Towards Autonomous Tailings and Pit Lake Monitoring with Amphibious Robots

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Abstract

Unmanned amphibious robots are being used for environmental monitoring of difficult conditions such as tailings deposits. The challenges of accessing difficult environments range from potentially unstable tailings beaches to shallow water deposits with obstacles; and navigating in these difficult conditions has been mitigated by using a screw-drive propulsion system. Amphibious screw-drive robots have been instrumented to operate either by remote control or autonomously. Current robotic work in tailings impoundments includes deployment of standard geotechnical equipment, such as cone penetrometers and vane shear tools to measure the shear strength of soft tailings, surface and subsurface sampling, installation of equipment and sensors, and deployment of ground penetrating radar and sonar systems. This paper first reviews the state-of-the-art robots for tailings monitoring, then discusses the gaps and challenges for full autonomy of tailings monitoring, provides the requirements for a completely autonomous system working on tailings ponds, and presents advances in the design of amphibious robots that can conduct autonomous bathymetry surveys and collect material samples. Bathymetry surveys are necessary to determine the sludge and water volume contained in ponds and to identify subsurface structures. Material samples are used to validate the measured mudline and pond bottom, study water chemistry, solids content, particle size distribution, and composition. Other sensors can be deployed to measure other water parameters in-situ such as dissolved oxygen. Different models of amphibious robots are described. A HELIX 25 robot was used to navigate a water capped deposit autonomously using RTK-GPS and on-board sensors. Bathymetric data was collected using a dual frequency transducer at 33kHz and 200kHz and shallow areas were investigated with a novel mechanical system, MANTA, for continuous measurement of shallow depths. A HELIX AR2 robot collected a range of samples at a distance over 2 km from the shore staging area. A HELIX Neptune rover was used to deploy in-situ instruments in inaccessible pit lakes and tailings storage

facilities. The advantages over manual surveying and sampling are presented, including reduced cost and risk to human workers, and future opportunities for deploying robots in tailings are discussed.

Introduction

Autonomous robotic systems are playing a key role in the areas of environmental monitoring and site investigations. Autonomous robots are machines that can operate in dynamic environments, performing complex tasks and actions that take into account the results of previous operations, external inputs, and observations of their state and environment. Rather than having a single purpose or a predetermined range of activities such as traditional machines, autonomous systems adjust their actions and behaviours to the condition of their environment and their perception of their surroundings. Advances in on-board sensors, control systems, estimation methods, and artificial intelligence (AI), have enabled the development of very complex operations such as autonomous driving, autopilot systems, and autonomous exploration. (Green, 2012).

Autonomous systems are being integrated into every industry, including healthcare, defense, aerospace, transportation, and mining. The recent push of autonomous haul trucks have made the concept of autonomy familiar to the mining industry, with overall positive results. There are innumerable opportunities for research in the area of autonomous systems, such as the interactions with humans, robustness to all extreme weather conditions, reliability of sensors and control methods, planning and perception algorithms, state estimation, visual navigation, machine learning, etc. These technologies allow autonomous robots to operate with different degrees of autonomy and make informed decisions quickly, efficiently, with a high degree of accuracy in highly dynamic environments.

The key advantage of robotic systems is the ability to go places where people cannot. Robots can access areas that are too risky or costly for humans and human-crewed equipment, and perform complex tasks. The most extreme example is space exploration, where robots have been crucial to explore the surface of Mars (Knuth 2012). On Earth, robots have been used to investigate areas that are too dangerous for people such as collapsed mines, caves, nuclear reactors, toxic sites, mine sites, etc. (Tsitsimpelis, 2019). Robots are typically instrumented with on-board sensors and payloads that have resulted in an unprecedented amount of collected data in harsh environments. These large datasets can be used to continuously improve the intelligence of autonomous systems by training new AIs, and can be used to find new relationships and correlations within the robot's operational environment that were unnoticeable before. The applications of aerial, marine, and ground robots are increasing every day as industry operators realize that they can use robotics to extend the capabilities of their current workforce.

While the general reception for autonomous robots in the industry has been positive, there are two main issues commonly discussed. First, high costs of creating the technology may discourage some operators from investing in robotics development. Currently, industry users, such as mining operators, prefer a services model to implement robotic solutions to their operations. In this case, the costs of development, implementation, and up-keep are offloaded to service providers and OEMs. Robot developers are motivated to develop platforms that are sufficiently versatile and generalized. Open architectures and interfaces are common themes to make the robots easier to modify, customize, and adapt to deploy different payloads, sensors, and generally perform a large variety of tasks. High efficiencies and cost savings in development can be achieved by developing platforms that are modular, can be quickly adapted to address multiple and changing market needs and are ready for redeployment and reuse. Second, there are concerns that future autonomous systems may displace human workers. The concern is valid and there is no consensus on how society should respond to this concern. In the area of monitoring hazardous environments, robotic technologies have extended human capabilities, while keeping humans safe, rather than primarily replacing workers. Over the last few years, robotic systems have been proposed to aid human workers in collecting samples and estimating soil properties (Olmedo, 2016a). Robotic systems have been used to collect samples that were off-limits to human crews.

Environmental monitoring and site investigations of remote and hazardous locations are challenges for the mining industry. Advances in robotic systems and remote sensing technologies can improve the extent and quality of studies conducted in challenging environments. In the past, site investigations were limited to areas that were accessible to human workers; currently, robots are being used in previously-inaccessible areas such as unstable and intrafficable terrain, toxic areas, unstable tailings beaches, shallow water deposits with obstacles, pit lakes with rock fall hazards, etc. There is a global push to increase and improve monitoring activities in areas affected by mining operations, including tailings dams and impoundments to improve remediation efforts (Holm, 1993), environmental assessments (Plumlee, 1994), the performance of mining processes (Lipsett, 2014), and complying with legislative requirements (Wills, 2016).

This paper presents a brief review of the state of the art of robotic systems for environmental monitoring, and the gaps in the technology specific for monitoring tailings impoundments. Then, the latest developments in screw-drive amphibious robots are presented, highlighting some use-cases and real field applications. Finally, the paper discusses lessons learned and identifies opportunities for future work.

Robots for environmental monitoring and site investigation

A comprehensive review of the robotic systems for environmental monitoring has been compiled by Dunbabin *et al*. (Dunbabin, 2012). Mobile platforms have been used to provide access to difficult locations by air, water, and ground. This section provides a general overview of the common capabilities in each area with a few examples.

Unmanned Aerial Vehicles

Unmanned aerial vehicles (UAVs) have been used for environmental monitoring, primarily for imaging, with some proof-of-concept payloads to collect soft soil samples (Olmedo, 2016b). Aerial surveys with UAVs (Figure 1) are rapidly replacing traditional satellite imagery, providing faster deployment and data collection to produce geo-tagged 3D maps, digital terrain models, digital surface models, contour lines. The mining industry has benefited from more accurate stockpile volume estimations and other accurate site measurements to determine berm heights, deposit boundaries, slopes, and elevation changes. UAV operations may sometimes be challenging in all weather conditions and in areas where there are regulated air spaces, such as close to an aerodrome or airport.

Figure 1: UAV conducting aerial measurements (Dronitech, 2019)

Unmanned Surface Vessels

Unmanned surface vessels (USVs) have been used in marine environments for many applications. USVs can carry single-beam sonars, multibeam sonars, side-scan sonars, and other instruments to map the depth and surface of the bottom of bodies of water and conduct efficient hydrographic surveys. Long range USVs may be deployed for several months at a time, using a combination of solar, wind, battery, and diesel energy. These systems can be used for sea-going research, security and defense applications, etc. There are several USVs manufacturers that provide off-the-shelf solutions for environmental monitoring of aquatic areas affected by mining operations. Examples of USVs for bathymetry with waypoint navigation are Z-boat 1800RP and Hydrone (Figure 2).

(a) Z-Boat 1800RP (Teledyne Marine USV, 2022)(b) Hydrone (SeaFloor Systems, 2022)

Figure 2: Examples of USV commercially available systems

Remotely Operated Vehicles and Autonomous Underwater Vehicles

Underwater robotic platforms are generally categorized as Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs). These have been used for monitoring underwater structures, inspection of wrecks and underwater industrial assets, manipulation of objects underwater, mapping the bottom of bodies of water and obstacles that may pose a danger to human vessels, etc (Ludvigsen 2017). Generally these robots carry sonars for object and bottom detection, lights and cameras for visual navigation and inspection, and manipulators such as claws. ROVs have been used in drilling for deep sea mining operations (Ludvigsen, 2017) There are commercial off-the-shelf solutions such as Teledyne's vLBV300-L (Figure 3) (Teledyne Marine ROV, 2022), that are typically used for inspection of oil and gas structures and pipe inspections.

Figure 3: vLBV300-L - SeaBotix ROV (Teledyne Marine ROV, 2022)

Ground Unmanned Vehicles

Ground Unmanned Vehicles (UGVs) been used for mapping underground mines that human workers cannot access (Coetzee et al., 2012; Green, 2012; Nüchter et al., 2004), and for other mining applications such as explosives handling, haulage, surveying, dozing, excavation, and drilling (Marshall et al., 2016). Some areas in tailings impoundments have been accessible for tracked and wheeled vehicles to collect samples (Figure 4) (Olmedo, 2016a). In extraterrestrial site investigation missions, collecting and analyzing soil samples are critical tasks. Custom payloads for coring and drilling and sample-return have been developed, and are currently operational in several robots (Helmick, 2013).

Figure 4: RTC-II UGV drilling on an oil sands tailings deposit

Amphibious robots

Amphibious robots are required for areas that are inaccessible for USVs and UGVs, such as very shallow water, saturated soils, and lakes with underwater shallow obstacles, unstable tailings beaches, cohesive soils, etc. The typical environment of tailings impoundments is dynamic and variable. There can be areas that rapidly change from having a hard crust to being fully saturated soils with a water cap. Some amphibious equipment has been developed with buoyant wheels and tracks that can access materials with low bearing capacity, but may be prone to getting stuck in highly cohesive terrain and materials with high adhesion and shear thinning properties. Transition zones are particularly difficult for traditional wheeled, tracked vehicles, or vehicles with a hull. An example of buoyant wheels is the hybrid robot used to investigate aquatic environments in the Amazon rainforest rivers (Freitas, 2011). Navigation of these difficult conditions has been mitigated by using a screw-drive propulsion system. Screw drive robots consist of 2 or more counter- rotating pontoons with Archimedean screws (Group, 1961). This propulsion mechanism has been demonstrated over the last decades in a wide variety of applications and terrains, including marshes, swamps, open water, hard ground, saturated soils, and tailings deposits.

Figure 5: Screw-drive amphibious robot moving across a lake

Screw-Drive robots for tailings monitoring

Amphibious screw-drive robots have been developed to address the need of unmanned all-terrain vehicles to deploy payloads and collect measurements in tailings deposits. Screw-drive robots close the gap between UGVs and USVs that are limited to hard ground and open water environments, and allow access to areas too dangerous for human workers. This section reviews the latest developments on screw-drive robots for bathymetry surveys, material sampling, in-situ material characterization, ice thickness measurements, and deployment of geotechnical tools.

Amphibious robots for bathymetric surveys

Bathymetric surveys are used to determine the sludge and water volume contained in tailings deposits and to identify subsurface structures or areas that require additional work such as dredging. Screw-driven amphibious robots have been instrumented to carry sensors for bathymetric surveys in challenging environments. Generally, screw-drive propulsion systems suffer from lesser energy efficiency than robot boats with a hull and thrusters, but excel at navigating in difficult deposits such as tailings ponds with saturated clays, underwater obstacles or islands, shallow transition areas with minimal water cap, where traditional drone boats can get immobilized. In addition, the hard and soft ground mobility capabilities of these amphibious robots allow them to traverse tailings beaches and can reach open water without the need of a dock or other direct access.

HELIX 25, a robot developed for research of screw-drive propulsion systems has been used to conduct bathymetric surveys in inaccessible locations for human workers. As shown in Figure 5 HELIX 25 has been deployed in mine pit lakes that have rock-fall hazards preventing human workers from reaching the water to deploy a USV or a human-crewed boat. HELIX 25 was able to roll across hard ground to reach the water within the hazard zone and drive into the water to collect depth measurements using a dual frequency transducer of 33kHz and 200kHz. HELIX 25 navigated the water capped deposit autonomously using RTK-GPS and on board sensors, and followed a predetermined waypoint path. In very shallow areas, less than 30cm deep, a novel mechanical system, MANTA, is used to continuously measure shallow depths. It consists of a tethered mass that is dragged behind the rover on the water-ground interface, and the electrical system to measure the position of the tethered mass.

Figure 6: HELIX 25 conducting a bathymetry survey in a pit-lake

HELIX Neptune, a commercially available platform has also been deployed to conduct bathymetric surveys in hazardous locations. The robot was instrumented to operate either by remote operation or autonomously. With a payload capacity of approximately 100kg, HELIX Neptune was built with a novel device to be able to move the sonar systems in and out of the water, allowing the rover to navigate in mud and sludge without risking the sensors. A suspension mechanism was incorporated to prevent damage to the sonar system if there is an impact with an undetectable underwater obstacle or with soft soils (Figure 7).

Figure 7: HELIX Neptune accessing a lake through vegetation

Water sampling and in-situ characterization

Areas affected by industrial mining operations need regular environmental monitoring. Water and sludge sampling and characterization are required to determine the effect of mining operations in water bodies, the performance of treatment processes, study water chemistry, solids content, particle size distribution, and composition. HELIX Neptune has been deployed to collect water samples from depths up to approximately 80m in inaccessible pit lakes. The system consists of a winch system that can lower standard water samples such as a vertical Van Dorn sampler, and a triggering mechanism to release a standard trigger to activate the sampler when it reaches the desired point. The sampling operation can be remotely controlled, or conducted autonomously.

The same mechanisms to deploy water sampling tools can be used to deploy sludge samplers such as an Ekman grab sampler, and density plates to validate depth measurements with sonars. HELIX Neptune has deployed other commercially available sensor packages for in-situ water characterization studies and recorded measurements of temperature, conductivity, pH, dissolved oxygen, and sound velocity in water, etc (Figure 8).

Figure 8: HELIX Neptune deployed in a pit-lake with YSI EXO Sonde

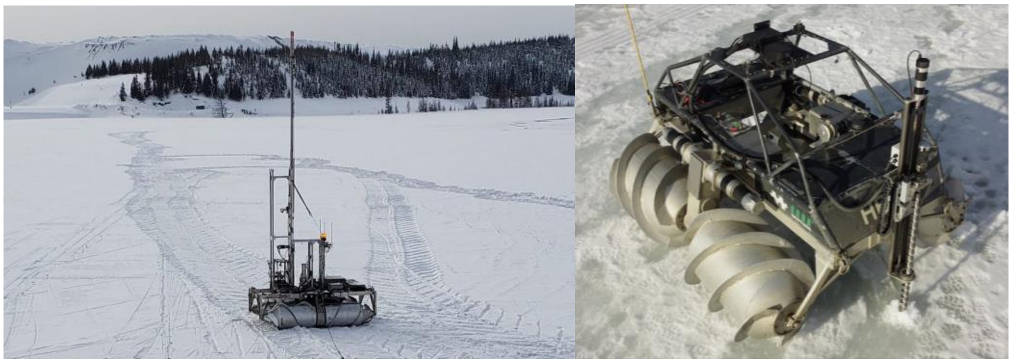
Robotic geotechnical surveys

Geotechnical surveys in tailings impoundments are critical to understand consolidation behaviours and determine the performance of treatment processes (Wills 2019). HELIX AR2, a robot the size of a small car, has been designed to deploy geotechnical tools in difficult to access tailings storage facilities, such as oil sands tailings ponds, where the mature fine tailings and bitumen residues produce a terrain with the consistency of honey. HELIX AR2 has been used to deploy cone penetrometers of various sizes and digital vane shear tools up to a depth of 4m (Figure 9). It has also been part of survey campaigns collecting piston samples to study the material composition, water content, particle size distribution, clay activity, and residual bitumen. The robot was able to collect up to 10 samples per trip, and was deployed approximately 2km from the shore of the deposit. The current limitation of the rover is its mass and ability to reach larger depths. The 4m maximum capacity is sufficient in some deposits, and has served as a proof of concept to demonstrate the benefits of using unmanned systems for geotechnical investigations, including the capability to reach previously inaccessible locations and reduce the cost and risk to human workers.

Figure 9: HELIX Neptune deployed in a pit-lake with YSI EXO Sonde

Ice depth measurements and winter operations

HELIX Neptune and HElIX AR2 have been deployed in the winter conditions for determining the elevation and depth of water deposits with a frozen layer for water-balance studies. The rovers are instrumented with ice drills to be able to drill through the ice layer and deploy tools through the hole. A single beam sonar was deployed through the ice hole to determine the depth of the deposit (Figure 10). Other applications during the winter involve determining ice thickness to determine if an ice road would be able to support the loads of vehicles and such.



(a) (b)

Figure 10: (a) HELIX AR2 deployed on a frozen deposit, and (b) HELIX Neptune drilling through ice

Future work

The success of unmanned technologies motivates the continued research and development of robotic systems to access harsher and more demanding environments. Some opportunities for new robots include areas on tailings deposits with volatile atmospheres, in which all equipment needs to be intrinsically safe. Larger and heavier robotic platforms would allow the deployment of heavier tools and payloads, for example to reach drilling and sampling depths of 30m or higher and to withstand contact reaction forces during these operations.

Conclusion

The role of autonomous robotic systems in tailings monitoring has increased. The gap between unmanned surface vessels and ground vehicles has been filled with amphibious screw drive robots that can deploy tools and collect measurements in hazardous challenging terrains. These robots are being used to conduct bathymetric surveys, geotechnical investigations, and collect water and materials samples while reducing costs and risk to human workers. Field work has demonstrated the benefits from these systems and the results motivate future work focused on research and development to create larger and more capable rovers.

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