Evolution and Field Performance of a Rescue Robot

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Abstract

Robots are slowly finding their way into the hands of search and rescue groups. One of the robots contributing to this effort is the Inuktun VGTV-Xtreme series by American Standard Robotics. This capable robot is one of the only robots engineered specifically for the search and rescue domain. This paper describes the adaptation of the VGTV platform from an industrial inspection robot into a capable and versatile search and rescue robot. These adaptations were based on growing requirements established by rescue groups, academic research, and extensive field trials. A narrative description of a successful search of a damaged building during the aftermath of Hurricane Katrina is included to support these claims. Finally, lessons learned from these deployments and guidelines for future robot development is discussed.

1 Introduction

Hurricane Katrina was the first Category 5 hurricane of the 2005 Atlantic hurricane season. The hurricane's eye made landfall at 6:10 AM CDT on Monday, August 29. The 145 mph sustained winds and the strong northeastern quadrant of the storm pushed record storm surges onshore smashing the entire Mississippi Gulf Coast. Florida Task Force Three (FLTF3) answered a request for aid from Biloxi, Mississippi. This sixty-three member team, pre-staged in the west Florida panhandle, responded with an arsenal of personnel and equipment from the Tampa Bay area.

Included in the cache of equipment was a newly developed variable geometry tracked vehicle (VGTV) manufactured by Inuktun Services Ltd. and American Standard Robotics. This robot platform and its predecessors have been an available resource for FLTF3 for more than five years. Through training exercises and continual feedback from search and rescue specialists, the platform has become a valuable tool for the search team.

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The iterative re-design of the VGTV robot has not been a quick, easy, or straight path. The original VGTV began as a small robot for industrial inspection. More than five years of academic and commercial development was invested in this platform due to its adaptive polymorphic chassis. The chassis (described in more detail in Section 3) was unique since it allowed the robot to adjust itself to the environment. This was ideal for unstructured environments, but other factors limited its usability in search and rescue. Through careful field analysis and the formulation of requirements, the VGTV matured into a robot cable of a "front to back door" search of a partially collapsed building. It demonstrated its capability in an apartment ravaged by the storm surge caused by Hurricane Katrina.

This paper is organized as follows. First a brief history of past live robot deployments is given, including the World Trade Center Disaster and the lessons learned. The impact on the re-design of the VGTV is then given along with a description of the VGTV-Xtreme's new capabilities. A post-hoc narrative describing the events of the Hurricane Katrina apartment building reconnaissance is provided and the lessons learned from this deployment are presented.

It should be noted that the description of the deployments herein is not a formalized data collection, but rather a narrative data set from a live search and rescue operation. This data was not procedurally recorded, is not reproducible, and is not statistically significant. That said, few papers of this type have been published for the research community. It is an unstructured data set that is extracted from digital video recorded in a highly disorganized environment. This analysis and the conclusions herein should only be considered the conjectures and opinions of the operator in an effort to produce improved guidance for future robot design and performance evaluation tools.

2 Background

Urban search and rescue (USAR) robots have a relatively short history and their use is relatively new. Inuktun Services Ltd. conducted the first documented investigation of using robots for search and rescue in 1993. Although academic interest in this application of robots dates back to the 1995 Oklahoma City Bombing and Kobe Japan Earthquakes, the first documented use of robots at a search and rescue site was shortly after September 11, 2001 in the aftermath of the World Trade Center (WTC) disaster. Retired Lt. Col. John Blitch led military, commercial, and academic robotic groups from around the nation to assist in the response effort. Although the robots used in the search were not originally designed for USAR, their successful performance during the response proved the robots' value as tools in USAR incidents. As with any first time event, difficulties and relationships within the environment were identified. This provided a baseline for future development of search and rescue robots.

2.1 World Trade Center Disaster (2001)

Many lessons were learned through using Inuktun robots during the World Trade Center disaster. From these lessons, seven stood out as critical to the short and long term success of robots in search and rescue. Without addressing these critical design changes, the rescue community would not accept these as true "tools" in their cache of supplies. These lessons became the focus of the VGTV's development after the World Trade disaster. For details on lessons learned, refer to (Micire, 2002) (Casper, 2002) (Blackburn et al., 2002) (Blitch, 2003) (Murphy, 2003).

The seven critical design changes were as follows (Casper et al., 2004):

A deployment system is needed. One of the most valuable lessons learned at the WTC disaster was the need for the robots and their accessories to be man-packable and quickly deployable. The packability of a robot is its ability to be carried on the body of the operator, or operators, who will be performing the search. The deployability is the ease and amount of time that it takes the robot system to go from a packed state to full deployment. The Inuktun robots were initially packed in hard shell cases. The weight and the awkwardness of these cases made their use unfeasible once it was determined how far the equipment had to be carried into the rubble pile before even deploying it. As a temporary solution, personal backpacks were sacrificed to use in transporting the Inuktun robots.

An auto focus camera with zoom capability is needed. The robots were equipped with a manual focus camera, requiring the operator to spend precious time focusing the camera. During the second deployment, an Inuktun MicroTracs reached a point in the void where it could not pass due to an obstruction. The void looked as though it may have opened up beyond the stopping point. A camera zoom would have been useful to see beyond the area where the robot was resting.

A longer tether with the strength to withstand tension is needed. The Inuktun robots were equipped with a 100-foot tether. The tether was used to lower the robots into voids, despite not being rated for such activities. There were instances when the tether was used to its ultimate length. The void explored during the fourth WTC deployment was a near vertical drop. The second operator had to keep constant tension on the tether to keep the robot stable for returning video.

An adjustable body clearance is needed. The robots operated in rubble varying from pebble sized pieces to tennis ball sized debris. It was common for an object to get caught under the belly of the robot. This caused the robot to get hung up and prevented it from maneuvering. The low ground clearance on the chassis was the main contributor to this failure. This decreased deployment mobility and search efficiency hampered the operation.

Multiple types of tracks to handle varied surfaces are needed. The robots were subject to wheel slippage in the environments in which they operated. Wheel slippage occurred when the wheels were not making sufficient contact with the travel surface. This problem was determined by two factors: the robots tracks and the surface on which the robot was traveling. Unfortunately, the only way to decrease this value was to increase the robot's traction with the traveling surface since the environment could not be changed. Possible avenues for improvement are more flexible tracks and better surface area.

A track mechanism preventing track derailment is needed. During a deployment at the WTC, the Inuktun VGTV lost its track while inspecting a void deep within the rubble pile. The track derailment may have been due to the heat in the void softening the track. The derailment deemed the robot immobile and no longer useful for inspection. A track mechanism designed to secure the track is needed to prevent losing precious time recovering from a derailment.

A waterproofing of the robots is needed. The Inuktun robots were not effectively decontaminated after running in the rubble pile. Disaster environments are not clean. The World Trade Towers were fully functional buildings with both water and septic systems. The rubble pile encompassing the towers contained a large amount of bio-hazard materials and chemicals. During deployments, the Inuktun robots ran through this material. To prevent spreading contamination, the operators wiped down the robots and tether as thoroughly as possible. The best way to decontaminate the robots would have been to submerge them in a 10% bleach solution. The robots would need to be waterproofed to survive this kind of cleaning (Casper et al., 2004).

These lessons became requirements during the re-design of the VGTV. The VGTV had proven its potential on the rubble pile, but since virtually every VGTV failed during the deployments, clearly it was not a mature platform. To the credit of the original designers, this robot was never designed for such a radically unstructured environment. This became the impetus for the VGTV-Xtreme. The VGTV-Xtreme's features and development will be described more completely in Section 3. While the VGTV-Xtreme was available to the technical search specialists of FLTF3 and Center for Robot Assisted Search and Rescue (CRASAR) during the 2004 and 2005 hurricane seasons, it would not see another deployment until the 2005 La Conchita Mudslides.

2.2 La Conchita Mudslides (2005)

Weeks of constant rain lead to a massive mudslide in the oceanfront community of La Conchita, California on January 10, 2005. Approximately 500,000 tons of mud released from an unstable hillside above a residential community, burying 15 homes and killing 10 people. On January 11, CRASAR was deployed by the Los Angeles County Fire Department to assist in the search and rescue effort (Murphy and Stover, 2005). The group brought two VGTV-Xtreme robots to the site with expectations of searching the damaged houses deemed too dangerous for human entry.

The VGTV-Xtreme was unsuccessfully used during the 2005 La Conchita Mudslides. During this deployment, the VGTV-Xtreme was inserted into two separate houses that had been structurally damaged by the mudslides. In both cases, the robot was unable to travel far into the structure. In fact, the performance was found to be no better than could be achieved with a simple human operated pole camera. The problem was the tracks fell off the robot. Although this was a relatively benign environment, the robot was unable to operate for more than a total of ten minutes (Murphy and Stover, 2005).

Although the La Conchita deployment was considered a failure by most measures, it reinforced a critical lesson learned from the World Trade Center. The track system must be robust and virtually impossible to de-track. If the robot loses its mobility, it is of little use to the search task. Additionally, the robot may not be recovered once it loses its ability to move within the damaged structure.

3 VGTV Evolution

The development of the VGTV is unique in that it does not derive its heritage from military or explosive ordinance robots. The iRobot Packbot, Foster Miller Tallon, and Remotec Andros are examples of such military based platforms that have attempted to cross over into the search and rescue domain. Conversely, the VGTV was originally designed for industrial and air conditioning duct inspection. These indoor environments are typically clean and unobstructed which is very different from those of collapsed structures. On the other hand, its small size and polymorphic shape-changing abilities made the VGTV robot extremely capable in confined spaces. As such, the VGTV had some unique features that could be exploited for search and rescue.

The VGTV's unique design allows the chassis to change shape during operation. The tracks take the shape of a conventional crawler in its lowered configuration, as seen on the left in Figure 1. This configuration provides stability and increased traction. The VGTV can also be raised into a triangular configuration, seen on the right in Figure 1, providing the camera a higher vantage point from which to observe the surroundings. Between these extremes, the profile of the tracks allows the robot to climb onto obstacles. The crawler remains fully operational throughout these shape changes and allows the operator to position the vehicle in any intermediate position.

The need for variable geometry is quickly exposed when operating in the field. Namely, the environment is not going to change significantly for the robot; the robot needs to be able to adjust to the environment. For example, if the traction surface is wet carpet, then the robot must lessen its traction surface to allow smooth turning. If the traction surface is slick wet floor tile, then it must increase the traction surface to maintain mobility. As stated above,

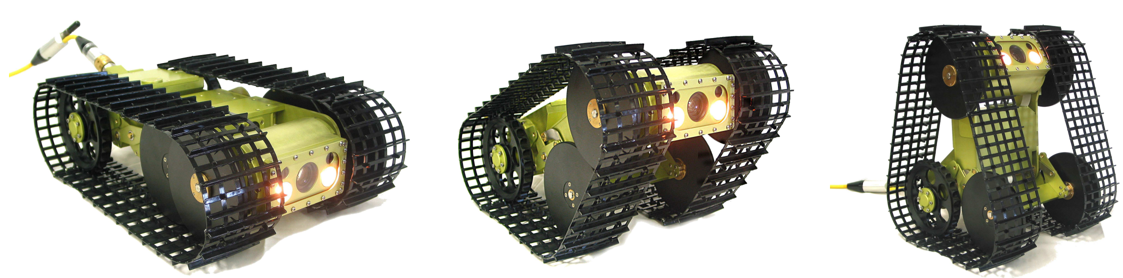

Figure 1: Photos of the VGTV in its three main positions. In the lowest position (left), the crawler has good traction but lacks a high vantage point and climbing ability. In the middle position (center), the robot has good climbing ability but has sacrificed traction surface. The top position (right) provides the highest vantage point but suffers from a high center of gravity.

the need for flexibility in geometry has been empirically shown to be important for camera height, robot height, climbing ability, and center of gravity.

The VGTV uses a forward-facing camera on a tilt unit for video and bi-directional audio for sound transmission. Movement is facilitated through the use of a dual tank-style traction belt system and two motors. This allows for differential steering and maximized traction while the robot negotiates small obstacles.

While the VGTV is fully competent in its intended domain, the main limitations are related to the track system. This accounted for three of the seven limitations found at the WTC. Concentrating on just the tracks, the problems in Table 1 were identified.

Table 1: Problems identified with the original VTGV track design for USAR applications.

Original VGTV	**Limitation of original design**
Tracks adapted from traditional timing belts	The solid nature of this belt material does not give debris sufficient opportunity to leave the drive system before it is pulled into the drive pulley mechanism. This contaminates the belt lugs and can often lodge debris sufficiently large enough to stop the belt and forward motion.
Traditional timing pulleys used for belt drive	Each of the lug grooves and the outer flange provides no means for the departure of debris from the drive pulley. Mud and soft dirt quickly become packed into the grooves, effectively eliminating the pulley's ability to move the track belt. This slippage eventually stops forward motion.
Ground clearance of 5/8 inch regardless of configuration	The chassis of the crawler easily becomes snagged on items in the environment such as rocks, sticks, or uneven terrain. Debris underneath the chassis accumulates and eventually stops forward movement resulting in the crawler's inability to regain sufficient traction to free itself under its own power.
Crawler cannot operate while inverted	If the crawler is flipped over during its use, there is no way for the crawler to operate in an inverted position. This will prevent the user from correcting the inversion without manually removing the crawler from the environment or dragging it out, upside down, via the tether.
Inability of the track to flex on uneven surfaces	Uneven terrain and culvert pipes pose a problem for this design, as the tracks do not laterally flex to match the terrain. In culvert pipes, for instance, the tracks remain parallel to the chassis surface. This is sub-optimal, as the surface beneath the track is actually at an angle to the chassis. This configuration greatly reduces the vehicle's traction and can cause it to become stuck.
No self centering or self aligning track	Once the track deviates from the flange-guided position, it will continue to "walk off" the pulley and subsequently become wholly disconnected from the chassis.

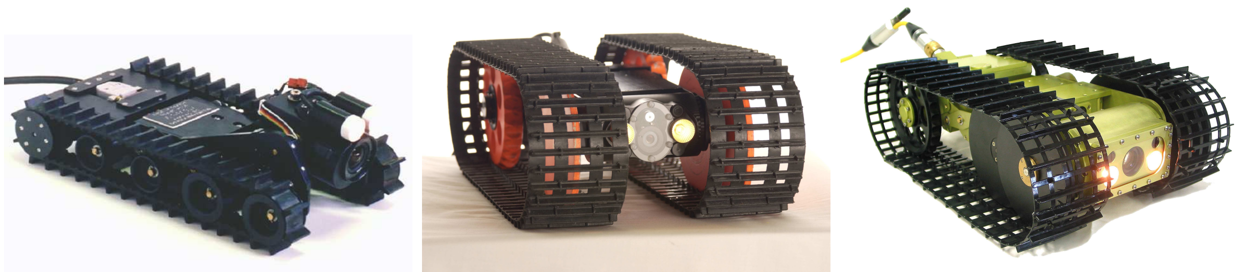

Figure 2: Photos showing the iterative growth of the Inuktun VGTV. The original design (left) was created for industrial and air conditioner duct inspection. This was adapted to search and rescue by American Standard Robotics through a prototype (center) and later in the waterproof VGTV-Xtreme production model (right).

Redesigning the track and pulley mechanism to operate optimally in unstructured and contaminated environments was critically needed. The improved system uses an open-sprocket, dual-track, differential steering system. This track system passively moves debris and materials through track openings spaced evenly throughout the track. Additionally, the rear drive spoke does not accumulate debris in the spoke groove, and actively removes packed material through normal forward or reverse movement of the track.

The re-design of this track system increases the ground clearance of the crawler from 5/8 inch to two inches. This design change uses the novel approach of interleaving the two front idler wheels. This maximizes the size of the wheel diameter, while retaining the shape-changing capabilities of the chassis. Prior to this approach, the largest wheel diameter conceivable for this crawler was 2.75 inches in diameter. Five-inch diameter or larger wheels are now possible. In addition, the crawler can operate in an inverted position, although the ground clearance is less than in the upright configuration.

Finally, the centralized position of the guide wheels allows for passive optimization of traction. The track is able to flex so that the weight of the crawler chassis bends the track to meet the traction surface. The surface contact area of the tracks increases and passively maximizes the friction with the ground surface. The angled nature of the dual rear drive spokes, combined with the positioning of the spokes on the belt's center, also helps to ensure that the track will self-align if it becomes dislodged from the drive mechanism.

The new track mechanism solved three of the seven recommendations described in Section 2.1. The robot was redesigned to withstand three atmospheres of static water pressure (approximately 100-foot depth rating). This was not done with the intent of submerging the robot, although the robot has since been tested at ocean depths of up to 70 feet. Rather, the three atmospheres static water pressure rating approximates what the robot might see from the dynamic pressure of a hose during decontamination. The pressure rating was empirically found using increasing static pressure calculations and then tested against the much more complex "real world" dynamic pressure. This satisfied the waterproofing requirement sufficiently and provided for rapid field decontamination.

A high quality Sony NTSC camera with auto-focus and zoom capability was fitted into the head of the robot. With the addition of a pair of sealed 10W halogen lights, the robot could now see further into the rubble eliminating the need to manually focus the camera. It should be noted that the operator was given the ability to override the auto-focus at any time. Mud on the protective glass or dust in the environment can often confuse the auto-focus mechanism in the camera. Finally, the tether was extended to a maximum of 300 feet to provide long deployment runs. Since the robot had larger wheels and tracks, motors sufficiently strong to pull all 300 feet of tether were used. This is a considerable task for a robot of this size. At 300 feet, the weight of the copper tether begins to approach the weight of the robot, approximately fourteen pounds.

The final addition to the VGTV system was a deployment system. The configuration found to be most useful is based on the "LA Rescue Speed Gear" field harness system used by Federal Emergency Management Agency (FEMA) USAR groups. This system uses a central harness from which additional bags are hung. In the robot's case, a custom bag is made to connect to the back of the harness, creating a standard backpack configuration. This places the bulk of the robot's weight ergonomically on the operator's shoulders and upper back. The batteries, operator control unit (OCU), and accessories are then hung from the waist belt. The tether is packed into a rope bag in much the same way as a rappelling rope. This allows the free, unattended flow of tether out of the bag as the robot pulls on it. Finally, this system compliments the gear already used by FEMA search and rescue teams. Therefore, any gear operators were currently using required little reconfiguration. The complete system, including robot, OCU, and harness can be seen in Figure 3.

Figure 3: Backpack harness used by the VGTV-Xtreme USAR system. Based on the same harness used by the Federal Emergency Management Agency's USAR teams, this configuration provides a good balance of portability and deployment time.

After solving all seven problems from the WTC disaster, the newly named VGTV-Xtreme then went into testing. Over the next year and a half, the robot was used in training exercises, academic research, and the one failed deployment at La Conchita (Murphy and Stover, 2005) to expose further problems and design tweaks. It remained an active asset to Florida Task Force Three and was transported to all of the 2004 and early 2005 hurricanes. It was not until Hurricane Katrina on Monday, August 29, 2005, that the VGTV-Xtreme would see its first successful live mission.

4 Deployment

After the landfall of Hurricane Katrina, the VGTV-Xtreme was used to search two damaged building structures in Biloxi, Mississippi. The first was an apartment complex at the corner of Bayview Avenue and Matre Pitalo Drive North on the north side of the Biloxi Peninsula. The second building was a residence on Beach Boulevard on the south side of the Biloxi Peninsula. Unfortunately, all video documentation of the second building search was lost and, as such, is not included in this narrative. It should be noted that the performance of the robot in the second building search was as successful as the one described below.

Approximately 11:30 AM EST on September 1, the technical search specialist was called forward and robot equipment was requested for a search of an unstable structure. The search specialist gathered the backpack containing the robot, battery, cable, and recording devices that were pre-staged in the back of one of the team's automobiles. When the operator arrived at the forward team, the robot's role became very clear.

An apartment complex ravaged by the ten-foot storm surge was leaning precariously throughout the first floor levels, shown in Figure 4. Pushed by water and waves, an automobile had crashed through an exterior wall, removing the supporting beams and most of the wall covering. Directly above this gaping hole, the second floor of the building had begun to collapse, and it hung unsupported from the front wall of the structure. Gas leaks and the unstable nature of this structure caused the structural engineers and safety personnel to deem it unsafe for personnel or canine entry earlier in the day. Deceased victims in other areas of the apartment complex caused the command staff to reconsider this decision. The robot was tasked with a preliminary search to determine if shoring should be used to stabilize the building. The shoring would allow human and canine responders to search the structure in relative safety, but required significant time to construct.

First, utility personnel first crimped the gas line leading to this building to eliminate the natural gas that could be heard leaking from supply lines. The robot was waterproof and completely sealed from the outside atmosphere, but it was not intrinsically safe or bomb proof. This made the gas shut-off a critical step in the search process. The slightest spark or even static electricity could cause the gas to ignite under the correct air mixture conditions. Additionally, if the robot were to fall and break the glass covering the halogen lights in the head, a ready ignition source would be present, capable of causing a dangerous explosion.

Before the robot was staged outside of the structure, the command and safety personnel made it very clear to the operator that the robot must complete its task without failure or

Figure 4: Apartment building damaged by the storm surge, debris, and an automobile during Hurricane Katrina. Notice that the front of the building is structurally compromised and the second floor is partially collapsed. Buildings like this are ideal candidates for robot-assisted search since human search is dangerous at best.

entrapment. If the robot should fail, break, or become unable to leave the structure under its own power, the robot would be abandoned and left in the apartment for recovery when the building was demolished. Needless to say, the robot likely would be crushed and damaged in this demolition. This weighed heavily on the operator since this was the only robot available to FLTF3 for the duration of the deployment. If the robot were lost, the only technical search camera equipment available would be the pole camera systems.

4.1 First Building, First Robot Search

The goal of this search was to survey the area that was difficult to see behind the damaged automobile. The former living room or bedroom had a hallway at the rear that connected it to the other rooms in the apartment. It was thought that the hallway might provide easy entry into the other areas. Ultimately, the operator was tasked with getting as far as possible into the structure in the limited time between team-level searches. During this robot search, the rest of the team was taking a break. The operator was informed he had approximately thirty minutes to complete the task before they moved to the next search grid.

The robot was pre-staged on the northeast corner where the wall had been cleared from the structure. The automobile that had been pushed through the wall obstructed much of this view. This became an initial point of interest for the search specialists. The robot was unpacked and the tether was connected between the OCU and the robot. A structural specialist carried the robot to the corner of the structure and placed it on the concrete foundation of the building.

First, the robot operator traveled to the furthest point possible, in a straight line, inside the structure. This technique has several advantages. First, it maximizes the pulling power of the robot since turns will increase friction on the tether. By going to the furthest point, the operator needs to worry only about moving the tether within the structure opposed to constantly pulling new tether from outside. Also, the operator knew that there was a automobile directly between the OCU and the area that needed to be searched. Rubber tires are extremely problematic for tethers since friction increases if the tether becomes wedged under the wheel. The robot traveled to the far interior wall and easily made the turn around the automobile without snagging.

The operator noted that many of the interior walls of this apartment had been completely washed out by storm surge. During the hurricane, the drywall and plaster dissolved and gave way under the extreme forces of the waves and floating debris. This left the 2x4 studs of the inner walls exposed allowing the robot to see other rooms of the apartment even from its low vantage point. Interestingly, most of the debris left in the house was large bedding, couches, and appliances. Items less than 16 inches wide were washed through the walls, so even though the robot was able to essentially "see through walls," all the debris that was left was far too large to move or climb over.

The operator took care to observe everything that could be seen through the debris. After completing a quick search, the operator noticed that the hallway leading to the rear of the apartment was blocked by a mattress lying on the ground. For the VGTV Extreme, this was a considerable obstacle. He maneuvered from the side to the front of the mattress to see if there was a possibility of climbing up onto the mattress. Part of an aluminum door and some scrap wood were positioned at the corner of the mattress. This could provide a "ramp" for the robot to use to get up onto the mattress and raise its vantage point by approximately six inches. The robot could then climb off the other end of the mattress and continue searching further into the structure.

While this seemed possible, the maneuver also had three considerable risks. First, the ramp was very close to the edge of the mattress. If the operator did not carefully center the robot on the ramp and place all of the track surface on the mattress, there was a significant chance that the robot would slip sideways off the mattress and onto its side. This would be a dangerous position for the robot since it would likely be unable to free itself from the debris while trapped on the side of its tracks. Second, the mattress would create an extremely high traction surface. This particular robot had de-tracking issues in earlier deployments (Murphy and Stover, 2005), so this wet-cloth material posed a particularly risky situation.

Figure 5: Photos of the VGTV inside the partially collapsed apartment. The view from the insertion point showed that the walls had been destroyed and heavy appliances piled up on the wall studs. (Left) The robot was required to climb up on a mattress (center) to achieve the higher vantage point (left) during this search.

While turning on this surface, if the robot de-tracked, it would be extremely difficult or impossible for it to drive out of the structure under its own power. Finally, the mattress did not provide a stable surface. If the robot configured itself for a high perspective, the high center of gravity might tip it over causing the robot to have a difficult time recovering, depending on how it landed.

Taking all of this into consideration, the operator decided that the higher vantage point would be worth the risks. The robot was carefully positioned at the end of the ramp. The operator then drove the robot up the ramp keeping a steering bias to the right of the mattress. This guaranteed that if the left track slipped, the robot would not quickly steer too far left and fall off into the debris below. The robot was kept fully flat, which is the configuration that maintains the lowest possible center of gravity. The robot climbed to the top of the ramp and managed to get onto the mattress surface.

Then the operator raised the robot to an approximate 40 degree configuration. This mid-height configuration provided a slightly raised vantage point and reduced the traction that the robot had with the mattress. An overturned fold-away couch could be seen several feet in front of the mattress. Children tend to hide underneath couches and beds during disasters and house fires, so this area was searched carefully for any signs of human features. The zoom and light features of the robot helped cast light into the areas of interest. Finding nothing, the robot was turned to look down the rest of the hallway. The operator carefully raised the robot up to 75 degrees to see over a 2x4 that was blocking the view. Piles of soft wet carpet, clothing, and bedding littered the rest of the hallway. He could see that the hall turned right after approximately 10 more feet, and the debris field extended to the end of this portion of the hallway.

Moving forward into the structure from this point would be a risky proposition at best. The operator could not see if there were any "ramps" or opportunistically positioned debris that would allow the robot to return to the mattress once it dropped off the other side. Once the robot dropped off the other side, there would be no way to recover the robot by pulling on the tether because the automobile's rubber tires would bind up the tether. The structural specialist advised the operator that there was a possible entry from another point in the structure, allowing this area to be approached from another angle.

The operator was now presented with the task of exiting the structure. At full height, the robot was extremely unstable. Yet, the operator found this to be the quickest way to turn the robot on the high friction surface. The "trick" was to move the robot forward and rock it back on the rear drive wheels. While the robot proverbially "popped a wheelie," the operator turned the robot slightly. (This would be analogous to someone in a manual wheelchair leaning the chair back and turning without the front wheels touching the ground.) The operator constantly monitored the pitch indicator on the screen to make sure that the robot did not exceed a -15 degree pitch. Much past -15 degrees, and the robot was likely to flip onto its back.

The turning maneuver was repeated a dozen times until the tether of the robot could be seen, providing a guide for exiting the structure. This is a technique adapted from firefighting. If the firefighters cannot see anything else, the fire-hose always leads them out of the building and back to the truck. In this situation, the robot only needs to find its own tether to be provided with a path out of the building and back to the operator. The operator lowered the robot back to the fully-flat position and drove off the the mattress without incident. The robot proceeded down the path provided by the tether. On the way out, a quick look under the damaged automobile ensured that there were no search targets hidden under the chassis.

The robot drove to the corner of the structure's foundation and was quickly recovered for insertion into the structure from another entry point. This eight-minute deployment yielded only a small percentage of the first floor of this structure, so time was critical.

4.2 First Building, Second Robot Search

Within five minutes, the operator moved both the robot and the OCU and set up at the second entry location. The front door to the apartment had been destroyed. It was thought that the robot could enter through the front door and penetrate deep into the structure. The structural specialist on site tasked the robot with a "front to back door" search of the apartment. If the robot could accomplish this task, Command was willing to declare this apartment completely searched or "cleared" given the increasing time constraints.

The apartment was located at the front of the complex. The insertion of the robot was much more difficult than the first location. The apartment was leaning towards the operator's position, so unlike the last insertion, no one could walk up to the structure and place the robot on the foundation. A collapse zone had been declared directly in front of the structure for safety reasons. In fact, the safety officer mandated that personnel could be no closer than the curb on the street. Additionally, a large amount of debris had washed up on the porch area at the front of the apartment. Taking all of these factors into account, a search plan was developed. The robot would travel approximately 15 to 20 feet to the front of the building, travel over debris on the porch, make a ninety-degree left turn around a staircase leading to the second floor apartments, and then turn ninety degrees right into the front door of the target apartment. The two ninety-degree turns gave the operator some concern. These two turns would cause points of tether friction very early in the search. This might

Figure 6: Photos showing the VGTV inside of the apartment. Mattresses and lumber were found piled up at the back door due to storm surge (left). The operator only needed to look behind the robot to see the path out of the apartment provided by the tether (right).

be problematic if the robot did not have sufficient friction to pull the tether deep into the structure.

Positioned on the curb and using an external viewpoint, the operator drove the robot until it passed out of sight behind the staircase. The robot had little difficulty getting over the debris on the front porch and passed through the front door. Once inside, the floor was found to be a smooth vinyl composite tile covered in light mud and moisture. The tracks of the robot began slipping almost immediately due to the low friction surface and the high tether friction outside the door. The operator concentrated on making long and deliberate moves forward into the room throwing lengths of new tether from the curb to the bottom of the stair case outside. This lowered the drag on the tether enough to allow the robot to inch forward slowly.

Immediately to the left of the front door, a second couch was flipped onto its back in a former living room or foyer. The camera zoom was used to look under the corner of this couch for any human signs. Directly behind the couch and through the removed wall was a room filled three-foot-high with debris. This was the opposite side of the room seen in the earlier deployment, confirming that search in that direction was not going to be possible for the robot.

Following the search methodology of traveling as far as possible into the structure in a straight line, the operator decided to quickly look around this area and then extend far into the building. The back of the building was visible from just inside the front door, so the direction and obstacles were clear. This also solved the traction problem since the robot would not pull new tether from outside during the later part of the search.

The operator drove the robot through the center of the structure using the fallen dry-wall and debris for traction. In under a minute, the robot was at an impasse. It could not go any further into the structure because it had reached the rear exterior wall of the building.

To the robot's right was a wall. To its left was a pile of debris including two mattresses and lumber that had broken free from the structure. The height of this debris and the encounter with the mattress during the earlier search made climbing a daunting task. The operator decided to use the camera zoom to look for human signs under and around the mattresses and lumber. While this was happening, the operator was alerted by his commander that the search would need to end soon. If the robot had reached the rear of the structure, it should be collected so the team could move to another area.

The operator repositioned the robot facing directly into the structure. He then raised the robot to its highest configuration and tilted the camera to its highest angle. This unique position allowed the robot to look backwards (albeit upside down) and see its own tether. The operator wanted to quickly confirm that the robot needed to turn only 180 degrees and move forward to exit the structure without incident. Directly behind the robot, the yellow tether was seen extending from the rear of the robot out the front door of the building. The robot was then reconfigured to its lowest position to avoid tipping over while turning on the uneven drywall and debris. Guided by the tether, the operator exited the structure in under thirty seconds.

Just as the robot emerged from the structure and climbed back over the debris at the front of the apartment, the search leader told the operator to pack up because the team was moving on to the next search area. The operator informed the search leader that the robot had been able to accomplish the "front to back door" aspect of the requested search, but there were still rooms off of the main corridor that had not been searched. Although this was the case, higher priority search tasks in the city were needed.

5 Lessons Learned

By the standards set forth by the search team leader, the robot search of the damaged apartment was a success. A "front to back door" search had found no victims, removing this structure as a likely candidate for survivors. The search was performed without robot failure and within the time allocated. Finally, a digital recording of the entire deployment was created for possible post-hoc analysis by other members of the search team and command staff.

From an engineering and design stand point, the search was also a success. The robot completed the search without any of the de-tracking problems experienced by CRASAR at the La Conchita mudslide disaster (Murphy and Stover, 2005). This included a highly risky search on a mattress that, by all available measure, should have fully aggravated the de-tracking problem. This success is most likely attributed to two factors. First, the robot's drive pulleys were improved in the time between the two deployments. Second, there were significant inconsistencies in the track material used for the first iteration of the robot's production, which was the model used at La Conchita. These inconsistencies were resolved before the Katrina response.

Even with the success of this deployment, several take-home lessons were identified.

One robot size does not fit all. The VGTV-Xtreme is relatively small compared to other military-based robots. This was a significant advantage at the World Trade Center. However, in this deployment, a larger robot, such as a Foster Miller Solem or iRobot Packbot, may have been able to travel into the structure more effectively. In fact, the larger robot would not have had such a difficult time manuvering on the mattress and transversing other debris. That said, if there was a need for the robot to pass from one room to another, the VGTV-Xtreme would be uniquely capable since it is less than 16 inches wide. This happens to be the standard distance between 2x4 studs in the interior walls of most building construction. In the experiences of the 2004 and 2005 hurricane season, the partial removal of dry-wall by storm surge is a fairly common occurrence for structures near the shoreline.

Intrinsic safety mitigation. Currently, no robot platform is rated intrinsically safe or bomb proof. Intrinsic safety is a basic requirement for virtually all equipment used in hazardous material response. This deployment reinforced the fact that hurricane response is an "anything goes" scenario, and the robot may be presented with environments that are explosive. The VGTV-Xtreme was a sealed unit, but this is not sufficient for the safety of the responders, victims, or surrounding environment.

Portability. The ability of the robot to be carried by the operator without considerable fatigue is extremely important. During the World Trade Center disaster, the robots were haphazardly carried in standard school backpacks (Micire, 2002). The La Conchita mudslides (Murphy and Stover, 2005) and Hurricane Katrina response reinforced that in disaster situations the operator may need to carry the equipment many miles. These travels can be through extremely difficult terrain, fatiguing the operator greatly. The idea that robots could be carried in suitcases or a dedicated automobile is unrealistic for search and rescue applications. Backpack systems designed for search and rescue are already used by search and rescue personnel. The VGTV-Xtreme already makes use of a compatible harness system as shown in Figure 3, but other robot systems must adopt this as a basic requirement for field deployments.

Time criticality. All aspects of robot deployment must minimize time and maximize efficiency. As seen in Section 4, the search team leader gave a specific amount of time that the robot could be in the structure. Portability is important, but this must be balanced with the time needed for assembly. If the robot is highly portable, but requires more than five minutes to set up, then time is lost to the search. While in the Katrina deployment, the VGTV-Xtreme was quickly assembled and even moved from one location to another where additional improvements were made. A target setup time of under a minute is typical for most technical search equipment, such as pole cameras. When robots achieve this as a benchmark, then they will be on-par with other equipment already used.

Traction. Traction in differential tracked robots is a deceptively difficult problem. If the robot has a lot of traction and attempts to turn on surfaces like carpet, the robot may be unable to turn. If the robot has sufficient strength, it may in fact de-track itself through this action. Conversely, if the robot has insufficient traction, it will not be able to climb over obstacles and drag large amounts of tether. In the Hurricane Katrina deployment, both of these cases were observed. While on the mattress, the robot needed to raise to its highest profile and "pop a wheelie" to achieve the 180 degree turn required. On the vinyl composite tile floor, the robot barely had enough traction to pull the tether through the door. As such, materials and tread design need to be carefully evaluated for varying environments. The VGTV's unique ability to adjust the traction surface is a design that aids in this problem, but this feature alone is not sufficient.

Finally, several operation methods make the deployment of tethered robots easier. These "tricks of the trade" are not always obvious and are found only through extensive field experience. Three of these methods are described below:

- Tether management is key to a successful search deployment. One method of limiting tether friction points is to travel as far into the building structure as possible without turning or searching. This places the tether inside the structure ahead of the search process. In this way, the robot needs to pull only the tether immediately behind it and not all of the tether extended from the entry point.
- A lesson from basic firefighting has applications for tethered robots. Firefighters learn that the fire hose will always lead them outside the building if followed correctly. For robots, the tether also always provides a path out of the building should the operator become disoriented. This is a useful technique and should be used regularly to ensure that the tether does not loop around a stationary object.
- The robot should be tested to empirically find the tipping point while climbing over objects. In the case of the VGTV, this pitch is no less than +/- 15 degrees. This conservative estimate should be in the mind of the operator while performing difficult maneuvers over uneven debris and difficult terrain. The mattress in the Hurricane Katrina deployment was a good example of this becoming a issue critical to mission success.

At the time of this writing, a list of these techniques is being compiled by the author for future publication. In almost all cases, these "tricks" can be automated and provide good guidelines for tele-operators and future autonomous systems designs.

6 Conclusions and Future Work

The VGTV has had a long and awkward history. Although the robot was never intended for USAR, its polymorphic capabilities combined with some significant re-engineering made it a good candidate as a search and rescue robot. Its first live test was during the WTC disaster and the post-hoc analysis of the events provided a framework for future development. These guidelines drove the development of the first robot designed exclusively for USAR, the VGTV-Xtreme.

The platform still has a long way to go before it can be considered ideal for USAR. A considerable amount of skill and training is required of the operator to learn all of the "tricks" associated with using a tethered robot in a unstructured environment. That said, the VGTV-Xtreme's performance during the rescue efforts after Hurricane Katrina was a considerable improvement over the systems used in previous years.

Regrettably, American Standard Robotics and Inuktun Services have stopped development of the VGTV-Xtreme. As such, it is the hope of the author and Inuktun Services that researchers and responders will build upon these recommendations. There are approximately a dozen VGTV-Xtreme robots in existence, and two of them are currently being used by state search and rescue teams. In fact, the VGTV-Xtreme is the first robot to be purchased by a state responder group exclusively for search and rescue. This is a small step towards robots being used by every USAR team. With continued development and support, this number will only grow, and our rescuers' jobs will become a little bit safer than before.

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References

Blackburn, M. R., Everett, H. R., and Laird, R. T. (2002). After action report to the joint program office: Center for the robotic assisted search and rescue (crasar) related efforts at the world trade center. Technical report, SPAWAR Systems Center, SSC San Diego.

Blitch, J. (2003). Adaptive mobility for rescue robots. In *Proceedings of SPIE conference of Sensors, and Command, Control, Communications, and Intelligence (C3I) Technologies for Homeland Defense and Law Enforcement*, volume Vol. 5071, pages 315–321.

Casper, J. (2002). Human-robot interactions during the robot-assisted urban search and rescue response at the world trade center. Master's thesis, University of South Florida, Tampa, FL.

Casper, J., Micire, M., and Gang, R. (2004). Search and rescue robotics. In *Proceedings of the 3rd International Conference on Continental Earthquakes.*

Micire, M. (2002). Analysis of the robotic-assisted seach and rescue response to the world trade center disaster. Master's thesis, University of South Florida, Tampa, FL.

Murphy, R. (2003). Rescue robots at the world trade center. In *Journal of the Japan Society of Mechanical Engineers*, volume Vol. 102, pages 794–802.

Murphy, R. and Stover, S. (2005). Rescue robot performance at 2005 la conchita mudslides. In *ANS 2006: Sharing Solutions for Emergencies and Hazardous Environments.*