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Savannah River Site H-Canyon Process Exhaust Tunnel Inspection Crawler Development -- 20036

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ABSTRACT

This paper covers development of a remote crawler used to inspect a subterranean radiochemical process ventilation tunnel located at the Savannah River Site near Aiken, SC. The purpose of the inspection was to ascertain the apparent structural condition of the tunnel with video footage. Manned entry is prohibited due to the hazardous environment requiring a fully-remote approach. The inspection system used high-definition cameras to archive over 1000 linear feet in the tunnel. While previous inspections had been undertaken, this crawler was developed to overcome obstacles that had put tunnel regions out of reach of prior inspection platforms.

INTRODUCTION

This paper outlines the development, testing and deployment of a new remote inspection vehicle used during March 2019 to inspect the condition of a subterranean tunnel at the Savannah River Site (SRS). The tunnel is the ventilation exhaust shaft for the SRS H-Canyon Process Facility. The process is radiochemical and therefore renders the tunnel unsuitable for human occupancy. Accordingly, remotely-operated vehicles or pole cameras have been used for previous tunnel inspections. In order to inspect areas of the tunnel that were un-accessible with previous vehicles; a vehicle with both increased terrain-handling capability and camera range of motion was developed. Increased resolution of the captured imagery was also a requirement of the new inspection system.

DESCRIPTION & DISCUSSION

Background

The H-Canyon at SRS is a large concrete structure built in the early 1950s. Its mission being to chemically process surplus Highly Enriched Uranium (HEU) and research reactor fuel both foreign and domestic to produce a Low Enriched Uranium (LEU) solution suitable for commercial reactor fuel production. The process gases exhaust through a concrete tunnel that runs under the facility to a sand filter that scrubs the air before releasing it out a stack. The exhaust air that flows between the facility and sand filter is acidic and radioactive which degrades the interior surface of the concrete exhaust tunnel. Efforts in the past have been made to inspect the tunnel; however, large areas of the tunnel had not been inspected and condition of those areas was unknown. The objective for the 2019 inspection was to develop a tethered crawler capable of recording high-definition video of the current tunnel condition including areas that were unreachable in the past.

Design Requirements

Requirements governing tunnel entry or exit

- Access tunnel via a 30” diameter manway pipe suspended on a facility hoist hook
- Crawler weight is limited to 350 lbs. or less due to load limits of the manway building hoist
- The hoist hook is located 58” above the pipe flange at the inlet location
- Personnel located in a small building erected around the Manway opening will be in a radiologically-contaminated area wearing a fresh-air-supplied plastic suit. Multiple layers of gloves will limit tactile feedback and dexterity.

Requirements related to operation within the tunnel

- Handle the process environment (nitric acid fumes and low levels of radiation/contamination)
- Obstacle crossing, cables, steps, glass, sharp metal, loose sand/gravel, cross standing water, mud.
- Traction leading to capability to pull tether approximately 600-700’

- Lighting to support both navigation and high-definition image capture
- Travel approx. 600' in both directions taking video of the tunnel then return to the access port
- Vehicle shall have a tether that can be used to aid in vehicle recovery
- Tether capable of supporting weight of vehicle, power, control and data
- Perform its video function in 35 mph sustained winds
- Winds (35 mph) carry sand which can abrade the camera lens cover impacting video quality

Mechanical Design & Discussion

Vehicle – Mechanical Description

The vehicle (see Figures 1 and 2) consists of an aluminum body/frame to which four DC gearmotors are attached. Each gearmotor is fitted with a shaft (axle) and hub that drives a wheel. The wheels were fitted with sealant-filled pneumatic tires. There is no independent suspension of the wheels beyond the effect of the inflated tires. The vehicle is tethered, sending and receiving all power/signal across its tether. A cable reel spools the 700' of tether as required. A slip ring manages both power and signal transfer across the required rotating union. The rear of the body has a rigging connection point for a removable lifting bail. The bail is used to insert and remove the vehicle from the tunnel environment. The bail is removed from the vehicle after tunnel insertion and prior to crawler operation.

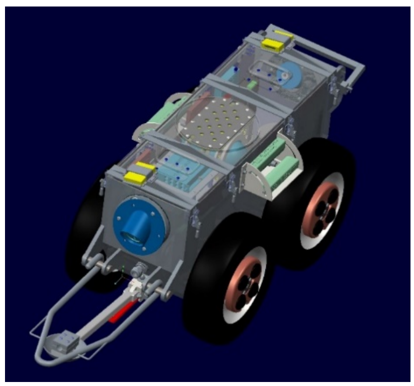

Figure 1: Assembled Vehicle

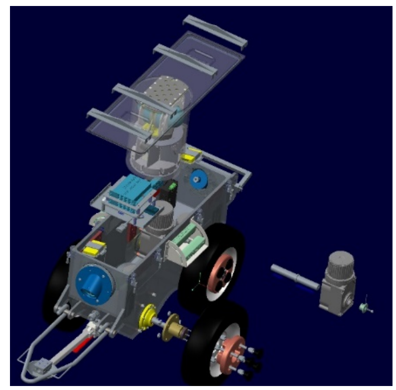

Figure 2: Vehicle Expanded View

Design Approach/Decisions to Address Requirements

<u>Vehicle Insertion Clearance</u>

During insertion into the tunnel (Figure 3), the vehicle is suspended from a rear-connected bail and passes nose down through a vertical passage (30" diameter pipe). The radial clearance is minimal. Cameras and other delicate equipment mounted to the outer shell of the 350 lb. vehicle are at risk of damage during insertion. The design approach with this crawler was to allow retraction of sensitive equipment into the body's internal cavity during lowering and then extension once the crawler was placed upright and ready for operation on the tunnel floor.

Figure 3: Crawler Insertion into Manway

<u>Entry/Exit Protection & Viewing Behind Duct</u>

The Zippermast makes possible the extension and retraction motion of camera and lights (Figure 4 & 5). The model attached to this crawler could provide approximately 5-1/2' of elevation to the camera and lights if needed. Due to space limitations, individual LEDs were arranged into arrays as needed to provide ample lighting and still be stowable

Figure 4: Camera, Lights, Zippermast


Figure 5: Mast Extended

Vertical adjustment of the camera was necessary to see behind the 36" diameter duct that blocks the lower portion of the south wall during previous inspections. Retraction was also helpful to minimize wind-blown sand scratches on the camera's domes during idle periods.

The Zippermast operates by driving three bands up that interlock and form a column as it extends. An electric gearmotor turns a worm gear that engages the center of each band and sends it up through a press which pushes the outer lengthwise edge tightly against the adjacent. Both edges have cuts or "serrations" shaped such that they will interlock "snap" together. Visualize each band behaving like the tape on a tape measure. Three bands in total make up the mast and they are oriented at 120 degrees to each other. A cross-sectional cut through the "zipped" and extended mast would reveal an equilateral triangle. The component is manufactured with different models based on various band widths. The Zippermast used in the 2019 vehicle is a hybrid between two standard sizes, it uses a model number ZM-8 base with larger model ZM-12 bands. The bands at 2-1/2" width provide increased mast rigidity needed to minimize sway from the 30 mph winds that continuously blow during imaging of the tunnel.

A cable that carries power and signal for the lights and camera is contained within the mast as it raises. A chamber located within the bottom of the Zippermast body stores the cable needed for the extension. There is no active reel or similar involved with the cable management. The cable must have the proper "stiffness" so it nests into the proper spiral arrangement (like grooves in a vinyl album). It is a simple approach that avoids the use of slip rings but does create limitations on the "allowable" cable. Additionally, a single manufactured cable bundle is required. The limitations on available cables, required simplification of the lighting control we had planned.

The Zippermast was mounted and housed in a well that protects it from damage during insertion and removal though the manway. The well is part of a lid that fastens and seals to the top of the vehicle (Figure 6). The well has a top that retracts and "shuts" when the Zippermast reaches the down limit. However, since the Zippermast itself is rated for submerged use, there was no need to create a tight seal upon closure; the design intent was the exclusion of sand and stone. It is important to note the vehicle cavity is completely sealed from the tunnel environment and the well. Within certain limitations, the lid can be exchanged to replace or modify the inspection technology with an alternate camera setup, Light Detection and Ranging (LiDAR) or other.


Figure 6: Lights On

<u>Marginal Traction and Obstacle Crossing</u>

The 2019 vehicle was designed with about 150% of the ground clearance of previous vehicles. This was necessary due to obstacles that must be crossed in the tunnel whether they are soft surfaces (sand or mud) or steps/hard objects. To increase ground clearance the wheel diameter was enlarged over previous vehicles and the wheel axles positioned very close to the bottom surface of the body. This was important while crossing the soft surfaces as the tires could dig in much further before the body began to drag.

The body at the front and rear of the vehicle was shaped to improve its approach and departure clearance over steps/inclines. The body shape also included a scallop at mid-length to improve clearance in the center when straddling an obstacle between front and rear wheels (Figure 2).

<u>Component Protection, Track Width, Ground Clearance & Stability – A Compromise</u>

The adjustments for ground clearance and steering were constrained by the 30" diameter manway pipe used to deploy the crawler. The geometrical equivalent of fitting the crawler through the manway is placing a rectangle inside of a circle. With that image in mind, considering the bottom of the tires would define two of the corners of the rectangle, it becomes evident how tire diameter affects insertion clearance. Continuing with the visualization, it can also be seen how track width increase would reduce manway clearance to the crawler. Increasing track width relative to wheelbase length has desirable operating traits as it improves skid steering effectiveness and lateral stability. Alternatively, increasing wheel/tire diameter for extra ground clearance enhances terrain-crossing capability. Balancing track width, ground clearance and stability while maintaining assembly clearance required compromise. In the end, the 2019 vehicle yielded a bit steering agility in favor of ground clearance.

Lateral stability is clearly important to keep the vehicle from overturning on a slope. This design consideration also requires compromise, in part due to the manway clearance limiting track width and increased ground clearance (larger diameter wheels) that raises the center of gravity. The option to stow and protect the camera and lights inside of a hard shell required a taller body cavity which further elevates the center of gravity. The final vehicle design overturns sideways at approximate tilt angles exceeding 42 degrees. A dual axis inclinometer was mounted to the vehicle and used to monitor tilt status both laterally as well as front to rear (pitch) during the operation. It had an adjustable alarm function to indicate excessive tilt, set at 30 degrees.

<u>The Tether – A Big Drag</u>

The weight of the tether creates difficulties for the crawler. The vehicle near each end of the inspection length pulled nearly 140 lbs. of tether to advance. Maintaining the traction to develop the necessary drawbar force was not trivial. While the crawler could manage to pull the tether straight forward, turning while continuing to advance was not always possible, especially when dragging 400' of tether or more. Since turning requires skid steer, the moment the inside wheels were slowed to accomplish the turning action, the outside wheels would begin to spin. At this point, turns sometimes required backing up as needed to slack the cable, then skid steering followed by pulling the cable tight in the new direction with all four motors (wheels) working together. When the cable retightened, some of the turn angle could be lost. In these instances, the turning process became iterative, with multiple occurrences of reversing and skid steering.

The Falmat tether has nine #16 conductors in addition to three coax cables. A Kevlar wrap rated at 2500 lbs breaking strength was part of the tether construction. The inclusion of the Kevlar was to ensure capability existed (at the crawler) to drag the crawler back to the manway location if it failed. Dragging the crawler could require more pull force at the reel than the current Hannay-built device can develop which is 450 lbs. In addition, a device accomplishing the tether management was placed in the manway for operation and used to control tether bend radius within manufacturer specified limits around two turns in the cable that are necessary between the reel and vehicle. The tether management would require a more robust design if a more powerful winch were used. The current cable management can handle the reel's rated pulling force for normal operation, but not if supplemented with a much more powerful winch. Additionally, reaction loads from the increased loading would have to first be analyzed or redirected to ensure protection of the manway structure itself.

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Approximately 50 pounds of ballast was required in the form of wheel weights to increase the crawler's traction sufficient to pull the heavy tether. A liquid ballast fill was considered for the tires. The tires are pneumatic and therefore subject to puncture, so a sealant (Slime) fill was also planned. The two products are incompatible and therefore necessitated a choice be made, the Slime-fill was chosen, and metal wheel weights were manufactured. The liquid-fill is partial and therefore has the advantage of lowering the center of gravity more than the wheel weights. Lowering the elevation of the center of gravity to enhance lateral stability was the reason for deliberating the issue.

<u>Wheels, Tires, Brakes and Drive Motors</u>

Pneumatic tires were used to help with traction in soft surfaces versus a more non-compliant solid tire. There are more compliant non-pneumatic "tire" options that simulate a pneumatic tire currently entering the marketplace, however none were identified for this size and weight of vehicle with a market search at the time of this design.

Each wheel is driven with a DC gearmotor. The gearmotor, a Brother VF3SC30-50N400L4 is a hollow-shaft motor with a 50:1 reduction gearbox. The bearings in the gearbox are robust enough to handle the weight of the crawler in operation, so no other bearing was required. The hollow-shaft motor simplified the fabrication somewhat since the axle and wheel could be cantilevered off the motor gearbox without additional bearing mounts. Likewise, assembly was made easier since the motor could be placed into the small space and the shafts then inserted through the side of the crawler body and fastened into the motors. The vehicle changes direction by skid steering.

The 50:1 gear reduction was adequate to keep the vehicle from rolling when stopped on all slopes encountered without the need of a brake. If the vehicle was manually pushed, occasionally the tires would slide rather than turn, dependent on the traction conditions.

<u>Vehicle Control Interface</u>

Control of the vehicle involved use of left and right joysticks on a gaming-style controller (Figure 7). The left stick would control the left-side motors while the right stick controlled the right side. Both the direction and speed of wheel travel followed the direction and extent to which the stick was moved away from the neutral position.

Figure 7: Vehicle Controller in use

Water Obstacles – Staying Dry Inside

The axles would be submerged for an unknown period during operation in water up to a foot or more in depth. A seal carrier was designed for attachment to the vehicle at each axle location (Figure 8). To prevent water inleakage, two o-ring seals were specified that would be housed in the carrier. In addition, a lip seal was added at the outboard location. This component would prevent the intrusion of sand or other abrasives to the o-rings located inboard. Large cross-section o-rings were used that would absorb more axle shaft deviation from center (run out and/or shaft deflection) and still retain the compression needed for effective sealing. Petrolatum was used to lubricate the seals during assembly and then injected into the cavity present between the seals to act as additional barrier to water ingress. A removable inspection plug was located opposite the grease injection fitting. The plug was removed and used to determine when the cavity was filled, then reinstalled.

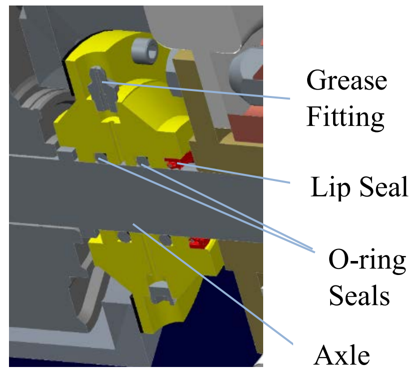


Figure 8: Seal Carrier

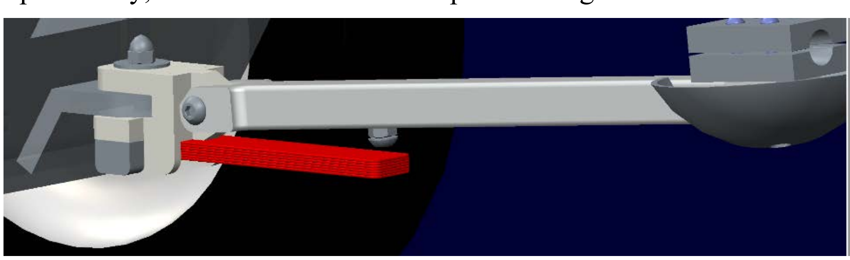
The tether entered the crawler cavity at an elevation located in the lower half of the rear panel. To prevent water inleakage a cord grip was used to seal around the tether jacket (Figure 9). The tether was hard-wired from the Hannay reel (Figure 10) to the crawler with no connectors located between those two components. Strain relief of the tether at the crawler location was accomplished with a swingarm that was connected to the vehicle rear in a drawbar fashion. A two-piece clamp fastened the tether to the end of the drawbar creating the grip necessary to provide strain relief. If the vehicle travel was reversed, the drawbar could pivot up vertically while it also rotated (swung) to the left or right. This action allowed the vehicle to backup further before the crawler would risk rolling over the tether.


Figure 9: Image of Cord Grip


Figure 10: Hannay Reel/Moog Slip Ring/Falmat Tether

Swingarm – Controlling Tether and Load

The underside of the swingarm was equipped with a stack of spring steel (301 Stainless Steel – shown in red) used to elevate the clamp (rear) off the ground (Figure 9). Alternatively, a simple hard stop could have been used, but the spring limits moment loads transmitted to the crawler body in certain instances. Specifically, if the crawler were to be pulled using the tether in a direction that would engage the hard stop (if used) and overload the body-welded aluminum tongue in bending. In this situation, the spring allows the swingarm to adjust position in a manner that limits bending moment.



Electrical Engineering Design/Discussion

Figure 11: View of Swingarm with Springs

Power

The crawler requires 300 Volts Direct Current (VDC) to power the drive motors and other internal electronics. This power is provided by a TDK Lambda Genesys 3U 15kW Model 300-50-3P208 DC power supply which requires 3-phase 208 VAC. The output of the Genesys is connected to the tether where each of the nine copper conductors are individually fused with 600 VDC 10A fuses (Figure 10). The crawler end of the tether penetrates through a cord grip into the crawler body where the copper conductors and coaxial cables are separated and routed. The 16 AWG conductors land on positive and negative terminal blocks which is then routed to DC-DC converters to step down the incoming voltage to 48 VDC and 24 VDC, respectively.

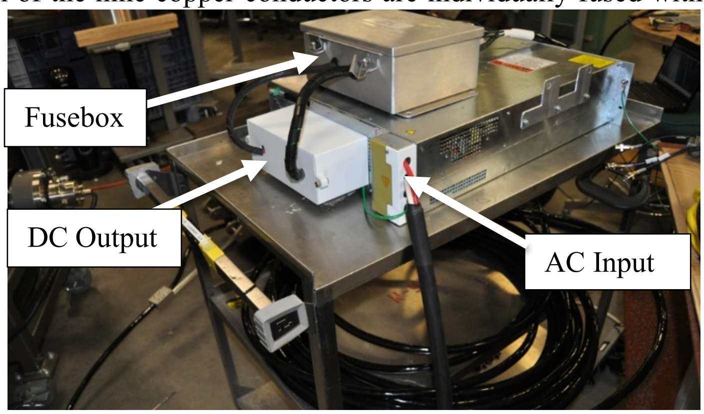


Figure 12: Rear View of Genesys DC Power Supply Showing AC Input, DC Output, and Fuse Box

The coaxial cables are terminated with 75 Ohm Bayonet Neill-Concelman (BNC) connectors and connect to the upper and lower ComNets (Figure 11) for network communication between the crawler and control station. The ComNets are 802.3at compatible and provide power to the inspection cameras, driving cameras, and Ethermega microcontroller.

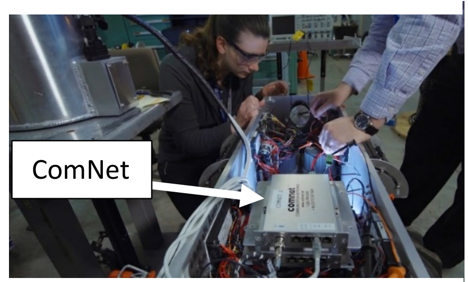


Figure 13: View (Crawler Lid Removed) Upper/Lower ComNet Switches w/ Coaxial Cables

Electronics

<u>DC-DC Converters</u>

Cosel DBS700B48 and DBS700B24 are switch-mode power supplies that take an input voltage of 200-400 VDC and step it down to the preferred voltage which in this case is 48 VDC and 24 VDC needed for the onboard electronics of the crawler. Output voltage ripple is managed using large electrolytic capacitors placed in parallel with the power supply output. The capacitance required was at least 1,000 μF for 48 VDC and at least 2,200 μF. Since the internal compartment of the crawler body is sealed to the outside atmosphere to protect the electrical components, all heat generated must be transferred outside through the crawler body. Heat generating components such as the power supplies are thermally coupled to the crawler body. The housing of the power supply was designed such that the side opposite the connector pins had an integrated heat sink which was coupled to the side walls of the crawler body with thermal paste for heat transfer.

Figure 14: Cosel DC-DC Converter. Metal Plate at the Bottom is the Heat Sink

Ethernet-over-coax Converter

ComNet switches (Figure 15) were used for transmitting and receiving data between the crawler and control station. The ComNet sends/receives ethernet packets long distances over coax cable using a frequency modulation method which is reassemble at either end into regular ethernet packets for network communication. The ComNets installed on the crawler end are 802.3at power-over-ethernet (POE) compatible and power the cameras and microcontroller.

Figure 15: ComNet Ethernet-Over-Coax Converter

Microcontroller

An Ethermega microcontroller from Freetronics (Figure 16) was used for crawler control. This microcontroller is connected to the upper ComNet on the crawler by CAT5e network cable and receives power over this network cable. The incoming 48 VDC is regulated down to 10 VDC by the power over ethernet (POE) regulator chip (Figure 17) installed on the microcontroller. The microcontroller is coded in C++ allowing it to extract commands from incoming ethernet packets and transmit data back to the control station computer such as temperature or tilt sensor data. The microcontroller operates by setting digital I/O pins high or low which controls connected logic level components. Sensor data is collected through the analog input pins.

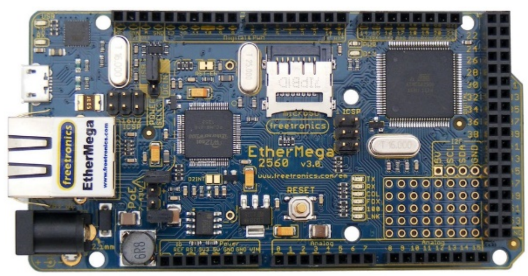


Figure 16: Ethermega Microcontroller

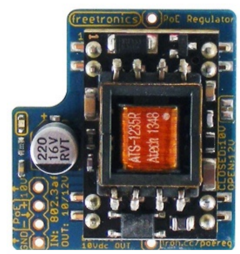


Figure 17: POE Regulator

DC Motors Motor Controllers

Brother VF3SC30-50N400L4 Gearmotors are 400 Watt 48 VDC brushless DC motors with hall sensor outputs used to determine rotor position. Anaheim Automation MDCSL150-050301 motor controllers (Figure 18) uses the hall sensor information from the gearmotors to determine the rotor position and provide the correct high/low output sequence to the motor phase wires. If the hall sensor information is not used, this can cause the motors to turn the opposite direction upon approaching the torque rating. The RUN/STOP, DIRECTION, and FREEWHEEL input pins are used to control the gearmotors by logic level high/low provided by the microcontroller. These pins are active low. The front and rear motors of each side are controlled as a pair to achieve differential steering. A jumper pin on the circuit board of the motor controller is set to allow for external speed control with a variable input voltage of 1 – 4 VDC. A Pulse Width Modulated (PWM) signal from the microcontroller is converted to a variable 0 – 5 VDC signal using an operational amplifier circuit and applied to the external speed pin (wiper) on the side of the motor controller.

Figure 18: Anaheim Automation Brushless DC Motor Controller

Lighting

There are two types of Light Emitting Diode (LED) type lights used on the crawler, custom built assemblies and prepackaged. The custom LEDs mounted on the Zippermast are Cree part number: XREWHT-L1-0000-00C01 (Figure 19). The LEDs are surface mounted to star therma
clad boards from Bergquist part number: 803122 (Figure 20) which is then attached to the light ring mount in the counter sunk holes using thermal adhesive tape and screws all epoxied in place.

Figure 19: Cree 3.3 V 1 A LED

The LEDs of each side (Left, Right, Top) are divided up into two evenly spaced pairs of six wired in series to a LuxBuck Puck 788-1095-ND constant current power supply (Figure 21). Due to the limited number of current-carrying conductors available on the Zippermast, the Buck Pucks were wires in series such that they formed zoned lighting consisting of: left and top, left and right, and right and top.

Figure 21: LuxDrive Buck Puck 1 Amp Constant Current Source

Superbright ORBM7-18WS-FL 7-inch LED light bars (Figure 22) were mounted as side lights on the crawler body with a pair per side wired in parallel. The LEDs on the Zippermast and light bars on the sides of the crawler are powered through a logic level driven solid-state relay board. The relay board is active high, and the lights turn on when the Ethermega outputs 5 VDC from the connected digital I/O pin. A pull-down resistor is not used on the logic side of the relay board which has the benefit of visually indicating the microcontroller, when powered, is in the process of starting up, ready, or error state by the momentary or constant flashing of the LEDs. Constant flashing indicates there is an issue with the microcontroller.

Figure 20: Star Thermal Clad Board

Figure 22: LED Lightbar Mounted on Sides of Crawler Body

Cameras

There are two sets of Hikvision Internet Protocol *(IP)* cameras which can be categorized into an inspection set with pan/tilt/zoom and a driving set. The driving cameras (Figure 25) connect to and receive power from the upper ComNet by CAT5e network cable terminated into a RJ45 connector. Due to the limitation with the number of conductors in the Zippermast, the CAT5e network cable was wired in a half-duplex type configuration using one-half of the twisted pair for each of the two inspection cameras. Referring to Figure 23 below, the connector of each end was terminated such that orange/white, orange, green/white, and green were terminated into were terminated into positions 1, 2, 3, and 6 for one camera, and blue/white, blue, brown/white, brown were terminated into another pair of RJ45 connectors in positions 1, 2, 4, and 6.

Zippermast

The cable provided by Zippermast was experimentally determined to be insufficient for the crawler needs due to the lack of unshielded twisted pairs necessary for ethernet packet data transmission. Without twisted pairs, crosstalk between the wires would cause the cameras to lose connection between the recording devices located in the control trailer and the inspection cameras mounted on the Zippermast. To solve this, the conductors had to be removed from the outer jacket and six of those conductorswere bundled together with a CAT5e network cable and manually pulled into the outer jacket. This provided six conductors available to switch the three lighting zones of LEDs and operate the inspection cameras.

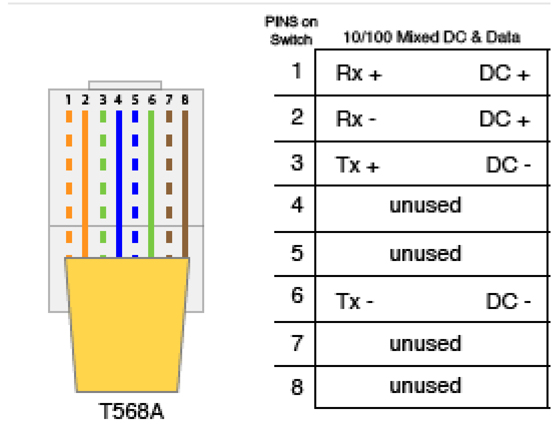


Figure 23: Pinout of the Special Termination for the Inspection Camera Network Cable

The Zippermast arrived with the motor and limit switches wired to a double-pole double-throw hand operated switch. The switch was removed and rewired such that the motor with functioning upper and lower limit switches would operate remotely. Originally, the vendor mentioned the motor required 2A of current to operate. After the assembled Zippermast was received, it was determined that the motor required four times the current to operate in the up position with a very short initial starting current spike of around 20A discovered later using an oscilloscope. The H-bridge circuit originally specified in the design had to be replaced since the currents were much higher than initially informed. A VNH5019 Motor Driver Carrier 1451 from Polulu was used. The limit switches were wired such that the control signal between the microcontroller and the VNH5019 would be opened when fully extended or retracted to disable the Zippermast motor from further travel in the respective limited direction. The side-effect of larger current spikes due to the vendor shipping the Zippermast with an undersized motor resulted in a temporary loss of network connection between the inspection cameras and the connected ComNet when raising the Zippermast.

Thermistors

Thermistors were placed in open air in the front and rear of the crawler and on one of the ComNet switches to monitor internal air temperature of the crawler. The shell temperature of the ComNet device was observed to be the hottest of the three thermistors. The thermistors were connected to the analog input terminals of the Ethermega, and the temperature data was displayed on the control window of the driving program for monitoring.

Inclinometer

A DOG2 MEMS-Series Voltage Inclinometer (Figure 24) was used to sense the pitch and roll of the crawler as it traversed through the tunnel. The sensor is capable of sensing ± 90° tilt in the X-axis and Y-axis directions. The signal wires of the inclinometer were wired to the analog input pins of the microcontroller. The microcontroller constantly transmits the tilt data to the control program which uses both a numerical and graphical display. A user-selectable tilt limit is available which would notify the driver by flashing red and audible alarm when exceed the value set.

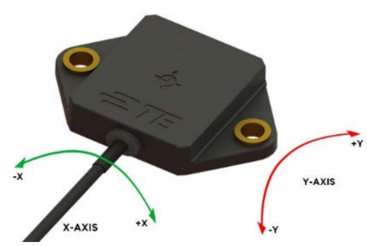


Figure 24: Dual-Axis Inclinometer Used For Sensing Crawler Tilt

High-Definition Cameras

The first camera set consists of the front and rear driving cameras (Figure 25). These cameras a 2 mega pixel (MP) ultra-low light Hikvision bullet driving camera has an IR range up to 30 meters with day and night settings to automatically turn to IR when the light is too low. At all times the camera outputs a 2 MP resolution which is significantly higher than the camera on the previous crawler. This type of camera is fixed meaning that it does not have pan, tilt, and zoom (PTZ). The IP rating is at IP67, which means the camera is protected for dust and immersion in 1 meter of water for 30 minutes.

Figure 25: Driving Camera

The second camera set consists of the two inspection cameras located at the top of the Zippermast (Figure 26). These cameras are 3 MP Hikvision network mini PTZ cameras. The resolution is 2048 X 1536P which is significantly higher than the previous crawler camera resolution of 640 X 480. The inspection cameras also have an IP rating of IP67 to offer protection from the dust and water in the tunnel. These cameras require a minimum level of lighting, which is why there a multiple light emitting diodes (LEDs) surrounding these cameras on the vehicle.

Figure 26: 3MP Inspection Camera

The higher definition cameras require additional video equipment that maximizes the resolution. A Hikvision network video recorder (NVR) is paired with the inspection cameras to record the top resolution video. Two 4K televisions are also paired with the inspection cameras to prevent any resolution loss. A Hikvision digital video recorder (DVR) is paired with the driving cameras to fully capture the 1080P resolution. Each recording device has a minimum of a 6 Terabyte hard drive that ensures ample storage for the video. This camera also had an optical zoom versus just digital zoom. The result is that resolution is maintained instead of a degraded mosaic picture when zooming into the object.

Software

The microcontroller, written in C++, is located inside the crawler and receives commands from the computer via ethernet. These commands are then interpreted and executed by the microcontroller. The software then responds by controlling an output and sending the input data back to the computer. The outputs include four motor controllers, the mast motor controller, and seven light zones. The inputs consist of two inclinometers and three thermistors. Due to the nature of the brushless motors adjustable delays are put in place to prevent motors from overloading the controllers.

The computer software is located on the laptop and sends commands to the microcontroller via ethernet. Data from the microcontroller is received via ethernet. The Microsoft© Windows based software was written in C# and utilizes SDL2, a gaming library, to receive and interpret the controller mapping and controller inputs. The values are run though a calibrated calculation to convert the stick values to motor power values. The software also has controls in the form of buttons for the lights and mast controls. These values are all sent to the microcontroller on a timed loop regardless of changes to allow for a headless communication check. The software interface contains temperature and inclinometer indicators to allow the operator to view the tilt and temperature of the robot easily. A speed setting allows the operator to adjust the max speed of the robot for finer control in certain situations.

Testing
A test plan was developed to address the operational challenges expected for the crawler during the inspection. The tests are each outlined in the following subsections.

Initial testing was significantly delayed due to a central component of the crawler arriving nearly four months late. This part was needed to complete assembly and wire the crawler. Due to this delay, findings during testing that could be addressed were limited to short lead-time fabrication or procurement. Also, if the testing were to damage a component, the crawler could have been rendered unusable and potentially miss the inspection window. Accordingly, the team "gently" tested the vehicle.

Test Mockup Areas
Four different areas were used to complete the full test plan on the crawler. One area was a dark room that simulated the tunnel surfaces, ductwork and low level of lighting (Figure 27). This first area was used to check camera and lighting level. The second area was the assembly area (Figure 28). In the assembly area, function and control of component assemblies was verified. In this same area a mockup manway pipe was used along with an engine lift to ensure insertion clearance with the planned pick points and bail. A large livestock watering tank was also co-located in the assembly area that allowed for leak testing. The third area was just outside of the assembly area, several obstacles were built in this area to operate the crawler over (Figure 33). The fourth area was also outside. A diesel-powered generator was used here to power the crawler (Figure 31). This location allowed a long distance (700 ft) tether pull to check traction (Figure 32). A generator was planned for the deployment in the field, so this setup allowed verifying no surprises due to the generator as well.

Figure 27: Outside (Left) / Inside (Right) of Dark Room

Figure 28: Testing & Assembly Area

In-Field Tether Replacment
This section of the test focused on tether replacement. Rather than a large connector attached to the rear of the body, a quick-release lid would provide access to the connection points in the internal cavity in the event the tether would require replacement. It is important to note the crawler remains in the shelter covering the manway access point for its useful life fully connected to the reel, so disconnecting the tether

is not normally required. It was noted that fitting a new tether would be very difficult in the field due to the protective clothing, multiple layers of gloves and cramped space under the lid.

General Operational Check

In this test the cart was driven and turned, ease of control was found to be acceptable. The Zippermast was raised and lowered. The up limit was verified. The mast was found to raise with lengths close to a foot long unzipped. The clamp used to cause the mast to zip up could have been tightened, but the motor was drawing high current. In time the current came down and the mast seemed to perform better, raising without unzipped lengths. In addition, the driving camera function was checked out and found to work properly with impressive low light function. The manway fit seemed good and the rigging plan with the removable bail worked well. One finding required rework; the crawler was stable resting on its front face and wheels when lowered to the floor. An adjustable front bar was manufactured and attached that resolved the finding, causing the crawler to rotate back onto its wheels when landing.

Tether Pull

The tether pull test (Figures 29 and 30) revealed more crawler weight was needed to have the requested 700 ft capability. The test was repeated with added weight attached to the wheels with an acceptable result. The added weight brought the crawler mass to the manway hoist limit. The extra traction allowed the reel to be unwound when it was shifted into neutral (free spin); however, it did create noticeable additional drag. In practice the reel was shifted into neutral and manually unwound to reduce drawbar load.

Figure 29: Control and Observation Station at 700-ft Tether Pull Site

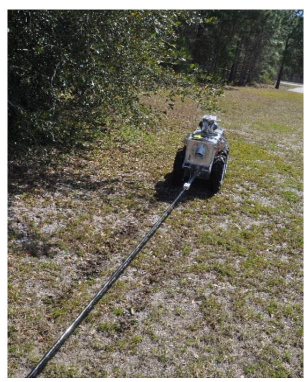


Figure 30: Approaching Traction Limit – No Wheel Weights

Temperature of Electronics inside Crawler

Heat generation and subsequent transfer out of the crawler cavity was a major concern during the development. During operation, the temperature gain was found to be no more than ~15C over ambient. Most of the heat-generating items were thermally coupled to the aluminum body. While the motors were not as well thermally-coupled, their duty cycle was of a magnitude to create an issue. The items that were noticeably warm were the media converters. One type was rated for operation in a 60C ambient temperature while the second could handle a 75C environment. The highest temperature experienced was

~40C. Options for mounting the converters due to their size were limited in the cavity space and the orientation was not optimal. However, this situation was expected to be satisfactory for our application which later proved to be correct.

Video

All test results of the inspection and driving cameras were successful. Initially, the field of view on the driving cameras was limited as the view angle was pointed too far down. The design/manufacture of the crawler required use of a fixed-position driving camera to provide forward viewing as well as see the front tire near the ground contact location. This would aid obstacle negotiation in addition to still allowing the forward driving view. In practice, the view angle was narrower than expected. The result was a driving camera that was disorienting as the horizon was above the view. A shim was fabricated to raise the camera to capture the horizon, this required compromise with the near-field view, but was a better overall solution.

The cameras proved impressive in terms of quality of the imagery returned. In conjunction with the cameras, the network keyboards were tested with positive results. The keyboards came with an integral joystick that allowed inspectors to pan, tilt, and zoom the inspection cameras. Additionally, the keyboards have a monitor which displays the inspection camera feed. Through testing it was determined that the cameras would need preset or default views selected via the keyboard. Once the preset views were added as an inspector shortcut control, the keyboard testing was deemed complete.

Terrain (Obstacles)

The crawler was operated over obstacles (Figure 33) that would simulate those anticipated in the field. It crossed wooden 2x4's strewn across the ground and climbed a 20-degree incline covered with smooth sheet metal. Rock bags were crawled over with varied success. A 1-foot tall step was set up to climb. It went through damp and dry sand with ~6" depth. In all these tests the 1-foot step was the most problematic. It would climb the step without hesitation with the front wheels while all four were driving but have problems once the front wheels were in air and while trying to finish the climb using only the two rear wheels. Crossing the rock bags could also result in a similar outcome. The rock bags were stacked against the step and in the end the crawler climbed over after several failed attempts. More gear reduction would raise the stall torque; however, the higher wheel speed capability was advantageous in negotiating other obstacles (e.g. mud). The torque output of the motor was affected by the fact it had been reduced to cope with electrical interference prevalent at higher settings although this reduction remained adjustable. The inclinometer was tested in this section as well and it was determined that the crawler would become unstable and likely tip at an angle exceeding approximately 42 degrees.

Leak Testing – Seal Integrity

Once fabrication and welding of the crawler chassis was complete, water ingress was checked before proceeding to the next stage of assembly. The crawler chassis equipped with motor, axles, wheels, and tether was placed in a tub filled with water to a depth of approximately 18-inches. The crawler chassis remained in the water tank for 30 minutes. The tank was long enough to allow rolling the crawler back and forth during the test. Leaks were checked using paper towels through the base of the crawler. One tiny leak was found. A water bead was observed along the weld that attaches the pipe fitting for the cord grip to the crawler chassis. The water tank was drained at the end of the 30 minutes immersion, and the crawler was removed. The area of the leak was dried with a heat gun, cleaned with alcohol and a Loctite Epoxy was applied to the pinhole. After cure, the area was retested for 30 min. with zero leakage.

Zippermast Stability – Wind Test

A strong fan was positioned directly in front of the fully extended Zippermast. It was aimed at the camera and lights. The video proved to be very stable.

CONCLUSIONS POST-DEPLOYMENT

The crawler functioned well in the tunnel environment. The deployment and retrieval systems worked as anticipated. The extra ground clearance was key in crossing a variety of obstacles. The cameras returned excellent high definition imagery despite the winds and other challenges. The camera lift allowed first-time viewing over a large duct. The lighting while adequate, did not pan and tilt with the camera. This did slow control at first, as the camera needed to be zoomed into any objects that were too dark so the iris would adjust to the darker field of view making dark details visible. However, after getting used to the issue, this was still very workable having little impact on progress. The wet and boggy areas were sometimes challenging. See images in Figures 31-33 taken during the tunnel deployment below.

Figure 31: Moving toward a Wet Area

Figure 32: Removing Crawler from Tunnel (Washdown)

Figure 33: Inspecting Tunnel

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