Imaging Abandoned Mines Using Synthetic Aperture Sonar Aboard The “Open Airship”

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[[1]](#footnote-1)

***Abstract*—This paper summarizes the problems encountered in imaging abandoned mines and looks at a few applicable technologies. Old mining sites can create health and safety risks to both the environment and human populations. Investigation and remediation of these sites is hazardous for human work. Instead, advances in autonomous robots and particularly unmanned aerial vehicles may lead to efficient imaging methods that do not risk human lives. Two recent papers are presented in detail with applications in interior imaging. First, a paper by Jedrzej Drozdowicz and Piotr Samczynski demonstrates the effectiveness of non-linear trajectories in synthetic aperture algorithms**[1]**. This suggests its usefulness with autonomous behavior and in restricted flightpath regions. Then an open source design of a low-cost airship by Gal Gorjup and Minas Liarokapis is presented**[2]**. This gives a starting point for future research and prototyping of systems to be flown on lighter than air vehicles. Lastly the output of CHAT-GPT is analyzed after it was asked to write on the same topic.**

# I. INTRODUCTION

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bandoned mining sites can be found across the united states, left over from the past two and a half centuries of industrialization[3]–[5]. Some of these, such as open pits and quarries, are easier to survey. The mines that extend underground however are largely unexplored due to their hazardous environments. Many of these do not have records of layout, or the records they do have are inaccurate or incomplete. In the western states alone, the Bureau of Land Management has identified over fifty-seven thousand sites and at this date 80% still require further investigation or action[6]. Despite their inactivity, they continue to impose risks on society and the environment. One example is the Quecreek mining disaster where active mining broke into a flooded abandoned mine. The trapped miners were eventually rescued, but the incident could have been avoided with an accurate map on file of the old mine[7]. Miners are not the only ones affected either. Forgotten mines can threaten any development above them with threat of collapse into a sinkhole and ground water contamination can occur[8]. Knowing the layout of an abandoned mine can also help biologists who study bat populations, as they are becoming an important habitat of last resort away from human developments[9]. Thus research is needed in finding ways to survey and explore these underground mines while minimizing risks to human personnel.

# II. Literature Review

## A. Hazards To Human Exploration

The official warning on abandoned mines of both the U.S Bureau of Land Management[10], and the U.S Mine Safety and Health Administration is “Stay Out – Stay Alive”[11]. This caution is not issued lightly, and will frame this next section as the hostile environment of abandoned mines are discussed.

The first hazard to mines is the difficulty of navigation. Like caves and other dark places, it is incredibly easy to lose one’s sense of direction without identifiable landmarks. Mines have a tendency to form mazes with passageways interconnecting, and also not adhering to a flat elevation. The maps often do not list the full excavation, if there is a map on file at all[12]. This lack of mapping can also hide vertical shafts or potential for collapse of tunnel into one below.

Structural hazards are inherent to abandoned mines. The use of drilling, digging, and blasting with explosives often create unstable passageways through the rock. During their active period, mines are maintained with support structures to buttress the walls and ceilings against collapse. While modern mining operations are required to leave mines in safe conditions, most abandoned mines used temporary supports such as wood; prone to rotting, rusting, and giving away. Cave-ins are possible at any moment, and can take very little to trigger[13].

Air quality is a risk inherent to any enclosed space. Without an active air flow to the atmosphere, the oxygen content can be depleted within an enclosed space. Mines have the added risk of various toxic gases arising from underground deposits, or the breakdown of chemicals such as explosives left behind.

Then there are risks imposed by flooded mineshafts. Pools of water can disguise both sharp debris and vertical drops or shafts. They can also isolate sections of a mine from air flow, creating hazardous air pockets. Upper sections of a mine can also become flooded, leading to their collapse into other sections.

Lastly, there are material and radioactivity risks. Rock deposits occasionally contain radioactive components, while some mines explicitly targeted uranium deposits (such as those within the Grand Canyon National Park[4]). The explosives and chemicals left behind by the mining company can present risks, as they can degrade and become unstable over time[12].

## B. Discussion of Problem and Solution Space

Given the many dangers for humans, the first criteria of any solution will be the level of dependency on the human operators entering the environment. While human personnel may be required in search and rescue efforts where there is a chance of saving lives, there are too many risks to allow humans into an abandoned mine for the purpose of general surveying.

One approach of research has been in external imaging leveraging geophysical and electromagnetic properties. Of particular note are the high resolution seismic imaging using p-waves (HRPW) and s-waves (HRSW), reverse seismic profiling, and of ground penetrating radar [14] [15]. However, these techniques are difficult to turn into an accurate 3-d model or mapping of the volume. They also cannot describe any environmental dangers such as gasses or materials.

The other active are of research are remote operated and autonomous vehicles. Robotic drones are an attractive solution path; they are replaceable and don’t need to breathe. They can also carry a variety of sensor packages to map the interiors, analyze structural integrity, and identify hazardous gasses [16].

The introduction of vehicles imposes a new set of logistical challenges: how does the vehicle move about the environment and its range. The difficult terrain caused by uneven rocks, debris, or collapsed sections limits the effectiveness of a land-based approach[16]. This makes an aerial vehicle a promising choice for surveying, and they can inspect the vertical aspects of shafts unlike land rovers. However, aerial vehicles are limited in their carrying capacity. They are unable to unspool long lengths of cable for power or communications, and underground spaces also quickly limit the use of wireless communications networks[17]. Thus, an aerial solution will need to be autonomous and account for size, weight, and power constraints if it is to explore to the furthest reaches of a mine.

Lastly, there is the matter of the cost of the solution. Most abandoned mines will likely not intersect with active mining operations flush with cash. The surveying projects and search and rescue teams will have a limited budget for specialized robotics. The solution will then need to be either cheaply replaced or be nearly foolproof on returning from the depths. After all, there will be no recovery mission for a downed robot.

The next sections take a deeper look at two enabling technologies: synthetic aperture imaging, and low-cost blimp style UAV. The first section will first investigate interesting developments in 3-D imaging using synthetic apertures on aerial vehicles developed by Jedrej Drozdowicz and Piotr Samczynski [1]. Then a cheap, open-source airship design developed by Gal Gorjup and Minas Liarokapis is presented [18].

## C. Analysis of Drone-Based Synthetic Aperture Imaging

### i. Summary of paper

Synthetic aperture radar (SAR) and sonar (SAS) are imaging processes that can leverage the movement of a sensor to mimic the effect of a much greater array. The basic principle is similar to standard array beamforming. With a static array, sensors are placed in a pattern whose net effect is the sampling of some greater aperture. For example, a linear array will approximate a line aperture and sensors placed in a circle will approximate a ring aperture. Then, beamforming can be performed by adjusting the phase or delay of each respective sensor to account for the difference in path length of an incoming wave. The sampled aperture will govern the characteristics and maximum resolution of the main lobe, e.g. a set of lines will only ever be as

A synthetic aperture is made by moving that sensor(s) about in space over time. The assumption is that the relative movement of the sensor with respect to the imaged object or scenery is known. Each position of the sensor can be combined back together to effectively sample a virtual aperture as if one had placed an entire sensor array in the same area.

This sampling is a critical part of the imaging algorithm and is the highlight of research done by Drozdowicz et al. Classically SAR and SAS have focused on linear, circular, or sinusoidal trajectory paths. This can be due to the familiarity to prior research with fixed arrays or due to trajectory constraints of common vehicles such as satellites and fixed wing aircraft. What Drozdowicz et al. note is that UAVs have the potential for much more complex trajectories, and are hampered by the long flight times associated with multiple pass trajectories.

A diagram of a plane

Description automatically generated with medium confidence  
Figure . An example of a rectilinear SAR trajectory, and associated point spread function (PSF). The main lobe width or vertical resolution 2\*δV is shown. The maximum height resolution, hmax, is half the distance between the peaks. [10, Fig. 1 and 2]

Rectilinear paths have an advantage in having well defined resolutions. An example of a multiple or dual sensor path (if a second sensor is suspended far enough from the first) is demonstrated from their paper above. A random sampling that is sufficiently dense would provide a sharper peak, but much more smearing of energy. They modeled the quality of the resulting PSF using the widths of the main lobe and the peak sidelobe ratios.

The next step was to create a defined algorithm for pathfinding. A set of way points on the outer edge of the desired synthetic aperture were selected, and then a path would be generated based upon the motion model of a quadcopter. Having a defined algorithm in place, and metrics for success allowed for optimization using a form of cost function minimization. Using cost function for optimization also allows the resource cost of the trajectory to be accounted for.

A diagram of a graph

Description automatically generated with medium confidence

Figure . The point spread function of a 5-pass trajectory from [14, Fig. 22]. Note that the total area covered by the paths is roughly equivalent to the following figure. Also note that the sidelobe patterns are largely in the vertical and horizontal directions, with a pattern that could be a sinc patten like a rectangular window would have.

A graph of a graph of a wave

Description automatically generated with medium confidence

Figure . The best case optimization with path and point spread function from [14, Fig. 23]. Due to the choice of algorithm, the path fluidly moves between waypoints and creates an efficient path. The beampattern is much more irregular and spread out, and has a lower peak-sidelobe ratio than the 5-pass case.

The end result is a fluid path through the same region as the straight-line paths. This optimized path was shown to effectively trade off worse integrated sidelobe ratios in favor of reduced flight time and improved peak sidelobe ratios.

### ii. Impact on the field and next steps

This paper demonstrates that non-traditional trajectories can be viable for 3-D imaging using synthetic apertures. Additionally, optimization algorithms can be set up to trade off resolutions, side lobe ratios, and flight times to acceptable bounds. In the context of imaging underground spaces, this could allow for setting a hard limit on the flight time so as not to exceed battery limits. It might be that a zig zagging path through areas provides a better resolution than a straight back and forth can allow.

One avenue to follow through on this would be to turn the problem around. Instead of optimizing a path for a desired synthetic aperture shape, could a trajectory be adapted during exploration to account for path deviations? For example, if the planned path was diverted for collision avoidance, could a new path be adapted to still provide the desired resolutions? What if there are wind conditions, should the UAV fly constantly fly against it or adopt a more energy efficient path? Further, could an autonomous behavior be learned such that a UAV would explore an unknown environment while still producing a useful image?

## D. Low Cost, Open-Source Airships

Over the past decade there have been significant improvements in the field of autonomy and controls for UAV flight. Much attention has been paid to variations on quadcopter or other helicopter styles[1], [17], [19]–[25]. The control algorithms are fairly sophisticated and allow precise path following, rotation in place, hovering, and other complex maneuvers [26]. Advances in electronics has also shrunk down the weight to allow tiny sizes that fit in a palm [27]. However, a major constraint of these systems is flight time, as all must operate under batteries limited by weight. In their paper, Gal Gorjup and Minas Liarokapis[2] propose a new architecture of lighter-than-air craft as an alternative to hovering UAVs. The next section II.D.i summarizes their work , and the following section II.D.ii suggests next steps.

### i. Summary of paper by Gorjup and Liarokapis [2]

Lighter-than-air vehicles have intrinsic advantages compared to quadcopters and other rotorcraft. The most distinct is the reduced energy consumption to stay at altitude. A conventional quadcopter might be limited to less than 20 minutes of hovering, but an airship would be able to maintain its altitude for significantly longer. They can also be lower cost to build. The lack of high velocity rotor blades also lets them be near silent and safer for indoor use. However, the lower adoption of airships has left design and control challenges for future research to face. Gorjup and Liarokapis focused on developing an open-source platform to aid in future research and development.

A key design decision in an airship is the balloon material, lifting gas, and shape. Using helium as the lifting gas is the standard option; hydrogen is highly reactive [28], hot air both requires heating elements (adding weight and complexity) and provides less lift. Other gases were ruled out due to toxicity, flammability, or minimal buoyancy. Given helium as the lifting gas, the porous quality of balloon material is important for long term usage. A study was conducted on various commercially available materials to determine leakage rates and equating that to a yearly operating cost. Latex materials, treated and untreated, were found to be undesirable due to high leakage and easily bursting against rough surfaces. The bubble material had the advantage of the best surface to volume ratio, reducing the overall size of the balloon for a given quantity of gas. The downside was the lack of commercially available balloons in sizes greater than 40cm, limiting the applications possible. Meanwhile Gorjup and Liarokapis found the availability of micro foil and its tensile strength make it a strong choice for small aircraft designs.

A close-up of a graph

Description automatically generated

Table . Experimental helium leakage rates from [21, Table 1] . Evaluated materials from Qualatex (from top to bottom) were untreated latex balloon, latex treated with UHF, Bubble, and microfoil.

The other significant contribution Gorjup and Liarokapis made is demonstrating controllability of the prototype. A simple and non-optimal proportional control scheme was used to demonstrate proof of concept. With this simple control scheme, the airship was shown to be simultaneously stable in altitude and horizontal path following.

### ii. Next steps

A pathway for future research involving airship platforms has been created via the open-source design and control software developed by Gorjup and Liarokapis. The gondola design is flexible enough to incorporate additional sensors, and the open-source software used will make it much easier to start new projects in this field. It will be much easier to test concepts proven on other aerial platforms on an airship using this standard model.

# III. Next Steps

The work done by Gorjup and Liarokapis to create a low-cost platform for airship development leaves open the question of how many missions currently accomplished by quadcopters could better be done with an airship design. In the context of underground exploration, the potential for longer mission durations is immediately valuable. A longer flight time would allow farther reaches of the mine or cavern network to be explored without the complexity of accompanying robots to provide charge stations. If an airship can be proven capable of navigating tight enclosed areas, and of turning around or backing up in such areas; then an airship design would be viable for the exploration of underground caverns. The low cost of the design would also be beneficial, as error would be more tolerable when the vehicle is easier to replace. In the future other gases may also be revisited, as the majority of operation would take place far enough away from people. Of course, this may still be unacceptable as a hydrogen reaction would likely cause a tunnel collapse. Though a toxic gas leak may be acceptable inside the mine if future human exploration has already been fully abandoned; otherwise, it would also be unacceptable as it creates a non-removable hazard.

With the lower acoustic noise of an airship, there is also a lot more potential for sound-based imaging technology. Research has been done with quadcopters using sonar and echolocation [20], [27] and proven effective. However, a lower noise floor would improve the resolution and sensitivity of these techniques. This in turn may allow the same sensor suite to detect at farther distances or targets with a lower reflection strength. Conversely, a lower power of speakers could also be used to achieve a minimum detection range leading to a lower weight and smaller balloon envelope. The first steps here would be to replicate prior sonar research on the airship platform. The balloon itself poses a new risk to sound based sensors, as it may act as a high strength reflector causing oversaturation of the receivers. Future research would need to determine the effect of the balloon and provide means to reduce undesired effects. The balloon may also end up useful if it can be utilized as an acoustic source.

This also pairs with the work done by Drozdowicz and Samczynski on SAR. The airship design at the current moment appears to have less sophisticated control algorithms than quadcopters. This means that an airship would not be capable of the linear trajectories required by traditional synthetic aperture algorithms. However, their paper demonstrates that non-linear trajectories can be as successful. An interesting concept for future research would be to see whether the airship paths are capable of quality SAS or SAR images, and then to determine a method of achieving desired resolution parameters. This may include developing a machine learning algorithm capable of adapting airship control algorithms to provide consistent quality of images.

# IV. Analysis of CHAT-GPT 3.5

An important first note on CHAT-GPT’s only citation is both incorrectly formatted (IEEE format is initials then last name), and entirely fictitious to the best of the author’s knowledge. While the periodical *IEEE Robotics and Automation Letters* does exist, the referenced paper does not. The title has zero returns on *ieeexplore.com* and on google scholar. No first names were given, and the last names are very common. And the page numbers are incorrect for that volume; the 2019 issue 4 starts with page number 3113.

The next failure of Chat-GPT is to go into depth on any particular topic. Many of the statements do appear to have truth to them but lack any real depth. It is certainly impressive that it can pull up technical buzzwords that are applicable such as SLAM and LiDAR. Surprisingly, the generated paper does break out the SLAM acronym but doesn’t go much further. Each concept gets mentioned as useful for the topic, but it never goes into detail about strengths, weaknesses, or relevant properties of the technologies. The best it can do is group similar concepts together, as it can list a set of sensors used in this field. However, it also lumps gas detector in a statement that appears to focus on mapping. It also seems to list out thermal sensors quite often, which have little use when mines and caves have the lowest temperature gradients (the surrounding rock keeps a consistent temperature and humidity [9]). As for imaging technologies, only the physical modes are listed and not the signal processing techniques. The term LiDAR by itself really only means “Light detection and ranging” and does nothing to tell how one would use it to create a map.

Optimizing the energy consumption of autonomous robots through advanced power management, battery technologies, and **renewable energy sources** for prolonged mapping missions.

-CHAT-GPT 3.5 (emphasis the author’s)

There are also some other strange comments. For example, there is the line above regarding power efficiency. It starts out sounding correct since energy consumption is an important topic, and battery technologies and power management are factors in this. But where would you get renewable energy sources within a mineshaft?

Most of the sections are very surface level, and overall is more of a first pass at an outline. At best the output is a relevant jargon salad with little substance, and at worst misleading with fake citations.

Overall, the use of CHAT-GPT to produce any technical work is ill advised. Its use in brainstorming is also questionable as it is not capable of separating relevant technology concepts from unapplicable ones.

# Appendix

## Important warning of AI Generated Content

The section that follows was generated through the use of a large language model (LLM) trained using supervised and reinforcement learning techniques based on a dataset scraped from the internet without express consent of the originating authors. This algorithm is unable to provide an explicit citation reference to the works specifically used in the generation of this content. It may also generate partly or wholly fictitious citations and facts. This article was generated for the purpose of examining the relevance of large language models only, and nothing within this content should be taken as the opinion or belief of the author. Any unattributed content within is a result of the large language model Chat GPT. If any such content appears, please contact the author so that proper attribution can be made in an amended references section.

The AI generated content will be prefaced by the heading “Paper Generated From CHAT-GPT” and will marked at the end with the heading “Conclusion of Paper Generated From CHAT-GPT”. Pages in between will have a special header and footer that will warn readers that the content is AI-Generated. Formatting was done by the author.

Prompt: “You are writing a paper summarizing the importance of mapping abandoned mines and the state of art technology in autonomous robots that can image underground mines. The paper will be published in IEEE transactions format. Include references and summaries of prior research with correct citations. Cover at least one research paper in detail; explaining the contributions made and the impact to the field of surveying abandoned mines. At the end will be a section recommending future research topics related to the autonomous mapping of abandoned mines.”

# **Paper Generated from Chat-GPT**

# Mapping Abandoned Mines: Technological Advances and Future Prospects

**Abstract**—The mapping of abandoned mines is a critical endeavor, encompassing environmental remediation, safety assurance, and resource evaluation. This paper underscores the significance of abandoned mine mapping and examines state-of-the-art technologies in autonomous robots designed for underground imaging. Furthermore, it delves into a detailed analysis of the seminal research paper by Li et al. (2019), highlighting its contributions and impact on the field of surveying abandoned mines. The paper concludes by proposing future research avenues for the autonomous mapping of abandoned mines.

# I. Introduction

Abandoned mines pose multifaceted challenges, including environmental contamination, safety risks, and untapped resource potential. Accurate and efficient mapping of these mines is indispensable. Traditional methods, fraught with hazards and inefficiencies, have prompted the exploration of autonomous robots equipped with advanced sensing technologies for this purpose.

# II. Importance of Mapping Abandoned Mines

## A. Environmental Stewardship

Abandoned mines can be sources of environmental degradation, contaminating surrounding ecosystems. Precise mapping is pivotal for identifying contamination sources and planning remediation strategies.

## B. Safety Assurance

Structural instability, noxious gases, and potential collapses in abandoned mines necessitate thorough mapping to enhance public safety and direct targeted mitigation efforts.

## C. Resource Assessment

Many abandoned mines retain valuable resources, such as minerals and geological data. Mapping facilitates resource evaluation, supporting responsible resource utilization.

# III. State-of-the-Art Technology in Autonomous Mine Mapping

## A. Robotics and Sensing Technologies

Autonomous robots have revolutionized mine mapping with a suite of sensors, including LiDAR, thermal cameras, gas detectors, and multispectral imaging devices, enabling precise data collection and mapping of intricate mine structures.

## B. Autonomous Navigation

Advanced algorithms and obstacle avoidance systems empower robots to autonomously navigate complex mine networks with minimal human intervention.

## C. Real-time Data Processing

Real-time data processing enhances safety and efficiency by enabling on-site decision-making and rapid response to changing conditions.

## D. High-Resolution Imaging

Modern robotic platforms generate high-resolution images and 3D models, facilitating geological analysis, structural assessments, and environmental monitoring.

## E. Cost-Efficiency

Autonomous robots offer cost-effective mine mapping solutions by reducing human labor requirements, minimizing safety risks, and increasing mapping efficiency.

# IV. In-Depth Analysis of Seminal Research: Li et al. (2019)

This section delves into the influential research paper by Li et al. (2019) titled "Autonomous Robotic Mapping of Abandoned Mines using LiDAR and SLAM." This work significantly contributed to the field of surveying abandoned mines by introducing a novel approach to autonomous mine mapping. Li et al. (2019) proposed an integrated system that combined LiDAR-based mapping with Simultaneous Localization and Mapping (SLAM) techniques. This approach addressed several critical challenges:

Contributions

Robust Mapping: Li et al. (2019) demonstrated the feasibility of accurately mapping abandoned mines, even in GPS-denied environments, using LiDAR sensors.

Real-time SLAM: Their work presented a real-time SLAM algorithm tailored to mine mapping, allowing for simultaneous data collection and mapping generation.

Obstacle Detection: The research introduced advanced obstacle detection capabilities, crucial for navigating through complex mine networks.

Impact

Li et al.'s (2019) research significantly impacted the field of mine mapping by providing a robust and efficient solution for autonomous underground mapping. Their work laid the foundation for subsequent advancements in autonomous mine mapping technologies.

# V. Future Research Directions

Building on the progress achieved in autonomous mine mapping, several research directions deserve further exploration:

## A. Multi-sensor Fusion

Exploring the integration of diverse sensors (e.g., LiDAR, thermal, and acoustic) to enhance the accuracy and capabilities of mine mapping systems.

## B. Collaborative Mapping

Investigating the potential of using multiple autonomous robots to collaboratively map extensive mine networks more efficiently.

## C. Environmental Monitoring

Extending autonomous robots' applications to long-term environmental monitoring of abandoned mines, tracking changes in water quality, gas emissions, and subsurface stability.

## D. Human-Robot Interaction

Developing intuitive human-robot interaction interfaces and communication protocols to facilitate seamless cooperation between human operators and autonomous robots in complex mine environments.

## E. Energy Efficiency

Optimizing the energy consumption of autonomous robots through advanced power management, battery technologies, and renewable energy sources for prolonged mapping missions.

# VI. Conclusion

Mapping abandoned mines holds paramount importance for mitigating environmental hazards, ensuring safety, and harnessing resources. Autonomous robots, equipped with cutting-edge technologies, have proven to be invaluable tools for this task. Seminal research, such as Li et al. (2019), has significantly advanced the field, providing innovative solutions and inspiring further exploration of autonomous mine mapping. Future research in this domain promises to unlock new frontiers in mapping technology and address the unique challenges posed by abandoned mines.

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[2] [Additional relevant citations in IEEE format]

Note: Please ensure that the paper adheres to the IEEE Transactions format guidelines and includes accurate citations in the references section.

# **Conclusion of Paper Generated From Chat-GPT**

Additional references[1]–[5], [7]–[29], [29]–[35]

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1. [↑](#footnote-ref-1)