ROBOTIC APPROACHES TO SEISMIC SURVEYING

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Abstract:

Due to the remoteness and harshness of some environments, integrating mobile robotics and seismic surveying to automate the process becomes very attractive. Because robotic applications to seismic surveying have been extremely limited, this paper represents a base for sparking novel techniques that can potentially be employed in any environment and potentially on other planets. It also presents a categorization of techniques involving robotic seismic automation. Traditional seismic methods are analyzed in terms of robotic automation possibilities and compared in terms of strengths, weaknesses, reliability, relative cost, and complexity. Futuristic seismic methods such as Hybrid Streamers and a Multi-Robot Seismic Surveying Team are also discussed in detail, along with simulation results from a multi-robot grid formation study.

Keywords: *robotic seismic, seismic automation, hybrid streamers, mobile robots, seismic surveying .*

1. Introduction

At the University of Kansas, the Center for Remote Sensing of Ice Sheets (CReSIS) [9] performs polar research to gather data and model ice sheets to better understand global warming and its possible effects. We have designed, built, and utilized mobile robots to autonomously traverse polar terrain in Greenland and Antarctica. The problem we are faced with is to increase efficiency of seismic data acquisition in these types of environments. Integration of automated technology into seismic methods can potentially improve and enhance the process.

One of the sensors used to perform this research is a seismic sensor, or geophone. These highly sensitive geophones detect vibrations in the ground which can be recorded as images. These images, for example, can show characteristics of the subsurface, detect cracking (fault) locations, as well as provide information on what is beneath the ice sheets. Although research focused on a polar environment, the presented techniques could be employed in and applied to any environment.

Research in the field of robotics has been focusing on accurate sensing and autonomy, mostly in normal environments such as factories and homes. Robotic applications involving seismic surveying in harsh environments have, however, been limited. Not only are navigation and actuation in severe environments difficult problems, autonomous tasks are even more challenging [28].

Another important aspect of integrating robotics and seismic surveying is that it limits human involvement, the most costly portion of a survey. For harsh environments, this becomes extremely important for safety reasons. Furthermore, robotics increases precision and introduces repeatability into a time-consuming and complex human task.

The focus of this paper involves robotic deployment and retrieval of seismic sensors. Comparing existing technology associated with seismic, mobile robotics, and robotic manipulation provided insight into what would be reliable under many conditions. Because seismic deployment is labor-intensive, expensive in terms of time and cost, and possibly dangerous, autonomously performing such tasks using mobile robots can be beneficial. Therefore, the goal is to combine robotics research with seismic systems to autonomously image the subsurface. A classification of robotic deployment and retrieval techniques for seismic sensors is presented in this paper, accompanied by related challenges and results from a multi-robot grid formation simulation study.

2. Background

This section provides an overview of seismic sensors, seismic surveying, polar mobility, and our experience with autonomous polar robots. Integration of these efforts is the focus of the remainder of the paper.

2.1. Seismic Sensors and Surveying

Seismic sensors, also known as geophones, are extremely sensitive devices which transfer vibration waves as a series of analog signals, based on the composition of the material beneath the surface and the travel times of the measured seismic waves. They are activated by a seismic source, which can range from striking the ground to a very large explosion. The source sends elastic vibration energy down into and through the subsurface so as to eventually reflect and refract back after interaction with the internal layers. Based on the travel times, wave velocities, and received signals from a series of geophones, seismologists can digitize, filter, and analyze the results to learn such facts as water table depth, fault location, and rock layer boundaries.

When attempting to reconstruct the paths that the waves traveled, both refracted and reflected paths can provide structural information of the subsurface [24]. Refracted paths represent those that are principally horizontal, such as traveling between two rock layers. Reflected paths travel vertically and involve waves traveling initially downward that are reflected back to the surface by rock layer interaction. The physical properties of the rocks and layers affect travel times of seismic waves. These travel times, along with the waveform and spectra, are then used to deduce information about the subsurface and internal layering.

Various styles and models of seismic sensors exist for many applications on land, snow, and at sea. Most models employ a coil hanging from a spring in a magnetic field. When the case and spike are moved, the mass induces small currents into the coil as it moves about in the magnetic field. A geophone element is what contains this technology, which is then placed in a case and attached to a spike to plant into the surface.

Primarily used for oil and gas exploration, seismic sensors can be utilized to determine subsurface composition at many scales. They are also available at several frequencies for differing situations, so as to capture lower or higher frequencies. Generally, the higher the frequency, the more expensive the unit becomes due to required sensitivity. A single geophone and linear array of deployed geophones are shown in Figure 1.

Deployment of geophones translates into how each is inserted into the ground (or alternatively, rests on the surface). During manual deployments involving tens or hundreds of geophones, each is typically stepped on or hand-pressed into the ground. If necessary, holes are dug prior to deployment to create a shelter for the sensor to record its data. Instruments may rest on the surface, rather than being inserted or buried, if the surface is hard.

Many factors affect deployment and the resulting quality of recorded data. The most important characteristic a geophone must exhibit when deployed is how well it is coupled with the ground. Coupling directly affects the data quality and frequencies that can be recorded. For desired coupling, the geophone spike must be tightly surrounded by the ground or snow and, in general, must be accurately deployed in all directions to acquire reliable data.

Seismic arrays can be formed to acquire a map of the subsurface, allowing detailed imaging at many resolutions and depths. Higher frequencies and close (sub-meter to tens of meters) spacing results in a highly detailed, shallow image of the subsurface. Deeper imaging requires sparse deployment and long distances from a powerful source, with spacing ranging from hundreds to thousands of meters. Furthermore, high frequency acquisition translates into more accurate images. In order to be reliable, geophones must be arranged in a centimeter-level precision grid of equal spacing while being oriented no more than 10° from the Earth's gravitational vertical. Achieving this level of precision requires tedious detail that can be cumbersome for a human, but also remains an extremely difficult task for mobile robots to perform.

If geophones are positioned in a straight line, a seismic survey will result in a two-dimensional (2D) image of the subsurface. Similarly, if the geophones are aligned in a square or rectangular grid pattern, a three-dimensional (3D) view of subsurface characteristics can result. A fourth dimension, namely time, can be introduced to image movement of the subsurface and flow of materials.

2.2. Mobility and the MARVIN II polar rover

Applications for automation have increased over the years. Robots have been used for planetary exploration, homeland defense, and surveillance operations. Environments can range from indoors (factory, home, or museum) to outdoors (deserts and remote locations, such as polar regions). The main application for this work is for a polar environment, where robots typically employ tracks for reliable mobility. Although wheels are the most common form of locomotion, they perform poorly over uneven terrain. Traction can also be an issue on predominantly ice or snow surfaces as wheels offer less contact surface area. Unless the wheels can pivot, obstacles with height of more than the radius of the robot's wheels can cause difficulty. They are, however, mechanically simple and easy to construct. Tracks represent a more complex and heavier mobility option, but are inherently less susceptible to environmental hazards and can negotiate larger obstacles. The ability to travel on snow and ice makes this the desired option for polar travel, as they exhibit a larger contact surface area with the ground. Tracks are, however, inefficient due to friction during turning and slippage within the tracks themselves.

The MARVIN II autonomous polar robot at CReSIS is a fully-tracked, automated All-Terrain Vehicle (ATV) that was built for the purpose of towing radar sleds and gathering data in polar environments. Autonomous navigation is performed using a high-precision GPS, with which it attempts to drive as straight as possible between a series of waypoints. The path precision of this robot is on the meter level, but can achieve decimeter accuracy for data after post-processing [3]. MARVIN II is mentioned in later sections as the main robot for certain robotic approaches to seismic surveying. Figure 2 shows the second-generation MARVIN II polar robot in Antarctica in 2006, and Table 1 lists platform specifications. It has been successfully deployed to support radar experiments in Antarctica, as well as long-term survival research for polar environments [2]. Figures 3 and 4 show the robot involved in towed radar experiments in Antarctica during the 2005-2006 field season.

Fig. 1. Conventional spiked geophone (left) and several deployed by inserting the spikes into the surface (right).

Fig. 2. The MARVIN II polar robot in Antarctica in 2006, used to autonomously gather radar data of ice sheets.

3. Related work

Very little work involving robotic deployment and retrieval of seismic sensors has been done to date. However, work done in regular environments can provide helpful information. As stated in [19], the future of seismic surveying on land is the elimination of cables. By doing this, surveying becomes more cost-effective and efficient. Seismic networks can also be of less weight and easily scalable in terms of network size, structure, and shape. By increasing overall productivity and abilities of a network, data acquisition will improve in the long run. The following related works have high correlation with the research presented in this paper.

The University of Kansas Geology Department recently developed an "autojuggie" [29] capable of planting 72 geophones in 2 seconds using a hydraulic press and structured array system. Several variations of the autojuggie have also been developed and field-tested [27]. These variations include automated deployment using farm equipment and deployment of closely-spaced lines of seismic sensors for ultra-shallow imaging. Structures were built to simultaneously press all sensors into the ground, and simultaneously retrieve all geophones when finished. Care was also taken to try to reduce crosstalk between sensors through the deployment structures. These approaches are still human-operated in that they use existing farm equipment as a means for deployment and retrieval. Scalability and robustness of this approach are limited.

Land streamers are a method inherited from the marine seismic community, which deploy a series of geophones by dragging them along the surface. Acquisition takes place when stopped, where all geophones typically rest on metal plates rather than being physically inserted into the ground. This increases deployment efficiency by reducing the time required for insertion and orientation of the sensors, as well as reducing transportation time from one site to another. In [26], multiple land streamers were pulled alongside each other at the same time using an ATV. Individual land streamers were spaced equidistant from one another on a towing structure so as to create a wider 2D array. Results were acceptable for relaxed seismic requirements, but would not be applicable under higher frequency situations. Other efforts have also been published [15],[21],[25] that employed single streamers in a polar setting, or specifically designed for shallow data acquisition [11],[12]. Survey requirements and weather conditions dictated the geophone spacing, streamer length, and materials used to construct the streamers. Several streamer designs have been attempted in these works, ranging from the 1970's to the present. The Kansas Geological Survey made their land streamer more rugged by encasing it and all wiring in a fire hose [20].

NASA, working with Georgia Tech and Metrica, Inc., developed an Extra-Vehicular Activity Robotic Assistant [7] capable of being handed a geophone and inserting it into soil using a seven degree-of-freedom manipulator and a three-fingered gripper [22]. The 4-wheeled mobile robot could not perform the full deployment task and was not made to retrieve the planted geophones. The main purpose of this robot was to assist activity-suited humans in the field by performing some tasks on its own. A trailer containing the geophones was pulled so the human could hand them to the robot or store other various supplies.

Table 1. MARVIN II Platform Specifications.

Dimensions (LxWxH)	2.4 m x 1.6 m x 1.8 m
Mobility	Tracks (1600 in² ground contact)
Track Width	394 mm (15.5 in)
Engine	34 HP Diesel (950 cc, 3-cylinder)
Tank Size	10 gallons (4-8 hours runtime)
Transmission	Hydrostatic
Ground Clearance	230 mm (9 in)
Weight	717 kg (1580 lb)
Hauling Payload	454 kg (1000 lb)
Towing Capacity	454 kg (1000 lb)

Fig. 3. MARVIN II polar robot preparing for a bi-static radar experiment.

For agricultural applications, robotic pickers, planters, row croppers, and harvesters have been incorporated into existing farm equipment to increase autonomy and control. Vision, size recognition, and color comparisons are being incorporated for better accuracy. Other robotic agriculture applications and designs are outlined in [13], [14]. As seismic sensors can be distributed like a sensor network, the field of wireless sensor networks [4],[5] will play a pivotal role in the future of wireless seismic.

4. Robotic approaches to seismic surveying

Many possible mechanisms exist for deployment and retrieval of seismic sensors [16],[17]. Automating the process makes detailed imaging much more reliable. Five categories of robotic approaches were analyzed in terms of cost, complexity, advantages, and disadvantages. The last two categories have not yet been attempted, and represent promising future methods for seismic surveying.

1. Individual Deployment
2. Array Deployment
3. Land Streamers
4. Hybrid Streamers
5. Multi-Robot Seismic Surveying Team

4.1. Individual Deployment

Individual deployment covers those methods that deploy and retrieve a single geophone at a time. This mechanism could be a robotic arm, crane-like apparatus, air-powered device, planter, or any other form of pick-and-place device. In many planting, weeding, and picking projects, robotic manipulators are utilized to help automate the process. This type of mechanism is responsible for pressing into, orienting, and pulling from the ground all seismic sensors and placing them in a transport area, charging station, or organized rack. Size, shape, and weight influence the overall design of platform(s) performing the task. Issues with this category involve orientation, positioning, and weather.

Fig. 4. CReSIS MARVIN II polar robot turning while pulling a radar apparatus.

Autonomously dealing with and keeping track of the tangling maze of seismic cable also represents a formidable challenge. A positive aspect of this approach is the millimeter repeatability and precision that manipulators offer. However, finding and retrieving geophones, manipulator payload, required pushing power, and gripping the geophone are all major difficulties inherent to this approach.

4.2. Array Deployment

Array deployment involves an array to deploy and retrieve a set of geophones, their cables, and all necessary storage equipment. Seismic sensors would be pre-set into the array, taken to the field location, and simultaneously (e.g., hydraulically) pressed into the ground at equal spacing, tilt, and elevation. When ready for retrieval, the structure is raised to remove the sensors from the ground. Multiple arrays could be pieced together to record larger areas. The design could also permit variable sensor spacing to perform different resolution imaging. Geophone spacing, orientation, and deployment depth are therefore controlled for the entire seismic array. Scalability in terms of size and imaging resolution is lacking due to being pre-built, however, and this approach is also still wired.

4.3. Land Streamers

The idea of land streamers came from marine seismic surveying, which involves constantly towing marine streamers under water with use of pulse guns for the sound source. Land streamers are a non-insertion seismic method where geophones are wired in series and towed on the surface to acquire seismic data. When the recording location is reached, the towing vehicle stops so that seismic acquisition can take place. One or more of these streamers can be towed in parallel to cover larger areas and perform 2D or 3D imaging.

Autonomous seismic acquisition can then be accomplished with, for example, the MARVIN II robot. The Webots [10] simulation environment was used to test GPS waypoint navigation, driving, and turning algorithms, whereas MSC visualNastran [23] was employed to simulate pulling and drag abilities of our autonomous rovers. Figure 5 shows a MSC visualNastran simulation involving three streamers, where each box represents an enclosed geophone.

This mechanism could extend to cover a long distance behind the rover as well as widen coverage width by using multiple streamers. An attractive aspect of this category is the ability to choose and change spacing of sensors within and between streamer lines. Other advantages of this approach are its ease of transport, efficiency, simplicity, and no need for geophone insertion. The main advantage to these types of systems is speed and the amount of seismic data that can be recorded with fewer personnel. The unattractive characteristic of this approach is its lower coupling. This may cause the geophones to miss higher frequencies, resulting in less detailed seismic images. Some research has shown that, in some environments, performance between conventional geophones and land streamers are very similar.

4.4. Hybrid Streamers

It has been proposed that a hybrid combination of land streamers with increased coupling would be a good alternative [16]. There are several design options to increase hybrid streamer coupling:

- Employ a trenching or plowing attachment to prepare the ground to drag the streamers below the surface for wind protection and to rest flat for orientation purposes;
- Add weight to each streamer node;
- Change plate size and/or geometry;
- Increase the surface area the plates have with the ground;
- Heat streamer plates for snowy/polar environments so the melt can refreeze to ice, giving a more rigid surface contact for the plates; and
- Drill the geophone into the ground like a threaded screw.

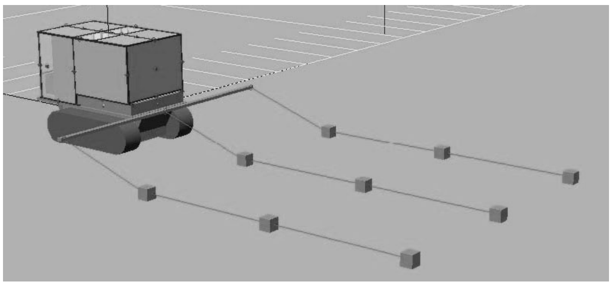


Fig. 5. Simulation image of an autonomous robot towing a three-streamer array, used for studying towing of streamers and how turning affects strain of the towing structure and travel of the streamer components.

Accordingly, a furrowing, plowing, or trenching apparatus could be attached to a mobile robot. The robot would power all equipment, have seismographs onboard for seismic data conversion and storage, and have a data cable which would act as both the data transmission and communication medium for the entire system.

The simulation images in Figure 6 illustrate several variations and configurations that could be utilized. One or more robots could be used and each could tow one or more parallel streamer lines. A single robot can tow a single hybrid streamer, or multiple robots can tow several parallel hybrid streamers and work together to image larger areas. The advantages of such an approach are better coupling, faster travel, and the potential to collect much more data with far fewer personnel involved. Complex coordination, communication, and node collisions are essentially avoided and there is no added attachment/detachment complexity for the streamer to the robot. Disadvantages to this approach are a single point of failure and overcoming coupling issues. Hybrid streamers represent a new seismic technique that has not yet been fully designed or attempted in modern surveying. CReSIS is in the process of designing and implementing these hybrid techniques [8] for polar deployment.

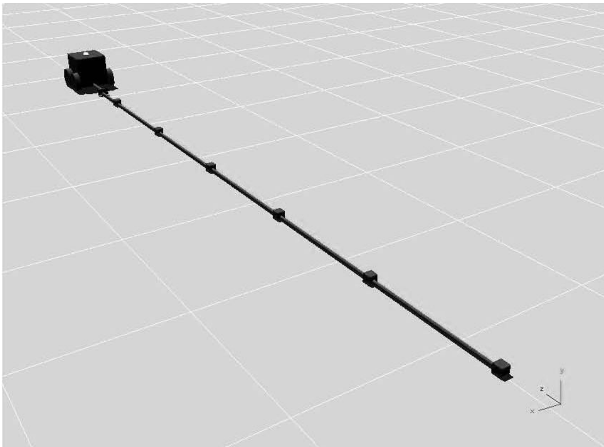
4.5. Multi-Robot seismic surveying team

Based on the demonstrated success of multi-robot systems (distributed robotics) [1],[6], we have proposed the use of a multi-robot seismic surveying team. The multi-robot seismic surveying approach involves a team of several autonomous, mobile robots that are smaller in size to deploy geophones and traverse the environment. They work together to precisely align into a seismic grid pattern. Each robot represents a mobile node that deploys and retrieves its own geophone. Power is provided by onboard sources, where each robot contains the necessary digitizing, storage, and communication hardware for seismic acquisition.

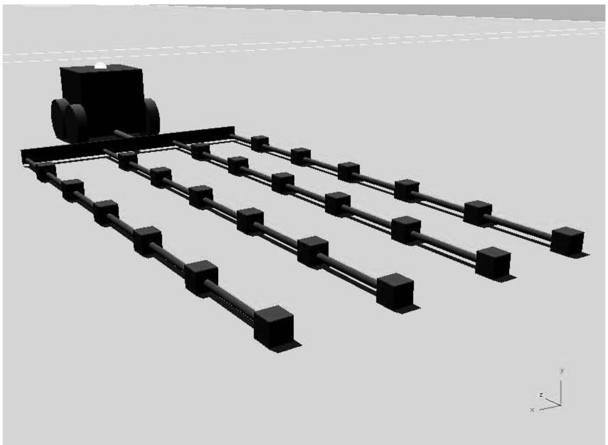
A mobile robot can inject into or place a geophone onto the ground while protecting the deployed sensors from the wind and weather using an environmental enclosure. Team size can be relatively small, such as a 25-robot team forming a 5x5 seismic grid, or extremely large, consisting of potentially hundreds of robots forming grids of any size, shape, and spacing for different seismic resolution applications. There are various ways that the team could move into position. Robots could move one at a time in a certain fashion, by rows or columns, or dynamically align while all moving at once. Positioning one robot at a time takes longer, but could help increase accuracy and reduce collisions [18]. Dynamically forming the seismic grid would take less time and would likely be a more flexible solution, but would suffer from inherently being less precise.

Figure 7 demonstrates that a team of 25 mobile robots could be transported to a location on a trailer by a larger robot. Once there, the team could get off the trailer and begin forming the desired shape at the desired spacing. For example, Figure 8 illustrates a shape formation scenario in simulation. The robots coordinate which GPS positions they travel to based on a desired grid shape and spacing, as provided by the main robot.

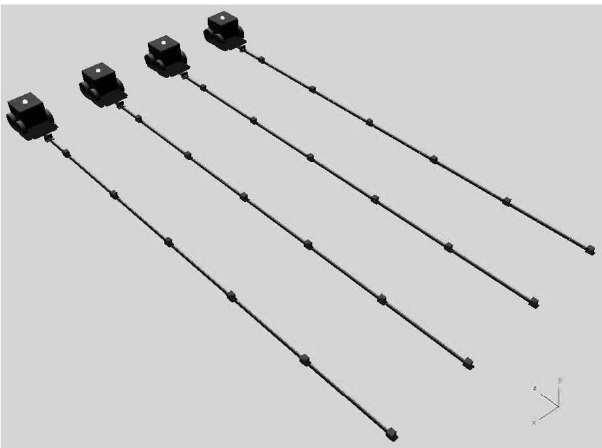
(a)Single robot, single hybrid streamer;



(b)Single robot, hybrid streamer array;



(c)Multiple robots, single hybrid streamers;



(d)Multiple robots, hybrid streamer arrays.

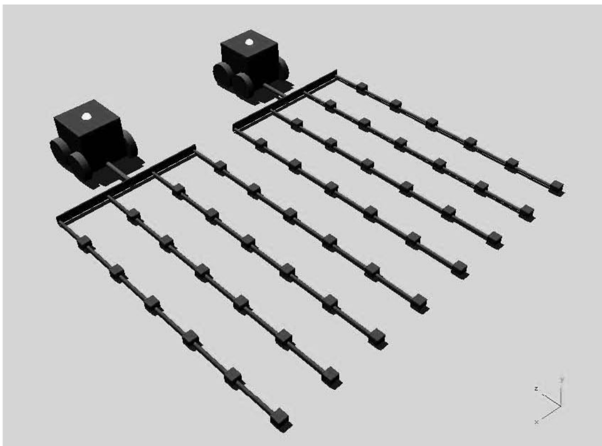


Fig. 6. Simulation images illustrating variations of hybrid streamers towed by mobile robots.

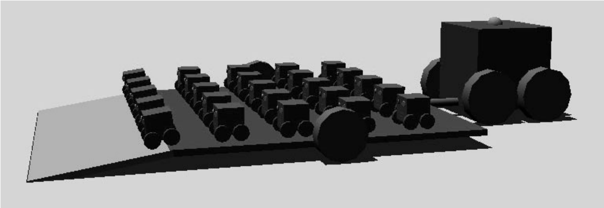


Fig. 7. Simulation image of a team of 25 mobile robots leaving a trailer pulled by a larger robot.

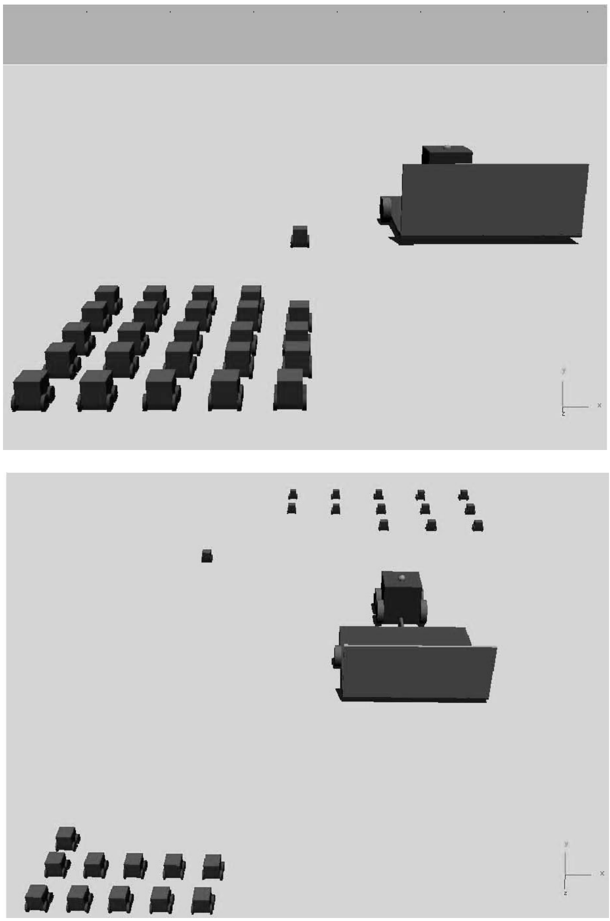


Fig. 8. Simulation images showing a team of mobile robots forming a square seismic grid, one-by-one from top-right to bottom-left.

Figure 9 shows completely formed grids, explaining that spacing can be dense 9a or more sparse 9b. Many grid shapes can be formed, ranging from lines to rectangles to squares. Figures 9a and 9b show a square grid pattern while Figure 9c shows a rectangular seismic grid. These simulation images show that spacing as well as grid geometry can be varied depending on the survey requirements.

The advantages of the multi-robot seismic sensor network approach are that it would be faster than a human team for large arrays, removes cumbersome wires from the system, and allows safe remote sensing while being able to dynamically adjust to the environment. This distributed methodology removes the single point of failure. This is also a new seismic method that has not yet been attempted, mainly because it remains too challenging at this time. The main bottlenecks lie in highly precise alignment of a team of mobile robots at any scale and any environment [18], along with properly aggregating the seismic data. This is the most desirable approach based on its mobility and ability to image at any resolution, shape, and scale. This might also provide faster network assembly, especially for a large and remote team. Dropping the robot team from an aerial vehicle to assemble, record, and perform multiple missions represents a futuristic option in this category. A design has been proposed for such a mobile robot team, as well as precise grid formation schemes such that the team could form a precise seismic grid one at a time or in a dynamic fashion [16], [18]. This category of seismic sensing has not been formally performed, but is currently being studied at CReSIS.

5. Multi-Robot grid formation simulation study

The results presented in this section are based on a simulation study, in which each mobile robot has its own GPS receiver and the ability to communicate with a larger, main robot. Each team robot is small, uses four wheels for mobility, and has an onboard battery. Precise robot positioning and grid alignment are achieved using a GPS-coordinate based incremental algorithm. This algorithm essentially removes collisions while forming grids of certain shapes and spacings, one robot at a time. As discussed later, this is an example of sacrificing overall time to essentially eliminate robot collisions. More detail can be found in [16],[18].

A larger robot is assigned to transport the team to a remote location on a trailer, if the team is small. A GPS base station is located nearby or onboard the carrier robot so each team robot can use GPS techniques (e.g., RTK or DGPS) for distance correction and precise positioning. If the team is too large, it can perform the egress (traveling out to the recording location) and ingress (traveling back to base) on its own using GPS waypoints.

5.1. Communication, context, and coordinates

Communication between the main robot and the team robots is established using wireless radio. The main robot is in control of the entire operation, telling each robot specifically where to go and when. Therefore, the main robot broadcasts a robot ID and context information to all robots. The robot called upon performs the desired action and reports back when it has completed that action (e.g., traveled to the provided waypoint). If a certain time buffer has been exceeded for a robot to report back, that robot has failed, is stuck, or has moved out of communication range. Actions could then potentially take place to find or replace this robot.

Here, the main robot is in complete control of computing the grid formation's shape, spacing, and the accompanying GPS coordinates for each mobile robot in the team. Individual robots then only need to consider traveling to the communicated GPS coordinate and fine-tuning for precision. This gives the main robot the ability to dynamically change grid shape and spacing so that a team could perform multiple formation sessions, each potentially of different shape and spacing. Previous figures have shown highly precise grid formations, demonstrating the differences in spacing and formation shape.

5.2. Precision and positioning

By knowing relative positions of all team robots with respect to the main robot, spacing between robots can also be guaranteed within a threshold. Thus, given that there are high-precision GPS receivers and a nearby base station, it can be guaranteed that the resulting robot grid will be of high precision with a limited amount of positioning error.

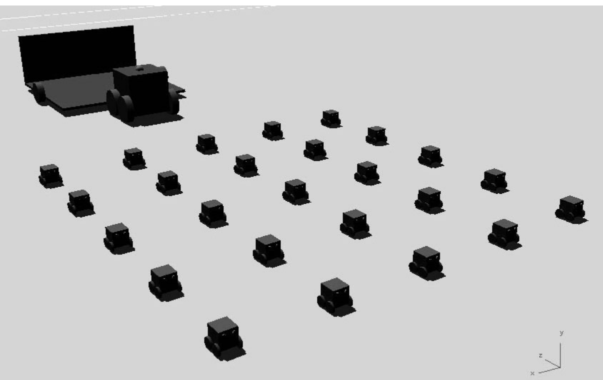
GPS error for each team robot and the main robot results in errors in precise absolute positions. Post-processing of location data (GPS log) can provide positioning accuracy to within several centimeters of the actual robot location, given that GPS devices capable of this level of accuracy are used. In the simulations, GPS receivers have accuracy on the level of several centimeters with randomized positioning error. GPS coordinates are ordered by the main robot in a manner to make sure that collisions are essentially avoided, positioning robots from the furthest locations to the closest locations, row by row, from one diagonal corner of the grid (top-right) to the opposite diagonal corner of the grid (bottom-left).

5.3. Assumptions

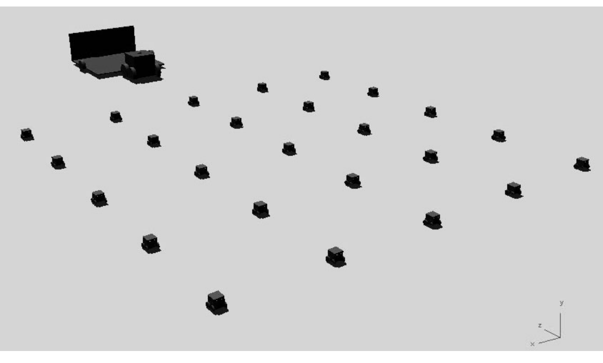
As there are a large number of variables in such a simulation, some assumptions have to be made to make comparisons more reliable:

- All GPS receivers are precise to several cm;
- Robots are initially placed 0.5 meters apart;
- All robots turn at 5% of full speed;
- All driving speeds are constant (non-changing);
- Robots can stop immediately (instantly);
- Battery usage: 99% motors, 1% CPU;
- No wheel slippage or wind force.

a) 5x5 square robot array, close spacing;



b) 5x5 square robot array, larger spacing;



c) 3x8 rectangular robot array, close spacing.

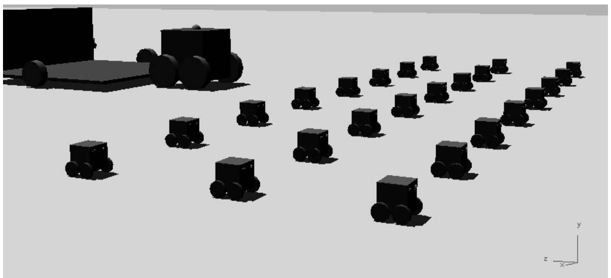


Fig. 9. Simulation images of completed robot seismic grids, demonstrating abilities to form various shapes of various spacings.

All simulations are setup to start with all 25 mobile robots positioned 0.5 meters apart in both X and Y directions. Keeping this initial formation constant ensures proper comparison of variables and results against one another. Some grid shapes do not involve all 25 robots. Robots that are not used can be there as backups, replacement in case of failure, or for direct use in a subsequent, different grid formation.

5.4. Experiments

The goal of this research is to gain a better understanding of relationships between traveling speed, grid spacing, formation time, energy usage, grid shape, and positioning error. Using an incremental deployment process, high precision can be attained so that these factors can be reliably compared and true relationships studied.

Experimenting with several grid formation shapes can provide information on which are more efficient in terms of robot energy usage and average travel time. The grid spacing between robots was kept constant at 10 meters (a grid with 10 meter spacing) for all experiments to concentrate on other relationships. As square, rectangular, and linear formations are the building blocks for most grid applications, the following formations were simulated:

1. Squares: 5x5, 4x4, 3x3, 2x2
2. Rectangles: 8x3, 6x4, 4x3, 3x2
3. Lines: 4x1, 8x1, 16x1, 24x1

For each of these grid shapes, the driving speed was varied to study its effects on positioning accuracy, average robot travel time, and average battery usage. The speed spectrum was divided into five sections: Very Slow, Slow, Normal, Fast, and Very Fast. In terms of accuracy, driving as slow as possible (e.g., 1% of full speed) would produce the highest precision alignment possible at the cost of increased formation time. On the other hand, driving too fast to the destination would likely yield a noticeably higher level of error. Thus, it would be more advantageous to compare the speeds of Slow, Normal, and Fast. The following speed variations were incorporated into simulations:

1. Slow: 25% of full speed;
2. Normal: 50% of full speed;
3. Fast: 75% of full speed.

Each combination of these variations was simulated four times. This was done to gain a more representative average for battery usage, travel time, formation time, and error. GPS error was random and therefore resulted in different error results for each iteration. A total of 12 shapes × 3 speed variations × 4 repetitions = 144 simulations were performed to gather the data for comparison.

Positioning error is calculated for each robot using the Manhattan Distance between each robot's final location and the desired grid GPS coordinate. Using this error measure, positioning error for each robot, overall team error, and average error given the driving parameters can be computed. For example, if the coordinate (x_1,y_1) is the desired coordinate and (x_2,y_2) is the final robot position, the Manhattan Distance (positioning error) is $|x_1-x_2| + |y_1-y_2|$.

5.5. Results and analysis

This section discusses the simulation results, comparing formation shapes and speeds with respect to total formation time and positioning error (accuracy tradeoff). Percentages are presented as the increase/decrease amounts for comparisons. The desired grid spacing was kept constant at 10 meters for all simulation experiments.

5.5.1. Formation completion time

Table 2 shows speed variation results for formation completion time in terms of percentages. The variations of doubling speed, tripling speed, increasing speed from Slow to Normal, and increasing speed from Normal to Fast are listed. All variations showed a decrease in time (–) with increasing speed.

This table shows that, in general, the more linear the shape was going away from the robot team, the longer it took to completely form. Also, a larger speed-up was experienced when increasing the driving speed from Slow to Normal compared to the same speed increase of 25% from Normal to Fast. Formation time was approximately 42% slower for square formations, 41% slower for rectangular formations, and 40% slower for linear formations when increasing speed from Slow to Normal compared to increasing from Normal to Fast.

Table 3 shows the five fastest and slowest grid shapes and speeds found during simulation. Driving slower causes formation time to increase because the mobile robots take longer to reach their destination. This table also shows that formations that are more linear took longer to complete, especially when more robots were involved. For example, an 8x3 rectangular grid took longer to form than a 6x4 rectangular grid, even though they both used 24 robots, because the formation extended the furthest from the initial team location. Figures 10 to 12 show formation time versus speed comparisons for square, rectangular, and linear grids. These graphs validate the previously discussed analysis.

Table 2. Formation Time: Speed Variation Results. Decrease in formation time (-) resulted from speed increase.

Variation	Square	Rectangle	Linear
Double Speed	-41%	-43%	-45%
Triple Speed	-55%	-57%	-59%
Slow to Normal	-41%	-43%	-45%
Normal to Fast	-24%	-25.5%	-27%

Table 3: Formation Time: Five Fastest and Five Slowest.

Fastest Times

Rank	Grid Shape	Speed
1	2x2 Square	Fast
2	4x1 Line	Fast
3	2x2 Square	Normal
4	4x1 Line	Normal
5	3x2 Rectangle	Fast

Slowest Times

Rank	Grid Shape	Speed
32	6x4 Rectangle	Slow
33	8x3 Rectangle	Slow
34	16x1 Line	Slow
35	24x1 Line	Normal
36	24x1 Line	Slow

5.5.2. Robot travel time and energy usage

Average robot travel time was directly related to total formation time. In fact, the percentages provided for formation time speed increases were exactly the same as those for average robot travel time. The maximum and minimum travel times varied depending on shape and spacing. Increasing travel speed lowered average robot travel time just as it lowered formation time for all shapes. As grid spacing increased, average robot travel time increased. Those robots that had to travel the furthest to reach their desired location used more energy, as energy/battery usage was directly related to travel time. In general, the longer it takes to complete the formation, the higher the average robot travel time will be.

5.5.3. Positioning precision

For square formations, positioning error was somewhat erratic. For larger square dimensions, doubling speed increased positioning error by much less compared to smaller square dimensions. Therefore, the results showed that doubling travel speed was a safer option for larger square dimensions. Tripling speed for square formations was also variable, ranging from an increase of 40% to 60% positioning error. Simulation results showed that, yet again, larger square dimensions were less susceptible to more of an increase in positioning error when speed was increased. Increasing speed from Normal to Fast showed the opposite, however, where smaller square dimensions were much less affected by positioning error.

Positioning error was somewhat erratic for rectangle formations as well. When speed was doubled, positioning error increased in the range from 25% to 33% and increased the most for the longest (most linear in shape) and shortest (smallest, most square in shape). Tripling speed behaved in a similar manner, where positioning error increased in the range from 28% to 57%. The longest and shortest grid formations again had the largest positioning error increases. Increasing speed from Normal to Fast exhibited a trend, however, where the grids that were longest (least like a square) had the least positioning error increase (10% compared to 19% for the smallest, square-like grids).

Linear formations provided more trend-like results. Doubling speed increased positioning error much less for longer lines (20%) compared to shorter lines (37%). Therefore, longer grid lines were less susceptible to error increase when speed was increased. Tripling speed behaved similarly for all simulated linear formations, where longer lines had error increased by about 45% and shorter lines had error increased by about 52%. On the other hand, increasing speed from Normal to Fast steadily increased positioning error more for longer lines (21%) compared to shorter lines (9%).

Table 4 shows the five fastest and slowest grid shapes and speeds found during simulation. This table also shows that overall precision was decreased as more robots were involved in the grid formation. As described in the next section, these results confirm that travel speed greatly effects positioning error (precision). Figures 13 to 15 illustrate error versus speed comparisons for square, rectangular, and linear grids. These graphs validate the previously discussed analysis.

5.5.4. Speed comparison

As shown in previous sections, speed greatly affected grid precision, formation time, average travel time, and energy usage. The faster a robot traveled, decreases were experienced in precision, formation time, average travel time, and energy usage. Therefore, the slower a robot travels, the more precise the grid will be. However, slower speeds also translated to more energy use and longer travel/formation times.

Table 4. Positioning Error: Five Lowest and Five Highest.

Lowest Errors

Rank	Grid Shape	Speed
1	4x1 Line	Slow
2	8x1 Line	Slow
3	3x2 Rectangle	Slow
4	2x2 Square	Slow
5	16x1 Line	Slow

Highest Errors

Rank	Grid Shape	Speed
32	6x4 Rectangle	Normal
33	4x4 Square	Normal
34	5x5 Square	Normal
35	6x4 Rectangle	Speed
36	5x5 Square	Speed

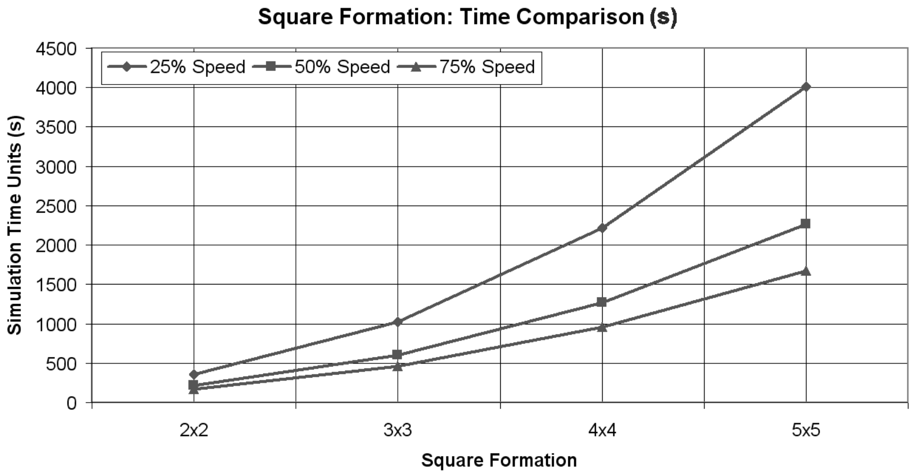


Fig. 10. Square Grid: Formation Time Versus Speed Comparison.

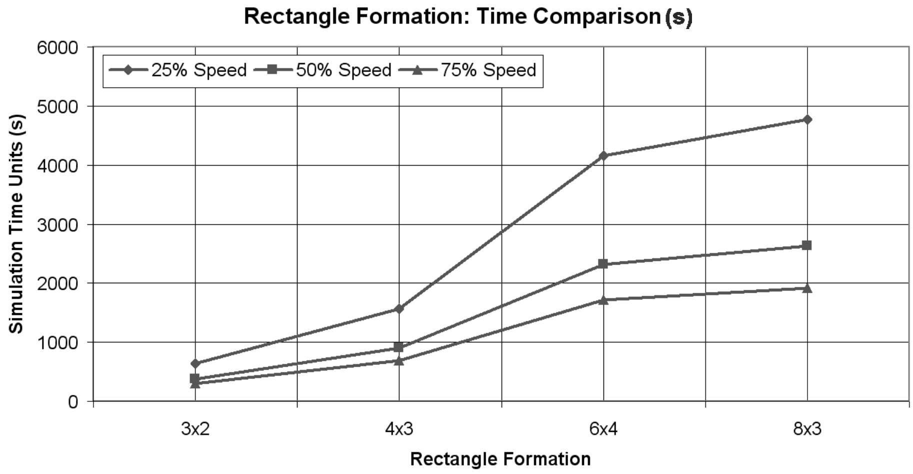


Fig. 11. Rectangular Grid: Formation Time Versus Speed Comparison.

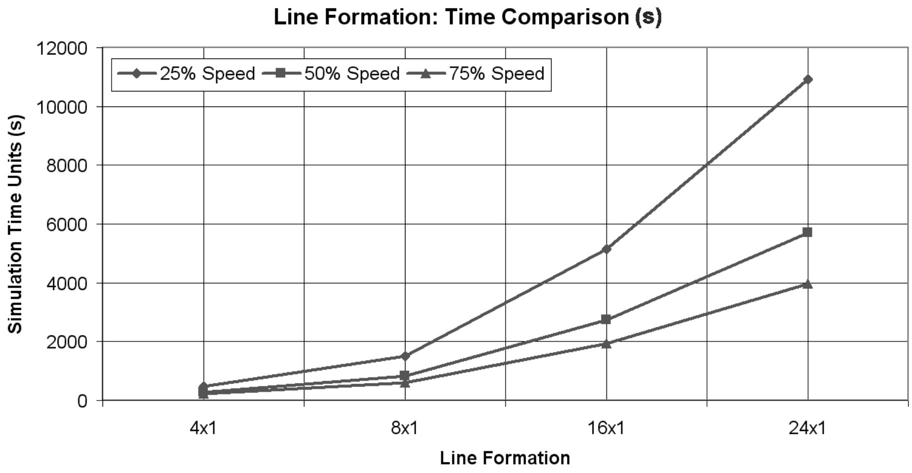


Fig. 12. Linear Grid: Formation Time Versus Speed Comparison.

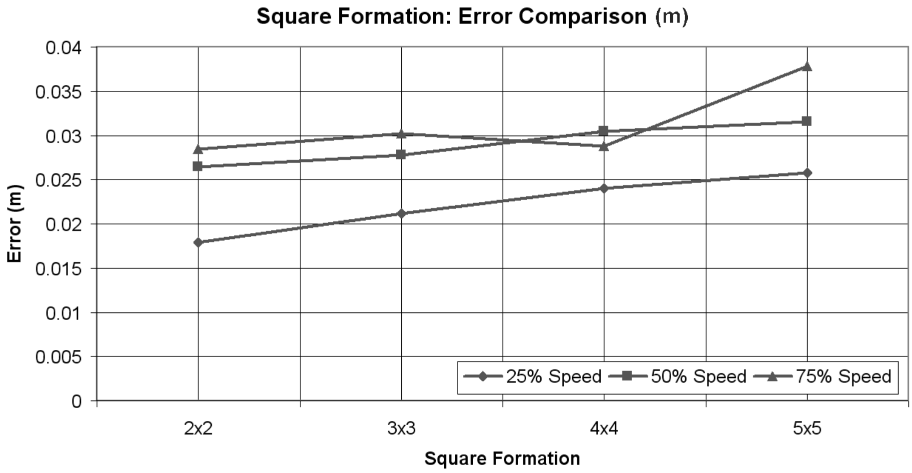


Fig. 13. Square Grid: Error Versus Speed Comparison.

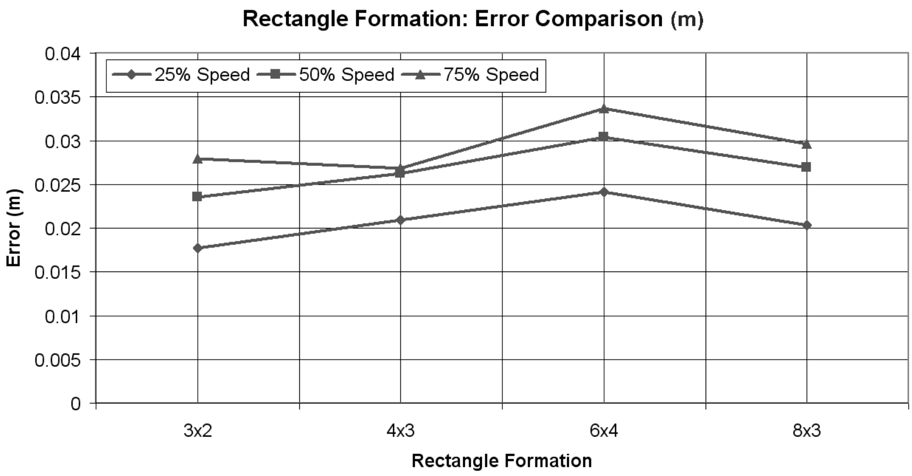


Fig. 14. Rectangular Grid: Error Versus Speed Comparison.

Driving slow decreased overall positioning error (increased precision), as seen in Table 4, where the most precise (lowest error) formations all traveled at a Slow speed. The least precise (highest error) formations all traveled at higher speeds. The reason why moving faster created more error is that the faster a robot moved, the more ground that is covered between sensor updates, especially with the presence of random GPS error. Thus, in general, increasing travel speed lessened precision but not in a truly linear fashion. Effects of speed can also be seen in Tables 2, 3, and 5.

5.5.5 Doubling shape dimensions

Table 5 shows the effects of doubling shape dimensions and increasing speed on formation time, average travel time, and overall positioning error. The results are expressed as percentages, where all increased (+). The shape dimensions used for this experiment were 2x2 to 4x4 (square), 3x2 to 6x4 (rectangle), and 8x1 to 16x1 (line).

This table shows that, in general, doubling shape dimensions translated to an increase in all major parameters. Interestingly, driving faster proved to steadily de-

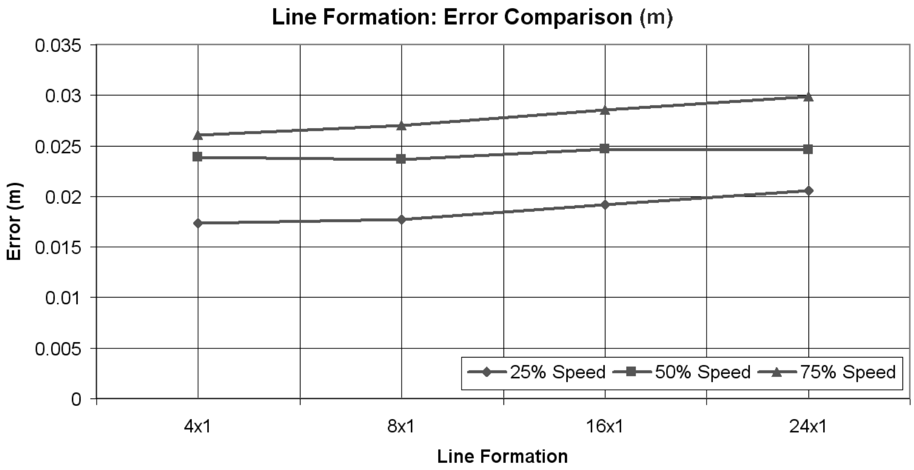


Fig. 15. Linear Grid: Error Versus Speed Comparison.

crease the effects of increased time and error. Also, the more linear the shape, the effects of doubling dimensions becomes more for formation and average travel times.

As for positioning error, an increase in speed had more of an effect on square formation shapes compared to the others. Rectangular and linear shapes were not affected as much, where linear formations stayed relatively the same. The odd result in this table is the slight increase in positioning error from Normal to Fast speeds. The random GPS error introduced for the experiments may have caused this. Note that this table is not stating that an increase in speed translates to a decrease in positioning error. Rather, these results express the direct comparison between results for shape dimensions that are double in size. For example, increasing square dimensions from 2x2 to 4x4 at Normal speed provided a 15% increase (+) in positioning error.

6. Comparison and discussion

Each of the presented robotics-based seismic surveying categories has their own set of distinct advantages and disadvantages. Depending on the desired application, environment, and scale of the surveying mission, certain categories may be more beneficial.

Individual deployment would likely be more suitable for an environment with a soft surface that has little wind and weather that could damage the deployment and retrieval mechanism. Keeping the deployment mechanism simple (e.g., linear actuator) also helps reduce complexity inherent to manipulators with several degrees of freedom. A flat surface would also reduce complexity, removing the need to worry about geophone orientation.

Array deployment is best suited for shallow surveys and environments that have a softer surface. Smaller surveys with a static number of geophones, array shape, and spacing fit this category very well. Limiting the number of channels in the survey also makes the array structure lighter and easier to carry or tow from one location to another.

Land streamers are ideal for missions which allow lower coupling and can afford to potentially sacrifice some of the higher frequency signals from the seismic source. As they are efficient and can be towed on the surface, this category can be tailored to perform 2D or 3D seismic data collection with reasonable scale.

Table 5. Effects of Doubling Shape Dimensions. Increase in time and error as grid shape doubled.

Square: 2x2 to 4x4	**Slow**	**Normal**	**Fast**
Formation Time	+518%	+478%	+450%
Avg. Travel Time	+55%	+45%	+38%
Positioning Error	+34%	+15%	+1%
Rectangle: 3x2 to 6x4	**Slow**	**Normal**	**Fast**
Formation Time	+548%	+508%	+479%
Avg. Travel Time	+62%	+52%	+45%
Positioning Error	+36%	+29%	+21%
Linear: 8x1 to 16x1	**Slow**	**Normal**	**Fast**
Formation Time	+241%	+227%	+216%
Avg. Travel Time	+71%	+64%	+58%
Positioning Error	+8%	+5%	+6%

Hybrid streamers exhibit the ability to acquire large amounts of data in less time with fewer personnel involved. Eliminating or greatly reducing the need for geophone insertion makes some of the techniques much less complex and more reliable. No matter the environment, these streamers can be towed along the ground by a robotic platform to autonomously gather seismic data. Benefits of increased coupling and protection make it more suitable for missions that require fast, efficient, better coupling, and higher frequency acquisition. Hybrid streamers are a step above current technology and could therefore provide results in the near future.

A mobile robot seismic surveying team represents the most futuristic and advanced method of robotically acquiring seismic data on a large scale. Compared to other methods, a team of mobile robots can dynamically adjust itself to form arrays of nearly unlimited size, shape, and spacing. They also exhibit the ability to decentralize the process, and potentially repair the grid if one or more robots fail or become stuck. This category does however represent the most expensive in terms of upfront cost for a complete team of geophone-deploying mobile robots. Significant design and testing time would also be necessary to determine what size of mobile robot would be needed to be effective.

Simulation results showed that controlled, incremental deployment essentially eliminated collisions at the tradeoff of a large increase in deployment time and grid precision. Subshapes or groups of robots could be deployed at the same time to decrease overall formation time, but then introduces a level of risk into the system due to possible robot collisions. Dynamically forming the grid at-once represents the fastest and likely the most energy-efficient manner of grid formation. However, it exhibits a higher collision risk along with inherently being less precise.

These results show several major patterns that effect grid precision. The faster the robots traveled, the quicker the formation was formed and average robot travel time was decreased. The longer robots must travel, more error was introduced. Energy usage was highly related to average robot travel time, where energy usage increased with travel time. More robots caused more overall grid positioning error. The results confirmed that higher precision could be attained by driving at slower speeds. This demonstrated the tradeoff between formation time, precision, and collision risk.

Out of the discussed robotic techniques, hybrid streamers and a team of mobile robots are more robust, offer more advantages in terms of time and space efficiency, and require limited levels of human intervention compared to other methods. Although these methods may incur higher deployment costs, the volume and quality of data will be increased. A team approach is unique in that each geophone is independently mobile, rather than transporting all geophones on the same vehicle or towing them in a tethered fashion. Investigations can also take place in the areas of efficient formation change, traveling from one location to another (flocking), and other intelligent techniques to enhance the process.

7. Conclusions

Integrating robotics into traditional seismic surveying helps in several ways. In addition to adding precision and removing the human element, more flexible and scalable seismic solutions can be created. Integrating several methods is likely best. For example, we have seen that hybrid streamers using heated spikes is a very plausible solution. A team of mobile robots that drill geophones into the ground could also become a reality for future missions. The main contributions of this paper were introducing the integration of robotics and seismic surveying, outlining challenges related to robotics based seismic, and presenting a categorization of approaches in which mobile robots are utilized. Simulation results also relate several aspects of multi-robot grid formation to energy usage, position error, and formation time. This research will hopefully allow the field of seismology to expand in terms of robotic automation.

Future work consists of extending the ideas of hybrid streamers and a multi-robot seismic team into designs. Hybrid streamer components will need to be designed and tested. Hybrid streamers will be fully implemented and deployed to autonomously collect seismic data in a future field season. A hybrid streamer system is currently being tested in snowy environments to determine length, plate design, overall weight, drag force, and other possibilities to increase coupling of a hybrid streamer. This system is going to be towed by the MARVIN II polar robot in the field in the near future.

A multi-robot seismic team will be designed and implemented on a small scale, including a geophone deployment mechanism for each platform. Designs will be validated using a single robot. Experiments will then take place with a small team, but will not collect field data in the near future. Upcoming field seasons will be the testing grounds for these two new robotics-based seismic methods.

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References

[1] Agah A., Bekey G.A., "Phylogenetic and Ontogenetic Learning in a Colony of Interacting Robots," *Autonomous Robots*, vol. 4, no. 1, 1997, pp. 85-100.

[2] Akers E.L., Stansbury R.S., Agah A., "Long-Term Survival of Polar Mobile Robots". In: *International Conference on Computing, Communications and Control Technologies (CCCT 2006)*, Orlando, Florida, July 2006.

[3] Akers E.L., Stansbury R.S., Agah A., Akins T.L., "Mobile Robots for Harsh Environments: Lessons Learned from Field Experiments". In: *Proceedings of 11th International Symposium on Robotics and Applications (ISORA 2006)*, Budapest, Hungary, July 2006.

[4] Akyildiz I.F., Su W., Sankarasubramaniam Y., Cayirci E., "A Survey on Sensor Networks," *IEEE Communications Magazine*, vol. 4, no. 8, August 2002, pp. 102-114.

[5] Arampatzis T., Lygeros J., Manesis S., "A Survey of Applications of Wireless Sensors and Wireless Sensor Networks". In: *Proceedings of the Mediterranean Conference on Control and Automation*, Limassol, Cyprus, June 2005.

[6] Bekey G.A., Agah A., *Group Behavior of Robots*, 2nd ed., ser. Shimon Y. Nof (Ed.) *Handbook of Industrial Robotics. New York*, New York: John Wiley & Sons Inc., 1999, pp. 439-445.

[7] Burridge R.R., Graham J., Shillcutt K., Hirsh R., Kortenkamp D., "Experiments with an EVA Assistant Robot". In: *Proceedings of the 7th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS-03*), 2003.

[8] Gifford C.M., Agah A., Tsoflias G.P., "Hybrid Streamers for Polar Seismic," *Eos Trans. AGU*, vol. 87, no. 52, Fall

Meet. Suppl., Abstract C41B-0335.

[9] CReSIS, *Center for Remote Sensing of Ice Sheets*, 2006. [Online]. Available: http://www.cresis.ku.edu/

[10] Cyberbotics, "Webots 5," 2006. [Online]. Available: http://www.cyberbotics.com/

[11] van der Veen M.V., Green A., "Land Streamer for Shallow Seismic Data Acquisition: Evaluation of Gimbal-Mounted Geophones," *Geophysics*, vol. 63, 1998, pp. 1408-1413.

[12] van der Veen M.V., Wild P., Spitzer R., Green A., "Design Characteristics of a Seismic Land Streamer for Shallow Data Acquisition". In: *Extended Abstracts of the 61st European Association of Geoscientists and Engineers (EAGE) Conference and Technical Exhibition*, 1999, pp. 40-41.

[13] Edan Y., "Design of an Autonomous Agricultural Robot", *International Journal of Applied Intelligence*, *Special Issue on Autonomous Systems*, vol. 5, no. 1, 1995, pp. 41-50.

[14] Edan Y., Bechar A., "Multi-Purpose Agricultural Robot". In: *Proceedings of the International Association of Science and Technology for Development (IASTED) International Conference on Robotics and Manufacturing*, Banff, Canada, July 1998, pp. 205-212.

[15] Eiken O., Degutsch M., Riste P., Rod K., "Snowstreamer: An Efficient Tool in Seismic Acquisition", *First Break*, vol. 7, no. 9, 1989, pp. 374-378.

[16] Gifford C.M., *Robotic Seismic Sensors for Polar Environments*, Master's Thesis, Department of Electrical Engineering and Computer Science, University of Kansas, August 2006.

[17] Gifford C.M., Agah A., "Robotic Deployment and Retrieval of Seismic Sensors for Polar Environments" In: *Proceedings of the 4th International Conference on Computing, Communications and Control Technologies (CCCT)*, vol. II, Orlando, FL, July 2006, pp. 334-339.

[18] Gifford C.M., Agah A., "Precise Formation of Multi-Robot Systems". In: *Proceedings of the IEEE International Conference on Systems of Systems Engineering (SoSE)*, San Antonio, TX, April 2007, Paper no. 105, pp. 16.

[19] Hollis J., Iseli J., Williams M., Hoenmans S., "The Future of Land Seismic", *Hart's E & P*, vol. 78, no. 11, November 2005, pp. 77-81.

[20] *Kansas Geological Survey*, "Land-Streamer," 2006. [Online]. Available: http://www.kgs.ku.edu/Geophysics2/Equip/LandStreamer/LandS4.htm

[21] King E.C., Bell A.C., "A Towed Geophone System for use in Snow-Covered Terrain," *Geophysical Journal International*, vol. 126, no. 1, 1996, pp. 54-62.

[22] Metrica, Inc., *Mars Manipulator*, 2006. [Online]. Available: http://www.metricanet.com/mars.htm

[23] MSC Software, *visualNastran 4D R2 User Manual*, 2002.

[24] Sheriff R.E., Geldart L.P., *Exploration Seismology*, 2nd ed. Cambridge University Press, 1995.

[25] Sen V., Stoffa P.L., Dalziel I.W.D., Blankenship D.D., Smith A.M., Anandakrishnan S., "Seismic Surveys in Central West Antarctica: Data Processing Examples from the ANTALITH Field Tests", *Terra Antarctica*, vol. 5, no. 4, 1999, pp. 761-772.

[26] Speece M.A., Miller C.R., Mille P.F., Link C.A., Flynn K. F., Dolena T. M., "A Rapid-Deployment, Three Dimensional (3-D), Seismic Reflection System", *Montana Tech. Prototype Design Proposal*, 2004.

[27] Spikes K., Steeples D., Ralston M., Blair J., Tian G., "Common Midpoint Seismic Reflection Data Recorded with Automatically Planted Geophones", 2001. [Online]. Available: http://www.dot.ca.gov/hq/esc/geotech/gg/geophysics2002/037spikes_cmp_auto_plants.pdf

[28] Stansbury R.S., Akers E.L., Harmon H.P., Agah A., "Survivability, Mobility, and Functionality of a Rover for Radars in Polar Regions", *International Journal of Control, Automation, and Systems*, vol. 2, no. 3, 2004, pp. 334-353.

[29] Tsoflias G.P., Steeples D.W., Czarnecki G. P., Sloan S.D., Eslick R.C., "Automatic Deployment of a 2-D Geo-phone Array for Efficient Ultra-Shallow Seismic Ima-ging", *Geophysical Research Letters*, 33, L09301, 2006.