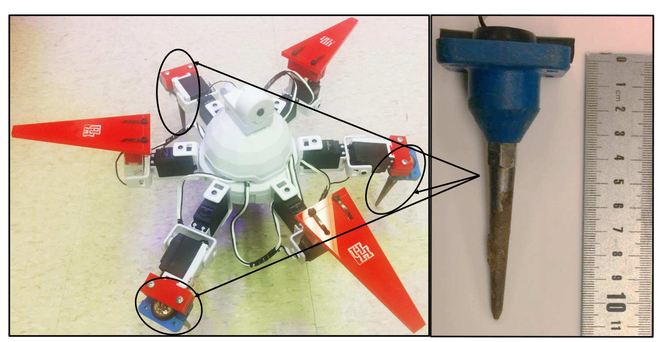

Fig. 10: The SeismicSpider is a six-legged mobile robot where three legs are replaced by geophones. It senses and records seismic data.

Traditional geophones are mounted in an insulated shock resistive enclosure on a spike. The spikes, varying in length,

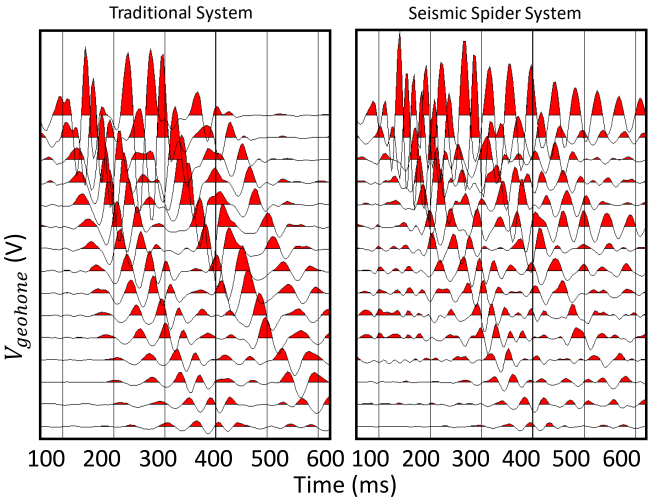

Fig. 11: Shot gather comparison of traditional geophones vs. SeismicSpider.

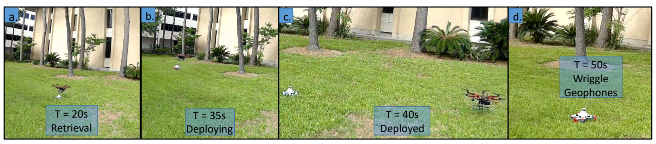

Fig. 12: SeismicSpider retrieval and redeployment. See video attachment.

are inserted into the ground to ensure a firm coupling with 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 were to compare amplitude response to that of a standard single station.

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

Data from the shot gather comparison is shown in Fig. 11. The response for three geophones in series was 5 dB greater than a single geophone. The geophone wires proved insufficient to insulate against 60 Hz noise. Hence the raw data from the traditional setup as well as the SeismicSpider was processed with a (3-50) band-pass filter. Finally, the SeismicSpider data was attenuated by -5dB to level the comparison.

B. Deploying and Retrieving Hexapod

The Seismic UAV's purpose is to deploy sensors at desired GPS waypoint locations. The SeismicSpider is a mobile robot, but it is substantially slower than the UAV. Fig. 12 shows the SeismicSpider being retrieved and then redeployed by a UAV. The UAV carrying the SeismicSpider was manually piloted to a specific location. The deployment mechanism included a hook controlled by a servo attached to the UAV. The UAV lowered to the ground, then the servo was triggered to unhook the SeismicSpider. The SeismicSpider was then wirelessly powered on. After walking to the goal sensing location, the SeismicSpider was controlled to shake its three non-sensing legs to plant its geophone legs into the ground. The SeismicSpider has an onboard GPS to navigate to a specific waypoint. Currently autonomous deployment of sensors is implemented, but the retrieval is piloted. Combining the mobility of the SeismicSpider with the speed of the UAV enables reaching locations inaccessible by air or impossible to penetrate by SmartDarts.

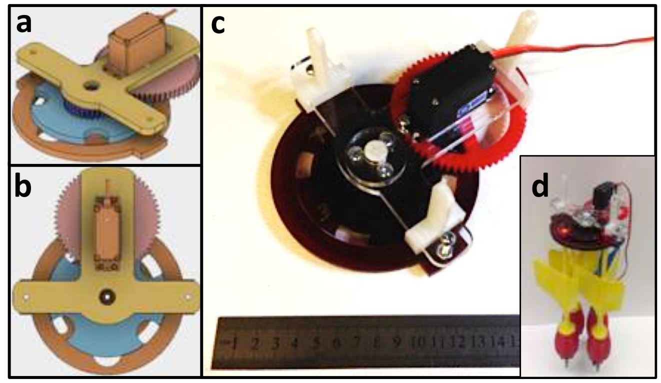

Fig. 13: Deployment system for dropping SeismicDarts from the UAV. Pictured design holds 4 darts, but can be scaled according to the UAV's carrying capacity.

V. UAV and deployment unit

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

The deployment mechanism allows the UAV to carry four SeismicDarts 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. A servomotor rotates the dart tips through the rectangular slot-path, allowing darts to release from a circular opening, as shown in Fig. 13.

A. Autonomous drop demonstration and accuracy

The current UAV can place the SeismicDart within ± 1 m of the desired location. This range is within tolerances for seismic surveys because: (1) often features (rocks, water, etc.) exist that require this amount of error from theoretically assigned locations, (2) some survey designs include a random placement component to improve noise cancellation.

The critical factor is to know within $\approx$10 cm accuracy the geophone location. Such accuracy can be obtained through Real Time Kinematic GPS systems. Knowledge of the exact location compensates for placement inaccuracy.

For the accuracy test, six sets of darts, four 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

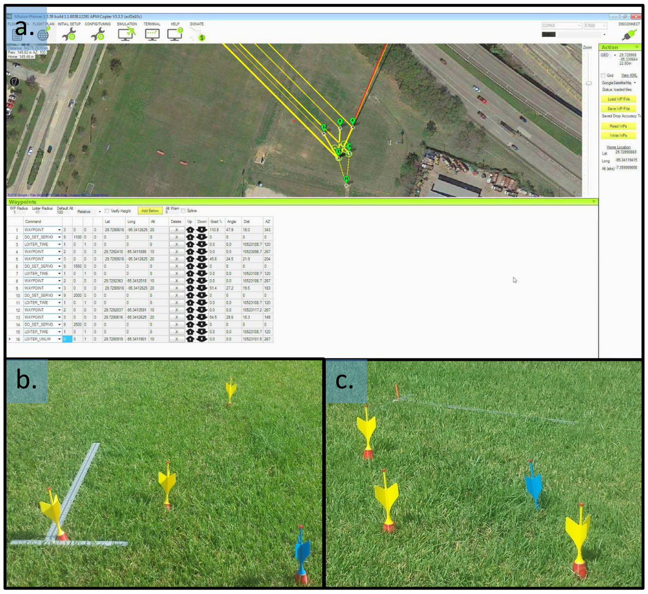

Fig. 14: a.) Flight plan of accuracy test. b.) First set of darts with reference axes. c.) Third dart set.

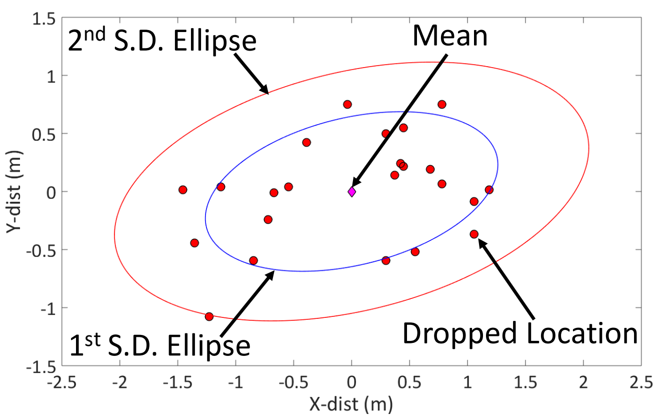

Fig. 15: Landing locations of 24 darts, each commanded to drop at the same GPS location.

Fig. 14a. The UAV then 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. 14b), hence the first data point was (0,0). A 1-m T-square was placed with the origin at the dart's drop point to establish reference axes.

After the first set of data was 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. 14c. The T-square was kept in place and mason twine was suspended to lengthen the reference axes. Future deployments were measured using the reference point and axes. Results are shown in Fig. 15.

B. 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 3.3 kg/cm^3. Harder soils may require faster impact velocity, so

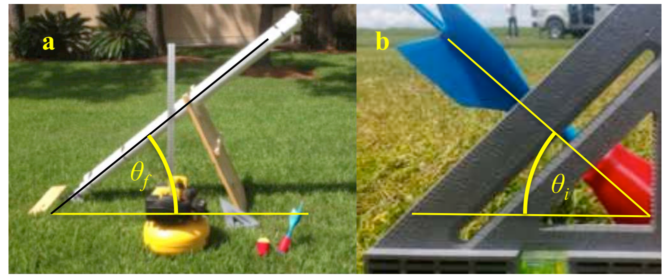

Fig. 16: A pneumatic launcher for SeismicDarts. Ballistic dart deployment has limited usefulness because the incident angle is equal to the firing angle.

this section examines possible impact velocities as a function of drop height. For ease of analysis we will assume the SeismicDart 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 $\rho \approx 1.225\text{kg/m}^3$. The dart body is 0.06 m in diameter so $A = 0.028\ \text{m}^2$. We will assume the dart C_d is between that of a streamlined body $C_d = 0.04$ and that of an arrow $C_d = 1.5$ [20], and choose that of a sphere $C_d = 0.47$. The terminal velocity is then

$$v_T = \sqrt{\frac{2mg}{\rho A C_d}} \approx 59\ \text{m/s}. \tag{1}$$

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

$$v_{impact} = v_T\sqrt{1 - e^{-\frac{\rho A C_d}{m}h}} \approx 59\sqrt{1 - e^{-0.008h}}\ \text{m/s} \tag{2}$$

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 SeismicDart is suitable even for much harder soils than tested thus far.

VI. Comparision

A. Ballistic Deployment

To compare an alternate deployment mechanism we built the pneumatic cannon shown in Fig. 16a. The pneumatic cannon is U-shaped, 2m in length, with a 0.1 m (4 inch) diameter pressure chamber and a 0.08 m (3 inch) diameter firing barrel, connected by an electronic valve (Rain Bird JTV/ASF 100). The cannon is aimed by changing the desired firing angle θ_f and azimuth angle, and filling the pressure chamber to the desired pressure. The reachable workspace is an annular ring whose radius r is a function of the firing angle and initial velocity v. Neglecting air resistance, this range is found by integration:

$$r = \frac{v^2}{g}\sin(2\theta_f) \tag{3}$$

Initial velocity is limited by the maximum pressure and size of the pressure chamber. The cannon used SCH 40 PVC, which is limited to a maximum pressure of 3 Mpa (450 psi).

We charged our system to 1 Mpa (150 psi), and achieved a range of $\approx$ 150 m. This is considerably smaller than the

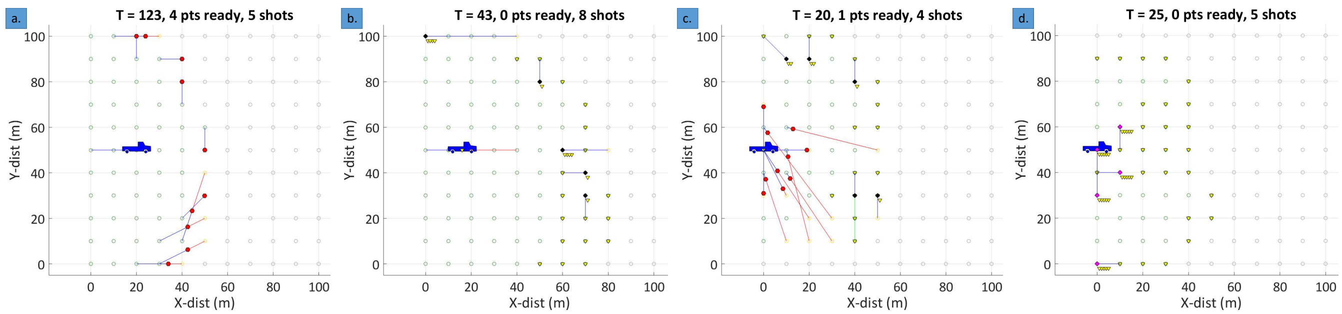

Fig. 17: Screen shots of simulations that were performed to estimate time take by different sensors surveying 100x100 m grid a.) Only SeismicSpiders b.) SeismicDarts and deployment system c.) Heterogeneous System d.) Human workers

Test	Type	Numbers of Units	Survey Time (s)	Velocity (m/s)
1.	SeismicSpiders	5000 SeismicSpiders	73,893	0.2
2.	UAVs, SeismicDarts	500 UAVs, 5000 SeismicDarts	1,216	20
3.	Workers	500 Workers, 5000 Sensors	7,371	1.38

TABLE I: Comparison of different deployment modes highlights the efficiency of UAV deployment.

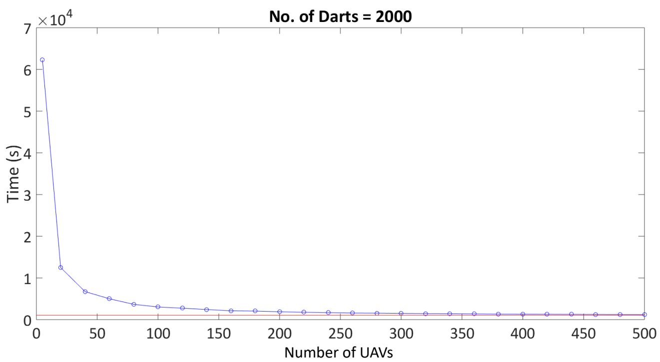

Fig. 18: Survey time for a 1km x 10 km region for different numbers of UAVs.

UAV's range, which when loaded can complete a roundtrip of ≈ 1.5 km.

A larger problem, illustrated in Fig. 16, is that angle of incidence θ_i is equal to the firing angle θ_f. Maximum range is achieved with $\theta_f = 45°$, but this angle of incidence reduces the geophone sensitivity to $\cos(\theta_f) \approx 0.7$. The placement accuracy of the cannon is lower than the UAV because a fired dart must fly over a longer distance than a dropped dart. Safety reasons also limit applications for a pneumatic launcher.

B. Simulation Studies

A scheduling system to compare time and costs for seismic surveys with varying numbers of UAVs, SeismicSpiders, SeismicDarts, and human laborers was coded in MATLAB, available at [21]. Frames from four different cases are shown in Fig. 17.

This tool allows us to examine engineering and logistic trade-offs quickly in simulation. For example, Fig. 18 assumes a fixed number of darts, and examines the finishing time with 5 to 500 UAVs. The time required decays asymptotically, but 140 UAVs requires only twice the amount

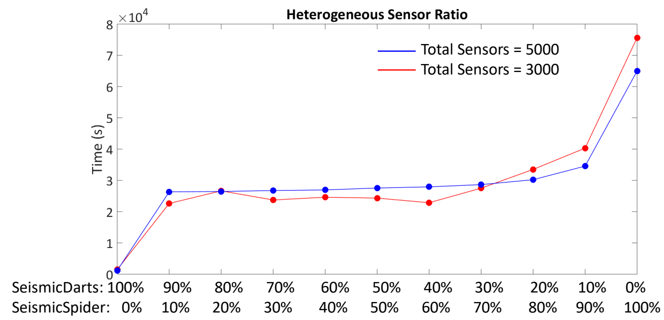

Fig. 19: Survey time for different sensor ratios. The total number of sensors {5000, 3000} were kept constant. Ten darts were provided for each UAV.

of time required for 500 UAVs, indicating that 140 UAVs are sufficient for the task. Substantial cost savings can be obtained by selecting the number of UAVs required to complete within a certain percentage greater than the optimal time.

The tool is useful for comparing the effectiveness of heterogeneous teams. Table I compares surveying a 1 km x 10 km strip of land with teams of (a) 5000 SeismicSpiders, (b) 500 UAVs and 5000 SeismicDarts, (c) 500 humans and 5000 geophones. Team (b) completed 6 times faster than team (c). Since SeismicSpiders are slower than UAVs and humans, and are expensive compared to the SeismicDarts, their use is limited to special occasions. The Seismic UAV has the ability to deploy the SeismicSpider at a given waypoint. This attribute was not considered in the simulation but would improve deployment speed of SeismicSpiders.

In Fig. 19, the total number of mobile agents are constant, but the percentage of UAVs and SeismicSpiders are varied. The goal is to analyze ratios of different sensors to optimize cost and time. 10 SeismicDarts were provided for each UAV. Increasing the percentage of UAVs lowers the deployment time. This is obvious since UAVs move at 20 m/s whereas SeismicSpiders move at 0.2 m/s. The difference in velocities makes UAV deployment time efficient. The SeismicSpiders are ideal for hard surface sensing or regions difficult for UAVs to access such as 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 of manual laborers. Three components were introduced, SeismicDarts, a mobile SeismicSpider, and a deployment unit. Field and laboratory hardware experiments demonstrated the efficacy of the robotic team compared to traditional techniques. The SeismicDart's output were comparable to well-planted geophones. For hard surfaces where the SeismicDart 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 UAVs.

Autonomous deployment was conducted using GPS, proving human involvement could be 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 optimized for cost, robustness, range, and speed.

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