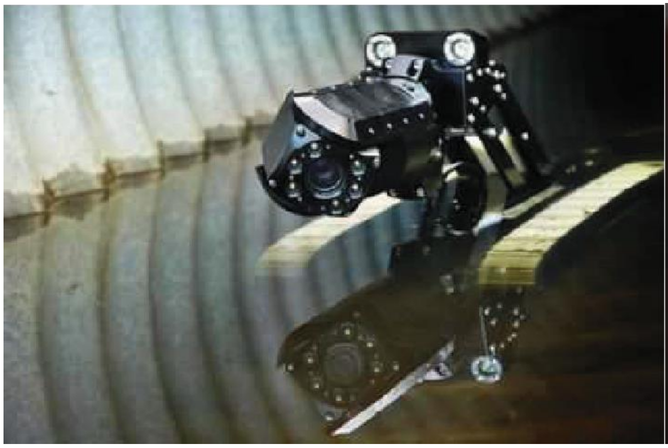
Evaluation of New or Emerging Remote Inspection Technologies for Conduits Ranging from 12” to 120” Spans



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16. Abstract

Traditionally, highway agencies relied mainly on man-entry approach for assessing in-service conditions of their culverts. And, this direct approach left many drainage structures unapproachable and uninspected. This is because a large number of drainage structures are often small (diameter or rise less than 4 ft), inaccessible (entrance restricted by a catch basin or manhole, or entrance located at the bottom of a steep slope), or obstructed (filled with water or sediment). These undesirable culvert conditions are particularly common in Ashtabula County, where a majority of culverts range in diameter from 12 to 36 inches and are sometimes obstructed partially by sediment and/or water. In addition, the outlet ends of the drainage structures along the northern boundary of this county, draining to Lake Erie, are situated on steep unstable soil slopes.

The main goal of the study was to identify for the ODOT Ashtabula County garage workforce remote culvert inspection technologies which are cost effective, easy and safe to operate, reliable, capable of performing post-installation inspections.

After several months of extensive literature review, online data search, discussions with the Ashtabula County garage workforce, and discussions with TAC members, several promising remote inspection systems surfaced that are believed to be helpful for the Ashtabula County garage. These systems varied from small pipe crawlers, to larger multi-sensor platform units as well as micro UAVs. The team's recommendations are accompanied with a set of decision three charts, system matrices, comparison tables, risk analysis, and cost analysis. The team also identified emerging technologies that need to be explored in the near future.

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List of Acronyms

AUV	Autonomous Underwater Vehicle
CCTV	Closed Circuit Television
CFR	Code of Federal Regulations
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FPV	First Person View
GPR	Ground Penetrating Radar
GPS	Global Positioning System
HD	High Definition
HIVE	Hydraulic Inspection Vehicle Explorer
Laser	Light Amplification by Stimulated Emission of Radiation
LED	Light Emitting Diode
LiDAR	Light Imaging, Detection, And Ranging
LiPo	Lithium Polymer
ODOT	Ohio Department of Transportation
PARC	Persistent Aerial Reconnaissance & Communications
Sonar	Sound Navigation and Ranging
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
VLOS	Visual Line of Sight

Executive Summary

Traditionally, highway agencies relied mainly on man-entry approach for assessing in-service conditions of their culverts. However, this direct approach left many drainage structures unapproachable and uninspected. This is because a large number of drainage structures are often either too small (diameter or rise less than 4 ft), inaccessible (entrance restricted by a catch basin or manhole, or entrance located at the bottom of a steep slope), or obstructed (filled with water or sediment) for man-entry. These undesirable culvert conditions are particularly common in Ashtabula County, where a majority of culverts range in diameter from 12 to 36 inches and are sometimes obstructed partially by sediment and/or water. In addition, the outlet ends of the drainage structures along the northern boundary of this county, draining to Lake Erie, are situated on steep unstable soil slopes.

The main goal of the study was to identify workforce remote culvert inspection technologies for the ODOT Ashtabula County garage which are cost effective, easy and safe to operate, reliable, capable of performing post-installation inspection, capable of measuring deflections, capable of measuring crack sizes, and capable of providing enough data to allow accurate ratings for each culvert remotely assessed.

After several months of an extensive literature review, online data search, discussions with the Ashtabula County garage workforce, and discussions with other TAC members, several promising remote inspection systems surfaced that are believed to be helpful for the Ashtabula County garage. These systems varied from small pipe crawlers, to larger multi-sensor platform units as well as micro-size UAVs. The team’s recommendations are accompanied with a set of decision tree charts and system matrices. In order to support the recommended solutions, the team has done initial testing of micro-UAS, and addressed UAS risk assessment and crawlers/UAS cost issues. The team also identified emerging technologies that need to be explored in the near future, with respect to the remote culvert inspection systems.

Project Background

There are over 80,000 culverts under Ohio's roadways that the Ohio Department of Transportation (ODOT) is responsible for maintaining. An essential component of effective culvert management is periodic inspection.

Traditionally, highway agencies relied mainly on man-entry approach for assessing in-service conditions of their culverts. This direct approach left many drainage structures unapproachable and uninspected because they are often too small (diameter or rise less than 4 ft), inaccessible (entrance restricted by a catch basin or manhole, or entrance located at the bottom of a steep slope), or obstructed (filled with water or sediment) for man-entry. These undesirable culvert conditions are particularly common in Ashtabula County, where a majority of culverts range in diameter from 12 to 36 inches and are sometimes obstructed partially by sediment and/or water. In addition, the outlet ends of the drainage structures along the northern boundary of this county, draining to Lake Erie, are situated on steep unstable soil slopes.

Every time a new culvert is placed or an old deteriorate culvert is replaced under a state/interstate highway in Ohio, it must be inspected right after installation (post-construction inspection) and periodically thereafter per ODOT requirement. ODOT has Construction & Materials Specifications (CMS) Item 611.12 that dictates how the post-construction culvert inspection must be conducted in Ohio.

Within the last two decades, there has been a constant push in industry and academia to develop portable remote sensing systems for inspecting underground pipelines. The technologies that were tapped into included camera, closed circuit television (CCTV), optical scan (digital imaging), laser-scan, and ultrasonic scan (sonar). Some researchers also looked into potential benefits of several other indirect techniques, such as acoustic measuring, light detection and ranging (LiDAR), and ground penetrating radar (GPR), for assessing conditions of culverts. Recently, there has been an outbreak of development in unmanned aerial vehicles (UAVs) or drones. This technology appears to hold potentials to be useful for inspecting inaccessible infrastructure including bridges and culverts.

In summary, there is a need to study the current and emerging technologies and identify the most promising remote inspection systems that can be used to inspect culverts that prohibit traditional man-entry inspection. This effort is needed immediately to help the ODOT Ashtabula County maintenance forces manage their culvert infrastructure more completely, which will lead to improved safety for motorists in their area.

The main goal of the study was to identify for the ODOT Ashtabula County garage workforce remote culvert inspection technologies which are cost effective, easy and safe to operate, reliable, capable of performing post-installation inspection (according to the ODOT Item 611.12), capable of measuring deflections, capable of measuring crack sizes, and capable of providing enough data to allow accurate rating for each culvert remotely assessed.

The Ashtabula County garage workforce already had a push camera, a HIVE (a RC-control vehicle), and a wheel-powered pipe crawler suitable for inspecting pipes that range from 8” to 48” in diameter. The crawler comes with a CCTV camera, and a laser ring profiler is also available. They utilized these inspection systems occasionally and experienced some issues with each. The push camera is useful for very small diameter pipes, but its camera head has a tendency to hang up against small debris and at joints due to offsets/gaps. The HIVE is limited, as it currently has difficult lighting control, does not support a wide range of pipe diameter sizes, has poor pan-and-tilt control on the camera, accommodates only one sensor (a camera), tends to lose traction on top of wet sediment, and has limited software and data analysis support. And, the small pipe crawler system is relatively heavy, too large for very small size pipes, has insufficient lighting, and is wheel-powered and has a tendency to have its wheels get stuck at joints.

ODOT acquired some remote inspection systems over the past few years, including mobile vans (to support CCTV inspection systems), CCTV-camera pipe crawlers, and micro UAVs. These systems are going to be positioned regionally in the state and will be made available to any ODOT garage workforce. Recommendations coming out of this study intend to help the Ashtabula County garage and also expand and strengthen the plans ODOT has with their existing systems.

Research Context

This 6-month Phase-1 study was initiated in the summer of 2017 to identify remote culvert inspection technologies that can be beneficial to the ODOT Ashtabula County garage workforce, so that they can safely inspect and rate culverts that have not been assessed for years due to their field conditions that make them unavailable for the traditional man-entry inspection. With these new capabilities, the ODOT Ashtabula County garage workforce will be able to identify additional culverts that need to be rehabilitated or replaced before they experience sudden structural failure. The added capabilities in managing culvert infrastructure will lead to cost savings for the garage and higher degrees of safety for local motorists.

In order to achieve the main goal stated above, the research team was assembled from two research institutions – Ohio University (Athens, Ohio) and Applied Research Associate (Randolph, Vermont). The team performed the following 5 tasks during the Phase 1 study:

Task 1: Review ODOT specifications & manuals related to drainage conduit maintenance

Task 2-Part 1: Meet with ODOT Ashtabula County maintenance forces and visit some culvert sites

Task 2-Part 2: Conduct an extensive literature search on existing and emerging remote inspection technologies

Task 2-Part 3: Classify the commercially available and custom-made inspection systems by their technology (sensor) types and capabilities; Prepare decision tree charts that can aid in the system selections. Develop matrices that list and rank currently available systems that are potentially beneficial to the Ashtabula County garage personnel and changes that are needed on them (if any).

Task 3: Issue draft Phase 1 report and draft Fact Sheet.

Task 4: Have an End-of-Phase 1 review meeting with ODOT Ashtabula County garage workforce.

Task 5: Develop detailed plans for Phase 2 if it is determined in Task 4 to take the current study into Phase 2 (field demonstrations phase).

Research Approach

Task 1 was necessary so that first of all the research team understands fully what inspections are required for culverts by ODOT and what observations/measurements are to be taken during each culvert inspection work.

Task 2 (part 1) was a customary initial event in any ODOT-funded research project. The start-up meeting took place at the ODOT Ashtabula County garage. Through this meeting, the research team members learned firsthand the challenges that the Ashtabula County garage workforce is facing in managing culverts in their area. The meeting day activities also included visits to nearby culvert sites to reinforce what were discussed earlier during the indoor meeting.

Task 2 (part 2) commenced right away, following the start-up meeting. The team understood early on that the solution to the challenges facing the ODOT Ashtabula County garage workforce cannot be a single robotic system. The team members spent many days, looking for information on the latest commercially available remote inspection systems of different types and capabilities through technical journals, trade magazines, and online search engines. Any promising system that surfaced was first discussed among the team members and then its information was distributed periodically to the TAC members for their questions and comments. During these exchanges, the team members also learned about the existing inspection tools that the Ashtabula County garage personnel had been using or would be able to take advantage of because of the ODOT's recent acquisitions.

In parallel to gathering the information on commercial systems, the team members also spent time on developing ideas for custom-design systems. This effort was necessary to overcome shortcomings that many commercial systems possess and also to look into the emerging technologies.

Once a variety of promising remote inspection systems for culverts were identified, in Task 2 (part 3) the team classified them into separate groups, compiled comparison tables within each group, attempted to rank the systems in each group, prepared decision-tree charts, and developed a concise matrix per system group. In addition, the team attempted some basic analyses related to risk and cost aspects. All these efforts were needed so that the team can arrive at the best solutions for the Ashtabula County garage workforce.

The alternative for Task 5 is to revise and submit the Phase 1 interim report as the final report (in case a decision was made in Task 4 not to go into Phase 2).

The table below is the time schedule chart that the team included in their proposal and followed closely during the project.

Table 1: Time Schedule Chart

Task	Month During Project:					
	1	2	3	4	5	6
1						
2-a						
2-b						
2-c						
3						
4						
5						

[Note] Task 1 (review of ODOT specifications), Task 2-a (initial project meeting), Task 2-b (extensive search/review of information), Task 2-c (dissemination of information), Task 3 (issuing of draft Phase 1 report), Task 4 (final project meeting), and Task 5 (issuing of final Phase 1 report).

Research Findings

Task 1 (Review of ODOT Specifications)

ODOT defines four different types of culvert inspection, which are listed in Table 2 below. Frequency of inspection required is summarized in Table 3.

Table 2: Four Types of Culvert Inspection

Inspection Type	Purpose
Inventory Inspection	First inspection to collect inventory data & baseline conditions; Specific areas of focus & monitoring may be identified for future inspection; May be the same as the post-installation inspection
Routine Inspection	Regular scheduled inspection; Any changes from baseline conditions are noted
Damage Inspection	Special inspection to assess structural damage; Inspection data used to make a decision on load rating or repair work
Interim Inspection	Special inspection to monitor specific areas identified

Table 3: Culvert Inspection Frequency Requirements by ODOT

Category	Inspection Frequency
12" to 48" in Span	Prior to routine roadway maintenance activities (ex. resurfacing) or every 10 years, whichever is less
48" to 120" in Span	Every 5 years
General Rating Score < 4	Every year
New Installation	Within 30 days of project completion
Modified Structure	Within 120 days of modification

ODOT developed detailed 0-9 scale culvert rating methods for concrete, metal, and thermoplastic culverts (see ODOT Culvert Management Manual, 2016). ODOT lists primary and secondary inspection assessment elements for each type.

For concrete culverts:

- Primary conditions assessment elements are material, joints, footings (if any), protective coating (if any), inlet & outlet, slope & settlement, and horizontal alignment.
- Secondary assessment elements include roadway surface, guardrail, embankment, headwall/wingwall, channel, sediment (inside culvert).

For metal culverts:

- Primary conditions assessment elements are shape, deflection, metal surface, joints/seams, protective coating (if any), inlet & outlet, slope & settlement, and horizontal alignment.
- Secondary assessment elements include roadway surface, guardrail, embankment, headwall/wingwall, channel, sediment (inside culvert).

For thermoplastic pipes:

- Primary conditions assessment elements are shape, deflection, metal surface, joints/seams, protective coating (if any), inlet & outlet, slope & settlement, and horizontal alignment.
- Secondary assessment elements include roadway surface, guardrail, embankment, headwall/wingwall, channel, sediment (inside culvert).

Tables 4 through 9 present the numerical rating systems ODOT issued for assessing conditions of metal, concrete, and thermoplastic culverts. Tables 4 through 6 focus on material conditions in the culverts. The next two tables provide systems that are used to evaluate the shapes of the flexible metal and thermoplastic pipe structures. Table 9 addresses alignment conditions for various types of culverts. It is noted here that the conditions that are relevant to material/alignment ratings can be assessed by having a high-resolution camera and bright lights. For assessing the culvert cross-sectional shapes, additional equipment such as a laser or a sonar profiler will be needed.

Table 4: ODOT Material Rating Scale for Concrete Culverts

Rating	Descriptions
9 (excellent)	Like new; Superficial & isolated damage from construction
8 (very good)	Hairline cracking with no rust staining or delamination; Isolated damage from construction
7 (good)	Hairline cracking with no rust staining; Crack running along traffic direction; Crack width < 1/16”; Light scaling of <10% of area, <1/8” deep; Delaminated/spalled <1% of area;
6 (satisfactory)	Hairline map cracking; Crack width <1/8”; Minor leakage; Scaling of <20% of area, <1/4” deep; Delaminated/spalled <5% of area; Rebars exposed
5 (fair)	Map cracking w/ rust staining; Crack width <1/8”; Leakage; Scaling of <30% of area, <3/16” deep; Delaminated/spalled <10% of area; Rebars exposed
4 (poor)	Crack >1/8” in traffic direction w/ leakage & rust staining; Spalling at many locations; Extensive scaling of invert, >1/2” deep; Rebars exposed on the invert and/or top; Scaling of invert >3/4” deep
3 (serious)	Extensive cracking w/ spalling & delamination; Slight differential movement; Rebars exposed extensively; 50% of thickness loss over invert; Concrete softening
2 (critical)	Full depth holes; Extensive cracking >1/2”; Spalled area >50%; Rebars exposed >25% of area; Rebars having sectional loss
1 (failure imminent)	Culvert partially collapsed or collapse is imminent

Table 5: ODOT Material Rating Scale for Metal Culverts

Rating	Descriptions
9 (excellent)	Like new; Galvanizing intact; No corrosion
8 (very good)	Discoloration of surface; Galvanizing partially gone over invert; No rust; No pinholes
7 (good)	Discoloration of surface; Galvanizing gone over invert; No rust; Minor pinholes at ends
6 (satisfactory)	Galvanizing gone over invert; Layers of rust; Sporadic pitting over invert; Minor pinholes at ends
5 (fair)	Heavy rust & scale; Pinholes throughout; Perforations at ends
4 (poor)	Extensive heavy rust & scale throughout; Deep pitting; Perforations over invert; Metal loss up to 20%; Easy puncture with Prospector's pick
3 (serious)	Basically the same as above; Metal loss up to 25%
2 (critical)	Perforations throughout invert; Metal loss > 25%
1 (failure imminent)	Culvert partially collapsed or collapse is imminent

Table 6: ODOT Material Rating Scale for Thermoplastic Pipes

Rating	Descriptions
9 (excellent)	Like new; No discoloration; No signs of distress
8 (very good)	Isolated rip or tear (>6" in length; caused by construction or debris); Minor discoloration at isolated locations
7 (good)	Pipe split (<6" in length) at 2 or 3 locations; Split opening <1/4"; Ends damaged due to construction or maintenance; No backfill infiltration; Perforations due to abrasion within 5-ft end sections
6 (satisfactory)	Basically the same as above; Split opening <1/2"
5 (fair)	Basically the same as above, Split opening >1/2"
4 (poor)	Pipe split (<6" in length) at several locations; Split opening >1/2"; Backfill infiltration; Perforations due to abrasion, throughout pipe
3 (serious)	Pipe split (<6" in length) at several locations; Split opening >1"; Backfill infiltration; Sectional loss due to abrasion, especially over invert
2 (critical)	Basically the same as above, Pipe split (>6" in length) at several locations; Split opening >1"
1 (failure imminent)	Pipe partially collapsed or collapse is imminent

Table 7: ODOT Shape Rating Scale for Metal Culverts

Rating	Descriptions
9 (excellent)	Like new; Minor construction-related damage at ends; Span up to 2% larger than design
8 (very good)	Smooth curvature; Span up to 5% larger than design
7 (good)	Top half smooth & curved; Minor flattening of bottom; Span up to 7.5% larger than design
6 (satisfactory)	Basically the same as above; Bottom flat; Span up to 10% larger than design
5 (fair)	Significant distortion in top at one location; Bottom has reversed curvature at one location; Span up to 12.5% larger than design; May have nonsymmetric shape
4 (poor)	Significant distortion throughout; Lower 3rd may be kinked; Span up to 15% larger than design
3 (serious)	Extreme deflection at isolated locations; Top flattened; Bottom having reversed curvature throughout; Span larger than design by more than 15%; Extreme nonsymmetric shape
2 (critical)	Extreme distortion & deflection throughout; Span larger than design by more than 20%
1 (failure imminent)	Culvert partially collapsed with reversed curvature in top

Table 8: ODOT Shape Rating for Thermoplastic Pipes

Rating	Descriptions
9 (excellent)	Smooth wall; Span up to 2% larger than design
8 (very good)	Smooth wall; Span up to 5% larger than design
7 (good)	Relatively smooth wall; Span up to 7.5% larger than design
6 (satisfactory)	Minor dimpling in isolated areas (<1/16 of circumference); Dimples <1/4" deep; Span up to 10% larger than design
5 (fair)	Minor dimpling in isolated areas (<1/8 of circumference); Dimples <1/2" deep; Span up to 12.5% larger than design
4 (poor)	Wall crushing or hinging over length <3 ft; Pipe deflection <15%
3 (serious)	Wall crushing or hinging over length >3 ft; Dimples >1/2" deep; Wall tearing/cracking; Pipe deflection <20%
2 (critical)	Wall crushing or hinging throughout below roadway; Dimples >1/2" deep; Severe wall tearing/cracking leading to pipe splitting; Pipe deflection >20%
1 (failure imminent)	Pipe partially collapsed or collapse is imminent

Table 9: ODOT Alignment Rating Scale for Metal, Concrete & Plastic Pipe Culverts

Rating	Descriptions
9 (excellent)	Straight; No settlement; No misalignment
8 (very good)	Minor settlement or misalignment
7 (good)	Minor misalignment at joints; Offset <1/2”; Minor settlement at isolated locations; Ponding of water <3”
6 (satisfactory)	Minor misalignment/settlement at isolated joints; Ponding of water 3”-5”
5 (fair)	Minor misalignment/settlement throughout culvert; Ponding of water <5”, Ends dislocated and dropping off; Four or more sections having offset <3”
4 (poor)	Major misalignment/settlement throughout culvert; Ponding of water <6”, Ends dislocated and dropping off; Four or more sections having offset <4”
3 (serious)	Significant ponding of water >6” due to sagging or misalignment, Ends dislocated and dropping off; Four or more sections having offset >4”
2 (critical)	Culvert not functioning due to serious alignment issues throughout
1 (failure imminent)	Culvert partially collapsed or collapse is imminent

Table 10 lists common deterioration/distress modes that the team members observed while inspecting hundreds of metal, concrete, and thermoplastic drainage structures in the state.

Table 10: Common Culvert Deterioration/Distress Modes in Ohio

Material Type	Common Defects Observed in Ohio	
	Category	Conditions
Reinforced Concrete	Material	Pitting, Spalling, Cracking, Slabbing, Chloride attack
	Joints	Cracking, Opening, Offset, Backfill/water infiltration
	Others	Exposed rebars, Settling, Dropped ends, Voids in bedding/backfill
Corrugated Metal	Shape	Flattening (ovaling), Peaking, Racking
	Material	Rust & scale, Corrosion, Perforations, Cracking, Wall buckling
	Seams/Joints	Offsets, Cracking, Opening, Backfill/water infiltration
	Others	Sag in the middle, Water ponding; Voids in bedding/backfill
Thermoplastic	Shape	Flattening (ovaling), Peaking, Racking
	Material	Cracking, Dimpling, Wall buckling
	Joints	Offsets, Cracking, Opening, Backfill/water infiltration
	Others	Sag in the middle, Water ponding; Voids in bedding/backfill

ODOT CMS Item 611.12 (ODOT, 2016) addresses post-installation inspection of highway culverts. The key elements of this specification are summarized below:

- Performance inspection must be conducted for all drainage culverts that are longer than 20 ft and having slopes less than 25%.

- The initial post-installation inspection must be done between 30 and 90 days after the completion of the finished grade.

- The culverts with a rise of 12 to 36 inches must be inspected using remote inspection techniques. The culverts having a rise of 36 to 48 inches must be inspected either by the man-entry method or by remote inspection techniques. Culverts larger than 48” should be inspected by the man-entry method.

- Remote inspection should be carried out by a crawler equipped with a camera which can record the video. The culvert must be prepared for the crawler inspection by lowering the water level and removing large debris. A video recording must be produced for the entire length of any culvert inspected remotely.

- The crawler inspecting rigid conduits must be capable of measuring the crack and joint opening sizes with its camera. The crawler inspecting flexible conduits must be capable of measuring crack and joint sizes with its camera and inside diameters with its laser profiler.

- Performance inspection should provide a report which presents vital information such as the project number, roadway route number, inspection time/date, culvert type/size, a list of all measurements taken and defects. Data collected by a crawler equipped with a laser profiler should be converted to a 3-D graphical model of the entire culvert.

ODOT Supplemental Specification Item 902 (conduit inspection equipment) covers requirements for the crawler equipped with a camera and the crawler equipped with a laser profiler.

- The crawler inspecting RC culverts must be able to measure cracks as narrow as 0.2 mm.

- The crawler inspecting flexible culverts (CM, thermoplastic) must be able to measure the inside diameter changes down to 0.5% precision for culverts that are 12” to 48” in span.

- The video camera integrated into the remote inspection system must be effective inside culverts that are 12” to 120” in span. The camera must have a zoom ratio of at least 40:1. It must also provide a pan-and-tilt to a 90° angle, with a 360 ° rotation. All video files must be saved at a resolution of 720 x 480 for post-processing.

Task 2- Part 1 (Initial Meeting)

The main research team members (T. Masada – Ohio University, P. Riley of ARA) attended the project start-up meeting at the ODOT Ashtabula County garage on Aug. 16, 2017.

Below are some key information that the team gathered during the initial meeting:

- ODOT built a total of twelve RC pipe inspection vehicles (each equipped with a Go-Pro camera). They distributed these to all the districts. According to ODOT employees, this vehicle is useful for conducting visual inspection of culverts that are in the 24” to 36” diameter range and are dry and almost free of sediment/debris. The vehicle has a tendency to lose traction when it is on top of wet silty sediments. The wheels on the vehicle are not large enough to propel the vehicle inside metal culverts consisting of 6” x 2” corrugation plates. The Wi-Fi signal does not bounce off the walls well inside thermoplastic pipes. The car can go only 50 ft max. In concrete and metal pipes, this is not an issue and the vehicle can go much further.

- Ashtabula County has many culverts. Most are corrugated metal pipes, but there are some concrete and a few very old sandstone box culverts as well. Most culverts in Ashtabula County are 36” or smaller in diameter. This statement applies both to the culverts along SR-531 (Lakeshore Drive) and to those that are often under water. The partially submerged culverts may have up to 12” of water typically and 0”-8” of silty sediment on the bottom. There may be some exceptions. Among all the culverts in the county, less than 15% may be always under water. For those that are under water, flow velocity is very slow and does not pose challenges.

- The Ashtabula County garage has one worker (John Arcaro) who is dedicated to culvert inspection. There are a lot of culverts in the area that he cannot inspect because of a number of issues. First of all, he is often the only person in the field. Per OSHA requirement, two workers are needed for culvert inspection work. This is particularly crucial, when he is trying to inspect culverts that are less than 5 to 6 ft in diameter. Some culverts are under more than 20 feet of soil cover, with the road embankment slopes being very steep and unstable. It is dangerous for the inspector to try to walk down to the culvert end alone.

- The culvert inspector provided the team a list of his top 11 culverts to inspect in the future with remote inspection systems) and explained us why he is unable to inspect some culverts. This list is included in Appendix B.

- There are a total of 22 metal culverts under SR-531 (Lake Rd.) that runs 32 miles along the lake shoreline. Many of these culverts range in size between 12” and 36”. The inlet is typically tied to a small concrete catch basin located below the road edge and is difficult to access and view (there is a 5” wide rectangular opening at the top of the catch basin). The outlet end is also very difficult to access because it is on a steep lakeshore soil slope that is eroding and very unstable.

They suspect that many culverts along the lake shore has headwall issues at the outlet ends. They really need to take a look at each culvert's end so that they can develop repair plans.

- There are also some instances where the culvert outlet belongs to a private property (no easement for ODOT), and the land owner does not want ODOT culvert inspectors trespassing their property.

- It is costing them a lot of man hours and money to inspect some of their culverts. For example, the inspector may spend all day and come back with no culverts inspected. He may go back to some of the sites to figure out exactly what assistance may be needed. In some cases, they request a camera crew and vacuum-jet equipment (for culvert cleaning) to travel all the way from Akron. [Note] The garage has now two vacuum-jet equipment and a few remote inspection systems.

Next, the team members were taken to four culvert sites located near the garage to observe exactly what challenges/difficulties the garage personnel are facing. Below presents a summary information on each of the site:

- <u>Site 1 (96" dia. CMP under SR-11, along lake shore</u>)
  The access to the inlet end of this large CMP was difficult, as the roadway embankment slope was long (at least 40') and steep due to years of gully soil erosion. A few large fallen trees were seen blocking the entrance to the culvert. John also cited the OSHA confined space regulation as the reason for his inability to inspect the culvert. The culvert is about 300' in length and dark inside.

- <u>Site 2 (36" dia. HDPE Pipe under SR-531, near lake shore</u>)
  This pipe was located under SR-531 (Lake Rd.) close to the lake shore. We did not approach its inlet end. It is supposedly tied to a catch basin located below a roadway slope, covered by dense vegetation. The outlet end was on the opposite side of the road, at least 30' below on a steep soil slope. It is not safe for any inspector to walk down to inspect this pipe from its outlet end.

- <u>Site 3 (12" dia. CMP under SR-531, along lake shore</u>)
  This small diameter CMP runs from a small concrete catch basin located below the road edge and is very difficult to access and view. There is a 5"-6" narrow rectangular opening at the top of the catch basin. The outlet end is very difficult to get to because it is on a steep lakeshore soil slope that is eroding and very unstable.

- <u>Site 4 (24" dia. CMP running from city street to the lake</u>)
  This small diameter CMP starts from a gated catch basin located by a busy city street. It is difficult to access this pipe from its inlet. The pipe runs a few hundred feet and outlets on a very steep and dangerous soil slope that sits between a

private land property and the lake. Years of soil erosion, numerous fallen trees, and rising lake water level (due to global warming) are making its outlet end impossible to access. We observed the concrete headwall sitting in the sand by the water's edge. So, the garage personnel know that this culvert needs some major repair.

After the site visits, the team members talked more with the garage personnel about the issues they are facing and the needs they have.

- The garage currently has two remote inspection systems. One is a push camera system that can go only 25' into a culvert (due to some issues). Another one is a HIVE or a 35-lb RC vehicle equipped with a camera (mentioned earlier). It is heavy and does not propel at all whenever there is a pool of water or a wet sediment.

- The garage workforce would like to have a pipe crawler that can measure the pipe wall thickness even when the pipe is partially or nearly completely filled with water and/or sediment.

- The culvert inspector expressed his needs to have services from a drone that can fly over the lakeshore slope area and give him nice video of the culvert outlet end conditions. The drone should be able to automatically fly back to the pilot whenever it goes out of RC signal or its battery power level gets low. The drone should be able to avoid trees and other objects while flying through with its collision-avoidance capability activated. The drone also should be able to float on water in the case it goes down into the lake. Finally, the drone should be able to go into the culvert end and record a 360-degree view video if possible

Task 2 - Part 2 (Extensive Literature Search/Review)

Immediately after the initial meeting, the team members digested all the information collected and came to the following realizations which guided them through the study:

- The solutions for the challenges facing the ODOT Ashtabula County personnel in inspecting their culverts cannot be a single robotic system.

- Possible solutions should be searched among the commercially available systems. This is because these systems were designed by a group of knowledgeable engineers and already went through extensive testing and fine-tunings. The commercial products are usually more affordable than custom-designed products. Also, each commercial system comes with a set of well-defined capabilities and limitations.

- Custom design/construction and/or modifications to a commercial system should be considered only if none of the commercially available systems can meet some of the essential criteria that were requested by the Ashtabula County garage personnel.

- The ODOT Ashtabula County garage definitely needs drone flyovers along the lake shore. The questions are the type of drone that is best suited for their needs and the logistics of doing the flyovers.

- The ODOT Ashtabula County garage also needs a flexible crawler kit that can be used to assemble a small size crawler that can go inside 8” diameter pipes (through a 4”-5” opening) as well as a larger size crawler that can advance through larger diameter (up to 120” in diameter) pipes.

- The crawler should come with a camera and a reliable locomotion system so that it can move forward/backward easily when partially submerged in water and when it is on top of a wet sediment layer.

- The crawler may come with an option of supporting an additional sensor such as a laser profiler and/or a guided wave device.

- Thermal camera may not be useful in culvert inspection work. This is because the amount of sun light is limited and there may be a good thermal equilibrium among all the elements (culvert material, reinforcement if any, water, sediment) found.

- The ODOT Ashtabula County garage may not benefit much from having a rafter or a submarine inspection system. This is because in this area the water depth is typically less than 12” and flow velocity is very slow.

In the second part of Task 2, the team conducted an extensive literature search to locate magazine articles, online videos, presentation files, conference papers, journal papers, reports issued by other state DOTs and federal agencies as well as municipalities, books, and theses/dissertations that looked into the use of indirect culvert inspection techniques. The research team also combed through trade magazines and a variety of websites (government, universities, vendors, etc.) to identify currently available and emerging technologies that appear to be relevant to the project.

The team members came across several journal articles that evaluated the effectiveness of various remote inspection devices/sensors such as CCTV camera, laser ring profiler, sonar, and acoustic methods. These publications were concerned with water mains and sewer pipelines, not with highway culverts. The team also located more than a few technical reports issued by state DOTs that evaluated the usefulness of using aerial drones for inspecting bridges and other transportation infrastructure. These publications are all summarized in Appendix A.

The online searches brought to the team information on a variety of remote inspection systems that have potentials to be useful when inspection culverts. These systems can be grouped into several classifications based on their fundamental designs and functionalities, as shown in Table 11 below.

Table 11: Classifications of Remote Sensing Inspection Systems for Culverts

System Classification	Type	Variations
Crawlers	Bottom Crawler	Wheel-powered vs. Track-powered
		Flexible kit vs, Rigid (single)
		Military-grade vs. Industry-quality
		Waterproof, Splash proof, Nonwaterproof
		Tethered vs. Untethered (RC)
		Camera only vs. Multi-sensor
	Elevated Crawler	Wheel-powered vs. Track-powered
		Waterproof vs. Nonwaterproof
		Camera only vs. Multi-sensor
Crawler-Drone Hybrids	NA	Wheel-powered w/ rotors; Rotor-powered wheels; Track-powered w/ rotors
Drones	Standard	Quad-rotor, Hexa-rotor, …
	Collision avoidance	Caged (passive) vs. Uncaged (active; equipped w/ collision avoidance sensors)
	Water resistance	Splash resistance, Water floatation, Water-submersible
	Sensors	Camera only vs. Multi-sensor
	Connectivity	Tethered vs. Nontethered
Rafters/Boats	NA	Camera only vs. Multi-sensor
Submersibles	NA	Underwater drone vs. True submarine
		Camera only vs. Multi-sensor
Others	Multi-leg Walking Robot	Camera only vs. Multi-sensor
	3-D laser scanning	Advanced land surveying

<u>Crawlers</u>

There are two fundamentally different crawler types – the traditional crawler design that basically traverses over the invert (bottom crawler) and a newer type that operates at an elevated position above the culvert bottom (elevated crawler). Most of the commercially available crawler systems are bottom crawlers whose designs involve motors powering their locomotion system and a chassis that supports lights, a camera, and a lift arm. Some of the bottom crawlers contain a DC battery and are operated wirelessly (controlled through a radio-control unit). Others are tethered to receive power and transmit images captured by the camera to external devices for real-time viewing and recording.

Most of the bottom crawlers are designed to inspect relatively small diameter water and wastewater pipelines (that are free of sediment and large debris), so they are usually compact and come with wheeled propulsion. However, there are some crawler packages that include modular components so that the crawler can be reconfigured with larger wheels, larger chassis, and camera lifting arms to become capable of inspecting larger size drainage structures. Some of these crawlers can function submerged under water, and others cannot. Some of these crawlers comes with an option of having a sensing unit, such as a laser ring profiler, as an add-on.

Apart from these industry-grade pipe crawlers intended for water/sewer lines, there are crawlers that are designed for military and law-enforcement uses. These systems appear to be more rugged and come almost always with caterpillar-tracked locomotion (opposed to wheel-based locomotion) system and can be tagged as 'military-grade all-terrain vehicles.' These systems are high priced, and they are often not truly water-resistant (only splash-resistant; not submersible). Availability of these systems may be limited to military and law enforcement offices.

Another variation of the traditional crawler design is the crawler that comes with legs extending out and supporting locomotive wheels or tracks. These crawlers are intended to operate at an elevated position above the invert to stay clear of water, sediment, and small debris.

Lastly, a few companies have put together large crawlers that support multi-sensor platforms, which can include technologies such as LiDAR, sonar, and GPR. These types are heavy and expensive. The best way to utilize them may be through a contractor.

Appendix C has brief information on and pictures of some of these crawler types. At the end of the appendix are tables that compare various crawler systems. This appendix also provides brief information on laser profiler and underwater laser scanner, as well as a mobile van (for supporting CCTV camera inspection).

<u>UAVs or Aerial Drones</u>

There has been an explosion of new developments over the past ten years in the so-called 'Unmanned Aerial Vehicles (UAVs)' or 'drones.' Most UAVs are small and powered by four or more propellers (rotors) to generate air lift to fly and maneuver in the air. Many come with a light-weight on-board camera supported on stabilized arms (gimbal) and thus function as agile visual surveillance systems. Due to many developments, some variations exist in terms of collision-avoidance, water-resistance, and multi-sensor capabilities.

Appendix D has brief information on and pictures of some of the notable UAVs. At the end of this appendix are tables that compare various drone systems. Appendix I describes initial tests that the team conducted in flying a UAV through a pipeline structure. Appendix J presents some discussions on the UAV risk assessment and measures that can be taken to minimize its chance of crashing.

<u>Crawler-Drone Hybrids</u>

Currently, there are only a few commercially available crawler-drone hybrid systems on the market. The designs vary depending on how the rotors and wheels are treated. There is a type that looks like an RC car with rotors mounted on the body (wheels and rotors function separately). Another design has the rotors integrated into the wheel assembly so that rotors generate propulsion for the wheels. The third design has rotors powering its tracked locomotion system. Regardless of the type, these hybrids are all currently very limited as they share toy-like qualities and suffer from short operation times. Appendix E has brief information on and pictures of these hybrid systems.

Rafters/Boats

Some companies marketing their robotic crawler systems also developed floating remote inspection systems. These basically look like a raft or a boat with a camera and lights mounted on the top. In some advanced design, a laser scanner and a sonar sensor are attached on the upper and lower sides of the boat to provide additional measurement capabilities both above and below water surface. At least one of the available boat systems have side extension arms to keep it positioned close to the center of the structure it is placed in. These floating systems rarely come with their own propulsion units, as they are supposed to be carried downstream by the current of the water flowing through the pipeline. Appendix F has brief information on and pictures of a few of these floating inspection systems.

Submersibles

In addition to the floating systems described above, there are some remote inspections that are designed to operate under water. These systems range from underwater rovers (or underwater drones), to submarines and UAVs that can dive into water. Some of these systems were developed to explore lake and ocean bottoms and ship wrecks and probably do not function well in sediment-laden murky water. At least one of the underwater rovers is shaped like a real fish to reflect the latest biotic design approach. The submarine type can be the most advanced and support multiple sensors. Appendix G has brief information on and pictures of some of these submersible inspection systems.

Other Systems

There are systems that do not belong to any of the classifications mentioned above. These are relatively new developments and include multi-legged, spider-like all-terrain robotic system and an advanced 3-D laser scan surveying system. Appendix H has brief information on and pictures of these unique systems.

Emerging Technologies

Finally, while conducting extensive online data searches the team learned of areas where the current commercial systems are still lacking. With this realization, the team members identified new technologies that should be integrated into the remote culvert inspection systems in the near future. Appendix K has brief information on these emerging technologies.

After gathering the information on a vast array of remote inspection systems currently available, the team drew comparisons within each system classification. The results of this effort were in the numerical ranking achieved across different systems available and recommended solutions for the challenges facing the ODOT Ashtabula County garage workforce. Here, main focus was placed on the crawler and UAV systems, as these systems types are believed to be most promising for resolving the challenges existing in the Ashtabula area. The comparisons/numerical raking tables for crawlers and drones are embedded in Appendices C and D, respectively. In addition, the team developed a series of decision-making charts that can be used as general guides when any DOT personnel are planning to conduct remote inspection of culverts. Finally, the team also attempted to address some cost issues (presented in Appendix L).

Task 2-Part 3 (Detailed Analysis of Information Collected)

In the third part of Task 2, the research team identified promising remote inspection systems in terms of conduit sizes – small (rise 12" to 36"), medium (rise 36" to 48"), and large (rise 48" to 120"). Once this was done, the team developed screening criteria and applied them to narrow down a number of currently available commercial and/or custom-designed remote inspection systems to those that should be tested at culvert sites in Phase 2.

Depending on the features and capabilities of the currently available systems, the research team looked into integrating additional sensors/techniques such as acoustic methods and LiDAR, which can transmit signals toward the conduit wall. The end products of Task 2 was a matrix of the currently available systems (classified in terms of conduit size, technology types, and other characteristics) and another matrix that shows changes that are needed to the currently available systems (including added features and new technology incorporation).

Table 12: Various Field Culvert Conditions

<table>
<tr><th rowspan="2">Culvert Size (in)</th><th colspan="2">Culvert Interior Conditions</th><th rowspan="2">Notes</th></tr>
<tr><th>Water Level</th><th>Sediment Level</th></tr>
<tr><td rowspan="5">Small & Medium (12 to 48)</td><td>none or very shallow</td><td>none or very shallow</td><td rowspan="2">These conditions are commonly encountered during post installation inspection</td></tr>
<tr><td>up to springline</td><td>none or very shallow</td></tr>
<tr><td>up to shoulder or higher</td><td>none or very shallow</td><td>This condition may exist where structure has a major sag in the middle or drains into a river or a lake.</td></tr>
<tr><td>none or very shallow</td><td>up to springline</td><td rowspan="2">These conditions develop usually after years in service</td></tr>
<tr><td>none or very shallow</td><td>up to shoulder or higher</td></tr>
<tr><td rowspan="4">Large (48 to 120)</td><td>up to springline</td><td>none or very shallow</td><td>This condition are commonly encountered during post installation inspection</td></tr>
<tr><td>up to shoulder or higher</td><td>none or very shallow</td><td>This condition may exist where structure has a major sag in the middle or drains into a river or a lake.</td></tr>
<tr><td>none or very shallow</td><td>up to springline</td><td rowspan="2">These conditions develop usually after years in service</td></tr>
<tr><td>none or very shallow</td><td>up to shoulder or higher</td></tr>
</table>

Research Conclusions

Solutions to Challenges Facing ODOT Ashtabula County Garage Workforce

The culverts along SR 531 (Lake Dr.) require:

- **A Drone** to fly out to their outlet ends and let the inspector view/record the general conditions. The drone must be easy to fly, come with a stable 4k camera, and provide FPV. The drone should have a collision avoidance capability, have a flight endurance of at least 15 minutes, fly back home automatically when going out of signal range, and either beep/vibrate or fly back home automatically when its battery power gets low. It is preferred that the system is waterproof and can float on water when it goes down. Another note is that the drone flyovers must be done according to the FAA's small unmanned aircraft regulation (14 CFR, part 107). The pilot must keep the drone in his/her visual line of sight all the time.
- **A Crawler** that is small enough to enter through the catch basin opening, is tethered, and comes with a powerful locomotion system, LED lights, a high-resolution camera that can pan-tilt-zoom, and a relatively long battery life (longer than 30 minutes).

Larger culverts (rise > 48”) that are hard to access due to steep/unstable embankment slopes and that are not usually filled with water/sediment require:

- **A Drone** to fly out to their outlet or inlet end and allow the inspector view/record the general conditions. If the culvert is large enough and accessible, the drone may enter the culvert to perform visual inspection. The drone should be easy to fly, come with a stable 4k camera, and provide FPV. It can be a caged collision-tolerant type or an uncaged type with an advanced collision avoidance capability. The drone must also have a flight endurance of at least 20 minutes, comes with LED lights, fly back home automatically when going out of range, and either beep/vibrate or fly back home automatically when its battery power gets low. Another note here is that the drone flights must be done according to the FAA's small unmanned aircraft regulation (14 CFR, part 107). The pilot must keep the drone in his/her visual line of sight all the time. Once the drone is inside the culvert, the FAA rules do not apply.

Relatively large size culverts that are easy to access but are usually filled with water require:

- **A Crawler** that can be configured to inspect pipes up to 120” in diameter, is tethered, is waterproof, comes with LED lights, a solid camera that can pan-tilt-zoom, a powerful locomotion system, a relatively long battery life (at least 45 minutes), and is equipped with a deformation measurement system.*

*[Note] Deformation measurement system can be either a laser/sonar combo or an underwater laser scanner.

Relatively large size culverts that are easy to access but are usually filled with water and sediment require:

- **A Crawler** that can be configured to inspect pipes up to 120” in diameter, is tethered, is waterproof, comes with LED lights, a powerful camera, a powerful locomotion system, equipped with a deformation measurement system,* a relatively long battery life (at least 45 minutes), and is equipped with additional sensing capabilities.**

*[Note 1] Deformation measurement system can be either a laser/sonar combo or an underwater laser scanner.

**[Note 2] Additional sensing capabilities are yet to be identified.

Sample Calculations for Flight Time Needed Assume that culvert end is located 400 ft away

Fly to culvert's end @ slow speed of 5 mph (= 440 ft/min) ⟶ 1 minute each way
Assume that there are only a few physical obstacles between the launch area and culvert end and it is easy to get around them
Assume that the drone hovers up to 3 minutes at the culvert end to take a peek.
Then, 5-6 minutes of time may be enough for each flyover.

A drone with flight endurance of 10-15 minutes may be sufficient for flying over to the outlet end and returning (no entry into the culvert structure).

Assume that culvert end is located 400 ft away ⟶ 1 minute each way
Assume that there are only a few physical obstacles between the launch area and culvert end and it is easy to get around them
Assume that culvert is 200 ft in length
Fly inside culvert @ very slow speed of 0.5 ft/sec (= 30 ft/min) ⟶ 7 minutes each way

A drone with flight endurance of at least 20 minutes may be needed to have it fly to the culvert end, navigate through the structure, go back to the entry point, and fly back home to the launch location.

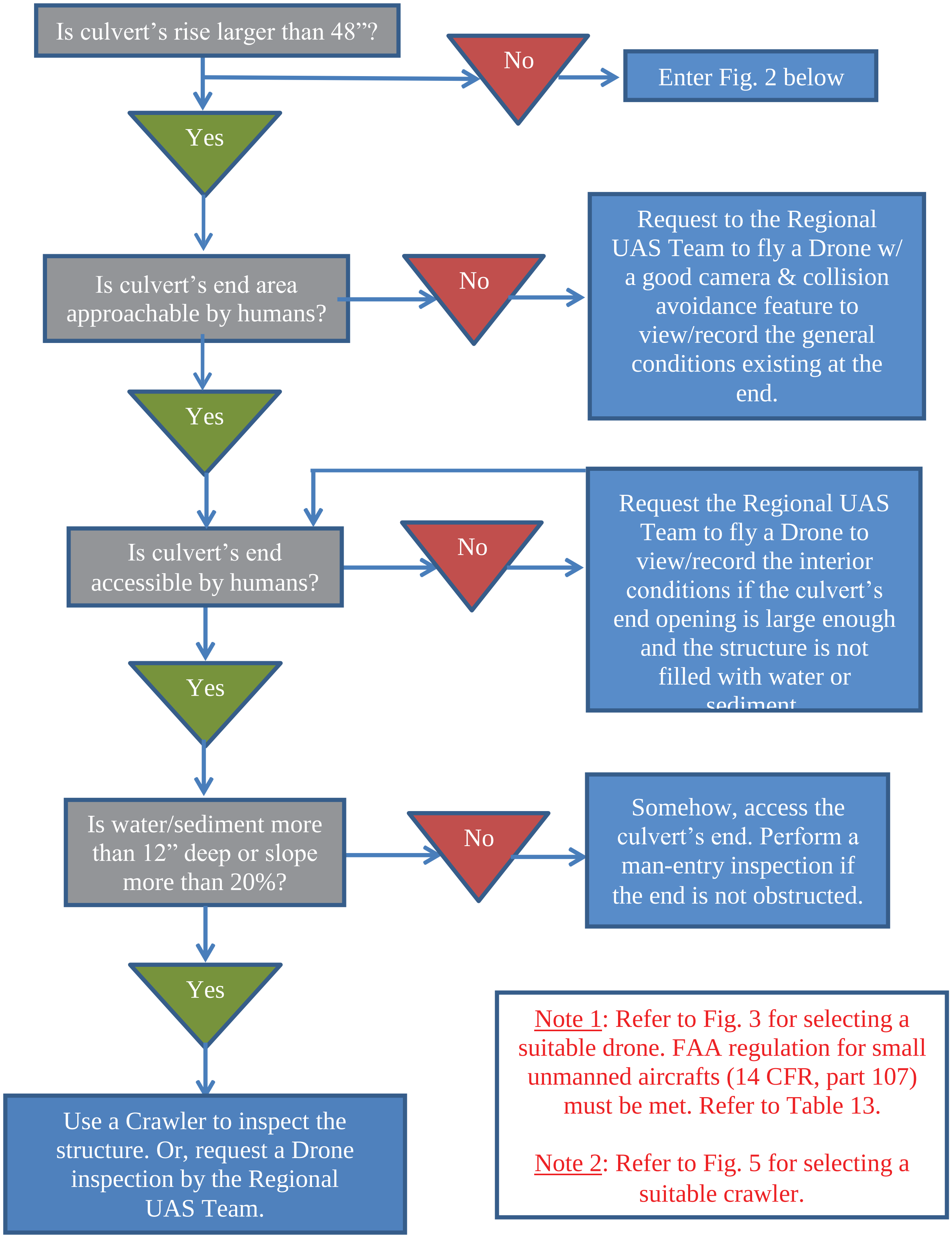


Figure 1: Decision Chart for Large Culvert Inspection

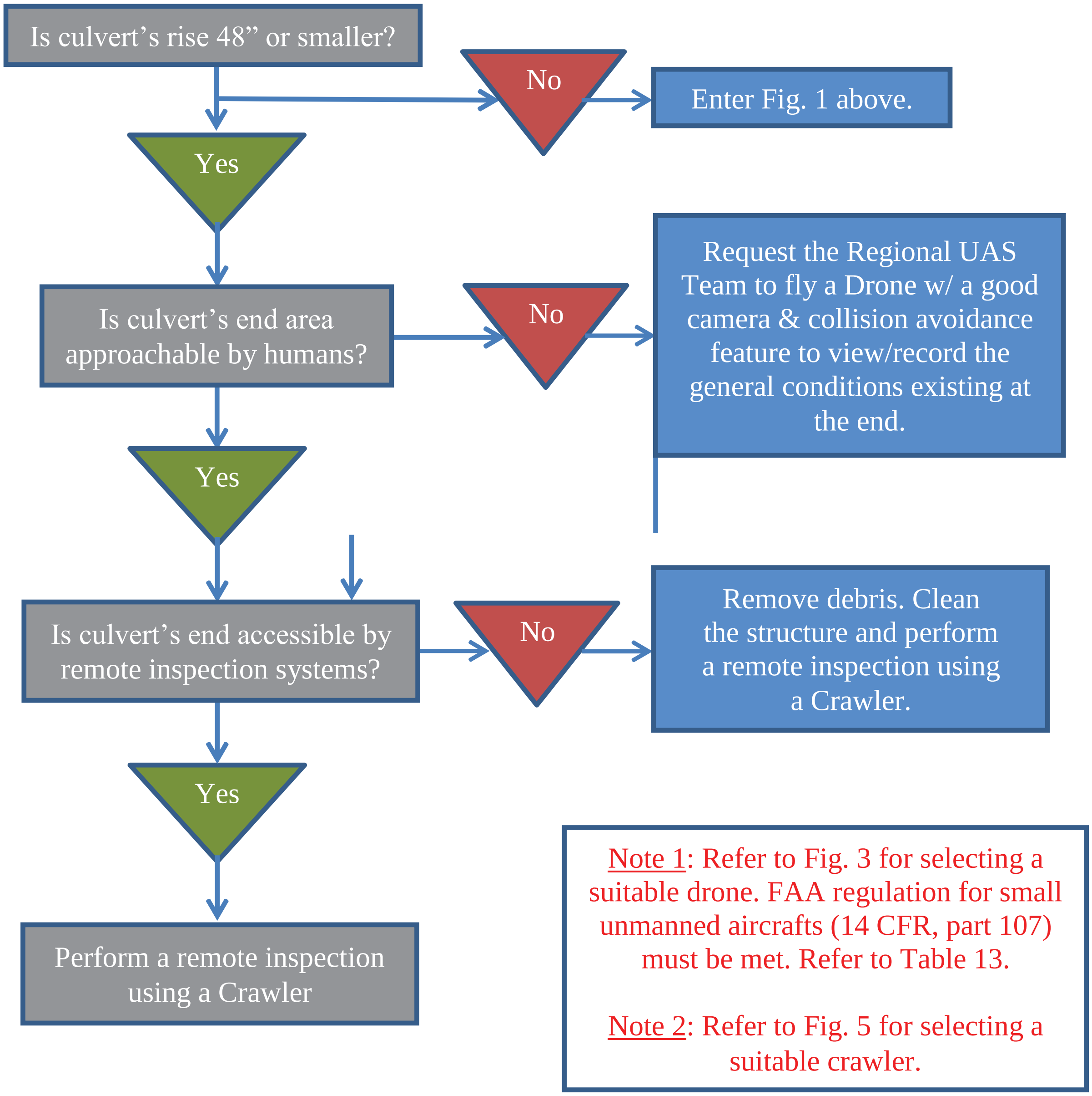


Figure 2: Decision Chart for Small Culvert Inspection

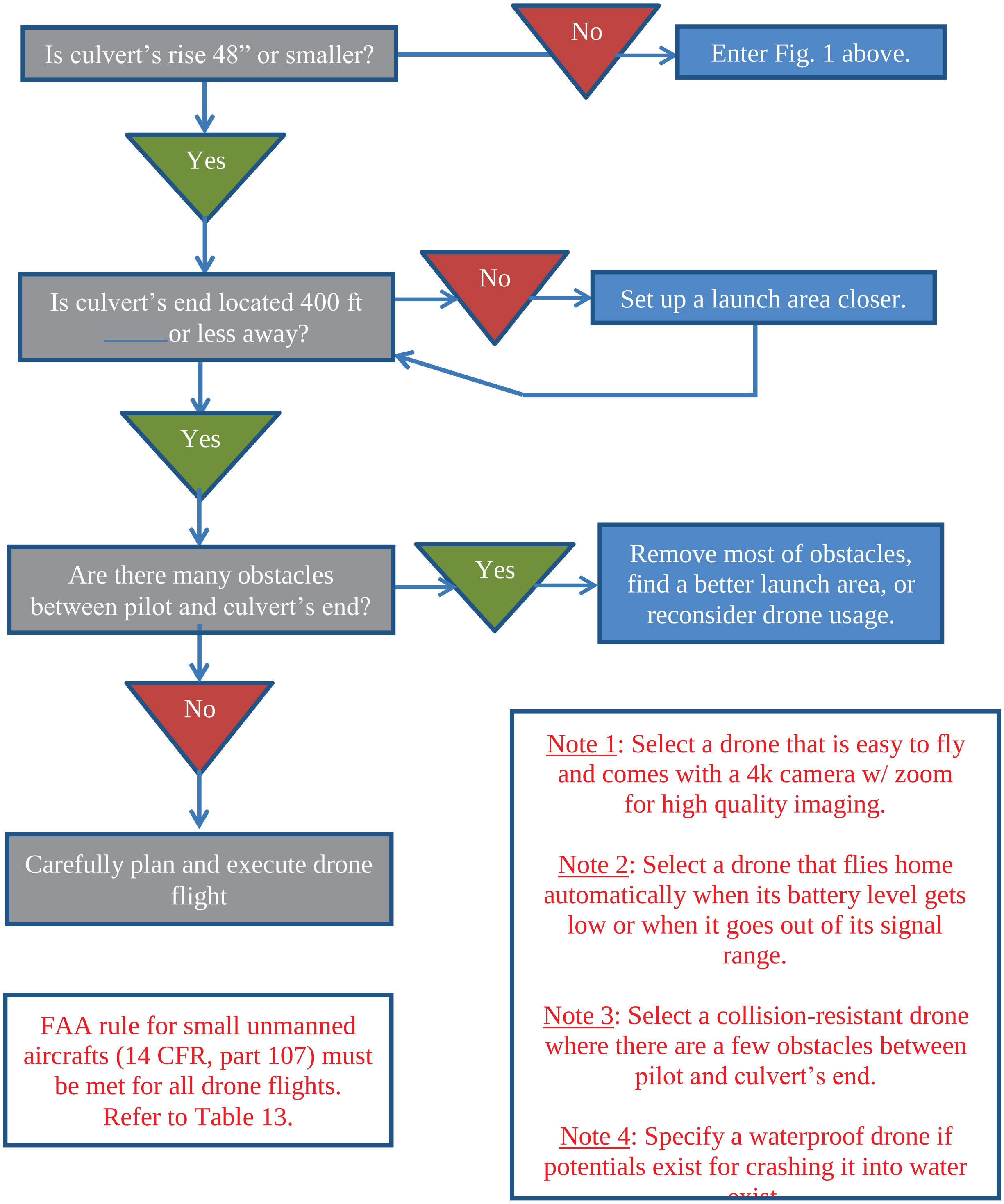


Figure 3: Decision Chart for Selecting a Drone for Viewing/Recording Culvert End Conditions

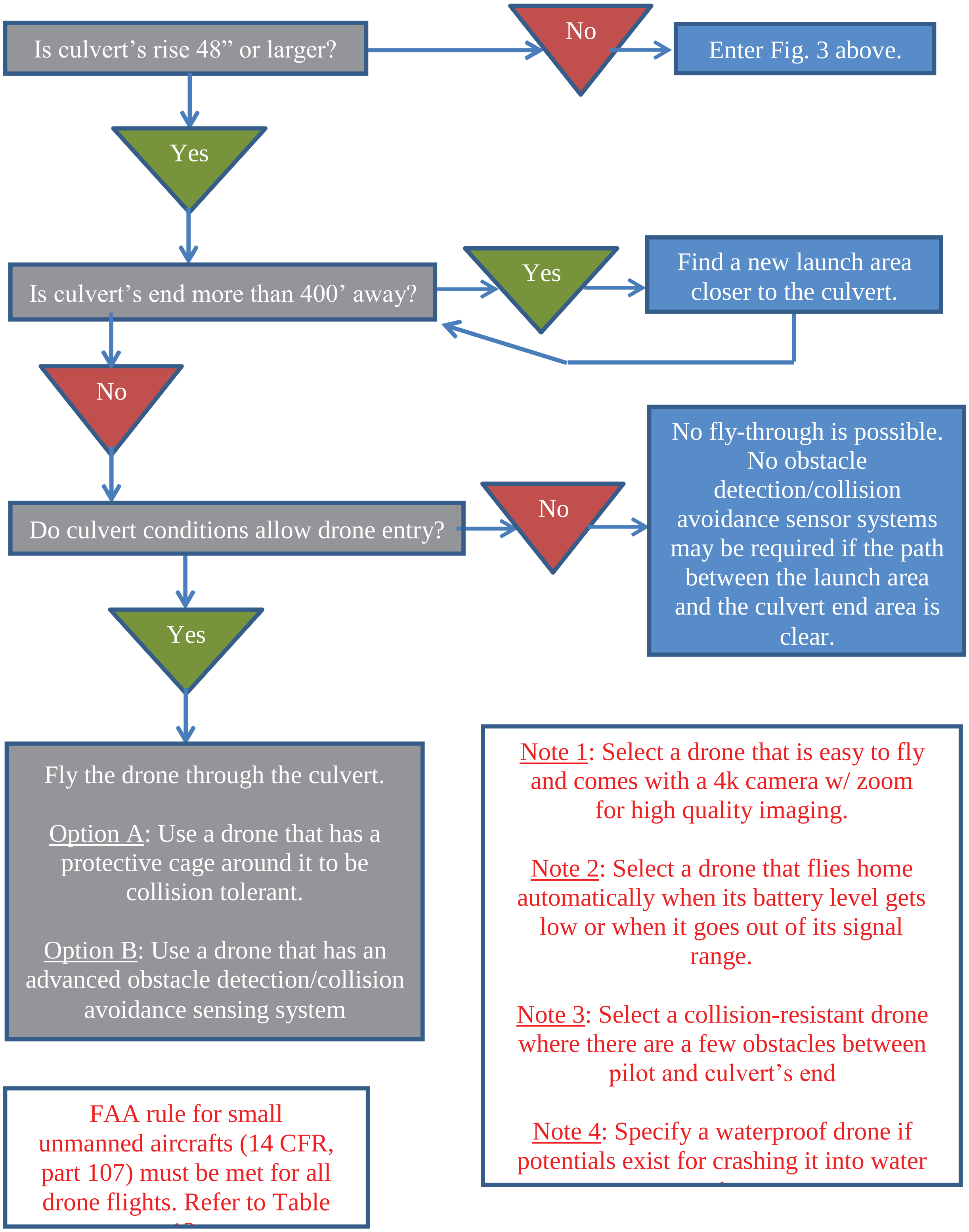


Figure 4: Decision Chart for Selecting a Drone for Flying Through Culvert for Visual Inspection

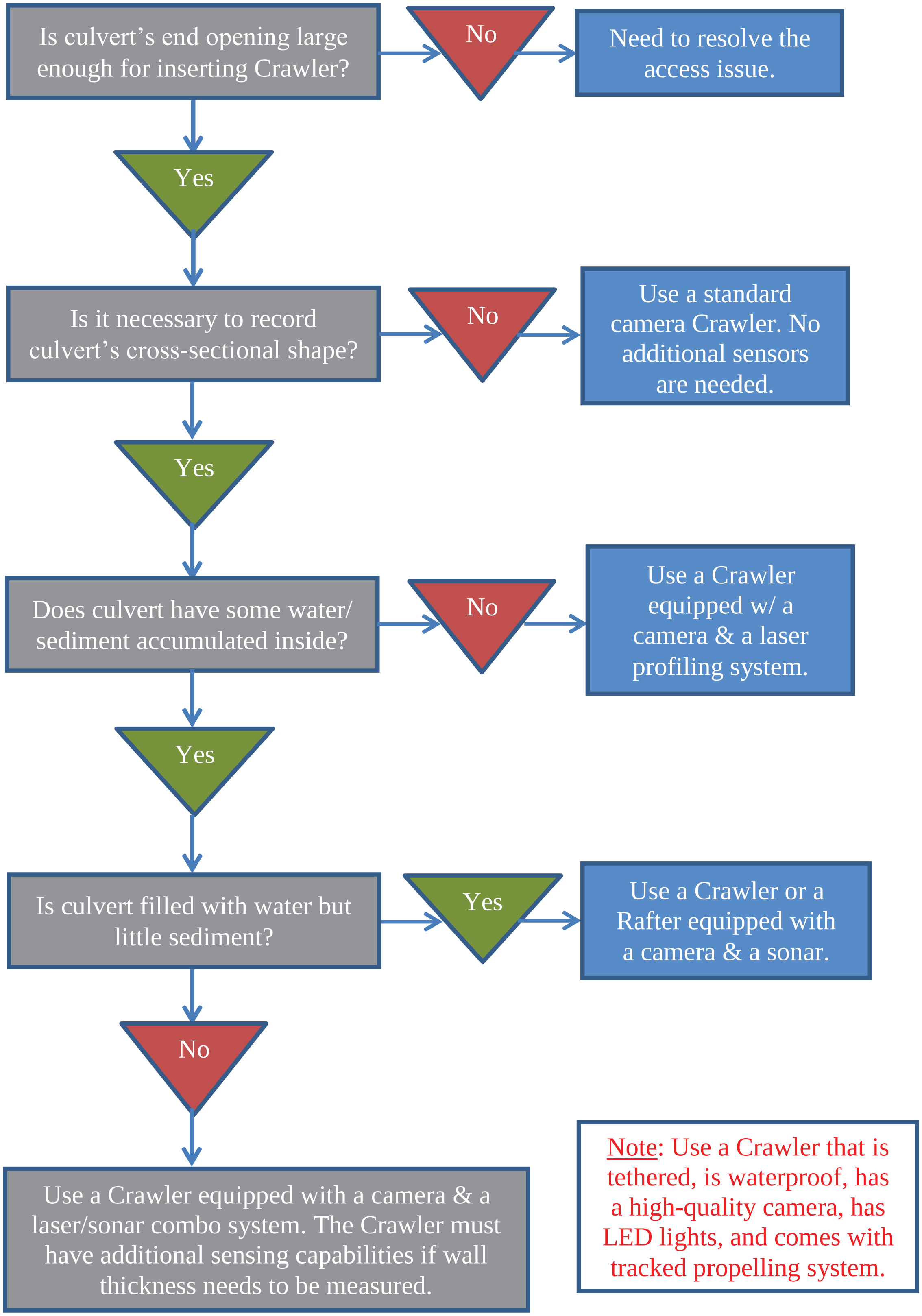


Figure 5: Decision Chart for Crawler/Rafter Inspection System

Table 13: Key Requirements of FAA Small Unmanned Aircraft Rule (14 CFR, Part 107)

Key Requirements	Check
Unmanned aircraft can be flown only by a person who holds a remote pilot certificate with a small UAS rating.	
Unmanned aircraft, including its payload, must weigh less than 55 lbs.	
Unmanned aircraft must be kept within the pilot's visual line-of-sight (VLOS) at all times.	
Unmanned aircraft must be flown only during day light hours (sunrise to sundown).	
Unmanned aircraft cannot be flown within any airspace.	
Unmanned aircraft must be flown only with weather visibility of 3 miles or more.	
Unmanned aircraft must not be flown over persons who are not directly participating in the operation.	
Maximum flight speed of the unmanned aircraft must be less than 100 mph.	
Maximum altitude of the unmanned aircraft must be no more than 400 ft above the ground level.	

Recommendations for Implementation of Research Findings

This section summarizes the team's recommended solutions for the problems facing the ODOT Ashtabula County garage in managing/inspecting their culverts. During the project, many remote inspection systems were examined. Although other potential systems (ex. all-terrain hex pod robot HEXA by Vincross, several different all-terrain waterproof rovers, floating systems equipped with laser & sonar) surfaced, the team members feel that crawlers and UAVs are the best remote inspection tools for highway culverts.

Crawler --- The pipe crawler systems, SOLO by Redzone Robotics and DT 340 by Deep Trekker, are each identified as a potentially useful remote inspection tool for culvert inspection work. This is because these systems are both caterpillar-tracked to be able to move through joints, small debris, and muddy sediment. SOLO is small enough to inspect pipes that are 8" to 14" in diameter. DT 340 with its track kit is useful for inspecting pipes that range from 14" to 36" in size. For larger size culverts, other crawlers (ex. Dragon Runner 20 by QinetiQ; Steerable Storm Crawler by Cobra Technologies; MudMaster by CUES; and Responder from Redzone Robotics) may be considered. The elevated crawler systems, such as the vertical crawler VT 150 by Inuktun and RMIS robotic crawler by Ryonic Robotics, may prove to be useful if any of the tracked crawler unit is not actually capable of advancing through wet sediment accumulated over the culvert bottom.

SOLO (Redzone Robotics)

DT 340 (Deep Trekker)

Responder (Redzone Robitocs)

Dragon Runner 20 (QinetiQ)

Versatrax 450 (Inuktun)

VT 150 Vertical Crawler (Inuktun)

Steerable Storm Crawler (Cobra Technologies)

MudMaster (CUES)

[Note 1] The Ashtabula County garage workforce has inspection systems available either inhouse or from their district to handle small to mid-size (6”-48”) diameter culverts. What they are lacking are systems that can inspect larger size (48”-120”) culverts.

[Note 2] The need for SOLO and DT 340 may depend on how well CUE’s wheel-powered pipe crawler (Steerable Pipe Ranger) works out at many culvert sites.

[Note 3] Dragon Runner 20 by QinetiQ is a light-weight all-terrain vehicle. It is not totally waterproof but can handle water splashes and puddles.

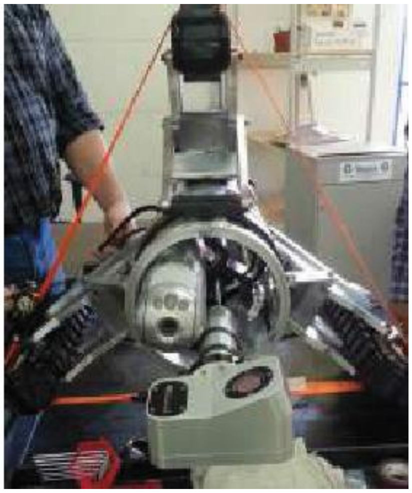
[Note 4] The multi-sensor platform crawler Responder (Redzone Robotics) is not recommended as highly as other systems, since it is very heavy and has to be contracted out for its deployment and complicated post-inspection data analysis.

[Note 5] The crawler kit Rovver X by EnviroSight may not be highly recommended as part of the solutions, since this modular system is wheel-based and has potentials to get stuck at pipe joints, between small stones, and on top of muddy sediment layers.

[Note 6] When some measurements are needed inside culverts, a laser ring profiler or a rotating laser profile-meter should be added to the crawler. These devices work only above the water surface.

[Note 7] The underwater laser scanner by 2G Robotics appears to be a great sensor tool to add to the crawler when inspecting culverts that are partially or almost entirely submerged under water. It appears that the sensor can function under some levels of turbidity.

Rovver X Crawler Kit (by EnviroSight)



Robotic Crawler (by Ryonic Robotics) Underwater laser scanner (by 2G Robotics)

The table below provides a matrix for crawlers.

Table 14: Matrix for Crawlers

Culvert Size	Culvert Conditions	Remote Inspection System(s) Recommended for:	
		Visual Inspection (Camera) Only	More Detailed Inspection with Measurements
4” to 8”	Dry	Push Camera (w/ a special attachment; see below)	None
8” to 15”	Varied	Option: SOLO	None
16” to 36”	Varied	Option 1: DT 340 Option 2: VT 150 Option 3: RMIS robotic crawler (up to 70” pipe size)	Option 1: A laser ring profiler attached to DT 340, VT 150, or RMIS Crawler Option 2: The underwater laser scanner attached to DT 340, VT 150, or RMIS crawler
36” to 120”	Varied	Option 1: Mud-master Option 2: Steerable Storm Crawler Option 3: Versatrax 450 Option 4: Dragon Runner 20 Option 5: RMIS robotic crawler Option 6: Responder	Option 1: A laser ring profiler attached to Mudmaster, Steerable Storm Crawler, Versatrax 450, Dragon Runner 20, or RMIS crawler Option 2: The underwater laser scanner attached to any of the systems mentioned above. Option 3: Responder with its LiDAR and sonar

[Note] SOLO by Redzone Robotics (page 66); DT 340 by Deep Trekker (pages 54-57); Versatrax VT 150 (vertical crawler; page 72) by Inuktun; RMIS robotic crawler by Ryonic Robotics (page 73), Laser ring profiler by EnviroSight (pages 52-53); Underwater laser scanner by 2G Robotics (pages 78-80); Mudmaster by CUES (pages 69-70), Steerable Storm Crawler by Cobra Technologies (pages 57-58), Versatrax 450 by Inuktun (pages 71-72); Dragon Runner 20 by QinetiQ (page 64); and Responder by Redzone Robotics (pages 66-67).

Camera Skid ($395)
RJM Equipment Sales, Inc.

Universal Roller Skid ($385)
RJM Equipment Sales, Inc.

Possible Attachments for Push Camera

[Note 8] Floating systems such as MSI MD Profiler (page 111) and CUES Floating Platform (page 110-111) will not be useful in the Ashtabula County area, since usually the water level is low and flow velocity is very slow. These systems with sonar usually require at least 3 feet of standing clear water.

Phase 2 Plans (for Crawlers): Effectiveness of the identified attachment to the existing push camera, crawlers, and crawler/sensor combo options will need to be evaluated in the field under various service conditions. Also, the possibility of employing the guided wave technology may be explored.

Regulatory Issues: None.

Technological Challenge: Development of noncontact acoustic (guided wave) technology by ARA & Ohio Univ. to penetrate through the sediment.

Business Aspect**:** Bring in commercial partners to enable technology transfer.

UAVs – The DJI Mavic Pro is identified as one of the best suited commercially available UAVs for doing flying-overs (to photo-document culvert end conditions) and also for quick peeking (into culverts). None of the commercial drones, including Mavic Pro, is capable of flying through the culverts because of RC control signal loss issue and collision avoidance.

DJI Mavic Pro

ELIOS by Flyability

[Note 9] The Ashtabula County garage workforce can have drone flyovers arranged with their district's UAS flight team, which will have systems such as DJI Inspire and Flyability ELIOS. What they are lacking is a UAS system that is waterproof and can float on water.

[Note 10] The collision-tolerant drone, ELIOS (by Flyability), can provide a simpler solution to the challenges of flying around obstacles and through confined space such as interiors of culverts as long as they keep receiving their control signal. Signal range for ELIOS can be extended by coupling it with a range extender antenna available from the same company. This accessary will be valuable to ODOT, since the flight time is limited to only 7 to 10 minutes for ELIOS.

[Note 11] The waterproof drones, such as Splash Drone 3 Pro (by Swellpro) and Quad H2O (by QuadH2O), are recoverable in the case they go down into a body of water. These drones are both waterproof and buoyant in water.

[Note 12] The tethered drone, such as Pocket Flyer (by CyPhy Works), is attractive if no major physical obstacles exist between the pilot and culvert end area. The strong thin microfilament tether can provide the drone an unlimited flying time and fail-proof fast communications.

Splash Drone 3 (by Swellpro)

QUAD H2O

Tethered Drone (by CyPhy Works) [Note 13] Currently, there are no professional-grade drone/crawler hybrid system, which can fly to the culvert end, crawl through the drainage structure (to collect data), and fly back to the pilot.

[Note 14] Due to major technical/logistic problems, it is not feasible to have a drone to carry a crawler and insert it into the culvert.

The table below provides a matrix for UAVs.

Table 15: Matrix for UAVs

<table>
<tr><th rowspan="2">Culvert Size</th><th rowspan="2">Culvert Conditions</th><th colspan="2">Remote Inspection System(s) Recommended for:</th></tr>
<tr><th>Flyover (w/Camera) + Potential Look-and-Go at End</th><th>Fly Through (w/Lights, Camera, Laser Scanning)</th></tr>
<tr><td>8”</td><td>Varied</td><td rowspan="4">Option 1: DJI Mavic Pro
Option 2: Splash Drone 3
Option 3: ELIOS
Option 4: Pocket Flyer</td><td rowspan="3">None.</td></tr>
<tr><td>10” and 12”</td><td>Varied</td></tr>
<tr><td>15” to 42”</td><td>Varied</td></tr>
<tr><td>48” to 120”</td><td>Little sediment, water, debris</td><td>A DIY modular mini-quadcopter assembled with lights, a camera & laser scanners, programmed to fly autonomously inside culverts</td></tr>
</table>

[Note] Mavic Pro by DJI (page 83), Splash Drone 3 by Swellpro (pages 87-88), ELIOS by Flyability (pages 81-82), and Pocket Flyer or PARC drone by CyPhy Works (pages 92- 94).

Phase 2: Effectiveness of the identified commercial drones will need to be evaluated in the field under various conditions. An advanced mini quadcopter drone with autonomous flight capability will need to be developed and tested.

Regulatory Issues: Meeting the requirements of the FAA’s Small UAV rule 14 CFR part 107 (especially visual line-of-sight requirement). A waiver may be needed for the part of the trajectory from the operator to the culvert opening where the drone becomes invisible for a duration of time through FPV or autonomy. A waiver may be also needed to fly a drone in some areas of Ohio (ex. Cuyahoga County) because they are in aviation air space. The fact that the use is only over a short distance (no further than 400 ft), typically not over people, and done responsibly in daylight by a government agency should help make the case to the FAA. It is anticipated that FAA rule will be further relaxed in the near future for UAS use for transportation infrastructure inspections. This is because some key state DOT studies are all indicating that UAS are very effective inspection tools.

Technological Challenges: Endurance time, waterproofing, autonomous flight in culverts, and recovery (in case of a crash)

Business Aspect**:** Bring in commercial partners to enable technology transfer.

Below is a summary of the cost analysis performed with some information provided by the ODOT Ashtabula County garage.

Table 16: Summary of Basic Cost Analysis

Inspection Type	System	Initial Investment	Notes
Small Culverts (6”-15”)	Push Camera w/ an Attachment	$400 (already in possession)	May cost $0.22 per foot; Need to purchase a $400 special attachment for the camera
	Steerable Pipe Ranger (CUES)	$0 (already available)	May cost $0.22 per foot
	SOLO (Redzone Robotics)	$90,000	May cost $0.22 per foot; Need to spend up to $100,000 to own the crawler system
	DT 340 (Deep Trekker)	$22,000	
Med. Size Culverts (16”-36 or 48””)	Steerable Pipe Ranger (CUES)	$0 (already available)	May cost $0.40 per foot; Need to spend up to $100,000 to own the crawler system
	DT 340 (Deep Trekker)	$22,000	
	VT 150 (Inuktun)	$90,000+	
	RMIS Crawler (Ryonic Robotics)	$95,000	Note: RMIS crawler can handle up to 70” size pipes.
Large Culverts (48”-120”)	MudMaster (QUES)	$200,000	May cost at least $0.5 per foot
	Steerable Storm Crawler (Cobra Technologies)	$165,000	May cost at least $0.5 per foot; Need to spend up to $200,000 to own the crawler system
	Responder (Redzone Robotics)	Contractor (no purchase)	$6.50 to $10.00 per foot plus $8,500 mobilization
Drone Flyover	ELIOS (Flyability)	$2,500	May cost $70 per culvert inspection.
	Splash Drone 3 (Swellpro)	$1,400	
	Tethered Drone (CyPhy Works)	$25,000	

Note: Refer to Appendix L for details.

The garage used to spend about $3.30 per foot for camera inspection. The above results show that owning or having access to good crawler systems can lead to tremendous cost savings.

There are always some risks for crashing whenever a drone is flown. The team came up with a series of tips that can be implemented to minimize the chance of drone crashing. In addition, the team has presented a few ideas about how to recover a downed drone in Appendix J.

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Arterburn, D., Ewing, M., Prabhu, R., Zhu, F., and Francis, D. (2017). FAA UAS Center of Excellence Task A4: UAS Ground Collision Severity Evaluation, Final Report (revision 2) for FAA, 148+ pp.

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Online Resources on Crawler Systems

www.cobratech.com	Steering Storm Crawler
www.cuesinc.com	Ultra Shorty III, Ultra Shorty 21, MudMaster
www.deeptrekker.com	DT 340
www.drrobot.com	RB-Sdr-77, RB-Sdr-96
www.envirosight.com	Rovver X
www.inuktun.com	Versatrax 150, 300, 450 & VT 150
www.officer.com	Pointman
www.reconrobotics.com	Dragon Runner 10 & 20, Scout IR
www.redzone.com	SOLO, Responder
www.ryonic.com	Ryonic RMIS Crawler
www.sarcos.com	Sarcos Guardian S
www.sewervue.com	SewerVUE Surveyor
www.superdroidrobots.com	Jaguar V4
www.turtlerover.com	Turtle Rover
www.cuesinc.com	Laser Ring Profile
www.envirosight.com	Laser Ring Profiler
www.rauschusa.com	Laser Scanning Profiler
www.2grobotics.com	Underwater Laser Scanner

Online Resources on Floating Systems

www.cuesinc.com	Floating Platform
www.redzone.com	MSI MD Profiler
www.uvstrenchless.com.au	Multi-Sensor Raft

Online Resources on Unmanned Aircraft Systems

www.aeryon.com	Aeryon SkyRanger
www.amazon.com	DJI & other drones
www.atlasdynamics.eu	Atlas Pro Drone
www.bergenrc.com	Bergen
www.cyphyworks.com	CyPhy Works Pocket Flyer
www.dji.com	DJI Inspire, 2, Mavic Pro, Phantom 4 Pro & Spark
www.flyability.com	Flyability ELIOS
www.getfpv.com	MTRI Blackout Mini H
www.goflyeye.com	Aerobot Flyeye
www.proxdynamics.com	Black Hornet 2
www.quadh2o.com	QuadH2O
www.roboticstrends.com/article/loon_copter_drone_flies_floats_swims_underwater	
www.sensefly.com	SenseFly Albris
www.swellpro.com	Swellpro Splash Drone 3
www.yuneec.com	Yuneec Typhoon H Pro

Online Resources on Underwater Systems

www.aquabotix.com	Aquabotix
www.cuesinc.com	Sonar Profiling System
www.deeptrekker.com	Underwater Drone DTG2
www.navaldrones.com	REMUS 100 AUV
www.openrov.com/products/trident	Trident Underwater Drone
www.redzone.com	HD Sonar Sub
www.videoray.com	Video Ray

Others

www.vincross.com/HEXA	All-Terrain Hex Pod Robot
www.leica-geosystems.com	Leica Laser 3-D Survey Scan

Appendix A. Literature Review

Selvakumar et al. (2014) reported a comprehensive study they conducted for the U.S. EPA in which they tested five indirect technologies at select field sites of buried wastewater collection infrastructure. The five technologies were Closed-Circuit Television (CCTV), zoom camera, digital scanning, electro-scanning, laser profiling, and sonar. CCTV was chosen since it has become the industry standard for inspecting wastewater pipelines, and it can establish baseline data. The other four technologies were brought in because they are commercially available but still relatively new and untested. The team provided the following notes on each of the five technologies:

- CCTV – This system can provide video representations of the interior conditions of the pipe above the waterline. CCTV can identify and locate specific defects so long as the pipe is precleaned and almost free of debris and water. CCTV cannot supply any quantitative data such as the size and depth of cracks in pipe wall or voids in backfill. CCTV data requires subjective assessment of its visual data. CCTV inspection can be time-consuming, as the camera is mounted on a crawler that moves through the pipeline at a slow steady speed.

- Zoom Camera – The operation of this camera-based system may be simpler and less time-consuming if the camera is mounted on a pole to simply peek in, pan 360 degrees, and zoom down the pipe as far away as 100 ft. The system produces still imagery or video recordings of the pipe's interior conditions above the waterline. However, the system may not be able to provide as much information as CCTV. This system may not require precleaning of the pipe if it is mounted on a pole.

- Digital Scanning – In this technique, a crawler or a floating platform equipped with one or two high definition (HD) digital cameras travels through the pipeline to collect HD video and still photo data of the pipe's interior conditions. Some digital cameras come with an inclination meter and gyroscope for alignment measurements. Wide-angle lenses are used often for larger size pipes. The advantage over CCTV is that with this system defect coding can be done easily in the office with post-processing software that permits the users to do virtual pan, tilt, zoom, and stop the image. The disadvantage of the system is that the image resolution declines with pipe diameter.

- Electro-scanning – This electric technique, based on ASTM F 2550-06 test method, is carried out by sending an electric voltage between an electrode attached to the nonferrous (clay, concrete, plastic) pipe and another electrode anchored on the ground away from the pipe. If the pipe is free of any defects such as cracks, holes, and open joints, high electrical resistance is measured between the two electrodes. Thus, this is basically a leak detection method. The measurement is taken at predetermined intervals along the pipe length. The technique can produce a graphical plot, in which spikes in the measured electric current indicate the location of the defect around the pipe's circumference. The method may be able to estimate the type of defect through computer data processing. The method is obviously applicable only to pipes that are almost fully filled with water.

- Laser Profiling – This system captures a two-dimensional geometry of the pipe interior wall at each location where it is operated. The system can be combined with a CCTV or digital scanning unit to provide needed quantitative information. If the scan shows the pipe interior to be deviating outside of the reference shape at one location, the pipe likely has badly deteriorated wall (perforation, pitting, slabbing, etc.) at that location. If the scan shows the opposite, the pipe likely has debris accumulation or localized wall warping/buckling. The laser profiling system should come with a motion monitoring system so that it knows its orientation/position with respect to the pipeline axis. If the system is veered off from its ideal position, it can provide largely distorted incorrect profile shape.

- Sonar – Unlike any of the systems described above, this sound wave-based technique can be used to inspect pipe conditions below the waterline. Sonar inspection is carried out usually by passing a sonar unit mounted on a raft, skid, or robotic tractor through the pipeline. The system emits high frequency sound waves and picks up with its head reflected wave signals coming from the pipe wall and debris. The system can be used in conjunction with the laser system so that a complete pipe geometry can be gathered for partially submerged structure. If sediment accumulation exists over the pipe's invert, the only information the sonar system can provide is the location and depth of sediment accumulation.

Liu and Kleiner (2013) conducted a state-of-the-art review of indirect inspection techniques for assessing physical conditions of water mains. A comprehensive review identified seven method groups for inspecting water distribution pipelines – visual inspection (CCTV), laser scan, electromagnetic methods (magnetic flux leakage, remote field eddy current, broadband electromagnetic, pulsed eddy current, ground penetrating radar, ultra-wideband pulsed radar), acoustic methods (sonar profiling scan, impact echo, smart ball, sahara system, leak detection), ultrasound methods (guided wave ultrasound, discrete ultrasound, phased array, combined ultrasound testing), radiographic methods (X-ray, gamma-ray), and thermography methods. The followings are some comments they made for the methods that are relevant to highway culverts:

- CCTV – Two cameras are needed to provide frontal view as well as 360-degree side view. The crawler speed should be set at 6 in./se (15 cm/s) or slower to ensure video quality. Alternatively, the system can have two scanning digital cameras, each equipped with a 186-degree fish-eye lens, to capture hemispherical images to create full 360-deg. panoramic images. Regardless of the system used, ample illumination is needed inside the conduits.

- Laser Profiling – The basic system comes with a unit that rotates the laser 360 degrees. No special lighting is needed. Accuracy of laser measurements is affected by rotational speed, sampling rate, crawler speed, surface color/roughness of the conduit. The newer system projects a ring-shaped laser light onto the pipe surface so that a camera can capture this image, and computer software can later analyze the exact shape of the pipe. All laser profiling systems available are for above waterline. No known laser systems function underwater.

- Sonar – This underwater acoustic technology emits a pulse (velocity 0.1-0.2 m/s) every 1.5 seconds which bounces back when encountering a solid object. Each echo received can provide the outline of the submerged pipe section. The resolution of the geometry data is proportional to the sonar frequency. Thus, small surface defects can be best detected at high frequencies. However, at higher frequencies sonar pulses attenuate fast (do not travel far from the emitter). To get the best of the both frequency ends, some sonar systems conduct a wide-frequency scan. A system equipped with both laser and sonar systems can provide the complete geometry for partially submerged pipes.

- Impact Echo – In this technique, the pipe is struck by a hammer to send stress waves across the pipe wall. The waves reflect back upon reaching any density contrasting boundaries (pipe/soil interface, a sizable anomaly in the wall such as a void) and are detected by a displacement sensor or an accelerometer positioned near the impact site. The technique has been used for pipes made of concrete, masonry, ceramics, and plastic. The ultrasound methods work in a similar fashion.

- Ground Penetrating Radar (GPR) – In this technique, electromagnetic radio waves are transmitted from an antenna, travel through a solid body, reflect off any density contrasting boundaries, and are detected by a receiver unit. The technique is commonly applied from the ground surface to locate a buried object. However, recently there are GPR systems that can operate from inside the pipe to collect data concerning the pipe wall and the soil fill outside the pipe. Similar to the sonar method, a wide range of radio frequency waves are needed to obtain the best results.

Liu and Kleiner prepared tables to summarize performance-related information for the inspection techniques (partially reconstructed in Table A.1). In addition, they listed multi-sensor platform pipe inspection systems that are available in the market (also partially reconstructed in Table A.2). Lastly, the authors commented that systems that need to be hooked up to an electric power chord are preferred over the cordless autonomous ones because the chord can function as a tether to recover the crawler in case it becomes stuck inside the pipe.

Table A.1: Performance Notes on Indirect Inspection Techniques

Method Type	Performance Related Notes
Visual Inspection	[CCTV] Quality of video image depends highly on skills of field personnel.
Laser Scan	Can provide an accurate profile geometry even in darkness, but needs data processing.
Acoustic Methods	[Sonar] Can provide accurate pipe cross-section. Accuracy may be less in turbid water carrying suspended solids.
	[Impact Echo] Works well for wall thickness up to 1.8 m. Accuracy is typically 2%.
Electromagnetic Methods	[GPR] The performance (penetration depth, resolution) in soil is highly dependent on soil characteristics. Penetration tends to be very limited in wet clays. No evidence of consistent ability to detect voids in soil. Significant work is needed to process and interpret the signal data.

Table A.2: Available Pipe Inspection Systems

System	Sensors	Notes
PIRAT	Video camera, 2D laser scanner	A non-autonomous, tethered surveillance system. Comes with a 250-m length cable.
KARO	Video camera, 3D optical scanner, inclinometers, ultrasound test system	A semi-autonomous, wheeled, and tethered experimental platform. Designed to work in pipes up to 12-inch diameter. Inclinometers help the system adjust its position.
KANTARO	Fish-eye camera, 2D laser scanner	A fully autonomous, self-propelling-steering, and un-tethered platform. Designed to work in pipes up to 12-inch diameter.
MAKRO	Camera, laser cross-hair projector, ultra-sound test system, infrared sensors	A fully autonomous, self-propelling-steering, and un-tethered platform. Consists of six jointed segments. On-board batteries can support up to 2 hours of operation.
Super-Pig	Ultrasound sensors	A non-autonomous platform for incorporating ultrasound sensors to measure pipe wall thickness loss, cracks, and other defects. Designed to work in pipes up to 12-inch diameter. Needs a vehicle to propel through the pipe.

The wastewater infrastructure (PVC and reinforced concrete pipes that varied in diameter from 8 to 72 inches) were examined using remote technologies in Kansas City, Missouri in August 2010. At the end of the field demonstration phase of the project, the team made the following notes:

- CCTV inspection identified locations of structural defects. Cracks, fractures, and broken pipe were the most common structural defects observed.

- Zoom camera inspection managed to cover only about 20% of the total length of the pipelines, since only a small number of manhole-to-manhole pipe segments had a sight distance of less than 50 ft. In addition, sight distance was sometimes limited due to spider webs, vegetation roots, and debris. Also, quality of visual data by this technique was reduced by condensation taking place on the camera lens. When functioning well, zoom camera inspection was able to identify defects that were observed by CCTV.

- The combination of laser and sonar scanners was able to identify, with engineering judgement, most of the locations of structural defects such as material loss.

- The sonar scan provided the information on the location and depth of sediment in the pipe accurately, which was unavailable by CCTV inspection.

Morris et al. (2013) of Robotic Institute at Carnegie Mellon University presented a new method of collecting detailed 3-D geo-survey data for subterranean spaces using a robotic crawler equipped with LiDAR, video camera, thermal camera, and other sensors. LiDAR stands for light detection and ranging. It is a laser-based remote surveying technique that can collect high-resolution contour data for any solid surface. This technology has been applied to map the surfaces of Earth, moon, and many other objects. The system is basically an advanced version of the laser profiler described earlier. It works only above the waterline.

A research team at Michigan Tech University (Brooks et al., 2015) recently looked into the use of quad-rotor drones, which are equipped with onboard camera and video recorders, for inspecting culverts. They tested four UAVs --- Bergen hexacopter, DJI Phantom Vision 2 quadcopter, Blackout mini H quad, Mariner Waterproof quadcopter, and a few micro UAVs. One of the objectives was to determine if UAVs can fly safely in confined spaces such as culverts. They stated that the drone will need a stable platform and onboard lighting to acquire high-quality image data. They also mentioned concerns for the ground effect, which is a phenomenon that lifts an aircraft higher when it is hovering close to the ground (propellers displacing the air beneath the craft, causing the air pressure to rise).

A recent issue of the *ASCE Civil Engineering Magazine* has an article related to the use of drones for inspecting bridges (Wells et al., February 2017). The article describes a recent program completed jointly by the Minnesota DOT (MinnDOT) and Collins Engineers, Inc. in which unmanned aircraft system (UASs) or so-called drones were used to conduct inspections of three bridges and one corrugated-plate arch structure. In the first phase of the program, the MinnDOT studied the Federal Aviation Administration (FAA) regulations applicable to the use of drones. For the second and main phase, the MinnDOT tested two different quad-rotor drone systems (Aeryon SkyRanger by Aeryon Labs, Inc. of Waterloo, Ontario, Canada; and Albris UAS by SenseFly SA, Cheseaux-sur-Lausanne, Switzerland) that were both equipped with traditional and infrared cameras. For inspecting the high arch culvert, the drone Albris UAS was equipped with ultrasonic detectors to avoid any obstacles. No GPS receiver was needed as the drone was only to fly along the straight culvert structure. The MinnDOT is still analyzing all the data gathered in the program. However, they stated that the program was successful and it is quite possible to use UASs without violating FAA regulations. The MinnDOT also reported cost savings of up to 66% when inspecting bridges with an UAS.

On Sept. 16, 2016, the Albris drone was tested in front of media and bridge engineers by the Ohio Turnpike & Infrastructure Commission, Ohio/Indiana UAS Center, ODOT, and SenseFly to demonstrate its effectiveness as a new tool for inspecting bridges. The drone was able to perform well during the initial phase of the remote inspection of the Sandusky River Bridge (length 970', width 102'). However, in the final phase it suddenly lost power and crashed into the water below the bridge. The company SenseFly was unable to retrieve their $35,000 UAS. (The Cleveland Plain Dealer, Sept. 16, 2016).

The Florida DOT Study (2012) looked into the use of UAVs in their transportation-related projects. Their key conclusions are listed below:

- Rotary-wing UAVs work better than fixed-wing UAVs.
- The weather & wind speed can impact the UAV's ability to obtain useful images and data. Smaller UAVs are more sensitive to wind and rain.
- Safe distance from target = 1 ft (ave. wind speed 7 mph, gust speed 10 mph); 3 ft (ave. wind speed 15 mph, gust speed 20 mph)
- Operators completed training in an average of 2.75 hours.
- Processing the UAV images into 3D models was a highly time-intensive process.
- The overall cost of purchasing a UAV (UAV platform, sensors, battery, etc.) may sum up to anywhere between $25,000 and $45,000. The UAV costs are coming down. [Ex.] DJI's Phantom series (less than $1,000).
- Key features must include a 360-degree camera.
- UAVs generally have a shorter flight endurance than manned aircraft.
- Although "sense & avoid" technology has been developing, UAVs still pose a potential for collisions.

The U.S. Forest Service (2016) conducted a study in which they examined the benefits and costs of using small unmanned aircraft in forest service operations. The range of operations included bridge inspections. They concluded that the UAVs can provide high-resolution images of the bridge structure from angles only possible from a UAV. However, they pointed out that it was often unable to capture images from interior sections of the bridge. They also noted that the real time UAV camera can detect cracks up only to 0.06."

The Minnesota DOT (June 2017) issued their latest study titled "Enhanced Culvert Inspections – Best Practices Guidebook." In this comprehensive study, a research team evaluated capabilities of inspection technologies such as CCTV, laser ring profiling, sonar, and Joint Photographic Expert Group (JPEG) mosaic inspection. Below are key comments the team noted on each of the technology options:

- <u>Closed Circuit TV (CCTV)</u>: Requires a crawler equipped w/ a CCTV camera, established low-cost technology backed by national standards. Potential negatives
    - = crawler's sensitivity to site conditions, operator experience, no shape
    - measurements, image distortion, cumbersome data storage.
- <u>Laser Ring Profiling</u>: Availability of the large laser scan unit (to work in 36"-118"
    - dia. pipes) may be limited.
- <u>Sonar</u>: The smallest unit can be deployed in 12" dia. pipe and needs at least 4" of
    - water. The large unit can survey up to 18'dia. pipe.

- [Note] For partially submerged culverts, a floating platform may be constructed so that a laser and a sonar sensor can produce images of the culvert above and below the water line, respectively.
- Joint Photographic Expert Group (JPEG) Mosaic Inspection: Sidewall scanning, Utilizes a crawler equipped with digital imaging cameras, Capture a continuous 360° image of culvert interior wall

Michigan Department of Transportation (2014) carried out a comparative demonstration study on camera inspection systems coupled with laser ring profiler. The test equipment was provided by companies including CUES, Rausch, and RST. After some field trials, they reached the following observations:

- The cost of camera systems ranged from $119,000 to $254,000, including hardware and software.
- Each camera system was able to provide data on pipe out-of-roundness.
- All camera systems had shortcomings that are inherent to the type of technology. For example, corrugated plates inside metal pipes produced a shadow effect, which made the data analysis difficult.

Appendix B. Local Culvert Data (Ashtabula County, Ohio)

The culvert inspector (John Arcaro) at the ODOT Ashtabula County garage provided a list of his top priority culverts. The table below provides some basic information on these drainage structures. The information was extracted from the ODOT's online-accessible Transportation Infrastructure Management System (TIMS).

No.	Old CFN	Location	Note
1	040112000	SR 11, North of Seven Hills Rd.	96" dia. CMP, 306' length, Slope 1.5%, Soil cover 30', Installed 1960;
2	040111990		36" dia. CMP, 128' length, Inlet @ manhole, Soil cover 5', Installed 1960
3	none	SR 531, Across from West Shore Drive, East of Kent State	(additional information not available.)
4	045310370	SR 531, East of SR 11	15" dia. RCP, 50' length, Slope 2%, Inlet @ catch basin, Soil cover 2'
5	045310380		15" dia. RCP, 50' length, Inlet @ manhole, Soil cover 2'
6	043070090	SR 307, 1.85 mi East of County Line	12" dia. vitrified clay, 66; length, Outlet tied to a metal pipe, Installed 1925
7	043070110		36" stone, Soil cover 19', Installed 1925
8	045340090	SR 534, North of SR 86	68" dia. CMP, 60' length, Both ends accessible, Soil cover unknown
9	045310080	SR 531, East of Myers Rd	36" dia. HDPE pipe, 125' length, Inlet @ catch basin
10	045310090		24" dia. HDPE pipe, 87' length, Slope 3%, Inlet @ catch basin, Installed 2014
11	040902060	I-90, East of SR 193	24" dia. RCP, 88' length, Inlet @ catch basin, Soil cover unknown, Installed 1958
12	040902080		60" dia. CMP, 398' length, Slope 4%, Both ends accessible, Soil cover unknown, Installed 1958
13	none	I-90 @ Conneaut Creek Bridge	(additional information not available.)
14	040901705	I-90 @ ATB River Bridge	15" dia. CMP, 114' length, Slope 0.5%, Inlet @ catch basin, Soil cover unknown, Installed 2012
15	040901710		24" dia. RCP, 126' length, Slope 0.5%, Inlet @ catch basin, Soil cover unknown, Installed 1958
16	040112020	SR 11 @ ATB River Bridge	18" dia. RCP, 75' length, Slope 3%, Inlet @ catch basin, Outlet @ manhole, Installed, 1960
17	040112010		18" dia. RCP, 92' length, Slope 1%, Inlet & outlet @ catch basin, Installed, 1960
18	040112340	SR 11 @ RR Bridge, South of SR 46	15" dia. RCP, 168' length, Inlet @ catch basin, Installed 1961

According to ODOT hydraulic engineer Matt Retta, most culverts in Ashtabula County are 36" or less in diameter. This statement applies both to the culverts along SR-531 (Lakeshore Drive) and to those that always have water ponding. The partially submerged culverts may typically have up to 12" of water and 0"-8" of silty sediment on the bottom. There may be some exceptions.

The table below lists the culverts that are located under SR 531 (Lake Rd.). Once again, all of the information was extracted from ODOT's TIMS.

No.	Old CFN	Location	Note
1	045310590	SR 531, west of Salisbury Rd.	30" dia. RCP, 50' length, Soil cover unknown, Inlet end open (not tied to catch basin)
2	045310580	SR 531, just west of the above	18" dia. RCP, Length & soil cover unknown, Inlet end open (not tied to catch basin)
3	045310570	SR 531, just west of the above	24" dia. RCP, Length & soil cover unknown, Inlet end open (not tied to catch basin)
4	045310560	SR 531, just east of Cleveland Dr.	18" dia. RCP, 40' length, Soil cover unknown, Inlet end open (not tied to catch basin)
5	045310550	SR 531, just west of Cleveland Dr.	24" dia. RCP, Length & soil cover unknown, Inlet end open (not tied to catch basin)
6	045310540	SR 531, just east of Poore Rd.	12" dia. vitrified clay, Length & soil cover unknown, Inlet end open (not tied to catch basin)
7	045310530	SR 531, just west of the above culvert	24" dia. cast iron, 50' length, Soil cover unknown, Inlet end open (not tied to catch basin)
8	045310520	SR 531, just east of Derbyshire Rd.	30" dia. HDPE, 50' length, Soil cover unknown, Inlet end open (not tied to catch basin)
9	045310510	SR 531, just west of Derbyshire Rd.	30" dia. cast iron, 50' length, Soil cover unknown, Inlet end open (not tied to catch basin)
10	045310500	SR 531, just east of Berkshire Rd.	48" dia. RCP, 50' length, Soil cover unknown, Inlet end open (not tied to catch basin)
11	045310490	SR 531, west of the above, east of Harmon Rd.	30" dia. cast iron, 60' length, 11' soil cover, Inlet end open (not tied to catch basin)
12	none	SR 531, west of Harmon Rd., handling a stream's flow	48" span stone box, Length unknown, 13' soil cover, Installed 1900, Both ends open
13	045310460	SR 531, west of the above	15" RCP, Both ends may be open & accessible, No other info available

No.	Old CFN	Location	Note
14	045310450	SR 531, west of the above	72" span concrete box, 55' length, Soil cover 4', Both ends open
15	045310440	SR 531, west of the above	15" RCP, Both ends may be open & accessible, No other info available
16	045310430	SR 531, west of the above	60" dia. RCP, 60' length, Soil cover 5', Installed 2006, Inlet end may be open & accessible
17	045310420	SR 531, just east of SR 193	15" dia. cast iron, 50' length, Soil cover unknown, Inlet end may be open & accessible
18	045310410	SR 531, between SR 193 and Englewood Ave.	12" dia. HDPE, No other information available
19	045310400	SR 531, west of Parkwood Dr.	12" dia. RCP, 50' length, Soil cover 4', Inlet @ catch basin
20	045310390	SR 531, west of the above	12" dia. RCP, 50' length, Soil cover unknown, Inlet @ catch basin
21	none	SR 531, west of the above	15" dia. RCP, 50' length, Soil cover unknown, Inlet @ catch basin
22	045310380	SR 531, west of the above	15" dia. RCP, 50' length, Soil cover unknown, Inlet @ catch basin
23	045310370	SR 531, west of the above, east of La Bounty Rd.	15" dia. RCP, 50' length, Soil cover 2', Inlet @ catch basin
24	045310360	SR 531, between La Bounty Rd. and Russell Rd.	42" dia. CMP, Gage 10, 75' length, Soil cover 12', Inlet @ catch basin
25	045310350	SR 531, west of the above	15" dia. RCP, 58' length, Soil cover 3', Inlet @ catch basin
26	045310340	SR 531, west of the above, east of rail road	24" dia. RCP, 80' length, Soil cover 1', Inlet @ catch basin
27	045310330	SR 531, just west of rail road	12" dia. vitrified clay, 40' length, Soil cover 2', Inlet @ catch basin
28	045310320	SR 531, west of the above	12" dia. cast iron, 40' length, Soil cover 2', Inlet @ catch basin
29	045310310	SR 531, west of the above, east of State Rd.	12" dia. cast iron, 40' length, Soil cover 2', Inlet @ catch basin
30	045310300	SR 531, just east of State Rd.	RCP with unknown diameter, No additional information available
31	045310290	SR 531, just west of Parkview Ave.	15" dia. cast iron, 35' length, Soil cover unknown, Inlet @ catch basin
32	045310280	SR 531 @ Manola Ave.	12" dia. RCP, Soil cover 2', No other information available
33	040112410	SR 531 @ SR 11	12" dia. RCP, 56' length, Soil cover unknown, Inlet @ catch basin, Installed 1961
34	040112400	SR 531 @ SR 11	12" dia. RCP, 95' length, Soil cover 8', Inlet @ catch basin, Installed 1961

No.	Old CFN	Location	Note
35	045310270	SR 531 @ Bristol Ave.	12” dia. RCP, 36’ length, Soil cover 2’, Inlet @ catch basin
36	045310250	SR 531 @ Stowe Rd.	12” dia. CMP, 51’ length, Soil cover 2’, No more information available
37	045310240	SR 531 @ Locust Dr.	12” dia. HDPE or PVC, 203’ length, Soil cover 2’, Inlet @ catch basin
38	045310210	SR 531, just east of Overlook Dr.	15” dia. vitrified clay, 46’ length, Soil cover 4’, Inlet @ catch basin
39	045310200	SR 531, between Walnut Dr. and Elm Dr.	36” dia. RCP, 36’ length, Soil cover 6’, Inlet @ catch basin
40	045310190	SR 531, between Century Bay Ave. and Morningside Ave.	27” dia. RCP, 53’ length, Soil cover 2’, Inlet @ catch basin
41	045310180	SR 531, just west of Shadyside Ave.	18” dia. RCP, 36’ length, Soil cover 2’, Inlet @ catch basin
42	045310170	SR 531, just west of Shadyside Ave.	18” dia. RCP, 48’ length, Soil cover 2’, Inlet @ catch basin
43	045310160	SR 531 @ Linwood Dr.	42” dia. cast iron, 66’ length, Soil cover 8’, Inlet end open and accessible
44	045310150	SR 531 @ Park Dr.	30” dia. RCP, 60’ length, Soil cover 4’, Inlet @ catch basin
45	045310140	SR 531 @ Russell Rd.	18” dia. RCP, 48’ length, Soil cover 1’, Inlet @ catch basin
46	045310130	SR 531 @ Rudd Rd.	12” dia. plastic, 47’ length, Soil cover 2’, Inlet @ catch basin
47	045310120	SR 531, west of the above	12” dia. CMP, 38’ length, Soil cover 2’, Inlet @ catch basin
48	045310110	SR 531 @ Ninevah Rd.	15” dia. RCP, 54’ length, Soil cover 2’, No more information available
49	045310100	SR 531, west of the above, handling a small river	84” dia. RCP, 112’ length, Soil cover 14’ max., Both ends open and accessible
50	045310090	SR 531, west of the above	24” dia. HDPE, 87’ length, Soil cover 10’ max, Inlet @ catch basin
51	045310850	SR 531, west of the above	24” dia. HDPE, 100’ length, Soil cover 15’ max, Inlet @ catch basin
52	045310080	SR 531, west of the above	36” dia. HDPE, 125’ length, Soil cover 2’, Inlet @ catch basin
53	045310070	SR 531, west of the above	72” dia. RCP, 33’ length, Soil cover 1’, Inlet end open and accessible
54	045310060	SR 531 @ Hawley Dr.	18” dia. plastic, 60’ length, Soil cover 3’, Inlet end @ catch basin
55	045310050	SR 531, west of the above	24” dia. HDPE, 60’ length, Soil cover 4’, Inlet @ catch basin

No.	Old CFN	Location	Note
56	045310040	SR 531, just east of Austin Rd.	15” dia. RCP, 36’ length, Soil cover 1’, Inlet end may be open and accessible
57	045310030	SR 531 @ Austin Rd.	15” dia. RCP, 60’ length, Soil cover 3’, Inlet @ catch basin
58	045310020	SR 531 @ Broxton Dr.	12” CMP, 60’ length, Soil cover 2’, Inlet end @ catch basin
59	045310010	SR 531, just west of Fairfax Rd.	12” CMP, 40’ length, Soil cover 2’, Inlet end @ catch basin

There are 59 culverts listed under SR 531 (Lake Dr.) in TIMS. Their diameters range from 12 to 84 inches. The longest length is 203 ft. The culvert materials vary. Basic analysis of the data compiled here is given below.

- Size Distributions --- 12” (17 culverts), 15” (12 culverts), 18” (6 culverts), 24” (7 culverts), 27” (1 culvert), 30” (5 culverts), 36” (2 culverts), 42” (2 culverts), 48” (2 culverts), 60” (1 culvert), 72” (2 culverts), and 84” (1 culvert).

- Length Distributions – Less than 50’ (24 culverts), 50’ to 69’ (16 culverts), 70’ to 89’ (3 culverts), 90’ to 109’ (2 culverts), 110’ to 150’ (2 culverts), More than 150’ (1 culvert), Unknown (11 culverts)

- Materials --- Concrete (32 culverts), Corrugated Metal (5 culverts), Ductile Iron (8 culverts), Vitrified Clay (3 culverts), Plastic (9 culverts), Stone (2 culverts).

- Shapes --- Circular (57 culverts), Box (2 culverts).

- Inlet Treatment --- Connected to Catch Basin/Manhole (33 culverts), Wide Open (18 culverts), Unknown (8 culverts)

Appendix C. Notable Commercial Crawler Systems
[Note] This section was put together largely by cutting-and-pasting photographs, specifications, and writeups from various vender websites.

Crawler Kit by EnviroSight - Crawler Rovver X

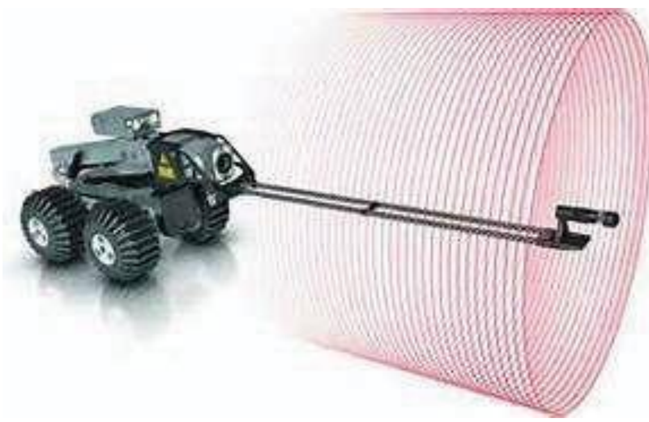
EnviroSight has a flexible pipe crawler kit, which has a 6-wheeled crawler named Rovver X, many different size/type wheels, a camera head, a reel with 1000 ft of cable, a twin joystick control unit, and tools (wrenches, etc.). The crawler is submersible, being constructed from aluminum and stainless steel (corrosion resistant). It weighs 13.2 lbs. It has dimensions of 12.2" L x 4.4" W x 3.2" H and is small enough to inspect 6" dia. pipes. The crawler comes with many quick-change wheel options. Each wheel is shaped and treaded to climb over obstacles and joint offsets and provide good traction.

Crawler Rovver X – Price $17,160
The camera RCX90 (Price $14,040) that comes with Rovver X has the following specifications:

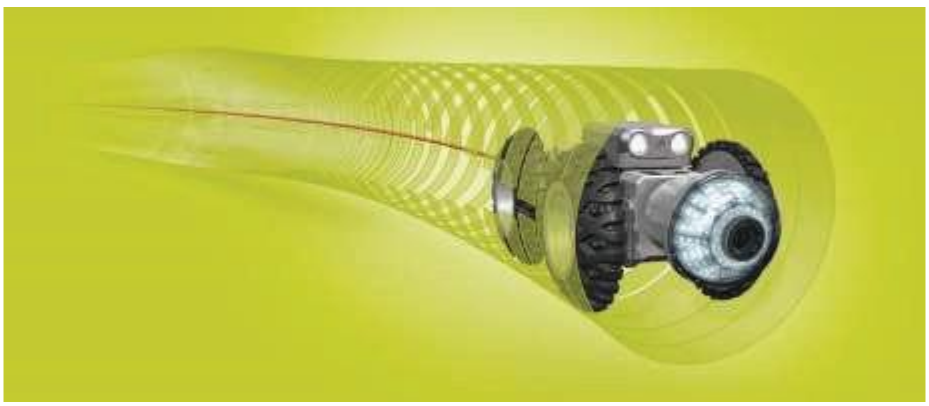
- Size: 6.6" L x 3.1" W x 2.8" H
- Weight: 3.3 lbs
- Resolution: 720 x 576 pixels
- Zoom lens: 120x (10x optical, 12x digital)
- Pressure rating: 1 bar or 33 ft of water
- Features: Auto shutter, auto/manual focus
- Illumination: Dimmable 40-LED array
- Articulation: +145 degree tilt; Infinite pan
- Sensing capability: Temperature, pressure, pan/tilt

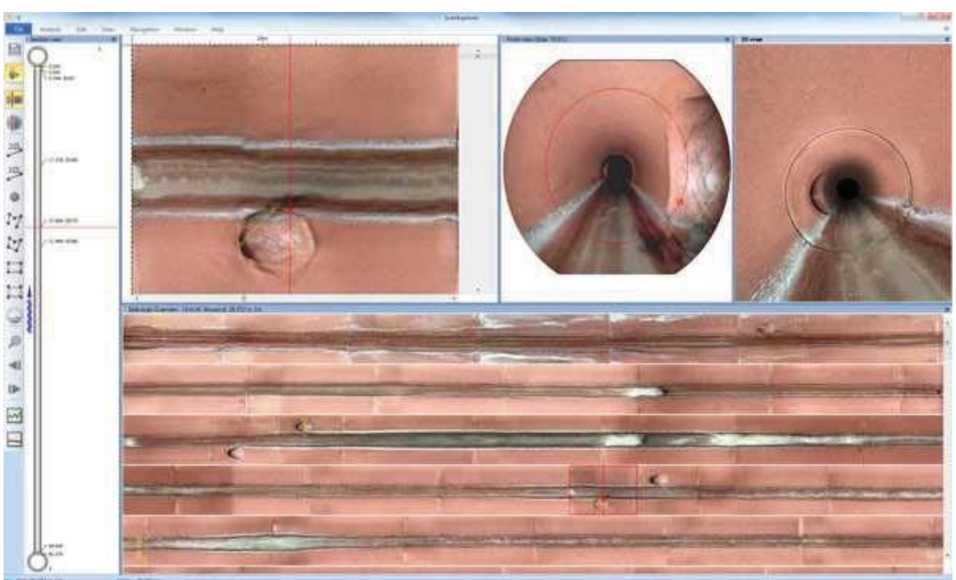
EnviroSight has an optional camera lift arm available, which can be attached to the crawler to raise the camera position by 3.1” to 10.2”. Price - $12,480
They also have two larger carriage systems for the camera, which will allow the system to inspect pipes up to 10 ft in diameter called XL Tractor ($10,400).

EnviroSight has a laser ring profiler available, which can be attached easily to the crawler Rovver X. This unit allows the system to capture pipe ovality data for pipes that are in 6” to 27” in diameter.




The latest option/accessory made available by EnviroSight is the side-scan camera, DigiSewer ($54,080).





With DigiSewer side-scanning, you capture footage at speeds up to 70 feet/minute without stopping to pan, tilt or zoom. And side-scanning generates detailed flat scans that can be reviewed and annotated in a fraction the time.

With all the time and money side-scanning saves, be sure to demand a system that handles all your pipe—no matter the material, condition and size. DigiSewer for ROVVER is the only side-scanner that adapts to real-world conditions, and the only one that also supports traditional CCTV inspection, giving you total versatility for your investment.

Best of all, DigiSewer remains the leading innovator in side -scanning, offering features like virtual pan/tilt, inclination graphing, joint/ tap auto-recognition, PACP color-coding, and full WinCan integration.

Not only is DigiSewer adaptable enough to scan the broadest range of pipe sizes and diameters, it runs on the ROVVER platform, which means it can also be reconfigured to perform traditional video inspection and laser profiling.

DigiSewer scans can be viewed and annotated using WinCan's ScanExplorer software. DigiSewer works in pipes ranging from 6" to 27" in diameter.

DT 340 Pipe Crawler (by Deep Trekker)
<u>DT 340S</u>

The DT340 S package includes everything you need as a professional pipe inspector. The system includes a pan, tilt and zoom camera to easily view your entire pipe system as well as a tether length counter to know where defects are found within the pipe system. The simple to use handheld controller with integrated viewing screen includes everything you need to operate your DT340 crawler. This package contains:

- DT340 Pipe Crawler with PTZ Camera Head
- 150m Tether on Reel with Tether Length Counter
- Handheld Controller
- Carrying Cases (2)

The DT340 L package includes everything you need to start out with pipe inspections, including a static camera, easily steer and maneuver through your pipelines with the handheld video controller. This package contains:

- DT340 Pipe Crawler with Static Camera Head
- 150m Tether on Standard Reel
- Handheld Controller
- Carrying Cases (x 2)

DT 340 Pipe Crawler

Dimensions: 28” L x 5.6” W x 6.0” H
Weight: 34.2 lbs
Material: Stainless steel, Aluminum
Pipe Size: 8” Dia. (min.)
Lights: Shadowless LED flood
Sensors: Camera, Water pressure, Inclinometer
Speed: 12 m/min
Temperature: 23 to 104 degrees F

The DT340 L Package is ideal for simple pipe inspections. Deep Trekker Pipe Crawler is like no other crawler on the market. With on-board batteries, the crawler can operate up to 8 hours on a 1.5-hour charge. Short ‘top-up’ charges on breaks can extend the DT340 pipe crawler use even longer. Using the hand-held controller with integrated viewing screen; easily maneuver your crawler throughout your pipe system as you watch live on the integrated super-bright screen the view from the static camera head. This system requires no additional or dedicated truck systems, the entire unit fits into two carrying cases so you can deploy from anywhere.

Static Camera Head Specifications:
Imager: Color 1/4” CCD
Resolution: 530 TVL, 1.0 lux

Zoom Lens: 10X Optical
Features: Auto/manual iris, auto/manual focus

The DT340 S Pipe Crawler is submersible in up to 50m (164 ft) of water. Inspect submerged storm, sanitary, or underwater pipelines with ease.

The DT 340 L system comes complete with 4 wheels designed to fit in an 8-inch pipe. Optional wheel sizes and tracks are available to properly position the camera head in the center of the pipe. Optional wheels and tracks can be added or removed in-field. The options bolt onto the outside of the standard wheels using four screws.
Package Price: $9,999

DT 340 Wheel Kit for 12" Dia. Pipes

These rubber wheels will properly position your camera head in the center of a 12 inch (300 mm) pipe. The additional wheels can be added or removed at any time. The wheels bolt onto the outside of the standard wheels included on the DT340 systems using 4 screws. Select from a complete 4 wheel set or select additional individual spare wheels.

Price: $1,199

DT 340 Elevating Arm

Pipe inspection best practices include centering your camera head in the middle of your pipe. Now, with this elevating arm you can add additional height to your DT340 Pipe Crawler experience at any time. Quickly bring your camera head to the center of the pipe to ensure that you reach the perfect viewpoint in pipes as large as 36" (914 mm) in diameter. Price: $2,999. Suitable for use with 10" or 12" wheel sets for the best stability.


DT 340 Crawler Tracks Kit

When in larger pipes or overcoming large objects, track option greatly improves your pipe inspection abilities. The track system can fit in pipes 14 inch (355 mm) in diameter or larger, and can be added to either the DT340L, DT340S, or DT340X packages.

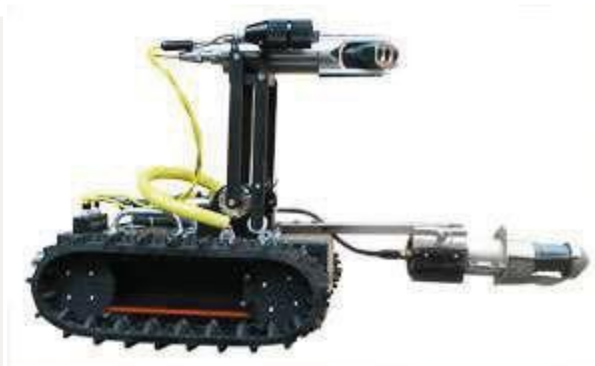
The track option is lightweight, durable, and self-cleaning, with anodized aluminum and UHMW construction to support polyurethane belts reinforced with steel cords.
Price: $5,623


Pipe Crawlers by Cobra Technologies

Cobra Technologies offers crawlers that can be configured with either wheels or tracks and can support a camera and a laser ring profiler.

Cobra Technologies introduces its powerful and unique track driven crawler designed for inspection of storm sewer pipes 24" to 120". The **Cobra Steerable Storm Crawler** utilizes a unique track system or wheels depending on the pipe size, type and condition. It has a 360° skid steer (joystick). Incorporating the distinctive, exclusive features of the powerful Cobra 8" Crawler (automatic freewheel/automatic drive engagement, variable speed, stainless steel swivel single connector, etc.), the Cobra Steerable Storm Crawler has unrivaled power and performance. A remote/manual elevator provides inspection capabilities to 120". The power elevator defaults to a closed position automatically should a power failure occur. Cobra systems incorporate necessary wiring to use the Cobra Steerable Storm Crawler without any system changes making Cobra Inspection Systems easily upgradeable to meet all your pipe inspection requirements. The Steerable Storm Crawler is water-submersible.

Steerable Storm Crawler (tracked)



Steerable Storm Crawler (w/ Sonar)

Price: $160k-$170k (w/ 500+ ft of tether)

Note: Cobra Technologies does not offer a laser ring profiler. It must be obtained from EnvironSight of CUES.

All Terrain Inspection Vehicles

The pipe crawlers listed above were both developed for sewer pipes in mind, which do not have much deposits inside. Highway culverts, however, often have sediment and large obstacles (boulders, bricks, tree branches, etc.). Thus, a robust all-terrain inspection vehicle may be more desirable.

Below is an all-terrain vehicle inspection robot available from a company called Inuktun. It may be also known as 'Delta Extreme Crawling ROV.' It has a camera and lights on its front face and is propelled by a tacked propulsion system. Youtube videos online show how easily this system can move on top of wet soil sediment. When inspecting larger pipes and/or navigating in a pool of water, it can function in a raised configuration, as seen in the picture on the right.

The next all-terrain portable inspection vehicle is shown below:

Jaguar V4 Mobile Robotic Platform by SuperDroid Robots is designed for indoor and outdoor applications requiring robust maneuverability and terrain maneuverability. It comes with up to four articulated arms and is fully wirelessly 802.11N connected. It integrates outdoor GPS and 9 DOF IMU (Gyro/Accelerometer/ Compass) for autonomous navigation. Jaguar V4 platform is rugged, light weight (< 30Kg), compact, weather and water resistant. It is designed for extreme terrains and capable of stair or vertical climbing up to 300mm (12”) with ease. The 4 articulated arms could convert the robot into various optimal navigation configurations to overcome different terrain challenges. The integrated high resolution video/audio and optional laser scanner provide remote operator detail information of the surrounding. Besides the ready to use control and navigation software, a full development kit including SDK, data protocol and sample codes, is also available.

- Dimensions: 38.5” L x 27.6” W x 7” H
    - Weight: 66 lbs
    - Speed: 0-5.5 km/h (0-3.4 mph)

    - Slope: Up to 55 degrees
    - Camera/Video: Color (640 x 480, 30 fps) with audio
    - Payload: 33 lbs max.
    - Controller: Gamepad Controller
    - Battery: LiPo battery (rechargeable)
    - Operation Time: 1.5 hrs
    - Temperature: -30 to 40 degree C
    - Mode: Remote control or autonomous navigation with GPS
    - Note: Shock resistant; Sealed weather-resistant construction
    - Price: $16,500

The third option is a system RB-Sdr-96 (treaded pipe and duct inspection robot w/ tethered controller) by SuperDroid Robots. Price: $9,659.31

Specifications:

- For pipes and culverts 10" inner diameter and larger
- Full pan and tilt dome front camera with 10X optical zoom mounted
- Pan goes 360 degrees and the tilt is 0 to +90 degrees
- All the camera functions are controlled from the remote as you stream the video
- Chassis: Custom Welded Aluminum Base with IG32 right angle motors. The robot is completely waterproof.
- Motors: 2 inch Wide Molded Track Set with custom wheels
- Battery: High Power Polymer Li-Ion Module 22.2V 3Ah
- Interface: Custom Controller with joysticks and 7inch color LCD. A 500 foot cable spool with rotary union is also included for easy deployment and winding of outdoor rated cable.
- Weight: 10lbs as configured
- Dimension: 8.5" wide x 17" long x 6.5" high. Designed to go into 10 inch ID pipes are larger.
- Assembly: The entire robot will be assembled, configured and tested
- Speed: 9 feet/sec
- Runtime: Up to three hours
- Camera System: PTZ dome camera 10X optical zoom.

The forth option is a system RB-Sdr-77 (compact tracked robot w/ stabilizer arms) by SuperDroid Robots. Price: $9,700.

It is a small rugged robot that can easily fit in backpack or carrying case. The robot weighs less than 8lbs. The MLT-F is equipped with a rear flipper arm and camera in the nose of the robot. The version with the flipper arm is drop resistant up to 10 feet and can be tossed into a room or up on a balcony, etc. The treaded design and rear flipper arms allow this robot to climb many obstacles other compact robots can't.

Small sized, rugged surveillance robot

- Treaded design and rear flipper arms
- Drop resistant up to 10 feet
- Climbs over objects up to 10"
- Includes audio and video surveillance
- Added visibility with high intensity LED lights
- Variable speed up to 120 feet per minute.
- Size: ~12.75"(L) x ~9.5"(W) x ~4.4"(H)
- Weight: Less than 8 lbs
- Tire/Tread size: 3.75" composite cogged wheels
- Run time up to 4 hours depending on use

Military-Grade Robotic Systems

Many robotic systems are being developed to aid military and law enforcement officers in conducting reconnaissance missions in hostile environment in both indoor and outdoor.

The first system to mention here is a compact throwable robot ‘Recon Scout IR’ by Recon Robotics (Minneapolis, MN). The Recon Scout IR is the world’s first throwable, mobile reconnaissance robot with the capability of seeing in complete darkness. It protects lives by enabling law enforcement personnel to maintain standoff distance as they gain inside knowledge about dangerous and hostile environments. Operators throw the Recon Scout IR through a window or doorway and use the handheld Operator Control Unit II (OCU II) to direct the movement of the robot. The Recon Scout IR transmits real-time video up to

100 feet (30 meters) through walls, windows and doors to the its handheld control unit or up to 1,000 feet (305 meters) to a mobile command post that is equipped with a Recon Scout Command Monitoring Station. Its infrared optical system automatically turns on when the ambient light is low. Specifications of Recon Scout IR are as follows:

- Dimensions = 5.6” (length) x 7.6” (width) x 3.0” (height)
- Weight = 1.2 lbs (0.56 kg)
- Speed = 1 ft/sec
- Range = 100 ft (indoor), 300 ft (outdoor)
- Run time = 60 mins. (on flat terrain; varies on uneven terrain)
- Image = black & white, 60-degree view, 30 fps
- Illumination = 25 ft
- Obstacle handling = Up to 4 inches tall
- Construction = water-resistant
- Drop shock resistance = 30 ft (vertical), 120 ft (horizontal)
- Control unit = 1.6 lbs (weight), 3.5” (screen size), 120 mins (run time)

[Note] The range can be extended up to 1,000 ft with the Command Monitoring Station antenna system.


The sale of the Recon Scout in the U.S. may be restricted to only military and federal government offices.

Another portable military-police grade throwable surveillance robotic system comes from ARA Inc. This system is called the ‘Pointman.’

Pointman is a Small Unmanned Ground Vehicle (SUGV). It is a compact, tactical robot that keeps the operator at a safe standoff distance while providing video surveillance. Pointman provides daylight and lowlight video in a robust and highly mobile platform. Pointman uses wheeled locomotion to move quickly over level terrain and a unique flipping motion to negotiate obstacles and climb stairs. Pointman's camera boom assembly lies flat allowing Pointman to conduct inspections under vehicles including automobiles, commercial vehicles, and aircraft. Its self-righting and stair-climbing capabilities allow Pointman to be dropped through a window or tossed through a door to conduct recon activities in multi-story structures. Pointman's compact footprint with a width of only 4” is ideal for operating in confined spaces such as culverts, warehouses, residences, and office space. Below are some key specifications on the Pointman.

- Dimensions = 15” L x 3.7” W x 6.75” H (can rise to 18” height)
- Weight = 17.5 lb (including battery)
- Speed = 3 mph or 264 ft/min (top)
- Control = wireless
- Range = 660 ft (outdoor), 330 ft (indoor)
- Run Time = 2-4 hours
- Water resistance = splash resistance (not submersible)
- Front Camera = 92° view, 420 lines of resolution, shift to B&W under low light
- Secondary Camera = 110° view, 380 lines of resolution, shift to B&W under low light

The last system is Dragon Runner 10 by a company named QinetiQ. Dragon Runner 10 (DR-10) Micro Unmanned Ground Vehicle (MUGV) is a compact, modular, light-weight, multi-mission remote platform. It has a base weight of 11 lbs and is an easily transportable system enable its operator to carry it into some of the most hazardous conditions and terrains found on earth. It can be remotely operated by a controller from many hundreds of meters away, providing protection and safety to their operators. It is built tough enough to be thrown and survive rough handling and adverse weather. DR-10’s day and night sensors allow it to serve as the forward eyes of the team while also being used to deliver remote sensors, emplace counter-IED charges, and more.

- Dimensions = 15.5” L x 13.8” W x 6” H
- Speed = 4 mph

- Range = 2,100 ft
- Run Time = 2-3 hours
- Camera = front & back, daytime, night
- Environmental = Survives hose down & puddles


Another version of the military grade crawler available from QinetiQ is Dragon Runner 20. The Dragon Runner 20 (DR-20) is a highly specialized unmanned system that provides situational awareness. The DR-20 is uniquely suited for ordnance disposal, reconnaissance, security, military operations and first responder applications. Originally designed for the U.S. Marine Corps, the basic model of the Dragon Runner 20 SUGV weighs in at only 20 pounds, measuring just 12.2 inches wide, 16.6 inches long and 6 inches high. Although not much larger than a child's remote-controlled vehicle, this powerful robot packs an array of mission-ready capabilities.

- Dimensions: 16.6" L x 12.2" W x 6" H
- Pan/tilt/zoom cameras
- Day and night cameras
- Flexible and reliable
- Impressive Dexterity
- Enhanced RF operating capabilities

All-Terrain Waterproof Earth Rover

A team of engineers who designed the NASA's Mars rover has recently unveiled a small all-terrain waterproof RC robot for earth, named 'Turtle Rover.' This robot is a remotely controlled, open-source platform that allows many modification possibilities, meaning you can add your own set of devices and sensors (ex. LED lights, 360-degree camera, LiDAR). The robot can be controlled via Wi-Fi through an app that has a control panel inspired by NASA's real space missions. Turtle Rover is currently available from Kickstarter (price = $1,500-$2,000).

- Dimensions: 18"W x 16"L x 7.5"H (without the robotic arm)
- Weight 17.6 lbs.
- Water-tight construction
- Equipped with one robotic arm (lifting capacity 500 g or 1.1 lbs.)
- Full HD camera and live stream
- RC controlled by a downloaded app
- Wi-Fi signal range up to 660 ft. (200 m)
- Up to 4 hours of battery power

Minnesota DOT

Technical Report – "Enhanced Culvert Inspections Best Practices Guidebook" (Youngblood, 2017)

Very comprehensive overview of culvert inspection technology from both the standpoint of sensors and vehicles. WRT to vehicles, details both more rigorous, expensive multi-sensor approach as well as a more cost-effective CCTV based/remote control approach which is currently being implemented by ODOT (HIVE). Redzone Robotics is who they worked with for the multi-sensor inspections.

Redzone Robotics
Implemented by MnDOT and detailed in the guidebook. Looks like a general rental/consulting agreements available but overall cost seems very high. Machines look robust with multiple sensor options to potentially address challenges with water and sediment filled pipes along with laser scanning.

SOLO

Solo is the world's first truly unmanned sewer inspection robot that is radically changing the way collection system managers approach operations and management. Typical daily production rates far outpace conventional methods. With Solo you never miss a defect. Field operator variability is eliminated as a factor influencing data quality. Video captured by Solo allows the viewer to Pan-Tilt-Zoom an entire pipe segment in 360 degrees from a PC in a controlled environment. PACP reports can be generated offline without requiring a PACP certified operator to deploy the equipment. When you couple Solo with RedZone's ICOM3 software you have full control over a wealth of information in a seamless closed loop environment that allows you to easily review inspection results and plan follow-up O&M activities. Solo robots also power the entire system program, giving you all the information you need, in one place. SOLO is designed to inspect small pipes between 8" and 12" in diameter. Its battery can last up to 4 hours.

Responder

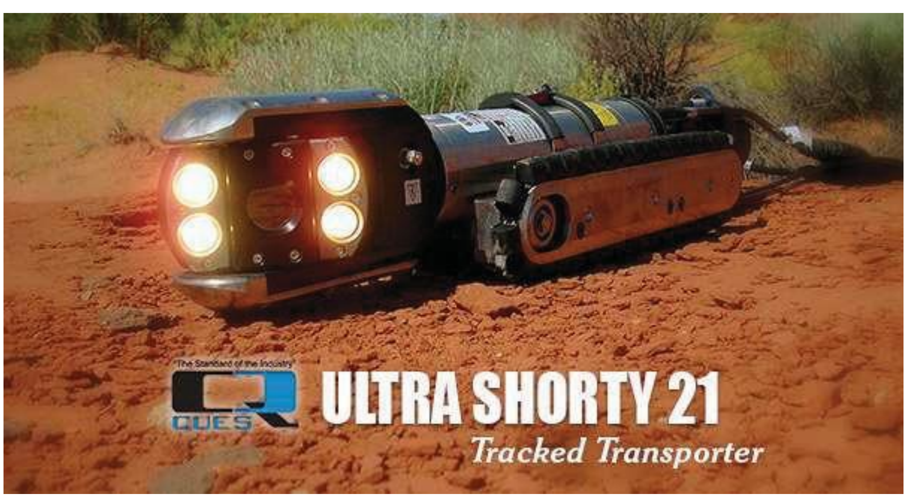
The RedZone Responder is a unique, remotely operated solution for the inspection and rehabilitation of large diameter pipes and tunnels. Through the combination of a robust design incorporating on-board hydraulic capabilities, Responder's 3D scanning LiDAR, coupled with Sonar, high resolution CCTV, gas and temperature sensors can collect information on pipe condition in the most demanding environments. The information then provided to municipalities allows a thorough assessment of pipe conditions.

Sometimes a picture alone does not tell the whole story. Pioneered by RedZone, Multi-Sensor Inspections (MSI) combine conventional CCTV with synchronized laser and sonar dimension information. This unique full 360° quantitative view of the pipeline can help to pinpoint which lines in your system require immediate attention, thanks to accurate measurements of corrosion, debris and ovality. The Responder can access drainage structures through a 24” size hole. It is fully waterproof and effective in pipes that range from 36” to 240” in diameter. The work involving the Responder is usually contracted out. A considerable amount of field time and post-inspection data processing will be necessary.

Crawler Systems by CUES

CUES is a company specialized in providing high-quality systems for closed circuit television video (CCTV) pipe inspection, pipe viewing and profiling equipment, inspection data collection/management software, and mobile vehicles that support their systems. Below are some products available from CUES.

Ultra Shorty 21 (Tracked Camera Transporter)



$17,000

The Ultra Shorty variable-weight, tracked crawler is designed for inspecting pipelines from 6” - 30” in diameter and is able to inspect 6" clay pipe with major offsets, meandering conditions, and protruding laterals. Dual 18" cleated track drive provides 50% more wall contact area than wheeled crawlers. This greater contact area assures maximum traction under all inspection conditions. Weighted pipe extenders assure maximum traction and debris clearance in lines from 8" to 24" diameter. A lift is available to optically center the camera in 30" to 36" lines. Measuring only 24" long, the Ultra Shorty is easy to insert in small manholes and dead end lines.

The Ultra Shorty 21 offers the same quality and proven performance as the Ultra Shorty III transporter but also provides a reduced length measuring only 21". This transporter can inspect 6" to 36" lines with major offsets and protruding laterals. A lift is available to optically center the camera in 30" to 36" lines.

- Freewheel reverse, power reverse, and power forward
- 1/8 HP heavy-duty drive motor; continuous duty motor
- Self-cleaning sprockets optimize performance in sand and dirt
- Variable speed from 0-55 fpm
- Waterproof motor with bulkhead connector
- Greater than 1" top and bottom clearance in 6" pipe

Steerable Pipe Ranger

The steerable Compact Pipe Ranger camera transporter can traverse up to 1200' under normal pipe conditions to inspect 6" relined pipe through 30" diameter pipe and larger. When assembled with the CUES OZIII zoom pan and tilt camera, the compact length enables the unit to negotiate most difficult entry conditions and standard sweeps. $17,000 (base price).

The superior pulling power of the CPR, combined with the optics and directional lighting of the compact OZ III zoom pan and tilt camera (with the ability to rotate in a 4" circle), creates video inspection quality that's unsurpassed in the industry. Multiple wheel sets are available to maximize bottom-clearance, traction, and optimum camera position. Ease of operation is accomplished with one joystick control for all transporter and camera movements. A variable "cruise control" setting is also available for transporter speed for hands-off operation.

- Optional mechanical or power camera lift is available to prevent the need for a operator to enter the manhole to position and reposition the camera height and to optically center the camera in varying pipe diameters
- Optional rear-viewing camera, which is mounted to the CPR transporter, is available to help avoid obstacles and potential tip-overs in the pipeline by providing visibility when retrieving the transporter or driving in reverse.
- Superior pulling power
- Wheels can be installed or removed from a single point of contact

- 2-speed transmission doubles the torque of the transporter for large pipe inspections
- Locking bayonet-style rear bulkhead connector - durable/stable
- Operates in 6” relined pipe through 30” diameter pipe and larger
- Full proportional steering and can complete a 360 degree turn within its own radius
- Multiple wheel sets to accommodate your needs
- High-traction wheels are available for slippery PVC pipe
- Operates with CUES OZIII & Nite Lite III cameras, multi-conductor cable

MudMaster (Steerable Wheeled Crawler)

The Mudmaster combines high ground clearance with pneumatic tires to provide the traction and camera stability that’s required for operation under the most adverse pipeline conditions including high flow, deep mud, sand and large amounts of debris. Optional tandem wheels are available. The Steerable Mudmaster offers all the same features of the Mudmaster but can turn 360 degrees within its own radius and traverse pipelines with multiple 45 and 90-degree bends. The waterproof remote operated camera lift can be inserted through a 19" diameter manhole with the camera in the lowest position to preclude the operator from confined space entry. This rugged all-wheel drive robot can traverse up to 2500 ft. depending on pipe conditions and can operate all CUES cameras, including OZ (Optical Zoom Pan and Tilt), and Night Lite pan and tilt. Its unique portable joystick stick controller enables the operator to control all transporter, camera, and camera lift functions with one hand.

- Four or eight (tandem) wheels provide greater traction in all types of pipe, under all conditions
- Remote operated adjustable camera lift; stable center of gravity when the camera lift is extended
- Can inspect 24" through 200" lines; up to 2500 ft. runs
- All wheel forward and reverse drive
- Rugged, durable and sealed to eliminate water intrusion
- 255 watt light system, variable, adjustable, 3 lamps

A Range of Crawlers by Inuktun Robotics

The multi-mission modular robotics company Inuktun has developed many parts that can be put together to build tracked crawlers of various sizes and accessories. Their website describes a few standard crawlers and a way that special custom crawlers can be also assembled with their components.

Versatrax 150

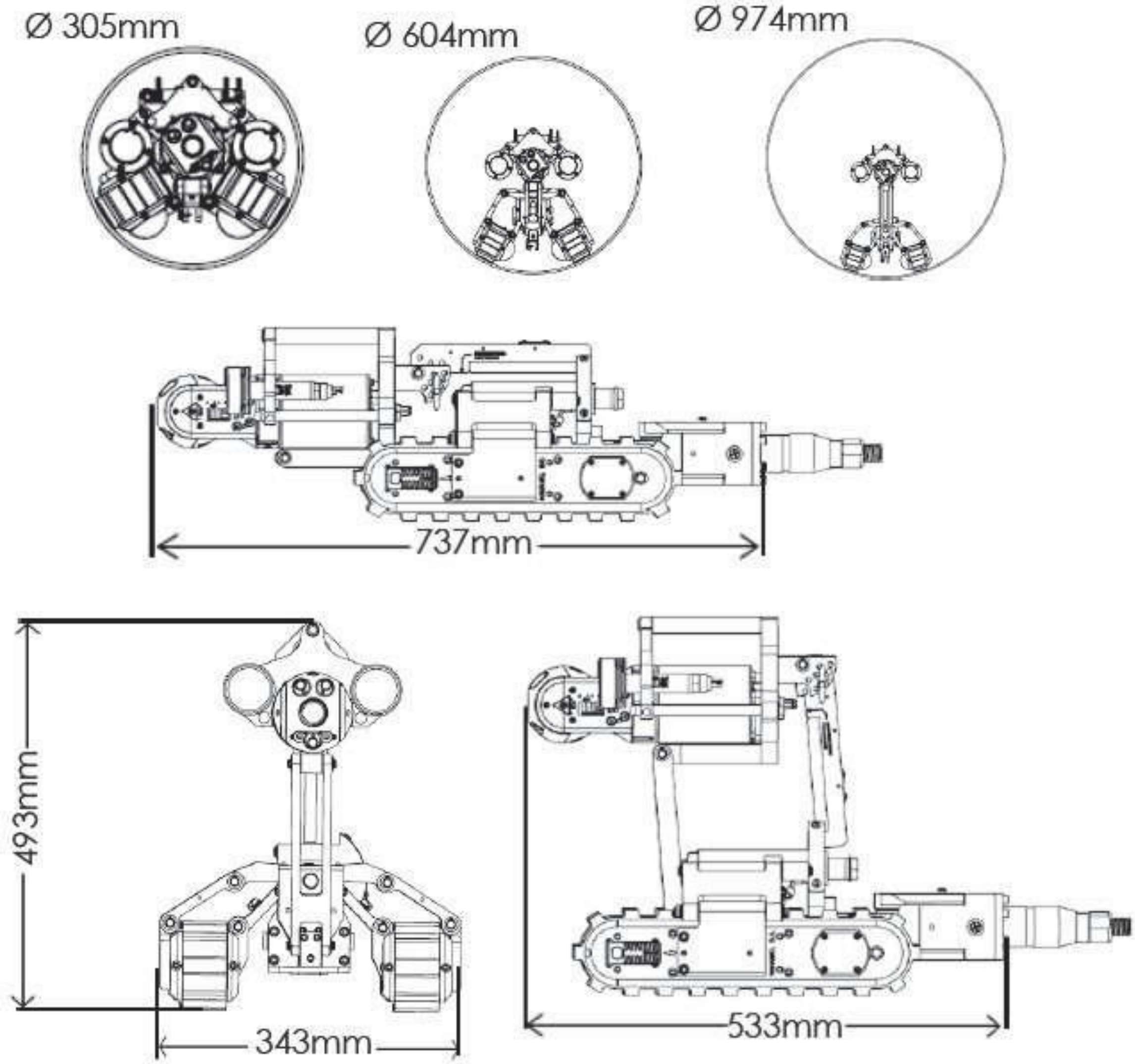
The Versatrax 150 is a configurable internal pipe crawler inspection system designed for long range use up to 500 feet. With a variety of configuration options, the pipe crawler inspection system can be adjusted for flat surfaces or round pipe operations with pipe diameters from 6 inches to 12 inches, or in a parallel configuration, 12 inches and up. The Versatrax 150 pipe crawler has a waterproof camera that gives the user a wide range of control options including pan, tilt and zoom. High resolution video can be viewed and recorded with optional storage. Price: $90,000 (w/ 1500' tether)

Versatrax 300

The Versatrax 300 is the solution to long range pipe inspection challenges. Able to inspect more than 2km/1.3mi of pipe in a single run, the Versatrax 300 includes multiple onboard video cameras, multiple sensor options and is operable in pipe as small as 12in internal diameter. Price: $500,000 (w/ 700' tether)

Versatrax 450

Designed specifically for hazardous environments, the Versatrax 450 is perfectly suited for a wide range of applications where remote handling and inspection are required. This compact system can be deployed in a matter of minutes, allowing you to inspect, capture, and safely remove dangerous materials from any site faster than by conventional means. Price : $250,000 (w/ 500' tether)



Engineering Illustrations for Versatrax 150 Crawler

Versatrax 300 Versatrax 450

Elevated Crawler

VT 150 Vertical Crawler

Inuktun's VT150 Vertical Crawler employs familiar and proven 7000 series Minitracs™ and a Spectrum 90™ pan, tilt and zoom camera. The vehicle operates in pipe ranges from 18 to 36 inches, easily adapting to its environment with a remote pipe adjusting chassis. Basic functions for control and maneuverability allows operators to quickly learn and navigate the flexible system. Support for nondestructive testing sensors and tooling is readily available to capture specific data requirements for custom projects. Originally designed for vertical and inclined pipework and caissons, steam headers, vertical air and seawater intakes, water and sewer pipelines, the VT150VC is the trusted solution for asset integrity condition assessments of those seemingly inaccessible industrial locations. What makes this crawler different from Versatrax 150 is that VT 150VC has three arms each supporting a tracked locomotion unit. With this design, it is possible that the system can stay above wet sediment accumulating over the pipe invert. Price: $90,000 (w/ 1500' tether)

VT150VC Crawler

RMIS robotic crawler (by Ryonic Robotics) with eight wheels acts as a suspended locomotive platform for performing visual and other data acquisition within confined space such as pipelines. The crawler is made from aluminum components to be relatively light weight (55 lbs) and is useful for pipes ranging in 14” to 70” in diameter. It comes with a camera. It can be operated wireless (up to 3,280 ft) or tethered (up to 1,640 ft). The crawler comes with a suite of software to allow detailed data analysis and report generations. If additional measuring sensors are required, the supported sensor can easily be interfaced into the crawler system. According to a recent quote from Ryonic Robotics, the crawler may cost $90,000 to $100,000 (including software, laser and other sensors, training), depending on whether the system size.

RMIS robotic crawler (Ryonic Robotics)

Comparisons Among Commercially Available Crawlers

System	Price	Runtime (min)	Speed (fpm)	Pipe Size	Camera	Weight (lb)	Software
EnviroSight Rovver X (with Side-Scan camera)	$17,160 ($54,080)	NA	50	6”-96”	0.4 MP, 10x optical	13.2	Yes
Deep Trekker DT 340	$20,620	480	40	8”-36”	530 TVL, 10X optical	34.17	Yes
Steerable Storm Crawler	$165,000	NA	30	24”-120”	420 TVL (Spectrum 45)	13.6	Yes
Jaguar V4	$16,500	90	300	30”-48”	0.3 MP, 30 fps	66	No
RB-Sdr-96	$9,659	180 max	90	10”-24”	PTZ dome, 10X optical zoom	10	No
RB-Sdr-77	$9,700	240 max	120	12”-24”	Camera can be added on	less than 8	No
Recon Scout IR	$40,000	60 max	60	10” 24”	B&W, 30 fps	1.2	No
Pointman	$40,000	240 max	260	18”-48”	420 lines resol.	17.5	No
Dragon Runner 20	$50,000	120-180	300	24”-36”	Front & back	20	No
Turtle Rover	$2,000	240 max.	NA	24”-48”	HD camera	18+	No
SOLO	$100,000	240 max.	30	8”-12”	HD camera	NA	Yes
Responder	250,000	NA	30	36”-240”	CCTV, LiDAR, Sonar	700	No
MudMaster	$150,000	NA	30	24”-200”	40:1 zoom, pan-tilt	NA	Yes
Versatrax VT 150	$90,000	NA	30	6”-12”	HD camera	88	Yes
Versatrax 300	$500,000	NA	30	12”-24”	HD camera	230	Yes
Versatrax 450	$250,000	NA	30	NA	HD camera	25	Yes
RMIS Crawler	$95,000	NA	NA	14”-70”	1980 x 1080, 60 fps, x20 zoom	55	Yes

[Note 1] Prices are roughly estimated for Steerable Storm Crawler, Recon Scout, Dragon Runner 20, SOLO, and MudMaster
[Note 2] NA = Not Available
[Note 3] fpm (speed) = ft per minute; fps (camera) = frames per second.

System	Control	Water proof	Dimensions	Locomotion	Laser Profiler
EnviroSight Rovver X	Remote (handheld pendant)	Yes	12.2”x4.4”x3.2” H	Deep treads multiple size tires	Yes
Deep Trekker DT 340	Tether 492 ft. (up to 1,312 ft. optional)	Yes	24”x5.55”x5.96”H	Deep treads multiple size tires; Track option	No*
Steerable Storm Crawler	Tether 100 ft.	Yes	11”x7”x5”H	Tracked	No*
Jaguar V4	Remote/Gamepad	Yes	38.5”x27.6”x7” H	Tracked	No*
RB-Sdr-96	Wi-Fi and tethered 250 ft.	Yes	8.5"x17"x6.5"H	2” wide track	No
RB-Sdr-77	Remote, not tethered	No	12.75”x9.5”x4.4”H	tracked	No
Recon Scout	Remote, not tethered	Yes	5.6” x 7.6” x 3.0”H	2 wheels	No
Pointman	Remote, not tethered	Splash resistant	15”L x 4” W x 7” H	4 wheels	No
Dragon Runner 20	Remote, not tethered	Splash resistant	16.6” x 12.2” x 6”H	Tracked	No*
Turtle Rover	Remote/Wi-Fi	Yes	18” x 16” x 7.5”H	4 wheels	No*
SOLO	Unmanned (battery powered)	Yes	4.8” x 5.8” x 20”	Tracked	No
Responder	Tethered	Yes	Folded to fit into a 24” size hole	Tracked	Yes (LiDAR, sonar)
MudMaster	Tethered 2500 ft	Yes	16” x 41.5”	4 wheels	Yes
Versatrax VT 150	Tethered 1650 ft	Yes	13.5”x 21”x 19.4”H	Tracked; 3 legs	No
Versatrax 300	Tethered 7000 ft	No	65” x 15” x 17.2”	Tracked	No
Versatrax 450	Tethered	No	20” x 14” x 20”	Tracked	No
RMIS Crawler	Tethered (up to 1,640 ft) or wireless (up to 3,280 ft)	Yes	Fit into 14” dia. pipe	16 wheels on four legs	Yes

[Note] * It may be possible to attach a laser ring profiler made by another company.

Scores on Several Commercial Crawler Systems

System	Price	Size	Locomotion	Camera	Control	Water	Obstacle	Sum
EnviroSight Rovver X	1	4	2	4	4	4	2	21
Deep Trekker DT 340	1	3	4	4	4	4	4	24
Steerable Storm Crawler	2	3	4	3	2	4	4	22
Jaguar V4	1	2	4	3	2	4	4	20
RB-Sdr-96	2	2	3	3	2	4	4	20
RB-Sdr-77	2	3	4	2	2	1	4	18
Recon Scout IR	1	4	2	2	2	4	3	18
Pointman	1	4	2	2	2	2	4	17
Dragon Runner 20	1	2	4	2	2	3	4	18
Turtle Rover	4	2	3	3	2	4	3	21
SOLO	2	4	4	4	3	4	3	24
Responder	1	1	4	4	3	1	3	17
MudMaster	2	3	3	4	4	4	4	22
Versatrax VT 150	2	2	4	4	4	4	4	24
Versatrax 300	2	2	4	4	4	1	3	20
Versatrax 450	2	2	4	4	4	1	3	20
RMIS Crawler	2	3	3	4	2	4	4	23

[Note] Scores = 4 (excellent), 3 (good), 2 (average), 1 (poor).

It seems that the Deep Trekker crawler kit, SOLO, and Versatrax VT 150 all may have great potentials. The other systems that look promising include Steerable Storm Crawler (Cobra Technologies) and MudMaster (CUES).

Laser Ring Profiler or Laser Scanner Profiler

One of the crawler kits described earlier can come with a laser ring profiler. But, its effective is limited to pipes up to only 27 inches in diameter. A company named CUES has a laser ring profiler that works for up to 72-inch diameter pipes.

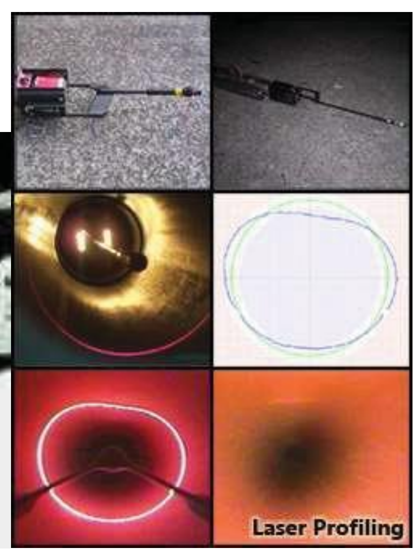
The Laser Profiler is designed to provide the contractor, municipality, or consulting engineer with the ability to determine internal pipeline conditions prior to and/or after rehabilitation. The Laser Profiler is a stand-alone, snap-on tool for use with a CUES CCTV survey system and CUES camera to collect survey data and create pipeline reports containing the measurement of faults and other features inside the pipeline. This includes measurements of pipe size, laterals, water levels and other features, as well as automatic analysis of pipe ovality and capacity up to 30 times per second. The Laser Profiler simply attaches to your existing CCTV Camera and the resulting CCTV images are analyzed using innovative machine vision software.

The concept is as follows:

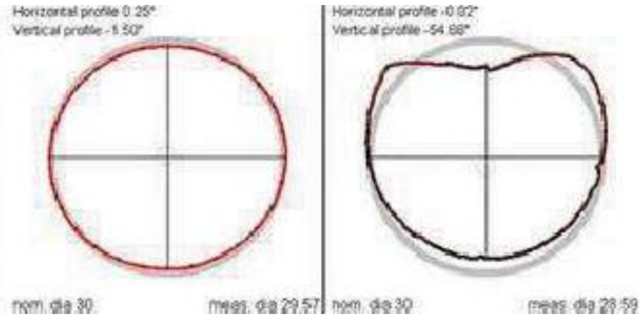
- A ring of laser light is projected onto the internal pipe surface
- Laser image is in the field of view of the camera while the camera moves through the pipe
- Analysis is performed on the ring of light using the Laser Profiler software to build a digital pipe profile
- For use with live or pre-recorded to video (tape, CD, or DVD)

Features & Benefits

- Can operate in pipe size ranging from 6" through 72"
- High-strength carbon fiber and aluminum construction
- Internally battery powered (rechargeable); no electrical connections are required No moving parts
- Software can be used on a TV inspection vehicle or on a remote computer
- Can capture a single frame of video from videotape, previously stored file, CD, DVD, etc., when utilized on a remote computer
- Designed to project a laser light in a radial plane perpendicular to the CCTV camera’s line of sight and create a red line on the inside wall of the pipe; laser is designed to provide sufficient intensity to view the video image with normal CCTV camera lighting
- Easily attaches to your existing CUES Camera or Transporter
- Designed to capture and display a single frame on the data monitor for measurement and analysis in Industry Standard Formats to include JPEG, BMP, or TIFF formats
- Text can be placed anywhere within the captured video image
- A line graph displays the cross-sectional amplitude over the entire length of the pipe run from entry to exit access
- Designed to obtain the actual degradation of the pipe by utilizing the laser profiling and measurement tools

Another company based in Germany, Rausch, has developed a laser scanning camera, KS 135.



The Rausch Laser Profiler features two laser diodes that are integrated into the KS 135 Scan camera head. When these laser diodes project laser dots onto the inner pipe wall, the camera head rotates to measure the diameter and all changes thereof via triangulation calculations. This method is called the "spinning laser" laser pipe profiling technology. Working in conjunction with the POSM software, the comprehensive scan generates easy to use reports to profile the pipe.

On the way into the pipe, the system is used to perform conventional CCTV video inspection, as well as measuring all joint widths. In addition, individual laser measurements can be taken at any time to determine the actual pipe diameter and deflection, called a single point scan. These diameter and deflection measurements then become a part of the inspection report.

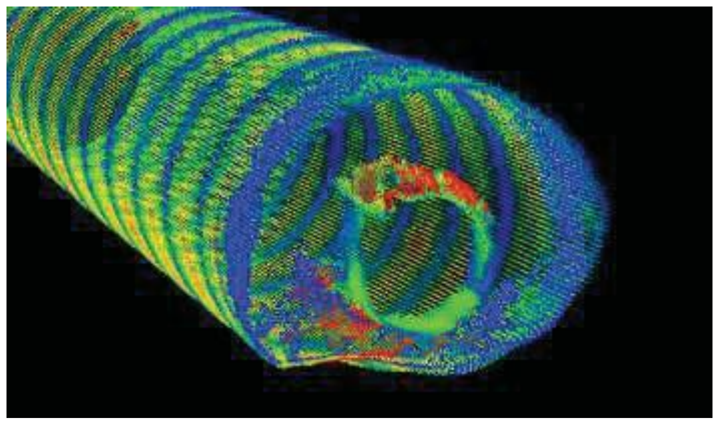
On the way out of the pipe, the system performs a "spinning laser" scan of the entire pipe length. The camera head swivels perpendicular to the pipe wall and rotates at a defined speed. Via triangulation the Scan software continuously calculates the precise pipe diameter and all deflections and deformations in the pipe profile. Once the run is completed, the software instantly generates graphs in 2- and 3-D. These graphs show any deflection, the average pipe diameter, and the inclination slope of the line. The KS 135 works for pipes 8” to 48” in diameter. For larger pipes up to 72”, additional equipment may be needed. Post inspection time with the laser scan data may be considerable, compared to processing laser-ring data.

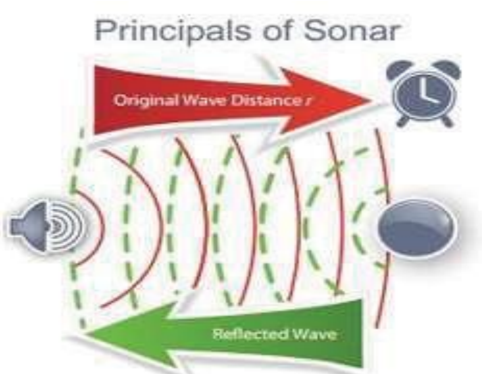
Underwater Laser Scanner

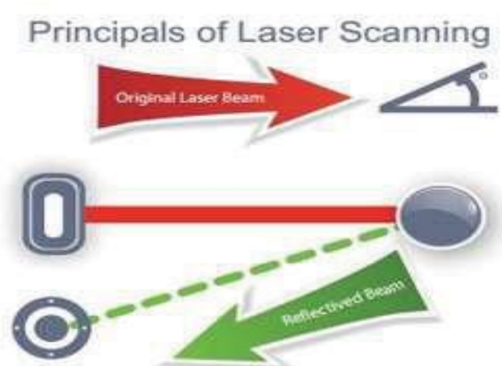
The crawler kits listed above come with either no or a limited pipe deformation measurement system. In order to have a true profiling capability, the crawler must be equipped with a laser/sonar scanning systems. The underwater laser scanner recently developed by 2G Robotics appears to be a stand-alone system and works better than sonars under water.

The underwater laser scanner is deployable by divers, ROVs, crawlers, centralizers, and frames. Its rugged and compact design makes it perfect for operation in confined spaces. Additional information about the scanner is listed below:

- Generates point clouds of targets such as pipes, tunnels, wells, and other underwater objects
- Small form factor and short range enables scanning in tight areas
- High Resolution Measurements
- Short-range scans (0.13m to 1m range) with 50° laser swath and 360° rotation
- Real-time and true-scale model generation
- Operational Efficiency
- Simple, configurable deployment and ease-to-use interface for rapid data acquisition
- No user calibration required







2G Robotics provide a short-range ULS-100 Scanner as well as a longer-range ULS-200 Scanner. Below are comparisons between them.

Characteristics	ULS 100 Scanner	ULS 200 Scanner
Size	Dia. 2.2” x Length 14.5”	
Weight	2.2 lbs (in water)	
Power	12 to 24 V (DC)	
Scan Range	6.7” to 39.4”	1.2’ to 8.2’
Vertical Angle & Resolution	50° (water), 68° (air) & 0.1°	
Rotational Range & Resolution	360° & 0.018°	
Range Resolution	0.00039” @ 6.7” Range 0.012” @ 39.4” Range	0.028” @ 1.2’ Range 0.19” @ 8.2’ Range
Points per Profile	480	
Max. Sample Rate	2,400 points/sec.	4,750 points/sec.
Sunlight & Silt Filtering	Adjustable by User	

Mobile Van for Supporting CCTV Inspection

CUES offers custom truck-mounted systems for all of your TV inspection and rehabilitation needs! The CUES Truck Design Team has over 75 years of combined pipeline inspection truck design experience and has designed thousands of pipeline inspection trucks. Made to withstand the most severe conditions and ergonomically designed for comfort and efficiency, CUES truck-mounted systems can include TV inspection equipment for sewer/storm/potable water lines, mainline joint or lateral sealing, and lateral reinstatement cutters for the relining industry. Also, the truck can come with a lift system to pick up and lower a crawler unit into a manhole. A truck chassis can be specified to contain all or any combination of the equipment.

Appendix D. Notable Commercial Drones

[Note] This section was put together largely by cutting-and-pasting photographs, specifications, and writeups from various vender websites.

Flyability ELIOS – Collision Tolerant Drone

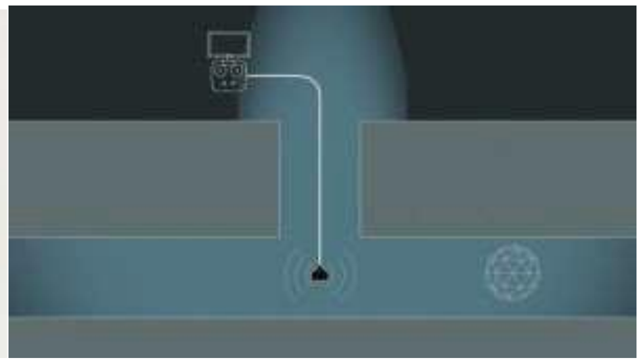
Swiss unmanned aerial vehicle belongs to a class of industrial drones. The main purpose of the model Elios unmanned air tool is to conduct inspections and monitor the status of engineering objects.

Elios is basically a spherical barrier cage wrapped around an agile drone. This unique design makes this drone collision tolerant. Elios comes in two diameters - 60 centimeters (24 inches) and 50 centimeters (16 inches).

The unmanned aerial vehicle is powered by three electric motors that provide high maneuverability and allow to accelerate to a maximum flight speed of 25 km/h. The effective range of the UAV limited 3 kilometers, and the flight endurance is limited to 10 minutes. Battery can be exchanged quickly. Elios automatically flies home when its battery power becomes low.

Elios is equipped with telemetry meaning it has electro and infrared camera in its structure that allows for the efficient operation of the drone, including, in the absence of normal visibility. The HD camera offers a wide view of 215° and a horizontal view of 130°, while the thermal camera offers a narrower vision (42° vertical, 56° horizontal). When flying in contact with a surface, Elios can gather close-up images with a resolution down to 0.2 mm/pix. The camera/video system records all data on a SD card housed in the payload head. Elios can stream visual data to the pilot when operating at a lower resolution setting.

In May 2017, the Swiss company introduced the Range Extender, an accessory for the collision-tolerant indoor drone Elios. The Range extender opens new applications for the most demanding indoor drone inspection and exploration missions, where communication between the drone and the pilot is particularly difficult. In environments such as underground galleries, stacks or mines, signal propagation can be limited by the geometry of the place to inspect and remotely operating a robot becomes difficult. By placing the remote control antennas to a better location, closer to the drone, it is possible to extend the range of the drone. To that end, Flyability has developed the Range Extender: an accessory that connects to Elios ground station, providing an extended signal reach for beyond line-of-sight operation.



Below are two additional collision tolerant drone designs.

XT Flyer Drone

Fleye Drone (by Aerobot)

The next four options are the best collision/obstacle avoidance drone currently available on the market.

DJI MAVIC PRO

With its powerful brushless motors, an elegant design and a plethora of features, it becomes pretty clear that this is not just a regular drone. Mavic Pro can go as fast as 40 miles per hour (roughly 65km/h) which is much more than any other selfie drone on the market. The same goes for the range. DJI Mavic Pro has 7 kilometers of range**,** while other selfie drones go around 100 to 300 meters (in best case scenarios).

The drone's four arms can be folded so that it becomes very compact and easy to carry. DJI Mavic Pro is an outstanding drone deserving of its own. With functions such as ActiveTrack, TapFly, obstacle avoidance (through 5 cameras and 2 sonars), navigation systems (both GPS and GLONASS), and a mighty 4K camera**,** DJI Mavic Pro stands toe to toe with one of the best drones.

DJI PHANTOM 4 PRO

The fourth installment of DJI's Phantom series has a 4K (30 fps) HD camera with amazing image and video quality. The camera is mounted on a state of the art gimbal stabilization system (3-axis, of course) which provides the 20mpx sensor with silk smooth environment for capturing breathtaking aerial moments.

Phantom 4 Pro has amazing 4.3 miles (7 km) of interference-free operating range. The powerful DJI's 5870mAh smart battery can last up to half an hour on a single full charge. The controller has remained the same from that of Phantom 3. Phantom 4 Pro is filled with various handy features: 5 direction obstacle sensing (best obstacle sensing/collision avoidance drone among the list here), intelligent flight modes, draw (represents DJI's brand new waypoints technology), ActiveTrack, TapFly, automatic home return and various gesture modes for easier flight experience. A study by Michigan DOT stated that this drone is very easily to fly and thus can navigate in tight spaces.

Additional specifications of the drone are listed below:

- auto takeoff and auto landing
- top speed of 45 mph
- 60-minute charge time
- 4 channels
- LED lights for night flights

YUNEEC TYPHOON H PRO

Typhoon H Pro is another incredibly popular drone, manufactured by Yuneec. This is the only hexacopter on this list here. This is the very first obstacle avoidance drone made by Yuneec. It sports their unique collision avoidance drone system that allows it to fly safe through the air without any worries. In addition to that, the engineers at Yuneec implemented a 5 rotor failsafe mode. This means that even if one of its 6 motors stops working properly in the middle of the flight, the drone will still land safely with the remaining 5.

Typhoon H sports a high quality 4K HD camera mounted on a 3-axis anti vibration gimbal. Some features of this outstanding drone include – 8 smart flying modes, automatic return to home, auto takeoff and landing**…** practically not much experience is needed in order to operate with this drone. And lastly, Typhoon H comes with 1 mile (1,600 m) of fluent operating range and roughly 25 minutes of flight time is just enough to make this drone an outstanding purchase to everyone looking for an extremely safe and reliable model.

Additional specifications are listed below:

- 120-minute charge time
- 16 channels
- Propellers fold for easy storage

DJI INSPIRE 2

Here is another outstanding drone developed by DJI. With professional image quality**,** efficient workflow systems and a dozen of highly sensitive sensors for various features (including obstacle avoidance, stability, navigation and more), intelligent flight modes and so on, it seems as though DJI Inspire 2 is not a typical consumer grade drone.

Inspire 2 is more expensive than Phantom 4. For its higher price, you will get a state of the art drone (which turns into a transformer once it gets up in the air) with high end stabilization and encoding systems that will provide you with class A image and video quality while eliminating the need for manual obstacle avoidance and that's just what professionals want and what they are willing to pay so much money for.

Additional specifications are listed below:

- four arms automatically swing up during flights and swing down for landing
- 90-minute charge time
- 8 channels
- Operating range 4.3 miles (7,000 m)

DJI SPARK

Here is the fifth drone on the list that is made by DJI. The Spark shares technology with the Mavic Pro such as obstacle detection, dual-band GPS, and a visual positioning system that lets it hover in place up to 98 feet (30 m) above the ground -- indoors or outside. So, in a way the Spark is a smaller version of the Mavic. Also, while the competition relies on electronic image stabilization alone, DJI put the Spark's full HD video camera on a two-axis motorized gimbal for smooth results without sacrificing image quality. For $699, DJI bundles the Spark, extra props and a set of prop guards, two batteries and a charging hub for refreshing three batteries at once, a remote controller and a carry bag.

ATLAS PRO

Atlas Dynamics, a leading provider of drone-based solutions for the professional user, has announced that it will showcase its market-ready autonomous professional drone, the Atlas Pro, at InterDrone 2017. Atlas Dynamics is partnering with US-based, Erida Inc. to deliver the first Pros to customers in the third quarter of 2017.

According to Atlas Dynamics, the professional drone market is fragmented, and plagued by usability and integration issues. The Atlas Pro answers these challenges by providing a complete off-the-shelf solution that we can offer our clients. Atlas Dynamics' first product, designed and developed exclusively for the professional user, offers a market-leading combination of capabilities, including:

- Up to 35-minute flight time
- 31 mile (50 km) range
- Compact size for portability and accessibility (0.9 KG)
- Highly durable, light-weight carbon frame

- Weather resistant (IP52)
- Autonomous, easy to integrate operating system
- Versatile exchangeable payloads

Atlas Pro is designed to address several market segments, including infrastructure inspection, security, precision agriculture and emergency response. The company is also encouraging customers and users to collaborate to discover and define new applications using Atlas' software development kit.

The next two drones are water resistant and water buoyant.

SWELLPRO SPLASH DRONE 3 AUTO

This waterproof drone for professional use is coming from the labs of SwellPro. Its first generation was called 'Mariner.' Splash Drone 3 comes in 2 versions, Fisherman and Auto. In the next couple of paragraphs, the Auto version is described.

Splash Drone 3 Auto has an IP67 waterproof certificate**,** meaning there's no way it is going to get water damage. That's especially so when it comes to its 4K camera which is mounted on a 2-axis gimbal stabilization system. Both are fully waterproof and can be submerged in water. SwellPro Splash Drone 3 Auto is finely poised with plenty of smart flight modes such as Return to Home, Tap to Fly, Mission Planning, Follow me and more. All these flight modes are incredibly well-polished. As a matter of fact, the software is as good as DJI's.

Probably the most interesting thing about this drone is its Payload Release Mechanism**.** What this does is that it essentially allows you to attach up to 1 kilogram (2.2 lbs) of payload which you can easily release with a flick of a single switch on your controller. When this system is combined with up to 16 minutes of flight time and 1 km (0.62 miles) of range, there is no doubt it can do terrific things. So, if you're looking for a professional-grade waterproof drone with good payload capacity and excellent camera, SwellPro Splash Drone 3 Auto should be your choice.

[Note] This drone is basically a waterproof version of the DJI Phantom.

QUAD H2O

This waterproof done comes as a Do-It-Yourself (DIY) kit that includes all build ready frame and electrical components. In order to make the drone ready for flights, the company recommends the DJI NazaV2 flight controller, T-motor or Team Black Sheep propulsion systems and a 4S lipo for a really fast, punchy and agile flying experience. Additional specifications on this drone can be found on the comparative table on pages 25-26.

Drones Tested by MinnDOT (for Bridge Inspection Work)

Below are brief information on the two drones, Albris and Aeryon SkyRanger,that were tested by the MinnDOT. These drones are larger than the ones described earlier (see pages 13-25), but they each come with a nice zoom camera.

The Albris by SenseFly, Inc. is a sensor-rich platform with the widest camera breadth of any civilian drone. Its fully stabilised TripleView camera head allows you to switch between HD and thermal video imagery, live during your flight, plus you can capture high-resolution still images on demand. All of this data can be saved for further analysis post-flight, and all without landing to change payloads. The TripleView head features a 180-degree vertical range of motion, 6x digital zoom, active gimbal stabilization, and an unobstructed field of view. The Albris is capable of achieving a GSD of down to 1 mm at a surface distance of 6 m (19.7 ft). Its weight and dimensions are 4 pounds and 22” x 32” x 7”, respectively. Its maximum flight time is limited to only 21 minutes. The Albris can be operated up to a distance of 1.2 miles (6,336 ft).

According to Aeryon Inc., the SkyRanger’s airframe and integrated platform, is based on successful customer exercises and missions around the world. It is ideal for commercial, public safety, and military applications. The SkyRanger has the following characteristics -- real-time advanced video, a stabilized high resolution camera (30x optical zoom, 60x digital zoom), advanced radiometric temperature data, up to 50 minutes of flight time, vertical takeoff and landing, requiring no joystick control, operations in confined places, and stable flight performance in adverse weather (45 mph sustained; 55 mph gusts). Its weight and dimensions are 8 pounds and 39” x 39” x 10”, respectively. The SkyRanger can be operated up to a distance of 3.1 miles (16,338 ft).

Droned Examined by Michigan DOT

Michigan DOT had a comprehensive study conducted in 2015 by Michigan Tech Research Institute, titled “Evaluation of the Use of Unmanned Aerial Vehicles for Transportation Purposes (Report No. RC-1616).” In the study, several UAVs were tested --- Bergen hexacopter, DJI Phantom Vision 2 quadcopter, Blackout mini H quad, Mariner Waterproof quadcopter, and a few micro UAVs. One of the objectives was to examine if UAVs can fly safely in confined spaces such as culverts.

Bergen Hexacopter (by Bergen R/C Helicopters)

- Designed to carry a still or video camera
- Max. payload 11 lbs.
- Flight endurance 18 mins
- Cost $5,400 (w/o sensors)
- GPS receiver added to fly in “GPS-control” mode

DJI Phantom Vision 2 Quadcopter

- 14.6” x 13.2” x 8.3”, W 2.6 lbs.
- Cost less than $800
- Comes with a 14-megapixel camera, onboard GPS, a rechargeable battery, real-time video via WiFi and smart phone app.
- Flight endurance 25 mins
- Range up to 900 ft. (300 m)
- Easy to fly; Can fly in tight spaces

MTRI Blackout Mini H Quadcopter

- A small UAV assemble kit (11” x 13” x 3”)
- Costs less than $500, W 1.5 lbs.
- Flight endurance 15 mins max.
- An agile drone that allows customizations
- Can be paired with a flight controller, a GPS module, and a camera
- RangeFinder – Allows automatic positioning
- FatShark – Allows the first person view
- The team tested the drone to fly through a 48” dia. CMP. It was able to do so without relying on the GPS compass sensors.
- Flying a small drone inside a culvert requires more experience/ skills from the user.

FPVfactory Mariner Waterproof Quadcopter

- 24” x 24” x 8”, W 4 lbs.
- Cost about $1,000
- Controller for DJI Phantom
- Flight endurance 15 mins

Heli-Max 1 Si micro-UAV

- 5.5” x 5.5” x 1.8”, W 0.1 lbs.
- Cost about $200
- Flight endurance 10 mins
- Comes w/ a small camera (720p video or 1 megapixel stills) and a miscro SD memory card (32 gigabytes)
- Small enough to fit in a palm; Useful in confined spaces

Walkera QR 100S

- 5.7” x 5.7” x 2.0”, W 0.2 lbs.
- Cost about $?
- Flight endurance 10 mins
- Comes w/ a small onboard camera that transmits live video to a smart phone of tablet; No onboard storage
- Small enough to fit in a palm; Useful in confined spaces

Drone by CyPhy Works

CyPhy Works’ new Pocket Flyer drone fits inside a pocket and weighs a mere 80 grams (0.18 lbs.). It’ll fly continuously for *two hours* or more, sending back high quality HD video the entire time. What’s the catch? There isn’t one, except for the clever thing that grants all of CyPhy’s UAVs their special powers: a microfilament tether that unspools the drone and keeps it constantly connected to communications and power. CyPhy Works had the brilliant idea of bringing a thing back to robots that has (or had) a reputation of being somewhat of a crutch: a tether. Ideally, your robots would be efficient enough to be able to run on batteries, completely independently. And for ground robots, that’s usually not too hard to do, since they’re not fighting gravity all the time. With flying robots, though, endurance is a serious problem. Anything that can run on batteries (and hover) is probably only going to be aloft for 10 or perhaps 20 minutes at best. The microfilament, in contrast, provides a constant source of power to your robot, so you can fly any drone that uses the system until your base station (which doesn't have to move) runs out of power. If you're plugged into the grid, these robots could stay aloft for days.

Power may be the primary reason why the Pocket Flyer uses a microfilament tether, but there are a bunch of other reasons why it's a good idea. You get high definition video with no lag. You can put a lot of obstacles between you and your drone without having to worry about losing communications. The robot carries a spool of 250 feet (76 meters) of wire onboard, and feeds it out as it moves forward. This way, there's never any tension on the wire, and it can snag on stuff without affecting the performance of the robot.

The tethered drone is also called the Persistent Aerial Reconnaissance & Communications (PARC) platform. Here is an earlier military-grade version of CyPhy's Pocket Flyer drone.

Military-Grade Nano Drone – PD 100 Black Hornet 2

The PD-100 Black Hornet 2 by Prox Dynamics (Norway) is the first airborne and commercially available Personal Reconnaissance System. It provides end users with a highly mobile sensor system providing an immediate Intelligence, Surveillance and Reconnaissance capability. The Black Hornet 2 nano sensors are inherently safe and pose virtually no risk to other air vehicles or personnel, allowing the system to be operated almost anywhere at any time without prior airspace coordination. The Black Hornet's small size and electric motors makes it virtually inaudible and invisible beyond short distances. Specifications of the PD-100 are listed below …

- Rotor span 120 mm (4.8")
- Mass 18 g (weight 0.04 lbs.) including three cameras
- Maximum speed 5 m/s (16.4 ft/s or 11.2 mph)
- Flight endurance up to 25 minutes
- Digital data link beyond 1600 m (1 mile) line-of-sight
- GPS navigation or visual navigation through video
- Autopilot with autonomous and directed modes
- Hover & Stare, preplanned routes
- Steerable EO cameras (pan/yaw and tilt)
- Live video and snapshot images

Mission Examples

- Reconnaissance in confined areas
- Look behind, between and below obstacles
- Birds eye view for situational awareness

Benefits

- Transportable – complete system fits inside a pocket
- Ready to fly – airborne within one minute
- Fly it anywhere – in confined areas and outdoors
- Stealth – small and inaudible

- Easy to operate – requires little training and no pilot experience
- Safe – represents no risks to other aircraft or personnel
- Affordable – reusable or expendable


Comparisons among Commercially Available Drones

System	Base Price	Weight (lbs)*	Flight Time (min.)+	Dimensions
Flyability ELIOS	$2,500	1.8	7-10	16" dia.
DJI Mavic Pro	$1,100	1.7	20-27	9.5" x 11.4" x 7.1"H
DJI Phantom 4Pro	$1,400	3.1	20-27	14" x 16" x 9"H
Yuneec Typhoon H Pro	$1,500	3.8	Up to 25	17" x 21.2" x 12.5"H
DJI Inspire 2	$6,000	7.6	20-27	18" Dia.
DJI Spark	$700	0.7	Up to 16	6" x 6" x 2.5"H
Atlas Pro/Erida	$5,000	2.0	Up to 35	17"x18.5"x 6.5"H
Splash Drone 3 Auto	$1,700	5.3	12-16	18" dia. x 6.5" H
Quadcopter H2O	$850	3.5	Up to 12	22" x 15" x 11"H
SenseFly Albris	$35,000	4.0	Up to 21	22" x 32" x 7" H
Aeryon SkyRanger	$12,000	8.0	Up to 50	39" x 39" x 10" H
Pocket Flyer	$25,000	6.0	Unlimited	(dimensions unknown)
PD 100 Black Hornet 2	$195,000	0.04	25	4.8" (rotor span)

[Notes] * FAA regulations apply to UASs that weight 4.5 lbs or more.
+ Flight endurance depends on the payload carried and the weather conditions.

System	Speed (mph)	Water Proof	Range; Camera
Flyability ELIOS	16 max.	No	3.1 miles; video: 1080P @ 30 fps, image: 2.1 MP
DJI Mavic Pro	40 max.	No	4.3 miles; video: 4K @ 30 fps, image: 12 MP
DJI Phantom 4Pro	36 max.	No	2 to 7 miles; video: 720P @ 30 fps, image: 20 MP
Yuneec Typhoon H Pro	44 mph	No	1 mile; video: 4K @ 30 fps, image: 12.4 MP
DJI Inspire 2	58 max.	No	2 to 7 miles; video: 5.2K @ 30 fps, image: 20.8 MP
DJI Spark	31 max.	No	1.2 miles; HD 4K camera @ 30 fps
Atlas Pro/Erida	50 max.	Yes	31 miles; GoPro: video: 4K @ 10 fps, image: 12 MP
Splash Drone 3 Auto	36 max.	Yes	0.62 miles; video: 4K @ 25 fps, image: 14 MP
Quadcopter H2O	45 max.	Yes	0.62 miles; Supports Sonny FPV or Go-Pro Hero
SenseFly Albris	27 max.	No	1.2 miles; GSD down to 1mm at a distance of 20 ft; 6x zoom
Aeryon SkyRanger	45 max.	No	1.9 miles; 1080p24HDH.264 video, 15MP still images, 30x zoom (optical)
Pocket Flyer	40 max.	No	500 ft (microfilament length); a HD camera; Long range zoom (x 30)
PD 100 Black Hornet 2	11 max.	No	1 mile; a steerable EO camera; Live video feed & still images

[Note] 1 mile = 5,280 ft.

System	Additional Notes
Flyability ELIOS	Collision tolerant system; Splash proof; Best suited for industrial environment; Signal range extender available
DJI Mavic Pro	Lightest professional drone; Obstacle sensing range 2 to 49 ft
DJI Phantom 4Pro	Obstacle sensing range 0.6 to 23 ft; Payload 500 g (1 lb) max.
Yuneec Typhoon H Pro	Sonar collision prevention, smart safety feature limits its fly up to 400 ft above ground.
DJI Inspire 2	Heavy; Forward and downward vision of up to 100 ft enables protection when flying up to 34 mph; Payload 2 kg (4.4 lbs) max.
DJI Spark	Obstacle sensing 1-16 ft; Compact to fit inside a pocket
Atlas Pro/Erida	Supposed to be weather-resistant; No obstacle avoidance
Splash Drone 3 Auto	Flies home when going out of range; Auto landing; Low battery alert on RC control; Payload 1 kg (2.2 lbs) max.; Floats on water
Quadcopter H2O	Solid construction; Payload 600 g (1.3 lb) max.; Floats on water
SenseFly Albris	True inspection-purpose drone; Comes with a thermal camera; Range up to 6,340 ft (1.2 miles); Better suited for above-ground structures such as bridges; GPS-assisted 3-D mapping
Aeryon SkyRanger	Heavy; Supposed to be capable of flying in confined spaces
Pocket Flyer	Very Expensive; Splash resistant (up to 0.5" per hour); Tethered; Useful only when there are no obstacles
PD 100 Black Hornet 2	Smallest; No collision avoidance; Not waterproof

Below the commercially available drones are rated in terms of their ability to conduct flyovers and a quick peaking at the end (if permitted), while abiding by the FAA rule CFR 14 part 107. The drones are not rated here for their potentials to fly through culverts. In each category, higher scores indicate more superior performance.

Scores on Commercially Available Drones

System	Size	Flight Time	Camera	Control	Water	Collision	Sum
Flyability ELIOS	3*	1	4	4	2	3	17
DJI Mavic Pro	4	3	4	4	1	3	19
DJI Phantom 4Pro	3	3	4	4	1	3	18
Yuneec Typhoon H Pro	1	3	4	4	1	3	16
DJI Inspire 2	3	3	4	4	1	3	18
DJI Spark	4	2	4	4	1	3	18
Atlas Pro	2	3	4	4	3	1	17
Splash Drone 3 Auto	2	2	4	4	4	1	17
Quadcopter H2O	1	2	3	3	4	1	14
SenseFly Albris	1	3	4	4	1	1	14
Aeryon SkyRanger	1	4	4	4	1	1	15
Pocket Flyer	1	4	4	4	1	1	15
PD 100 Black Hornet 2	4	3	3	4	1	1	16

[Note] Scores = 4 (excellent), 3 (good), 2 (average), 1 (poor).
*Size score for Flyability ELIOS is based on its outer protective shell dimensions, not on the size of the drone inside.

It appears that the DJI Mavic Pro has edged slightly over the other DJI drones, Atlas Pro, Splash Drone, and ELIOS.

Appendix E. Commercial Drone-Crawler Hybrids

[Note] This section was put together largely by cutting-and-pasting photographs, specifications, and writeups from various vender websites.

The drones listed earlier can fly over culverts but may not be capable of going inside the culverts (unless culvert size is large and the drone is equipped with an advanced collision avoidance capability). The crawlers covered above can capture interior conditions of the culvert but are incapable of providing aerial views of the structure. It will be great if we can find a drone/crawler hybrid which can fly over any culvert, take a high-resolution video of its conditions from above, enter the structure from the end to inspect interior conditions, and then fly back to its pilot. Below are four types of hybrid systems that are commercially available.

Drone w/ Roll Cage

The caged drone (covered on page 13) can be designed so that the cage can roll like a wheel. An example of this type of drone is shown below. It is called a RC Roll Cage Quadcopter ($40-$50). It is available through multiple online stores. The drone does not come with a camera.

Its specifications are spelled out below:

- 4-Channel RC Drone Quadcopter with Roll Cage 2.4GHz
- Quadcopter
    - Max Flight Time: 7-9 minutes
    - Indoor Hovering Enabled by default
    - Operating Temperature Range: -10 ~ 40° C
    - Dimensions w/ Shell: 215 mm x 215 mm (8.6” x 8.6”)
    - Power Supply: LiPo battery
- Remote Controller
    - Operating Frequency: 2.4 GHz

  - Transmitting Distance: ≥ 50 m
  - Operating Temperature Range: -10° ~ 40° C
  - Battery: 2x AA battery (not included)
- Battery (drone)
  - Capacity: 350 mAh
  - Voltage: 3.7V
  - Battery Type: LiPo

Quadcopter Drone Car


Taotuo 2.4 G 8 Channel 4-Axis Dual Mode RC Flying Quadcopter Driving Car

Specifications:
Material: ABS Plastic
Price: $59
Product size: 23.5 * 17 * 6.5 cm (10” L x 7” W x 3” H)
Battery for RC Car: 750 mah 3.7 V (with CLP rechargeable battery protection board)
Battery for Remote Controller: 4 x AA Batteries (not included)
Remote Control Distance: 60-100 meters
Flying time: 8 to 9 minutes
Fuselage battery charging time: about 90 minutes
Plug type: USB
Remote Control Mode: Left Hand Throttle

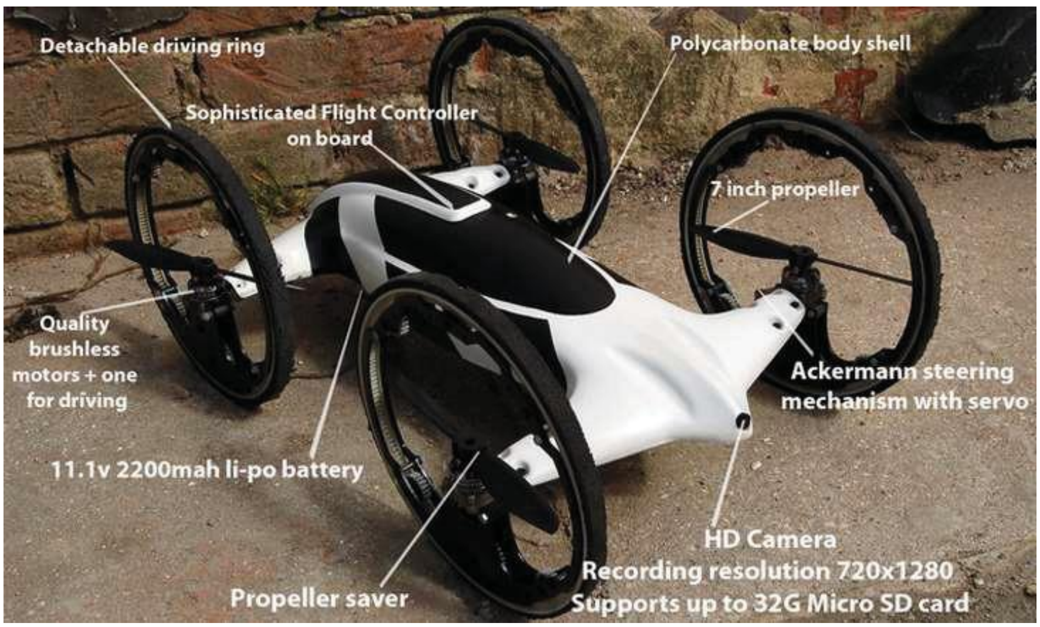
Function: 360-degree 3D Rollover Function, Up, Down, Forward, Backward, Turn Left or Right, Left or Right Side Fly Hover, Fast or Slow Shift, Light Control, "One key" Lock Heading, "One Key" Return, On the Ground Forward/Backward/Turn Left/Turn Right

DUAL MODE: RC Flying and Driving Quadcopter Car allows you to drive on terrain and instantly take off into flight. This item includes both wings and wheels. It can't only fly in the air but also travel on land. You can switch the mode casually as you like.

AUTO RETURN: When the Quadcopter is out of its control distance, just press the button. The Quadcopter will return to you automatically.

4-AXIS GYROSCOPE: Exceptional control for indoor and outdoor flying & hovering.
LED LIGHTED: Underside for Nighttime Piloting

Remote-Controlled Flying Car/Helicopter



With the ability to drive and fly, the B Remote-Controlled Flying Car/Helicopter ($560) can pretty much go anywhere. Its innovation lies in a patent-pending wheel and propeller design, which places each prop within the wheel. It can take off vertically, hover and fly, and return to the ground to continue driving. Durable polycarbonate construction means it can survive falls from the air and punishing terrain on the ground. A 720p on-board camera and 32G Micro SD card support makes this one capable reconnaissance vehicle. Now, if only they could figure out a way to make the battery last longer than 15 minutes a charge. Wheel diameter of 8” makes the vehicle gain fast speeds and climb over small obstacles.

Tank Quadcopter Drone

This drone weighs only 84 grams (0.2 lbs.). It can fly up to 9 mins or crawl for 18 mins andhas lights in the front and rear for operating in the dark. It can hold an optional 720p camera modules that either record to micro SD or broadcast live footage, Comes with an easy-to-use RC control. For $93, you can purchase a B-Unstoppable unit with transmitter and charger, or you can step up to the HD DVR Camera model for $131. Otherwise, at $156, you can pick up the unit with an FPV camera system for real time transmissions.

Comparisons Among Notable Drone-Crawler Hybrids

No detailed comparisons are made here among these systems, since they all share toy-like qualities and suffer from very limited operational capabilities.

Appendix F. Notable Commercial Rafters/Boats

[Note] This section was put together largely by cutting-and-pasting photographs, specifications, and writeups from various vender websites.

Redzone Robotics

This was implemented by MnDOT and detailed in the guidebook. It looks like a general rental/consulting agreement but the overall cost seems very high. The machines look robust with multiple sensor options to potentially address challenges with water and sediment filled pipes along with laser scanning.

MSI MD Profiler

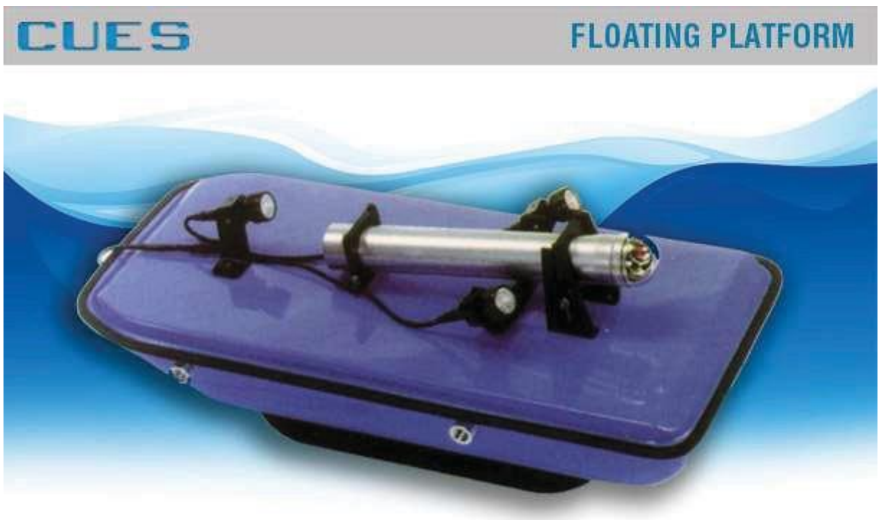
RedZone extends the industry leading multi-sensor inspection technologies (MSI) down to now perform inspections and condition assessment on smaller, or mid-diameter pipes.

Trunk sewers can be difficult for a city to adequately assess. Flow conditions can be unpredictable and inspection tools need to be able to capture valuable information in dry pipes, partially full pipes, or fully surcharged lines. Many of the conditions that plague 21″-36″ (380mm to 914mm) pipes are very difficult to diagnose using purely visual inspection. Determining levels of deformation, corrosion, and sediment build-up can help managers plan cost-effective maintenance and rehab, but can only be accomplished through the use of multi-sensor inspection.

Floating Camera System by CUES

CUES is a company that is specialized in providing high-quality systems for closed circuit television video (CCTV) pipe inspection, pipe viewing and profiling equipment, inspection data collection/management software, and mobile vehicles that support their systems.

Below is a boat type inspection system available from CUES.



The float system is designed to provide a stable floating platform for the television camera and its associated lighting when inspecting pipes ranging from 24” to 200”. Built with a rugged polyurethane filled fiberglass hull and catamaran style metal keel, the Float can operate in virtually any pipe, through sand and debris, without the need to divert or reduce flows. Measuring only 18 ½” wide x 42” long, can be inserted in a manhole without the need for the operator to enter a confined space.

Multi-Sensor Inspection Raft by UVS Trenchless Technology

The Multi-Sensor Inspection (MSI) Raft by UVS Trenchless Technology enables comprehensive inspection of a large diameter sewer pipelines. Developed by CISCREA of France, a design partner for UVS Trenchless, the MSI Raft has been proven with inspections conducted since July 2017. The MSI Raft dimensions of 1400 x 460 x 380 mm enables access through typical manhole entries. The MSI Raft also includes a deployable stabilizer system to support inspection and stabilization of the vehicle in large pipelines. Demonstrations have shown that comprehensive data can be gathered in just one pass of a sewer pipeline. The operator has access to real-time video with full data transmission to the surface and real time data fusion of laser (above water) and sonar (below water) data. The Multi-Sensor inspection suite includes:

- Pan-Tilt-Zoom Camera for detailed visual inspection
- Monitoring cameras with spot lights for overall imaging and control of the inspection
- Laser for accurate measurement and profiling above the water line
- Sonar for imaging and profiling of the pipeline and silt conditions below the water line

Comparisons Among Notable Rafters/Boats

No detailed comparisons are made here among these systems, since none of these buoyant systems are believed to become useful to the ODOT Ashtabula County water-garage workforce. The culverts in their area usually do not have much standing water. If they do, the flow velocity is usually very slow and water is going to lie above a sediment layer. If one of the floating system is to be recommended, it must be the one from CUES. The ODOT purchased four mobile vans and CCTV crawler inspection systems from CUES. With these supporting systems already in possession, it makes sense for ODOT to add the floating system. It may become useful in some other parts/culvert sites in Ohio.

Appendix G. Notable Commercial Submersibles
[Note] This section was put together largely by cutting-and-pasting photographs, specifications, and writeups from various vender websites.

Underwater Drones

VideoRay by RIT Inc.

The VideoRay PRO 3 GTO is an observation class ROV system capable of obtaining information when size really does matter. This system can fly through flooded pipelines, portholes, doorways, or other openings of 12 inches and greater to gather information quickly and efficiently. VideoRay systems have been utilized within shipwrecks, sunken airplanes, municipal water tanks, within pipelines, inside ballast tanks, tension leg platforms, bridge inspections and vessel hull inspections. This VideoRay system is transported within two pelican cases - combined weight of 135 lbs. (61 kg) that can be transported by hand to the job site by the technicians. Designed for rapid callout deployment, this system can easily be lifted by car, truck, boat, plane, or helicopter to the job site - rapid and reliable service within a small package.

AquaBotix (8GB Hydro-View Remote Controlled Underwater Vehicle Video & HD Photos)

HydroView's design was created by our engineers who were inspired by the sleek movements of marine life, inventing a product that flies through the underwater world. Weighing less than 10 pounds, the HydroView offers a one of a kind experience in an extremely portable and entertaining package. Simply drive the HydroView via motion-control on your iPad or the keyboard on your laptop and the vehicle will respond in the appropriate direction, translating your device movements into vehicle action. The HydroView even generates its own Wi-Fi, saving you the frustration of searching for a signal while on the water. The easy-to-use on screen display of the application makes its features very intuitive. The HydroView is your window into an exciting and invigorating underwater world, providing you with a measure of safety and the opportunity to discover and explore.

Price: $5,795.00 + $200.00 shipping

THE VEHICLE INCLUDES:
- LED lights.
- 8 GB Memory Card
- HD camera.
- Standard 75 foot cable.
- Waterproof carrying case.
- Topside box which produces vehicles Wi-Fi.
- Free download of the application to use on your iPad, PC or MAC computer.

COMMERCIAL USES:
- Inspect Sea Floor
- Evaluate Sea Wall
- Examine Lobster Pots
- Check Live Bait Cages
- Determine Water Depth
- Analyze Progress Done On A Project
- Inspect Underwater Cabling Support Systems
- Determine Strap Placement Before Removing Boat From Water

Power Vision Power Ray Wizard Underwater 4K ROV
Price: $3,999.00 & FREE Shipping

The Best Underwater Drone! Great for Fishing, Exploring, Mapping, Treasure Hunting, Studying Marine Life or Recording for Film Projects.
4K UHD Video, 1080p Real-Time Streaming- 98' Depth Rating, 210'
Tether See & Record in 4K UHD the Underwater World from Boat
PowerSeeker Fishfinder & Bait Drop Line
12MP Photos, 5-fps Burst Mode

Trident is one of the latest underwater video systems. Every aspect of the Trident de sign has been painstakingly thought out in order to optimize performance and usability in any situation. One of the secrets of its versatility is the unique,hydrodynamically offset thruster design. This configuration allows you to move through the water fast and efficiently when you want to rapidly search an area or run a transect, but also allows you to maneuver very delicately when in tight quarters or while looking at a particular target. By taking advantage of drag's exponential relationship with velocity, the off-center vertical thruster of the ROV can cause it to pitch at high speeds but also hover or change depth without pitching while operating at low speeds - similar to the way a traditional ROV works.

- Trident Underwater Drone
- 150-m (492-ft) heavy-duty tether
- HD camera & lights
- www.openrov.com

Deep Trekker Remotely Operated Vehicles (ROV) are completely customizable to achieve a multitude of underwater operations. Its portable and rugged design make it the ideal solution for military and navy dive teams. The DTG2 underwater drone fits conveniently into one carrying case and since it runs off of rechargeable, internal batteries, the ROV can be deployed in the most remote locations. The DTG2 Worker proves to be the exemplary system for military and navy underwater applications. To see its immediate benefits, you don’t have to look too hard; aside from the obvious feature in the two-function grabber arm, the ROV is packed with advanced sensors for navigation and environmental measurements. A sonar can be incorporated into DTG2 if visibility is not great.

- 150-m (492-ft) heavy-duty tether
- Camera & lights
- www.deeptrekker.com

Underwater Robot BIKI

BIKI is the world's first bionic underwater drone that is also the only underwater robot featuring automated balance, obstacle avoidance, and return to base. By supporting a 4K camera, BIKI presents the best view from underwater. BIKI, the smallest but strongest. Through this intelligent robot fish, you can visualize the underwater world from a completely new perspective.

The Sonar Profiler System by CUES is designed to provide accurate dimensional data on silt level, grease accumulation, pipe deformation, offsets, etc., below the waterline.

While CCTV is the standard acceptable method of visually inspecting pipelines above the waterline, it cannot provide visual information on internal pipe conditions below the waterline. In charged lines or siphons, the Sonar Profiler System provides the visual profile, profile comparison, and dimension data of significant items or defects. A sonar inspection of a fully or partially charged line provides a two-dimensional profile of the interior pipe wall similar to a medical MRI. Using the sonar software, a circle overlay is projected, sized, and moved anywhere within the image for checking erosion or remaining wall thickness. Accurate measurements can be made between any two points within the sonar image. Thus, offset, debris level, size of blockage, grease level, defects and so forth can be quantified. In partially charged lines, the Sonar can be combined with CCTV to provide a simultaneous composite image of the pipe both above and below the waterline! Two (2) different sonar systems, (1) for submerged pipelines and (1) for semi- submerged pipelines, are available to survey pipelines measuring 12" up to 18' in diameter. Both systems provide ‘real time’ cross-sectional views of the pipe by utilizing high resolution/short range sonar. For semi-submerged pipelines, the non-submerged portion of the pipe is displayed on the video monitor as a standard video image.

- Cues Sonar Profiling System
- Camera & lights

HD Sonar Sub (Redzone Robotics)
Leading underwater condition assessment product to get debris calculations and water level analysis in siphons and surcharged lines with long deployment capabilities.

Siphons in a sewer system can present a challenge to inspect and maintain. Access between manholes can often span thousands of feet, requiring a platform that capture data over long ranges. Inspections in fully surcharged conditions cannot be undertaken by conventional CCTV crawlers.

Hydroid announced in 2016 the release of the New Generation REMUS 100 AUV. The autonomous underwater vehicle features advanced technology and capabilities that are the first of their kind in the industry, enabling customers to have increased autonomy and creativity during missions.

The New Generation REMUS 100 AUV combines the reliability of the original REMUS 100 AUV that customers know and trust with new features and capabilities, such as advanced core electronics, a flexible navigation suite with an exclusive conformal Doppler Velocity Log (DVL) and an open architecture platform for advanced autonomy. The vehicle was created over a period of two years, and is designed based on feedback from the world's largest AUV user community.

"The New Generation REMUS 100 AUV has impressive capabilities not previously seen on a man-portable vehicle," said Duane Fotheringham, president of Hydroid. "We are confident that we have created a vehicle that fulfils our customers' needs for leading technology, while maintaining the core offerings of the REMUS brand they have trusted for years. Thanks to the New Generation REMUS 100, we are continuing to pave the way for future unmanned underwater technology."

- Remus-100 Sonar Profiling System
- Diameter 7.5 in
- Camera & lights, Sonar

Operators control the REMUS 100 UUV with laptop computer-based software for programming, training, post-mission analysis, documentation, maintenance, and troubleshooting. The software enables one operator to control as many as four REMUS 100 UUVs at the same time. The REMUS 100 is suited to marine research, defense, hydrographic and offshore energy applications. It is small enough to be carried by two people, and can perform intricate sonar and oceanographic surveys over large areas, Hydroid officials say. Typical REMUS 100 applications include mine countermeasures, harbor security, debris field mapping, search and salvage operations, hydrographic surveys, environmental monitoring, fishery operations, and scientific sampling and mapping.

Underwater Air-Water Surface-Under Water Drone

One of the latest developments in aerial drone technology is the rotor drone that can not only float on the water surface but also dive into water. One such system surfaced during the team's online data search.

Loon Copter (developed by Oakland University)

Loon Copter, a project out of Oakland University, is a drone that can fly, float, or swim underwater. Loon Copter has a "buoyancy chamber" that allows it to float on water. That chamber, however, can fill up with water, causing the drone to sink and tilt 90 degrees. Loon Copter then use its four rotors to swim around. To resurface, Loon Copter ejects all the water from the buoyancy chamber to return to the surface, at which point it can then take off into the sky. The design of Loon Copter won the Oakland University team an international design award.

Comparisons Among Submersibles

Once again, no detailed comparisons are made here among these systems. This is because none of these submersible systems are believed to become an essential tool for the ODOT Ashtabula County garage workforce. The culverts in their area usually do not have much standing water. If they do, the drainage water tends to be rarely clear.

Appendix H. Other Systems

[Note} This section was put together largely by cutting-and-pasting photographs, specifications, and writeups from various vender websites.

All-Terrain Hex Pod Robot

A start-up company Vincross has developed an all-terrain six-legged insect robot 'HEXA' that is agile, smart, and highly adaptable to its environment. HEXA is compact enough to fit into a backpack. Each leg has three servo actuators. Its head can spin full 360 degrees. With the degrees of freedom it comes with, it is capable of climbing an obstacle, walking across a gap, and moving through a small confined space (ex. under a bed) in a ducked position. HEXA is equipped with a 720p camera with night vision, an infrared transmitter, an accelerometer, and a sonar distance sensor. HEXA comes with a download control app, and it communicates through Wi-Fi. The control app has many features to make the robot do a lot of delicate and different movements.

- Dimensions = 15.7" Dia. (leg-leg) x 6" H

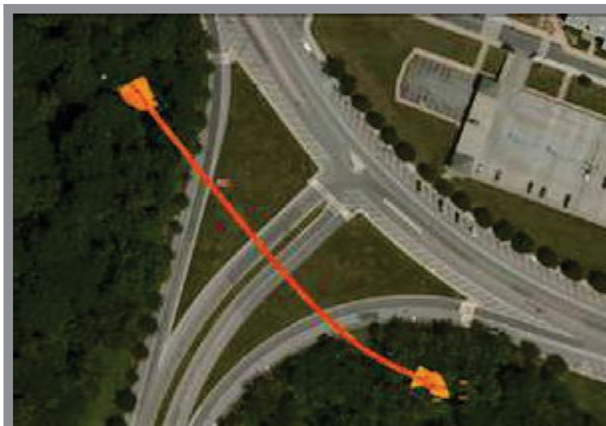
  [Note] It can walk in a ducked low position as well.
- Weight = 3.9 lbs.
- Pay Load = Up to 3.3 lbs.
- Walking speed = about 1 ft/s
- Battery life = 4 hours
- Battery charge time = 1.5 hours (wireless)
- Estimated price = $949 (available from Feb. 2018)

HEXA has many possibilities but is not believed to be water resistant.


3D Laser Scanning of Metal Culvert Pipe

Location:
Baltimore, Maryland

Task: To utilize 3D Laser scanning to laser scan an existing corrugated metal culvert pipe.



Point Cloud Data Overlaid and Aligned on AutoCAD Maps

Challenge: The client needed to fit a custom-sized liner to the interior of the metal pipe but because of settlement issues, rusting of the bottom of the pipe, deformation, and overall environmental damage sustained to the pipe, traditional methods would have made measuring the pipe difficult. Additionally, the pipe was almost completely dark on the interior, making it even more difficult to measure by traditional survey methods. Laser scanning does not require light to capture data, though, so the entire pipe could be captured through 3D laser scanning.

Solutions: By utilizing 3D Laser Scanning, the entire length of the pipe was captured within one day. TruePoint was able to register the data to existing survey control for the client's use and generate an accurate plan and profile view(s) of the culvert.

Deliverables: TruePoint generated AutoCAD Civil 3D Models, Navisworks files, AutoCAD files, and point cloud files in rcs format.

Added Value: TruePoint was able to mobilize within days of notification and scan the entirety of the culvert in one day and then began generating deliverables immediately upon completion of the scan. Information would have otherwise been difficult to measure due to lighting issues and the line of sight within the culvert. However, 3D Laser scanning is not dependent on light to capture data points and has a long range with which to capture distant features that might otherwise be missed.

TruePoint Laser Scanning Equipment

Data are captured with industry-leading survey-grade Leica equipment. Leica ScanStations can tie to survey control, achieve 2-4mm accuracy and have real time liquid filled dual axis compensation to help mitigate movement and ensure level scans. TruePoint scan technicians receive formal training from the scanner manufacturer, plus instruction from an experienced scan technician.


View from Inside the Culvert


Laser Scanning the End of the Culvert

Leica ScanStation P40

Appendix I. Initial Testing of UAS Technologies

The drone research team at Ohio University, headed by Dr. Maarten Uijt de Haag, tested a racing drone built by his team at the university's pipe research laboratory, where some pipe specimens are being maintained.

MTRI Blackout Mini H Quadcopter (a small UAV assembly kit; dimensions 11” x 13” x 3”) used in the flight tests had the following basic characteristics:

- Cost = less than $500
- Weight = 1.5 lbs
- Flight endurance = 15 mins max.
- Description = an agile micro-drone that allows customizations
- Equipped with a flight controller, a GPS module, radar scanners (x 2), LED lights, and a camera
- FatShark – Allows FPV
- Note – Drone not waterproof

The radar scanners mounted on the drone chassis were similar to the one described below.

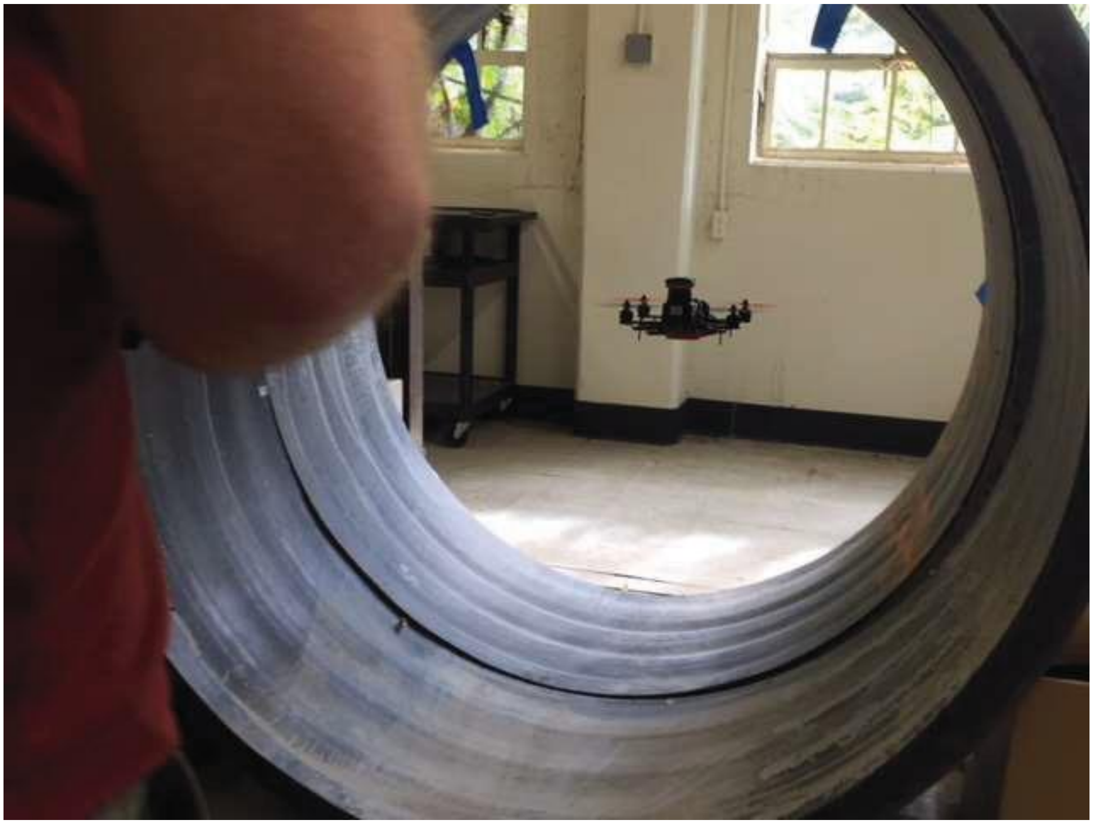
360° Sense & Avoid Radar Technology

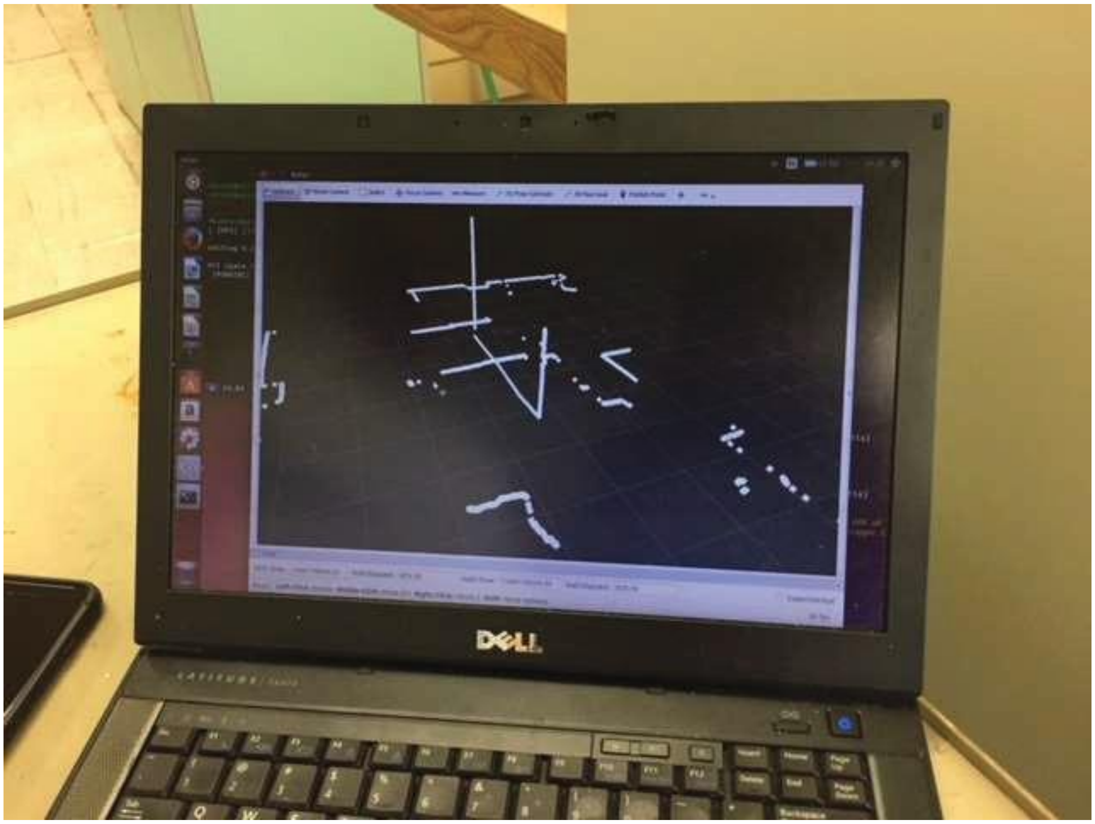
Drone technology has been steadily improving. The latest focus is on “sense-and-avoid”, which can enable truly autonomous flight of small UAVs and lead to a dramatic increase in real world drone applications. As of now, sense-and-avoid technology is still a work in progress. Despite drone manufacturers and technology providers touting the capabilities of their latest products and solutions, current sense-and-avoid systems simply cannot provide reliable obstacle collision avoidance in all environmental conditions and at all times. Even the latest and most expensive consumer drones can fail to avoid collision when faced with a number of real world situations due to limitations in the sensors being used: optical sensors which require good lighting, and LiDAR and ultrasonic sensors which require ideal weather conditions.

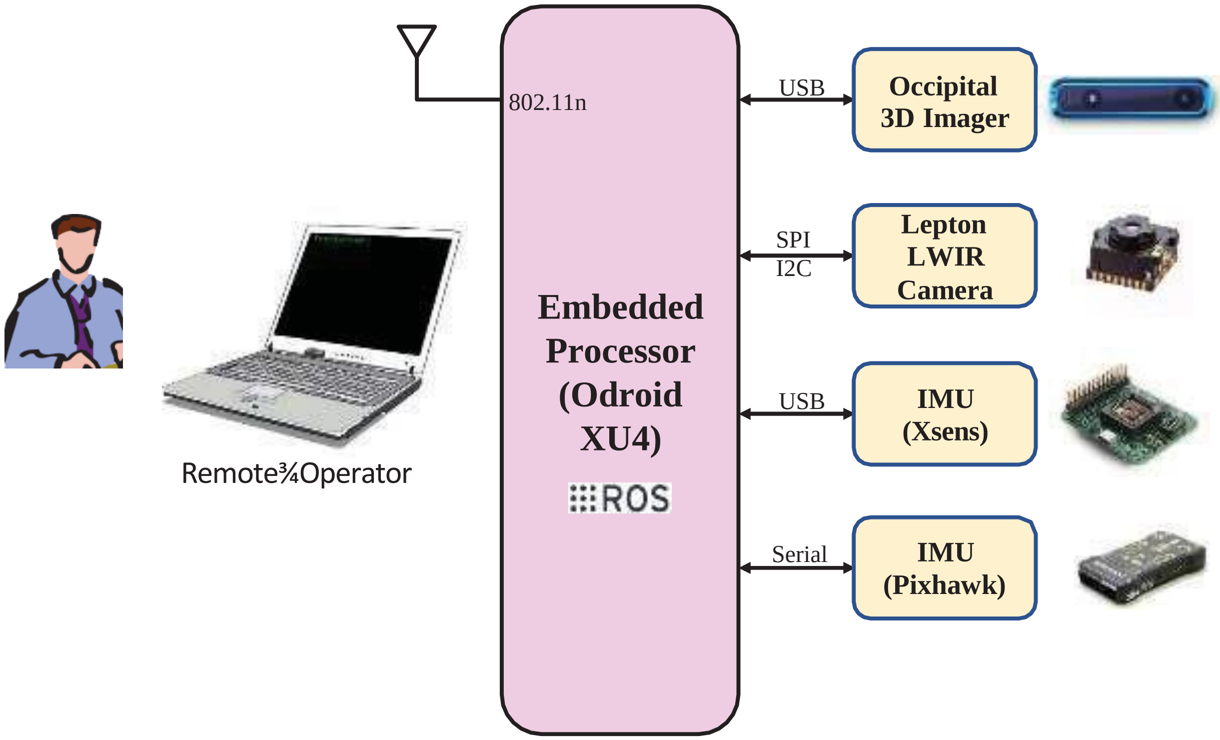
The team at Aerotenna has engineered and tested a microwave radar solution for obstacle collision avoidance. Aerotenna μSharp, a 360° sense-and-avoid radar small enough to be integrated into consumer drones, has the robust performance needed for reliable obstacle avoidance in any weather condition at any time of day or night. μSharp scans 360 degrees without blind spots, detecting and locating obstacles on the horizon quickly and reliably, which allows for correction of flight course in time to prevent collisions. The system incorporates adaptive sensing technology that optimizes its response, regardless of flight status. With its robust performance and integrated design, μSharp is a modern collision avoidance radar system for any UAV. It has the following features:

- 360-degree electronic scan without blind spots
- All-weather, day and night performance
- Miniaturized, compact and lightweight design (<150 grams) with low power consumption (<3 watts)
- Long range with adaptive sensing range adjustment based on flying speed (up to 200m)
- High accuracy (up to 2” or 5 cm range resolution)
- Fast response time (up to 90 Hz update rate)
- Advanced target detection and recognition algorithms

The team tested the drone by flying it manually through a 60” dia. HDPE pipe as well as a 28” wide chamber structure (positioned upside down). See pictures below.




DELL



A few observations made by the team are listed below:

- The drone created a good amount of air turbulence while flying through the pipe. It seems it induced some ground effect (uplifting air pressure coming from the bottom), which was quickly counteracted by the downward air pressure coming from the top. This helped to fly the drone manually through the 60-inch diameter pipe section. In contrast, it was not possible to maintain the same elevation for the drone when it was flying through the upside-down chamber section (with no top). The ground effect kept lifting the drone upward.
- Whenever the drone's position shifted off center, some air pressure was generated from the closer lower side wall, which led to air vortices. This points to the fact that the drone should be kept near the center of the pipe's cross-section.
- During the trials, it was not very difficult to keep the drone near the center of the cross-section through the 60-inch diameter pipe segment. This was obvious as the drone was flown in sight and only over a distance of about 12 ft.
- The 270° radar attached to the back of the drone scanned objects around it and provided scan mapping data to a laptop computer. The shape of the pipe showed up on the screen whenever the drone was inside the pipe segment.

The challenges remain in the following areas:

- Addition of two radar scanners, a camera, and LED lights $\longrightarrow$ Makes the drone heavier $\longrightarrow$ Reducesits flight endurance

- Addition of an outer protective cage ⟶ Makes the drone collision resistance ⟶ Makes it heavier ⟶ Reduces its flight endurance
- Waterproofing of the drone ⟶ Double-wall construction ⟶ Makes the drone heavier ⟶ Reduces its flight endurance
- Flight through the pipe (with GPS) ⟶ Fast processing of radar readings to compute the center position ⟶ Repositioning the drone
- Autonomous flight through the pipe (without GPS) ⟶ Need additional R & D to achieve indoor/confined space positioning
- A lack of features along the length of the culvert ⟶ Difficult to sense drone's exact location inside the culvert
- Recovery of the drone in case it goes down while flying through a culvert ⟶ A pipe crawler with robotic arms or a lager drone with a hook or robotic arms

Appendix J. UAS Risk Assessment

There are always some risks for crashing whenever a drone is flown. To this date, the FAA has not issued any historical/statistical data on drone crashes. This is because technological development has been outpacing effective data collection. So, it is difficult to perform a comparative risk analysis between drones and other remote inspection systems (ex. crawlers). The crawlers are by no means failure proof. They can malfunction, run out of battery power, lose traction in muddy soil conditions, sink into loose sediment deposits, get caught in between obstacles, get stuck in joint openings, jammed inside partially collapsing pipes, and swept by fast currents.

The FAA changed its rules (14 CFR, part 107) for the operation of small Unmanned Aircraft Systems. Key elements of the FAA rules are listed in Table 13. Recently, they issued a document to address/clarify the changes and reinforce their guidelines. Among the rules, one of the most critical one related to the UAS operation is Visual Line of Slight (VLOS). The language they use is that "the pilot must keep the small UAV in his/her sight at all times during flight." However, FAA does understand that the pilot may lose VLOS momentarily. They seem to be okay as long as VLOS can be regained by the pilot as soon as practically possible. They are concerned about the cases where VLOS cannot be regained.

The table on the next page offers tips that are generally cited for reducing the chance of drone crashes.

A critical literature review on UAS Ground collision severity evaluation and mitigation was issued recently by a team of researchers for FAA (Arterburn, et al. 2017). The report is very comprehensive and addresses many topics, including the best theoretical method (to quantify the UAS's impact kinetic energy), issues with lithium polymer batteries commonly found in micro UAS, types of human injuries that can result from collision with a UAS, and characteristics of each UAS type (that can influence the severity of human injury). It is not the aim of this appendix to present all of the points made in the report. Below are some key points made in the report:

- Despite the fact that UAS are noisy and highly noticeable to people, there have been many cases of laceration injuries to hands and arms.

- Most of the UAS sold commercially are of two frame design types – UAS having a single continuous smooth body (ex. DJI Phantom Pro) and UAS having a modular construction (ex. DJI Inspire, Yuneec Typhoon). Between the two types, the first type may be safer to humans. This is because this type offers a larger contact surface area during a collision. Also, the body can deform and distort upon impact to reduce energy transferable to a person. The second type, consisting of many parts, tends to have some sharp edges. It offers a smaller contact area during a collision and increases a chance for penetration and laceration injuries to head and arms.

Tips	Notes
Check Rotors & Camera	Make sure that all parts of the drone, essential for successful flight, are functioning well just prior to the usage.
Check Batteries	Make sure that the drone's battery is fully charged for the flight. Make sure the control unit's battery is also full.
Check Screws and Other Fasteners	Make sure all screws and fasteners on the drone are tight.
Check on GPS Lock	Make sure the drone comes with a GPS lock and it will be locked on the GPS coordinate of the current launch point.
Have a Quick Test Flight	Conduct a quick test flight over a short distance to make sure that the drone is fully functioning and can return to the launch area.
Fly in a sparsely populated area	Choose an area where the drone can be easily kept away from people, vehicles, and buildings. If it is necessary to fly in a populated area, develop an effective plan that keeps the drone clear of other people.
Know the Flight Area	Conduct a preflight examination of the flight area. Identify all physical objects, such as towers, poles, power lines, trees, buildings, that can serve as obstacles and block the pilot's view.
Have a Stable Take-off/Landing Area	The take-off/landing area is on the solid ground and away from people, vehicles, and building.
Identify at Least Two Emergency Landing Spots	Identify at least two spots, within the flight area, where the drone can have an emergency landing and can be recovered relatively easily later.
Have a Plan in Case VLOS Cannot be Regained	Develop a clear plan for situation in which VLOS cannot be regained (ex. immediate landing, returning home).
Activate Collision Resistant Feature	Make sure that the drone comes with either collision avoidance features or with a collision tolerant design if the flight area has a few obstacles.
Select Waterproof Drone When Flying over Water	Make sure the drone is waterproof and buoyant when the flight area contains a large body of water.
Fly only in Daylight	This is a requirement of FAA Part 107.
Fly only in Good Weather	Make sure the drone is used in the weather with little winds and no precipitations.
Do not Fly over a Long Distance	Keep the flight distance within 400 ft to maintain the drone in visual line of sight all the times
Have an Experienced Pilot	Make sure that the person controlling the drone had many practices.
Have a Spotter	Make sure that the pilot is accompanied with a person whose job is to keep an eye on the drone all the times with a viewing device (ex. binoculars).

- Propeller diameter can increase the severity of hand/arm laceration injuries.
- Propeller guards can be helpful in preventing laceration injuries during a collision. However, severe injuries can result if a human hand is accidently caught inside the guard.

[Note] Based on the above information, the team believes that the collision-tolerant type, such as ELIOS and Fleye (page 89-90), will be effective in preventing laceration injuries.

- Lithium polymer (LiPo) batteries commonly housed in commercial UAS can ignite if they are punctured, exposed to air or water, crushed, overcharged, or poorly maintained.

Additional Note: In January of 2017, Virginia Tech researchers described their testing, using crash test dummies equipped with sensors to measure the impact that a drone would have if it fell out of the sky and hit a person. The study concluded that the risks of a catastrophic head injury were less than 5 percent in an impact with a 2.6-pound (1.2-kilogram) unmanned vehicle, according to their results published in the Annals of Biomedical Engineering.

How to Prevent Drones from Crashing

- Implement the tips presented at the beginning of the previous page.
- Fly a drone that is protected inside a collision-tolerant shell (ex. drones shown on pages 80-81).
- Use a tethered drone (ex. drone by CyPhy Works, pages 92-94) ⟶ Provide unlimited flight time and thus prevent crash due to power failure.
- Attach a steel wire from end to end to the crown region of the culvert, so that the drone can be tethered to this cable system for recovery effort in case it crashes inside the culvert structure.

How to Recover a Downed Drone

- Use a drone that is waterproof and can float in water (ex. Splash Drone 3, pages 87-88) ⟶ Can be picked up by a person on a boat if the drone crashes into a body of water.
- Have a hook attached to the top center of the drone (so that it can be picked up easily). Use a larger drone to pick up a downed smaller drone.
- Deploy a crawler equipped with robotic arm(s) and a sufficient pay load capacity (ex. Jaguar V4, pages 59-60) to go in and recover the crashed drone.

Appendix K. Emerging Technologies for Crawlers & Drones

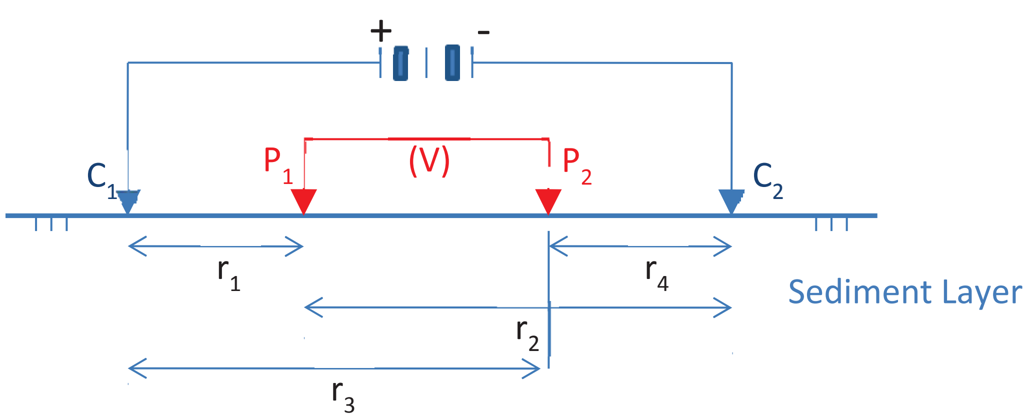
Crawlers

Crawlers equipped with a HD camera, LED lights, and a laser profile are believed to be sufficient for inspecting culverts that have little water and sediment inside. When the drainage structure is partially submerged under water (with almost no sediment accumulation), the crawler system can be still useful as long as it is water-sealed and the laser sensor is upgraded to a laser/sonar combo system or replaced with a more powerful underwater laser scanner.

Integration of additional sensors and technologies are sought when there is a need to evaluate the culvert's cross-sectional shape (or deflections) as well as its wall thickness measurement when the structure has a considerable amount of sediment accumulation. Below are a few technologies that have potentials to be integrated into the crawler design in the near future.

Electric Resistivity Measurement

One possible way of detecting the pipe invert through a sediment accumulation is through the electric resistivity method. For this method to work, a number of equally spaced steel pins (electrodes) can be pushed gently into the sediment. Two outermost pins are connected to a DC battery to send an electric current into the soil. Then, the system reads the voltage between two inner pins whose spacing increase gradually. This setting is shown in the drawing below.



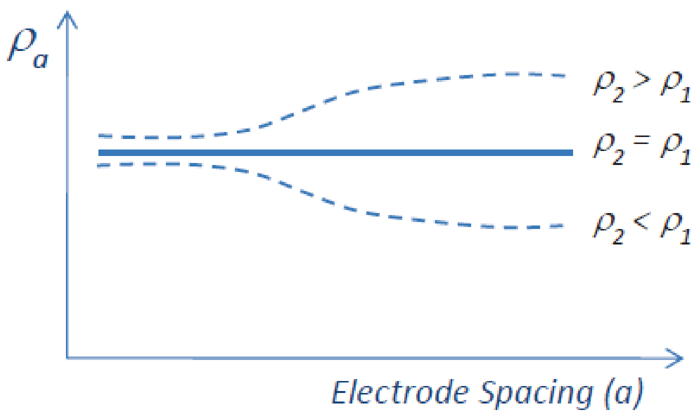
The data is then analyzed to calculate the resistivity readings by the following equation:

$$\rho = \frac{2\pi V}{i}\left(\frac{1}{\frac{1}{r_1}-\frac{1}{r_2}-\frac{1}{r_3}+\frac{1}{r_4}}\right)$$

where ρ = resistivity; V = voltage measurement between two inner electrodes; i = electric current; and r_1 through r_4 = distances (defined in the drawing above).

Results can be plotted in terms of resistivity vs. pin spacing. If the resistivity reading drops ($\rho_2 < \rho_1$) while the pin spacing is increasing, the bottom of metal pipe is detected. If the resistivity reading becomes much larger ($\rho_2 > \rho_1$) as the electrode spacing gets wider, it means that the bottom of concrete/vitrified clay/plastic pipe is detected. The readings should be taken along the length of the pipeline, not within the pipe cross-section (sediment depth will not be nearly constant). The measurement reflects mostly what lies at one specific depth zone, which is dictated by the spacing between the inner electrodes.

[Note] There is no need to find ways to adjust the electrode spacing, instead of having many of them.



Typical Electrical Resistivity Values

Material	Resistivity (Ω-m)	Material	Resistivity (Ω-m)
Water	20-2,000	Plastics	?
Clay (moist-wet)	1-20	Vitrified Clay	?
Sand (dry)	High 1,000s	Concrete	80-120
Sand (moist-wet)	10s-100s	Bedrock (fractured, dry)	Low 1,000s
Steel	10^{-7}	Bedrock (fractured, wet)	100s
Ductile Iron	10^{-8}	Bedrock (intact)	High 1,000s

Seismic Survey Measurement

Another possible approach to locate the culvert invert below a pile of sediment is to employ the seismic method. In this method, a shock wave is transmitted throughout the sediment layer and is picked up by a number of geophones. Again, the readings should be taken along the length of the pipeline, not within the pipe cross-section (sediment depth will not be nearly constant).

Analyzing the critically refracted wave data, the sediment layer thickness h can be estimated from:

$$h = \frac{t_i V_1 V_2}{2\sqrt{V_2^2 - V_1^2}}$$

Analyzing the reflected wave data, the sediment layer thickness h can be estimated from:

$$h = \frac{t_0 V_1}{2}$$

where t_i = intercept time (s); V_1 = compression wave velocity in layer 1 (m/s); V_2 = compression wave velocity in layer 2 (m/s); and t_0 = two-way travel time at shock point (s).

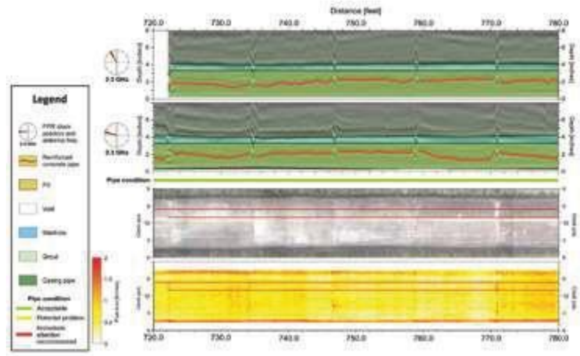
Ground Penetrating Radar (GPR)

A variation of the seismic survey method is ground penetrating radar (GPR). In this technology, radio frequency electromagnetic waves are generated and transmitted into engineering materials, rather than seismic (or shock) waves. The principles are the same between the two variations. In both approaches, arrival times for the wave that travels along the sediment surface and waves reflecting back from the interface between two dissimilar materials are analyzed to best estimate the sediment layer thickness. Once this is known, the vertical diameter of the rise of the drainage structure can be known.

Crawler with GPR Sensing

A specialized pipe crawler with GPR capability has been developed by a Canadian company SewerVUE. The system called the SewerVUE Surveyor is the first commercially available multi-sensor inspection robot that uses visual and quantitative technologies (CCTV, LiDAR, SonarR and PPR) to inspect underground pipes. The Pipe Penetrating Radar (PPR) inspection system is mounted on a rubber-tracked robot and equipped with two high-frequency PPR antennae. Radar data collection is obtained via two independent channels in both in and out directions, providing a continuous reading on pipe wall thickness, rebar cover and locating voids outside the pipe.

PPR radar is the underground in-pipe application of ground penetrating radar (GPR). As the radar pulse travels through a pipe some of the energy will be reflected and refracted by any sharp change in material properties, such as at the interface between pipe material and air, soil or water. The greater the difference in the material properties, then the greater is the amount of energy reflected back. These reflected waves are detected by a receiving antenna and are recorded. This process is repeated as the robot mounted antennas are moved along the pipe to build up an entire profile. This continuous data collection allows the PPR system to be a cost-effective method and to become a valuable information provider in pipe condition assessment. Using high frequency, high-resolution antennas the maximum signal penetration depth can be as much as 5 ft beyond the pipe wall with resolution as small as 1/8 in.



SewerVUE uses LiDAR and Sonar scanners for collecting the pipe geometry data above and below the water surface. These scanning techniques employed do not penetrate through sediment. The PPR sensing requires that the pipe wall be exposed (not covered under soil). SewerVUE can inspect metal (corrugated metal, ductile iron), concrete, and vitrified clay pipes that are 21” to 60” in diameter. It is quite heavy (300+ lbs). The crawler can operate under up to 100-ft deep water. It comes with 1,500 feet of cable. SewerVUE also comes with onboard positioning system for mapping x,y,z coordinates. The crawler is tethered for power supply and signal transmission. The system can be purchased.

Guided Wave Test (GWT) Measurement

This belongs to nondestructive (ND) metal loss/crack detection methods developed for oil & petrochemical industry pipelines. The acoustic method employs mechanical stress waves that propagate along an elongated structure while guided by its boundaries. This allows the waves to travel a long distance with little loss in energy. Nowadays, GWT is widely used to inspect many structures, particularly metallic pipelines. Guided wave testing uses very low ultrasonic frequencies typically between 10~100 kHz.

In Guided Wave Testing of pipelines, an array of low frequency transducers is attached around the circumference of the pipe at its end to generate an axially symmetric wave that propagates along the pipe in both the forward and backward directions of the transducer array. The Torsional wave mode is most commonly used, although there is limited use of the longitudinal mode. The equipment operates in a pulse-echo configuration where the array of transducers is used for both the excitation and detection of the signals.

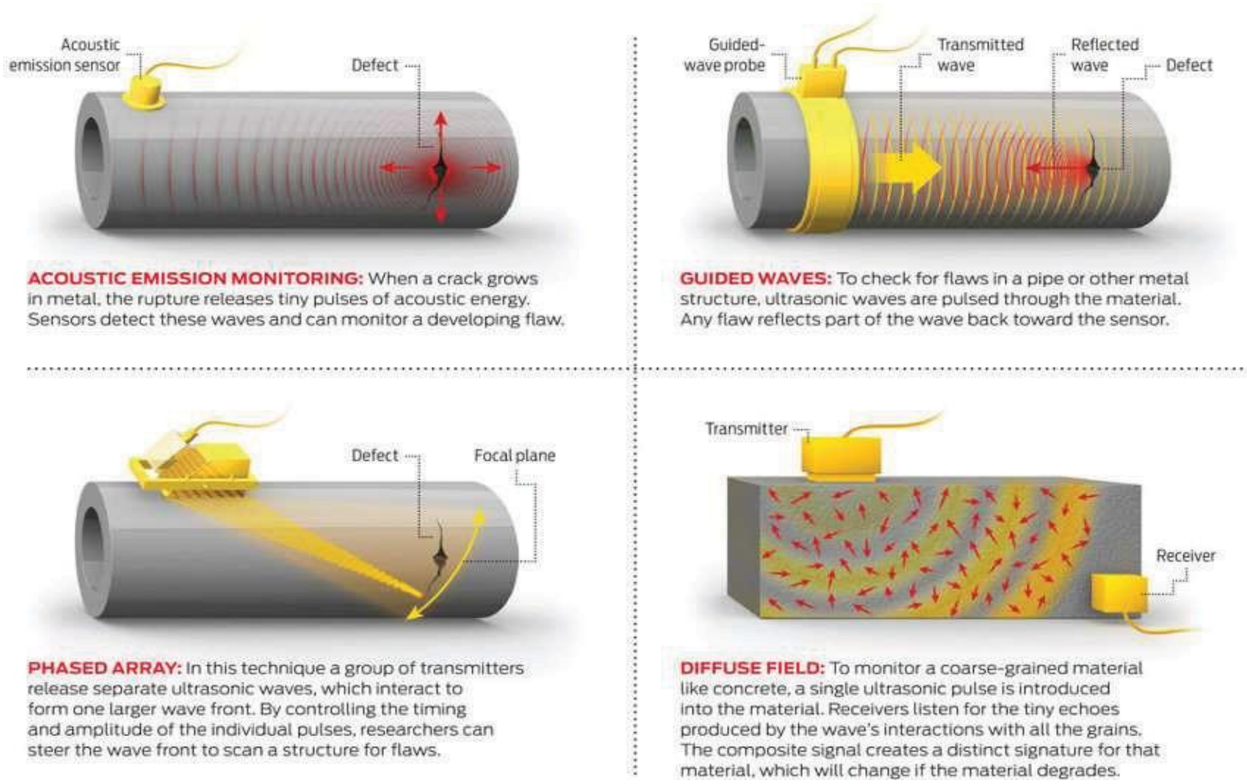
At a location where there is a change of cross-section or a change in local stiffness of the pipe, an echo is generated. Based on the arrival time of the echoes, and the predicted speed of the wave mode at a particular frequency, the distance of a feature in relation to the position of the transducer array can be accurately calculated.

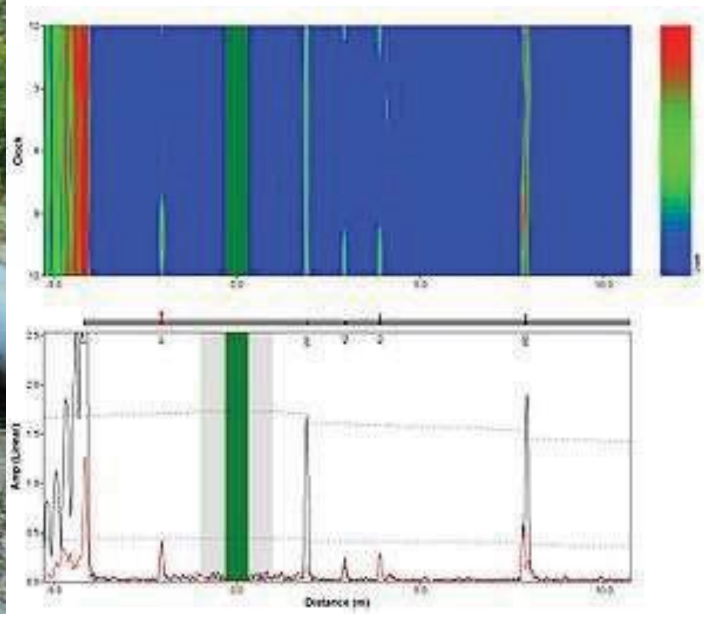
Advantages of GWT

- Rapid screening for in-service degradation (Long range inspection) - potential to achieve hundreds of meters of inspection range.
- Detection of internal or external metal loss
- Reduction in costs of gaining access - insulated line with minimal insulation removal, corrosion under supports without need for lifting, and inspection of buried pipes.
- Data is fully recorded.

Disadvantages of GWT

- Interpretation of data is operator dependent (requires experience).
- Difficult to find small pitting defects.





Air-Coupled Guided Wave Technology

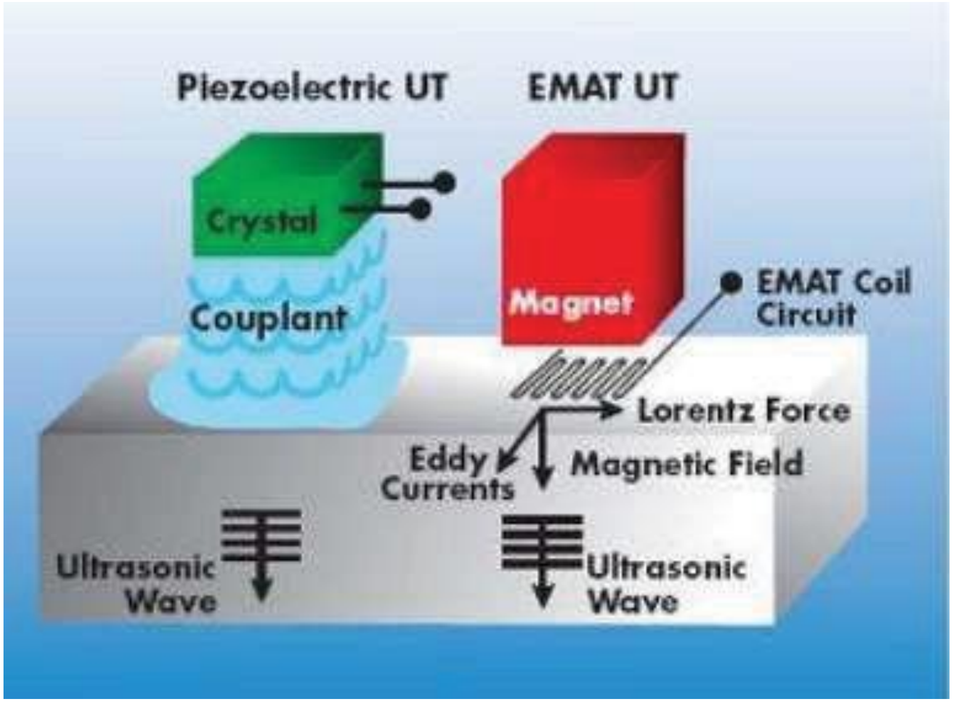
The guided wave technology addressed above may not be applicable to highway culverts, because these structures contain water and sediment and also consist of many seams and joints.

The research team is currently investigating the feasibility of integrating ultrasonic transducers using guided wave technology for thickness and corrosion measurement intended for culverts that are potentially sediment filled. The technology uses a transmitter/receiver pair that is operated within the culvert, and can potentially make the measurement without making contact with the culvert material itself. The instrument would most likely integrate an electromagnet stimulated by a source controlled within electronics mounted on the crawler itself. This would induce a wave along the circumference of the pipe at a distinct point. The amplitude of the received signal would provide information detailing variation in thickness along the circumference even in instances where the culvert is engulfed in sediment. Individual measurements along the length of the culvert would be used to create an overall thickness profile and could be used to identify areas of risk with respect to corrosion.

This instrument would constitute a new technology with respect to culvert evaluation, and as a result the team is evaluating the requirements associated with developing it. Challenges include the accurate angular control needed at the transmitter end of the instrument as well as battery/power requirements associated with making such a measurement over the large span of a culvert. The team hopes to further this investigation to validate the feasibility of integrating the technology on a crawler platform.

Guided wave technology has the potential to provide a relative non-contact thickness measurement a distance of pipe span (versus single point) beneath a sediment layer.

- EMAT
- Dry Inspection – noncontact
- Accommodates various surface conditions
- Shear horizontal waves
- Applied to allow wave to travel along surface Longer Range of defect/corrosion evaluation
- Relative measurement! noncontact – 2-5mm distance of coil plus proper positioning of magnet relative to coil
- Drawbacks of Piezoelectric transducer
- High mechanical pressure
- Couplants



Commercially Available Hardware

Innerspec OEM magnets, coils and sensor assemblies
Gas pipeline experience
PIG EMAT implementation

Olympus Sensor assemblies, Magnets, and Coils

What Will be Needed …

- Initial Testing of Technology
- Packaging into a Compact Unit
- Integration into Existing or Custom Robotic Arms

UAVs

Indoor or Confined Space Positioning

UAVs are capable of flying autonomously in the open air because of the GPS system set up by the satellites. When a UAV goes into a confined space such as culverts, the GPS and radio control signals are often both blocked, making the drone unable to navigate and unaware of exactly where it is positioned. Culverts pose unique challenges in a sense. In a way, autonomous flight through a culvert is simple (compared to flying inside a large multi-story warehouse building), as most culverts are straight and only mildly sloped. At the same time, a lack of features inside (looks about the same from entry to exit points) makes it difficult to tell exactly where the system is located. For those culverts consisting of many sections joined together, the number of joints that were passed can be visually recognized to get an idea about where the drone is roughly during its flight.

Currently, research efforts are on-going on a few different fronts. Below are two examples of some approaches that are being tested currently by drone manufacturers and research labs to set up indoor (or confined space) positioning. An indoor positioning system is a system to locate objects inside a building using radio waves, magnetic fields, acoustic signals, or other sensory information collected by mobile devices. There are several commercial systems on the market, but there is no standard for an IPS system.

Distance Measurement by Laser or Ultrasound: The location of a UAS flying through a long pipeline structure can be gauged by the laser or ultrasound distance measuring technology. Two UASs are employed in the field, with one of them stationed at the culvert end and the second one navigating inside the culvert. The stationary unit can transmit a laser beam and ultrasound wave, which can be reflected on the second unit, thus providing the position through distance measurement.

Visible light communication (VLC) is a data communications variant which uses visible light between 400 and 800 THz (780–375 nm). VLC is a subset of optical wireless communications technologies.

Appendix L. Cost Analysis

The report 'Enhanced Culvert Inspections – Best Practices Guidebook' by the Minnesota Department of Transportation (2017) contains some cost analyses on culvert inspection systems ranging from HIVE to CCTV to multi-sensor platforms. Their analyses were based on year 2016 costs. Below are some information extracted from the report:

- HIVE Camera Inspection: HIVE (a waterproof RC-controlled, 4-wheel-drive vehicle, equipped with a video camera) costs $1,500 to $2,000 per vehicle. The cost of a HIVE is paid off when 750 feet of culvert is inspected by contracted CCTV system. Assuming an inspection speed of 30 ft/minute (fpm), travel/site setup/takedown of 45 minutes per site, a typical culvert length of 200 feet, and MnDOT labor cost of $53/hour, it costs $0.23 per foot to conduct a HIVE camera inspection (labor cost only).

- CCTV Camera Inspection: Typical contractor charge for a CCTV camera inspection varies between $1 and $3 per foot. The cost of purchasing a new CCTV camera inspection system, including a mobile truck, is $120,000. Assuming an inspection speed of 30 fpm, travel/site setup/takedown of 45 minutes per site, a typical culvert length of 200 feet, and MnDOT labor cost of $53/hour, it costs $0.23 per foot to conduct a CCTV camera inspection (labor cost only). If two workers are employed, the labor cost will double to $0.46 per foot.

- Laser Ring Crawler Inspection: The above labor cost analysis may also apply to crawlers equipped with laser ring profiler, since most can travel 30 fpm. This is under the assumption that the crawler system has been already purchased.

- Advanced Multi-Sensor Platform Inspection: The cost of using a multi-sensor platform to perform detailed measurements such as laser scan, sonar scan is from $6.50 to $10.00 per foot plus $8,500 mobilization. A new multi-sensor inspection unit may be purchased at $140,000 to $230,000. Inspection speed of 4 to 5 fpm (or 250 to 300 ft per hour) may be achieved.

A recent ASCE Magazine article (Wells, J. et al. 2017) described a trial study that the Minnesota Department of Transportation conducted jointly with Collins Engineers, Inc. The purpose of the study was to evaluate how effective bridge structures can be inspected using UASs. It was demonstrated in the study that the UASs are very effective in inspecting especially larger bridges, capturing images of hard-to-reach areas and detecting defects. The article provided the following statement with regards to the cost savings aspect:

- The traditional inspection work on any large bridge can cost at least $59,000 (three snoopers over 7-8 days), not including equipment mobilization and travel expenses. In contrast, the UAS inspection can require roughly $20,000 and 5 days. Thus, the UAS inspection can lead to almost a 70% cost saving.

Cost Analysis for ODOT Astabula County Garage

According to the data obtained from the garage, their costs (labor + equipment) for culvert cleaning & camera inspection work prior to the 2015 summer were …

$10,947 for cleaning 17 structures …. average $644 per structure
$27,372 for cleaning 79 structures …. average $346 per structure
$7,298 for cleaning 187 structures …. average $39 per structure
$3,391 for cleaning 210 structures …. average $16 per structure
$29,406 for cleaning 71 structures …. average $414 per structure
[Note] Average cost = $139 per structure.

$4,167 for inspecting 11 structures …. average $379 per structure
$9,704 for inspecting 39 structures …. average $249 per structure
$13,634 for inspecting 43 structures … average $317 per structure
$6,940 for inspecting 14 structures … average $496 per structure
$9,131 for inspecting 25 structures … average $365 per structure
[Note] Average cost = $330 per structure.

The costs for the inspection work were more consistent than those associated with cleaning. Their costs for inspection from within the last two years are listed below …

$ 2,877 for 85 structures (8/9/15 to 12/13/15) …. average $34 per structure
$ 1,551 for 106 structures (2/23/16 to 9/19/16) … average $15 per structure
$ 316 for 16 structures (2/21/17 to 3/4/17) …….. average $20 per structure

The costs reported above are a lot less, since these inspection works involved no push camera/crawler equipment.

ODOT is going to position a UAS flight team and a CUES mobile CCTV pipe inspection unit in District 4.

In order to have a drone flyover, the UAS flight team (pilot & his assistant) will be first contacted with a request to do so by a garage or a district office. It is assumed here that a request will involve at least 3-4 sites that are located within the same geographical area. Then, the flight team will visit the sites to confirm their locations, assess the existing environment surrounding each site, identify the most suitable launch area, identify the drone system, and begin preparing a detailed plan for each culvert.

- Drone Flyover: Assuming a driving time of 60 minutes each way (to get to the area where the sites are located), initial reconnaissance time of 60 minutes per site, total flight time of 10-15 minutes per site, travel/site setup/takedown of 30 minutes per site, an average of 4 sites per day, and ODOT labor cost of $25/hr, it will cost about $70 per culvert to do a drone flyover inspection (labor cost only).

Small diameter (6” to 15”) culverts can be inspected by the Ashtabula County garage worker alone. There are two different approaches. In the first approach, the garage workforce uses its own push camera system in the field. In the second approach, the garage takes advantage of the district’s CUES CCTV inspection van and equipment (which includes the crawler Steerable Pipe Ranger).

- Small Culvert Inspection by Push Camera (Approach 1): A special attachment (cost $400) is needed to improve the advancement of the cameral head. Assuming travel/site setup/takedown of 50 minutes per site, an average camera speed of 30 ft/minute, typical culvert length of 100 ft, and ODOT labor cost of $25/hr, it will cost $22 per culvert (or $0.22 per foot) to do a push camera inspection. This is consistent with the unit cost mentioned in the MnDOT report.

- Small Culvert Inspection by Push Camera (Approach 2): Assuming travel/site setup/takedown of 50 minutes per site, an average camera speed of 30 ft/minute, typical culvert length of 100 ft, and ODOT labor cost of $25/hr, it will cost $22 per culvert (or $0.22 per foot) to do a push camera inspection. This estimate does not include the time needed to get and return the CUES mobile van from/to the district.

Medium size (16” to 48”) culverts require a self-propelled modular pipe crawler with a camera. For this size range, candidate crawlers are DT 340 (Deep Trekker), VT 150 (Inuktun), MudMaster (CUES), Steerable Storm Crawler (Cobra Technologies), and RMIS crawler (Ryonic Robotics). There are three possible scenarios. In the first scenario, the garage workforce purchases one of these crawler systems and employs it in the field. In the second scenario, the garage takes advantage of the district’s CUES CCTV inspection van and equipment (which include the Steerable Pipe Ranger).

- Medium-Size Culvert Inspection by Crawler (Scenario 1): This option will require an initial investment of $200,000 or more for the garage to purchase its own large crawler inspection system. Assuming travel/site setup/takedown of 90 minutes per site, an average camera speed of 30 ft/minute, typical culvert length of 100 ft, and ODOT labor cost of $25/hr, it will cost $39 per culvert (or about $0.40 per foot) to do this crawler inspection.

The time and cost may increase if two workers are needed to carry out the mid-size culvert inspection work. In addition, extra time and effort may be needed if a traffic lane has to be closed for a couple of hours for parking the vehicle close to the culvert inlet end.

- Medium-Size Culvert Inspection by Crawler (Scenario 2): This option will not require the initial purchase of a $200,000+ crawler. The estimated time and cost figures should be very similar to those listed above under scenario 1. The estimate does not include the time needed to get and return the CUES mobile van from/to the district.

  The time and cost may increase if two workers are needed to carry out the mid-size culvert inspection work. In addition, extra time and effort may be needed if a traffic lane has to be closed for a couple of hours for parking the vehicle close to the culvert inlet end.

Larger size (48” to 120”) culverts require a large self-propelled modular pipe crawler with a camera. For this size range, candidate crawlers are MudMaster (CUES) and Steerable Storm Crawler (Cobra Technologies). There are three possible scenarios. In the first scenario, the garage workforce purchases one of these crawlers and uses it in the field. In the second scenario, the garage takes advantage of the CUES CCTV inspection equipment (which includes the MudMaster). In the third scenario, the garage relies on the outside contractor (ex. Responder by Redzone Robotics) to get the inspection work done.

- Larger-Size Culvert Inspection by Crawler (Scenario 1): This option will require an initial investment of $250,000 or more for the garage to purchase its own large crawler inspection system. Assuming travel/site setup/takedown of 120 minutes per site, an average camera speed of 30 ft/minute, typical culvert length of 100 ft, and ODOT labor cost of $25/hr, it will cost $51 per culvert (or approx. $0.5 per ft) to do this crawler inspection.

  The time and cost may increase if two workers are needed to carry out the mid-size culvert inspection work. In addition, extra time and effort may be needed if a traffic lane has to be closed for a couple of hours for parking the vehicle close to the culvert inlet end.

- Larger-Size Culvert Inspection by Crawler (Scenario 2): This option will not require the initial purchase of a $250,000+ crawler. Other than this, the estimated time and cost figures should be very similar to those listed above under scenario 1. This estimate does not include the time needed to get and return the CUES mobile van from/to the district.
  The time and cost may increase if two workers are needed to carry out the mid-size culvert inspection work. In addition, extra time and effort may be needed if a traffic lane has to be closed for a couple of hours for parking the vehicle close to the culvert inlet end.

The time and cost may increase if two workers are needed to carry out the mid-size culvert inspection work. In addition, extra time and effort may be needed if a traffic lane has to be closed for a couple of hours for parking the vehicle close to the culvert inlet end.

- Larger-Size Culvert Inspection by Crawler (Scenario 3): In this option, the inspection work is contracted out to a company that has a large multi-sensor platform equipment such as Responder (Redzone Robotics). This will likely result in paying $6.50 to $10.00 per foot plus $8,500 mobilization

Below is a summary of the cost analysis performed in this section.

Inspection Type	System	Initial Investment	Notes
Small Culverts (6"-15")	Push Camera w/ an Attachment	$400 (already in possession)	May cost $0.22 per foot; Need to purchase a $400 special attachment for the camera
	Steerable Pipe Ranger (CUES)	$0 (already available)	May cost $0.22 per foot
	SOLO (Redzone Robotics)	$90,000	May cost $0.22 per foot; Need to spend up to $100,000 to own the crawler system
	DT 340 (Deep Trekker)	$22,000	
Med. Size Culverts (16"-36 or 48"")	Steerable Pipe Ranger (CUES)	$0 (already available)	May cost $0.40 per foot; Need to spend up to $100,000 to own the crawler system
	DT 340 (Deep Trekker)	$22,000	
	VT 150 (Inuktun)	$90,000+	
	RMIS Crawler (Ryonic Robotics)	$95,000	Note: RMIS crawler can handle up to 70" size pipes.
Large Culverts (48"-120")	MudMaster (QUES)	$150,000	May cost at least $0.5 per foot
	Steerable Storm Crawler (Cobra Technologies)	$165,000	May cost at least $0.5 per foot; Need to spend up to $200,000 to own the crawler system
	Responder (Redzone Robotics)	Contractor (no purchase)	$6.50 to $10.00 per foot plus $8,500 mobilization
Drone Flyover	ELIOS (Flyability)	$2,500	May cost $70 per culvert inspection.
	Splash Drone 3 (Swellpro)	$1,400	
	Tethered Drone (CyPhy Works)	$25,000	

The garage used to spend about $3.30 per foot for camera inspection. The above results show that owning or having access to good crawler systems can lead to tremendous cost savings.

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