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Developing Field Protocols for Using Robots to Supplement Structural Condition Surveys

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Abstract
When conducting structural condition surveys, robots have proven invaluable where physical access to interior voids cannot be accomplished. While global protocols exist for conducting structural condition surveys, only rudimentary protocols exist for the operation of robots within this domain. Therefore, application protocols and site-specific field protocols must be developed on a case-by-case basis when using robots. Specifically, robots can effectively identify and quantify the existence and extent of damage when properly equipped and operated. Robots can also provide real-time photogrametry as well as a means of recording pre-deconstructive conditions. This paper serves to identify state of the art use of robots within forensic engineering by discussing the proper outfitting, operating, and field use of robots to supplement limited destructive structural condition surveys.

Keywords
Robotic Surveys, Forensic Engineering, Robotic Protocols

1. Introduction

Structural condition surveys often require engineering personnel to enter into building crawl spaces and confined areas. While entry is required for a proper survey, these hazardous environments inevitably put a worker, or multiple workers, at risk for exposure to life threatening situations. OSHA classifies these hazards into two main categories:

- Atmospheric Hazards
  - Flammable/explosive
  - Inert gases and simple axphyxiants
  - Oxygen deficient air
  - Solvents
  - Toxic Gasses

- Physical Hazards
    - o Engulfment
    - o Falls
    - o Electrician
    - o Drowning

Since the environment is extremely dynamic and difficult to control, at best an engineering firm can only hope to lessen the risk to its personnel. These risks can be significantly mitigated through the use of robots. A camera equipped robot can provide the engineer with a pre-survey of the area requiring inspection, identify risks, monitor air quality, and determine if human entry is even required. Secondly, if human entry is required, the robot can act as a life-line from the inspector to safety personnel and other engineers outside of the confined space.

This paper begins with an overview of currently available technology for inspection tasks, a list of requirements and specifications to follow. Finally, we conclude with three real-world examples of inspections performed with the assistance of robot technology.

2. Robot Equipment

There are a limited number of inspection tools available for structural inspection. While sewer and pipe inspection civil engineering disciplines enjoy a plethora of manufacturers and equipment options, the market for robust robots for unstructured environments is relatively new. To date, American Standard Robotics, Inc. (ASR) is the only company building robot specifically designed for these tough mobility environments. Their flagship product for this market is the VGTV-Xtreme platform and is the focus of this overview.

The Micro Variable Geometry Tracked Vehicle (VGTV) was originally designed as a unique and versatile tethered system for remote inspection or observation applications. As the name implies, the vehicle's shape can be altered during operation. The tracks, in their lowered configuration, take the shape of conventional crawler tracks. This configuration provides stability and increased traction. When in the raised configuration, the tracks take the shape of a triangle. This allows the operator to have a higher view from which to observe the surroundings. The robot remains fully operational throughout these shape changes, allowing the vehicle to negotiate obstacles, operate in confined spaces, and over rough terrain.

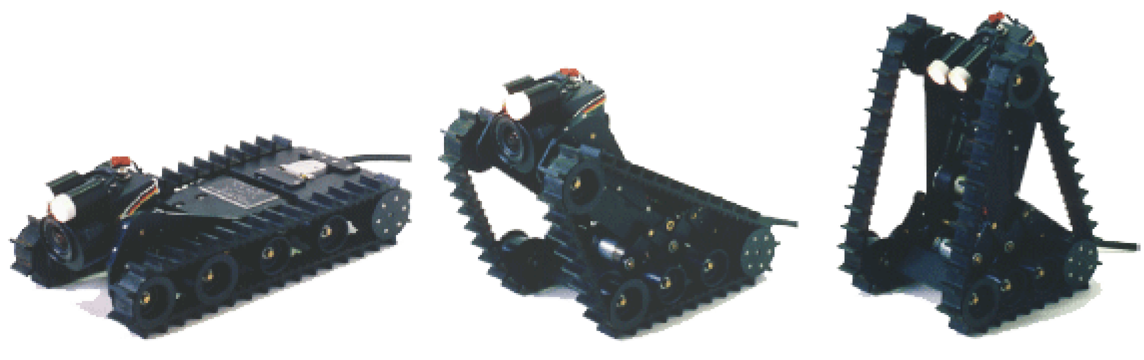

Figure 1: The original VGTV was designed for industrial pipe inspection and has the ability to "change its shape" depending on operational requirements.

Although this platform was not originally designed for difficult confined-space inspection, it has been adapted by ASR to this application through several significant mechanical improvements. First, the ground clearance of the robot was improved to allow the robot to transverse much more difficult terrain than previously possible. Second, the chassis and electrical connections were modified to allow the operator to quickly adapt new sensor payloads for the robot to carry. The ability to change sensor payloads in response to varying applications allows for a reduction in the robot's size and makes it possible to "tune" the platform to the mission requirements. This is vital to the usefulness of the robot since a single robot cannot carry all of the sensors for all potential applications. Finally, the chassis was designed to be waterproof up to 100ft. This allows the robot to be decontaminated easily in the field and keeps contaminates from damaging components.

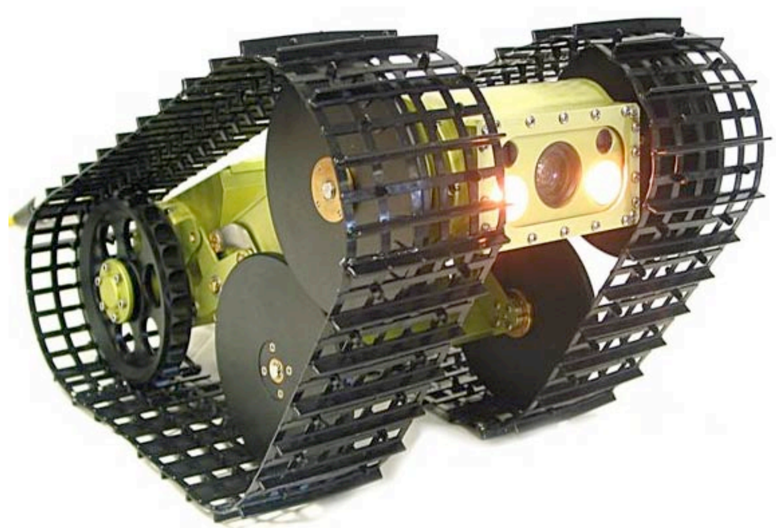

Figure 2: The redesigned VGTV-Xtreme is a capable robot for structural inspection tasks.

2.1 Forensic Engineering Requirements

The field demands for forensic engineering robots are unique and considerable. The following should be considered baseline requirement criteria when evaluating robot platforms for inspection tasks.

Camera - The robot must minimally provide a camera for visual inspection. This video must be able to be transmitted back to the operator and recorded for post-analysis and archival purposes. This camera system can optionally include zoom, wide-angle lenses, auto-focus, and thermal imaging capabilities. Interestingly, camera zoom and wide angle features can introduce visual errors in the video image. As a result the robot should employ active references such as laser sighting and size measurement aides. These features enable the engineer to conduct photogramitry.

Lights - Lighting must be carefully chosen based on the environmental hazards. Halogen lights provide the best luminosity and “throw” for low light environments. This is critical when zoom cameras are used to capture images in distant areas of the structure that the robot cannot reach. Unfortunately, Halogen lights operate at very high temperatures, so their use in potentially flammable environments is not ideal. LED or fully enclosed Halogen lights must be considered in these cases.

Audio - Two-way audio is a useful feature for communicating personnel inside of the confined space. This allows engineers and safety personnel outside of the confined space to monitor the progress of the inspection team and also allows senior engineering staff to guide the inspection tasks in real time.

Mobility – The robot must have a robust track or wheel system that will maximize traction in dirt, rock, and wet environments. It is ideal if the track system allows small material to pass through the track to minimize debris collection in the drive mechanism. In the event that the robot flips over, it is good to have a track system that allows inverted operation.

Flexibility - A final requirement is that the robot provides extensibility to the end user. In many cases, this can be as simple as extra wires in the communication tether for user supplied sensors and testing equipment. Examples might include metal thickness gauges, gas monitoring, manipulators or claws, and non-destructive testing sensors.

2.2 Specifications

The VGTV-Xtreme was designed with structural inspection specifically in mind. Figure 3 highlights some of the features and specifications of this equipment.

1. An Auto-focus 40:1 digital zoom camera provides high quality video in difficult lighting conditions and zoom capability allows precise inspection.

2. Camera tilt allows the user to look up, down, and even backwards while inspecting irregular confined spaces.

3. Simultaneous two-way audio allows the user to hear everything in the confined space including personnel.

4. 20W variable intensity lighting ensures that the user can optimize the amount of light injected into the space.

5. A shape-changing chassis allows the unit to be remotely optimized for pulling torque, climbing ability, and viewing height.

6. Multiple traction configurations allow flexibility based on mission requirements. High profile nylon tracks (shown here) provide maximum ground clearance and climbing ability. Optional low profile rubber tracks minimize robot profile for confined spaces and provide additional traction.

7. Up to 300 feet of high-strength tether is available for horizontal and vertical inspections. Tether sheathing minimizes friction and snags in the environment.

8. Self-aligning tracks maintain traction in the toughest environments. The robot can maneuver even while flipped over.

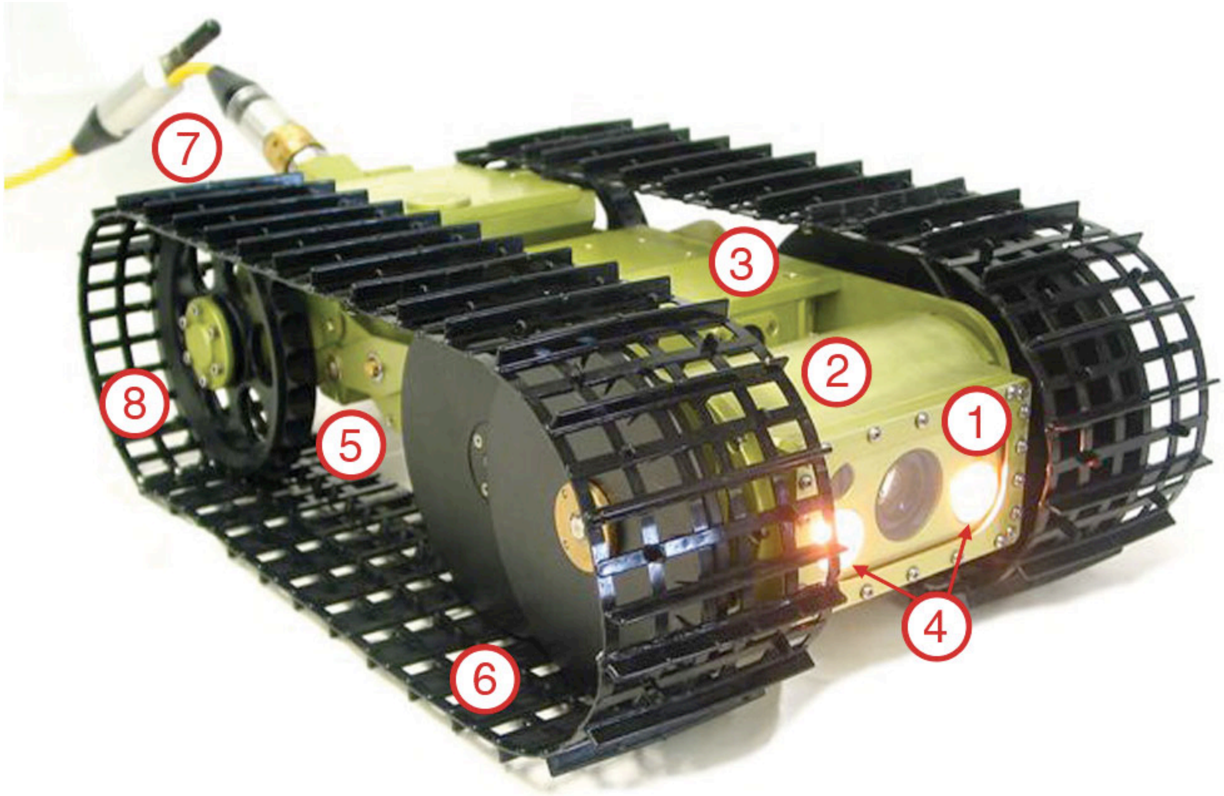

Figure 3: VGTV-Xtreme Robot for use in forensic engineering.

2.3 Operations

The robot is operated through a small operator control unit (OCU). This unit provides joystick control and a video display. Additional functionality for operations like tilt, camera zoom, and shape changing is provided with water resistant touch buttons on the control panel. Connections for power, tether, video, audio, and USB are located on the side of the unit.

Figure 4: Operator control unit for running the VGTV-Xtreme through a confined space.

This unit can be placed at the tailgate of a vehicle or virtually any stable horizontal surface at the work site. Typically a shaded and low-noise environment is ideal. This provides much higher clarity for the operator's video screen and audio.

3. Field Trials

The VGTV-Xtreme and its prototype-predecessor have been used in five contracted structural condition surveys. The following sections will highlight three of these surveys and the robot's contribution to the operation. While performing all of the inspections, a common operational theme emerged.

1. The engineering staff gives the robot operator an overview of the inspection task and a rough plan regarding how the robot might achieve these goals. This might include floor plans or an external survey of the building structure.

2. The robot is tested for operational readiness. Motor control, lights, camera, sensors, two-way audio, and video recording devices are verified before the robot is inserted into the confined space.

3. The robot is placed in the void and provides a pre-human inspection of the structure.

4. From the collected data, the senior engineer decides of the situation requires human inspection beyond the capability of the robot.

5. The inspection personnel are inserted into the confined space, closely followed by the robot. This provides visual confirmation to the outside crew that the inspection team is safe and operating within required inspection procedure guidelines. Additionally, two-way audio allows the team to talk to the outside team as if they were also within the confined space. This eliminates the need for error-prone radio communication through walkie-talkies or cellular phones.

6. Finally, upon completion of the inspection task the video is transferred to digital photographs and cataloged with the final engineering report.

3.1 Trial 1

The first trial was an inspection of a residence that had reported mold odors emanating from below the structure. The house had a raised floor and seemed to have sufficient ventilation for human entry. In this case, an early prototype of the VGTV-Xtreme was selected to perform a pre-survey of the structure and video tape the inspection.

The robot and operator control unit was set up outside the structure immediately adjacent to a crawlspace access. The robot was able to crawl into the void easily and the operator quickly observed the large about of dust that was created when the robot disturbed the dirt. This quickly indicated relatively low moisture content in the crawlspace.

The engineer then began to guide the robot operator through the underside of the sub-floor. This was to document the style of construction and approximate the age of the house. At a far corner of the house, a large drain pipe was noticed with discoloration of the soil below. The operator maneuvered the robot over to this area and it was immediately determined that there had been previous water damage to the sub-floor around this drain pipe. Mold and deteriorated wood was easily seen by the robot and confirmed the location of interest.

At this point, the engineering team had determined that the house was structurally sound and the location of damage. It was decided that two engineers would proceed into the crawlspace for first-hand inspection of the damage. Upon entering the space, the two engineers found themselves interacting with the robot as an active member of their team, asking the robot operator to "come take a look at this" and "can you get a picture of this joist". The robot was able to provide clear audio and video to the property owner and give them a first-person view of the damage that had occurred.

This first trial was significant for several reasons. It showed that the robot did have the ability to quickly identify problems within a structure. Contextual clues such as humidity (derived from dust) can give quick "hints" regarding the state of the confined space. The inspection team was able to communicate with the above-ground robot operator and property owner, giving them a play-by-play account of everything that occurred. Finally, the entire operation was digitally recorded for future analysis and reporting.

Figure 5: (Left) VGTV-Xtreme ready to explore the underside of a house to determine if engineers need to enter. (Right) The robot quickly identifies water damage to the sub-floor.

3.2 Trial 2

During the second field trial, the engineers were required to inspect a residence that was potentially suffering from sinkhole. The crawl space was extremely confined and there was little ventilation in the sub-floor. It was known that the house had been expanded several times, so a detailed sub-floor plan was not available.

The robot was set up within the living space of the house adjacent the point of entry so that the operator could operate the OCU and recording unit. A floor access space in the pantry allowed the robot to be quickly inserted into the sub-floor. The operator first noted that the HVAC ductwork was running through this sub-floor area and would significantly hamper the robots access to the extremities of the house. The operator also noticed that there was not a large amount of dust in the air despite the robot's movements. This indicated a high moisture level below the floor. A quick look around the robot confirmed that moisture was present due to rotting wood.

The robot then attempted to move toward the area of damage. Within 6 feet of the robot's initial position, a large HVAC duct was blocking the path. All attempts to circumvent this problem failed due to the sheer height of the duct compared to the robot. At this point, the senior engineer decided that human intervention was needed and the inspection engineer prepared to enter the space. Upon lowering himself below the floor, the engineer immediately noted the high moisture content in the air and surrounding soil. The engineer crawled to the robot and lifted it over the HVAC duct. He also climbed past this obstruction and the two slowly made their way to the damaged area. Interestingly, throughout this exercise, the engineer could talk through the robot as if it was an active member of his inspection team. As they progressed, he was able to ask questions of the residence owner and receive immediate replies.

The engineer reached a point where he could no longer continue forward due to pipes and other obstructions. Fortunately, he was able to help the robot push forward further into the structure and collect the necessary data.

This trial was unique in that it showed a tradeoff of abilities between the inspection engineer and the robot. First, the robot showed that the space was physically safe and required human inspection. Then the human was able to help the robot get past obstacles that it could not negotiate by itself. Finally, when the human approached an impasse, the robot was able to continue forward and complete the structural survey.

Figure 6: (Left) Operator and engineer do a rapid assessment of the sub-floor. (Right) The engineer helps the VGTV-Xtreme explore spaces he cannot reach.

3.3 Trial 3

The third field trial was a residence that suffered a partial collapse of the floor. The cause was not immediately known, but a sinkhole was suspected. This south Florida home had no ventilation for the sub-floor and no access. As a result, a contractor cut an opening in the floor adjacent to the problem area to be inspected. Atmospheric hazards associated with this closed airspace combined with the physical hazards of the collapse area made this an ideal candidate for robot inspection assistance.

The robot was lowered into the void and it was quickly noted that there was a large amount of debris immediately under the collapse area. Additionally, when the robot looked up, mold was attached to virtually every wood surface. This indicated high moisture content. The robot crawled over to the lowest part of the debris field and was able to look up to the floor joists. A large crack in the supporting 2x8 was immediately observed by the engineering team as the cause of the collapse. Since the surrounding supports appeared to be in good condition, it was determined that the inspection engineer could safely enter the sub-floor for manual inspection.

As in previous trials, the robot followed the engineer through the inspection. Since the sub-floor was compromised, the robot was able to allow the senior engineer to follow the progress of the inspection and monitor safety. Additionally, as the engineer recorded moisture levels of the wood he was able to dictate these readings to the senior engineer.

This trial showed the robot's ability to quickly identify the source of the problem and give the safety manager information regarding the dangers that the inspection team might face. In this case, the source of the collapse was identified and the damage was not significant enough to render the sub floor unsafe for human occupancy. While the inspection engineer was in the space, the robot was able to continue providing an information pathway to the safety manager.

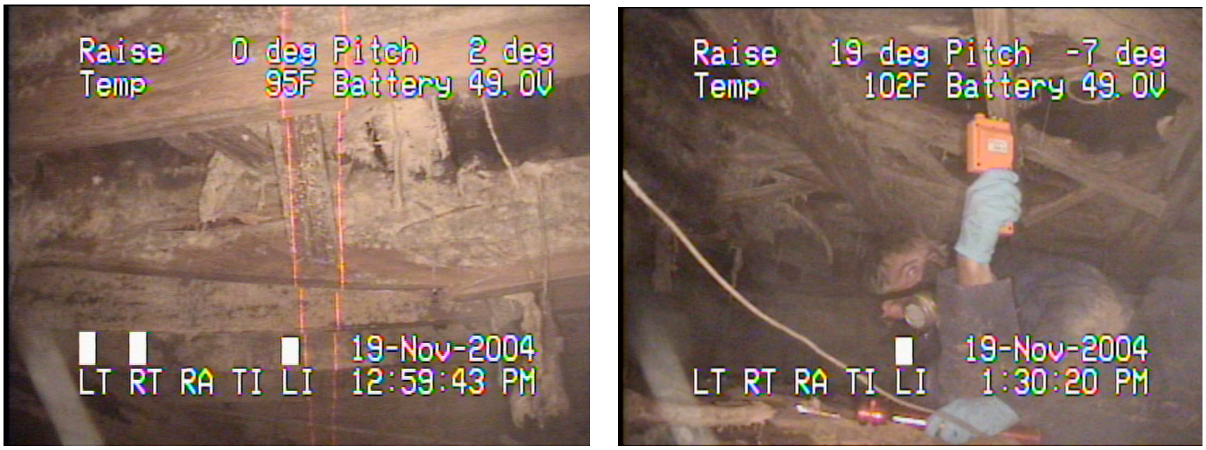

Figure 7: (Left) The robot notices two significant cracks in the supporting 2x8 structures. (Right) A safety officer above the floor observes the inspection engineer working as the VGTV-Xtreme records the inspection.

4. General Protocols

As a result of the trials performed, it has been found that the usefulness of the robot can be maximized by breaking the deployment into three phases. These are initial reconnaissance, inspection assistance, and deployment record. In the first stage, the initial reconnaissance is an information gathering stage. Information gathering related to safety and structural integrity is paramount. Additionally, observed humidity levels and rapid assessments of damaged areas can be performed. The second stage involves following the engineer into the confined space. If this is accompanied with two-way communication, active monitoring of the situation can occur. Finally, the robot can be used as a remote camera to record the inspection and act as either a dictation tool or a photogramitry for the engineer.

4.1 Initial Reconnaissance

During this phase the robot is used to survey the environment so as to establish if an environment is safe to enter or if additional safety measures are required. This phase begins with the engineer establishing the best point of entry with respect to the point of interest. It should be noted that the best point of entry is not always the closest point of entry. The engineer must consider obstructions, methods of access and potential hazards.

Once the point of entry is established the robot is deployed. Immediately upon deployment, the engineer and operator work in tandem to navigate and interpret conditions. When necessary the point of entry or method of deployment are reevaluated and modified. As the data is collected conditions are better defined and a decision on deploying the inspecting engineer is made. This phase also serves to establish if additional safety measures and equipment are required.

4.2 Inspection Assistance

Throughout this phase the robot serves as the deployed engineers safe second. The robot enables the deployed engineer to communicate thoughts and impressions as well to obtain additional information from outside of the affected area. Perhaps the best use of this two-way information exchange would be in a collapse scenario where the deployed engineer is able to correlate interior structural observation with the exterior monitoring observations. The robot also provides those outside of the affected area the ability to view real-time conditions as well as the safety of the deployed engineer.

4.3 Deployment Record

Environments best suited to the use of robots are not well suited to notating conditions by conventional means. Therefore the use of recorded two-way audio proves invaluable at capturing the thoughts and impressions of the deployed engineer. The use of digital video through this inspection process provides several key advantages

1. The recorded digital video can be post-analyzed by engineers outside of the field team. In many cases, the inspection team will miss details since they are under the stress of confined space PPE and low light conditions.

2. Because the video typically records at 30 frames per second, a highly detailed record of the surroundings is created. In many cases, details can be extrapolated from video shot “in passing” that would have otherwise been missed.

3. The digital video or photographs can easily be transmitted to specialists via internet or mail for detailed analysis.

4. The video record is a good way of allowing the inspection team to dictate what they are seeing and measuring. It is useful to remind the inspection team to talk out loud and record their data gathering so that it can be reconstructed if manually collected data is corrupted or destroyed.

5. Conclusions

The use of robots for conducting structural condition surveys is a relatively new technique. We have found that their use in extremely confined spaces is invaluable, but surprisingly, the robots are also highly useful in human-sized confined spaces. While only general protocols have been developed for this domain, the applicability of this equipment and the benefits that result are significant. Robots can quickly identify and quantify the extent of damage and hazards to personnel. As seen in the trials, real-time photogramitry and digital recording gives the engineering team a significant tool for field-analyzing, post processing, and archival purposes. Our qualitative observation is that this equipment will maintain a safer work environment for inspection personnel and provide a higher quality product to our customers.