Promising Remote Inspection Systems for Highway Culverts

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Background

• ODOT manages 80,000+ culverts statewide.
• Culverts must be inspected regularly to assess their physical and functioning conditions.
• Many of these culverts do not permit traditional man-entry inspection due to their sizes and/or obstructed service conditions (by water, sediment).
### Various Culvert Conditions

<table>
<thead>
<tr>
<th>Culvert Span (in)</th>
<th>Culvert Interior Conditions</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water Level</td>
<td>Sediment Level</td>
</tr>
<tr>
<td>Small (12 to 48)</td>
<td>Dry to low</td>
<td>None to very shallow</td>
</tr>
<tr>
<td></td>
<td>Up to springline or higher</td>
<td>None to shallow</td>
</tr>
<tr>
<td></td>
<td>Dry to low</td>
<td>Up to haunch or springline</td>
</tr>
<tr>
<td>Large (60 to 120)</td>
<td>Dry to low</td>
<td>None to very shallow</td>
</tr>
<tr>
<td></td>
<td>Up to springline or higher</td>
<td>None to shallow</td>
</tr>
<tr>
<td></td>
<td>Dry to low</td>
<td>Up to haunch or springline</td>
</tr>
</tbody>
</table>
• **ODOT CMS Item 611.12 (2016)**

• Performance inspection is required for all culverts that are at least 20’ long and having slopes less than 25%.

• Initial post-installation inspection is required in 30 to 90 days.

• Culverts with rise dimensions ranging from 12” to 36” must be inspected by remote inspection techniques.

• Culverts with rise dimensions between 36” and 48” must be inspected either by the traditional man-entry (direct) method or by the remote inspection (indirect) method.

• Culverts larger than 48” should be inspected by the man-entry method.
## ODOT Procedure

- **ODOT Culvert Management Manual (2016)**
- **Culvert Inspection Types**

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

- Inspection Frequency

<table>
<thead>
<tr>
<th>Category</th>
<th>Inspection Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>12” to 48” in Span</td>
<td>Prior to routine roadway maintenance activities (ex. resurfacing) or every 10 years, whichever is less</td>
</tr>
<tr>
<td>48” to 120” in Span</td>
<td>Every 5 years</td>
</tr>
<tr>
<td>General Rating Score &lt; 4</td>
<td>Every year</td>
</tr>
<tr>
<td>New Installation</td>
<td>Within 30 days of project completion</td>
</tr>
<tr>
<td>Modified Structure</td>
<td>Within 120 days of modification</td>
</tr>
</tbody>
</table>
ODOT Procedure

- **ODOT CMS Item 611.12 (2016)**

- Remote inspection may be done by a crawler equipped with a camera. The culvert must be prepared for the remote inspection by lowering the water level and removing large debris.

- The crawler inspecting rigid RC culverts must be able to measure crack and joint opening sizes.

- The crawler inspecting flexible CM culverts must be able to measure inside diameters (by a profile-meter) in addition to the crack and joint opening sizes.

- A video recording must be produced for the entire culvert length during any remote inspection work.
• **ODOT CMS Item 611.12 (2016)**

• After the field inspection work, a report must be issued to provide all vital information about the culvert and its conditions.

• Profile-meter data collected by a crawler must be converted to 3D graphical plots for the entire culvert.
• **ODOT Supplemental Specification Item 902**

• 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.
### ODOT Procedure

#### Common Distress/Deterioration Modes in Ohio

<table>
<thead>
<tr>
<th>Culvert Material Type</th>
<th>Common Defects Seen in Ohio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reinforced Concrete (RC)</strong></td>
<td>Material: Pitting, Spalling, Cracking, Slabbing, Chloride attack</td>
</tr>
<tr>
<td></td>
<td>Joints: Cracking, Opening, Offset, Backfill/water infiltration</td>
</tr>
<tr>
<td></td>
<td>Others: Exposed rebar, Settling, Dropped ends, Voids in bedding/backfill</td>
</tr>
<tr>
<td><strong>Corrugated Metal</strong></td>
<td>Shape: Flattening (ovaling), Peaking, Racking</td>
</tr>
<tr>
<td></td>
<td>Material: Rust &amp; scale, Corrosion, Perforations, Cracking, Wall buckling</td>
</tr>
<tr>
<td></td>
<td>Joints: Cracking, Opening, Offset, Backfill/water infiltration</td>
</tr>
<tr>
<td></td>
<td>Others: Sag in the middle, Water ponding; Voids in bedding/backfill</td>
</tr>
<tr>
<td><strong>Thermoplastic (PVC, HDPE)</strong></td>
<td>Shape: Flattening (ovaling), Peaking, Racking</td>
</tr>
<tr>
<td></td>
<td>Material: Cracking, Dimpling, Wall buckling</td>
</tr>
<tr>
<td></td>
<td>Joints: Cracking, Opening, Offset, Backfill/water infiltration</td>
</tr>
<tr>
<td></td>
<td>Others: Sag in the middle, Water ponding; Voids in bedding/backfill</td>
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</tbody>
</table>
• **ODOT Culvert Management**

• HIVE (a RC 4-wheel-drive vehicle w/ a video camera & lights)

• Low cost ($2,000)

• Speed 30 ft/min

• Inspection cost $0.25 per ft

• Poor control on lighting

• Poor pan-tilt control on camera

• Does not support a range of pipe sizes

• Tends to lose traction on wet sediment
A recent study for ODOT – “Evaluation of New or Emerging Remote Inspection Technologies for Conduits Ranging from 12 to 120 inches in Span”

The main objective of the study was to identify the best remote inspection systems for each culvert service condition.
Team Assembled

- Dr. Terry Masada (Civil Engineering, Ohio University) - PI
  - Specialized in soil-pipe interaction problems; Experienced in field inspection of metal, concrete, and plastic culverts; Familiar with deterioration/distress modes of culverts in Ohio; had some but limited experience with remote inspection of highway culverts.

- Dr. Maarten Uijt de Haag (EECS/Avionics, Ohio University)
  - Highly specialized in navigation systems and UAVs.

- Paul Riley (Sr. Electrical & Robotics Engineer, Vertek Division, Applied Research Associates, Randolph, VT); Co-PI
  - Has extensive background in sensor technology & remote-sensing system development.
  - Supported by a team of skilled researchers/engineers at ARA Inc.
Tasks

1 - Literature Review
   - ODOT current specifications & practice; Studies by other DOT’s; Systems/technologies developed or under development

2 - Culvert Site Visits
   - Meet w/ ODOT personnel and visit culvert sites to identify challenges & needs

3 - Classify Available Systems & Technologies

4 - Perform Preliminary Testing
   - Perform preliminary testing of select system(s)

5 – Develop Recommendations
• **Minnesota DOT (June 2017)**

• **Enhanced Culvert Inspections – Best Practices Guidebook**

• Evaluated capabilities of inspection technologies such as CCTV, laser ring profiling, sonar, and Joint Photographic Expert Group (JPEG) mosaic inspection.

• **Closed Circuit TV (CCTV):** 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.

• **Laser Ring Profiling:** Availability of the large laser scan unit (to work in 36”-118” dia. pipes) may be limited.
• **Minnesota DOT (June 2017)**

• **Sonar**: 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.
Literature Review

- **Minnesota DOT (July 2015)**
- Completed a study in which the use of UAVs was evaluated for bridge inspection work.

  - **Phase 1** – Review of FAA regulations, inspection of four bridges by drones, identifying advantages & disadvantages of using drones

  - **Phase 2** – Inspection of four additional bridges (including one large culvert-like structure) by drones

- Tested two commercial UAVs – Albris Drone (SenseFly, inc.) and SkyRanger Drone (Aeryon inc.).

- No GPS receiver was needed as the drone just flew along the straight culvert and Albris was equipped with ultrasonic detectors.
Literature Review

- Minnesota DOT (July 2015) – Drones Tested
• Minnesota DOT (July 2015) – Drones Tested
• **U.S. Forest Service (August 2016)**

• **Benefits, Costs, and Recommendations for Using Small Unmanned Aircraft in Forest Service Operations**

• **Report No. DOT-VNTSC-USDA-16-06 (2016)**

• Evaluated the use of UAVs in a range of Forest Service program activities (including bridge inspection).

• The UAVs can provide high-resolution images of the bridge structure from angles only possible from a UAV. However, it was often unable to capture images from interior sections of the bridge.

• The real time UAV camera can detect cracks up to 0.06.”
Literature Review

• U.S. Forest Service (August 2016)
• Florida DOT Study (2012)

• Rotary-wing UAVs work better than fixed-wing UAVs.
• 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 a average of 2.75 hours.
• Processing the UAV images into 3D models was a highly time-intensive process.
Literature Review

- **U.S. Forest Service (August 2016)**
- **Florida DOT Study (2012)**

The overall cost of purchasing a UAV (UAV platform, sensors, battery, ...) 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 is advancing, UAVs still pose a potential for collisions.
Literature Review

- **Michigan DOT (April 2015)**
- A recent study by Michigan Tech Research Institute
- **Evaluation of the Use of Unmanned Aerial Vehicles for Transportation Purposes (Report No. RC-1616)**
- Tested several 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 examine if UAVs can fly safely in confined spaces such as culverts.
Literature Review

- Michigan DOT (April 2015)
Literature Review

- Michigan DOT (April 2015)
Literature Review

- **Michigan DOT (April 2015)**

- The team tested the MTRI Blackout Mini H Quadcopter to fly through a 48” dia. CMP. It was able to do so without relying on the GPS compass sensors. It was noted that flying a small drone inside a culvert requires more experience/skills from the user.
Literature Review

- Unmanned Aerial Vehicles (UAVs) or Drones

- **FAA Definition**: a UAV is an aircraft operated without the possibility of direct human intervention from within the aircraft.

- UAVs can fly autonomously or are controlled remotely by a pilot stationed on the ground.

- UAVs can carry a wide range of imaging technologies (still-image camera, video camera, infrared sensor)
**Literature Review**

- **FAA Regulations on UAVs**
- Part 107, small unmanned aircraft regulations (2016)
- Three classifications for UAVs

<table>
<thead>
<tr>
<th>Class</th>
<th>Weight</th>
<th>Size</th>
<th>Altitude</th>
<th>Speed</th>
<th>Radius</th>
<th>Endurance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nano</td>
<td>&lt; 0.55 lb</td>
<td>&lt; 1’</td>
<td>&lt; 400’</td>
<td>&lt; 25 mph</td>
<td>&lt; 1 mile</td>
<td>&lt; 1 hr</td>
</tr>
<tr>
<td>Micro</td>
<td>0.55 to 4.5 lb</td>
<td>&lt; 3’</td>
<td>&lt; 3,000’</td>
<td>10 to 25 mph</td>
<td>1 to 5 miles</td>
<td>1 hr</td>
</tr>
<tr>
<td>Small</td>
<td>4.5 to 55 lb</td>
<td>&lt; 10’</td>
<td>&lt; 10,000’</td>
<td>50 to 75 mph</td>
<td>5 to 25 miles</td>
<td>1 to 4 hr</td>
</tr>
</tbody>
</table>

- Regulations now apply to all UAVs that are classified as “Micro” and “Small.”
- All drones weighing 0.55 – 55 lbs must be registered before any outdoor flights.
Literature Review

- **FAA Regulations on UASs**
  - UAS operator is required to pass the aeronautical test to become certified.
  - The drones must be registered.
  - The drones must not be flown within 5 miles of any airports.
  - The drone must fly within the visual line of sight (VLOS) of the operator. VLOS can be lost momentarily but must be regained quickly.
  - The drone must not fly after dark.
  - The drones must avoid flying over nonparticipants.
Literature Review

- **FAA Regulations on UASs**

- A public agency can obtain a certificate of waiver or authorization (COA) from the FAA for a drone flight that does not meet all of the requirements listed above.

- FAA has not issued many waivers.

- No permit may be needed to fly an UAV through a culvert.
Literature Review

- **Relevant Technology**
- **Camera/Video**
- **Light Weight:**
- **FPV:** First Person View
- **Resolution:** up to 30 megapixels
- **Frame Rate:** 24 frames per second (fps) enough for cinematic image recording, most can do 60 fps
- **View Angle:** human eyesight (40°), GoPro - Narrow (64°), Medium (94°), Wide (118°), Some have up to 120° view
Literature Review

• **Relevant Technology**

• **Camera/Video**

• **Specs:** 4K HD

• **Onboard Memory:** Micro SD card for 32, 64, or 128 GB storage for 4K video

• **Battery:** 45 to 120+ mins.

• **Other Features:** Built-in stabilizer, waterproof, Wi-fi, auto low-light mode, time-lapse or continuous shooting mode
Literature Review

• Relevant Technology - Thermal Camera

• Thermal imaging captures heat discrepancies, catching what the human eye cannot see. Videos and stills record calibrated temperature data.

• Regular thermal scans are an early intervention tool to monitor heat variations, reveal problems, and avoid mounting damage and costs.

• Valuable tool for exposed infrastructure such as bridge decks and pavements → May not be useful inside culverts
Literature Review

- Relevant Technology
- Laser Ring Profiler
- Continuous laser ring profile/camera system
- Can work inside 8” to 118” diameter pipes
- Requires a considerable amount of data processing
Literature Review

- **Relevant Technology - Laser Profile-meter**
- Rotating-head laser profiling system
- Requires a considerable amount of data processing
Literature Review

- **Relevant Technology**

- **Ultra Sound (or Sonar)**

- **Sonar = Sound Navigation & Ranging**

- Provide shape measurement underwater

- May need to adjust sensitivity to penetrate through murky water

- Some penetration into sediment at lower frequencies

- May not work well in highly turbid water (scattering) or fast current flow
Literature Review

- **Relevant Technology – Acoustic Detection Methods**

**ACOUSTIC EMISSION MONITORING:** When a crack grows in metal, the rupture releases tiny pulses of acoustic energy. Sensors detect these waves and can monitor a developing flaw.

**GUIDED WAVES:** To check for flaws in a pipe or other metal structure, ultrasonic waves are pulsed through the material. Any flaw reflects part of the wave back toward the sensor.

**PHASED ARRAY:** In this technique a group of transmitters release separate ultrasonic waves, which interact to form one larger wave front. By controlling the timing and amplitude of the individual pulses, researchers can steer the wave front to scan a structure for flaws.

**DIFFUSE FIELD:** To monitor a coarse-grained material like concrete, a single ultrasonic pulse is introduced into the material. Receivers listen for the tiny echoes produced by the wave’s interactions with all the grains. The composite signal creates a distinct signature for that material, which will change if the material degrades.
Literature Review

• **Relevant Technology – Ground Penetrating Radar (GPR)**

• Send radio waves having a range of frequencies across culvert wall; Waves reflect back at any contrast in material properties; Effective in detecting wall thickness, material deteriorations, and voids in backfill

• Requires a transmitter & a receiver. A good contact is a must → Not suitable for corrugated wall
Literature Review

• Relevant Technology

• LiDAR

• Light Detection And Ranging - measures the time it takes laser light (green or infrared) to bounce off the object and return to a sensor – at 300,000 light pulses per second and 250 elevations per square foot, resulting in high resolution, 3-D models.

• GPS data and stable stationary positioning are essential for accurate 3-D models.
Literature Review

- **Recent Development**
- **Underwater Laser Scanners**
  - 2G Robotics (Waterloo, Ontario)
  - [www.2grobotics.com](http://www.2grobotics.com)
  - ULS-100 Scanner (range 6”-39”)
  - ULS-200 Scanner (range 10”-98”)

"OTEC 2018"
Literature Review

- Recent Development
- Underwater Laser Scanners
- Supposed to be more high-resolution and accurate than sonar
Literature Review

- **Recent Development**
- **Microwave Radar**

- A sense-and-avoid radar system, small & light-weight enough to be integrated into consumer drones.

- Scans 360° with no blind spots, detecting and locating objects quickly (90 Hz) and reliably. Works day and night in any weather condition.

- The drone can then correct its flight course in time to prevent collisions → Requires fast data processing & positioning.
Literature Review

- **Recent Development**
- **3D Cameras**
- Use 2 lenses or 1 lens with shifted position to add depths to the images
Literature Review

• **Recent Development**

• **3D Cameras**

• Testing of a drone equipped with a 3D camera, inside the underground tunnel at OU
## Inspection System/Tool Options

<table>
<thead>
<tr>
<th>Option</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Zoom Cameras or Snake Cameras</td>
</tr>
<tr>
<td>2</td>
<td>Crawlers</td>
</tr>
<tr>
<td>3</td>
<td>Aerial Drones or UAVs</td>
</tr>
<tr>
<td>4</td>
<td>Underwater Drones</td>
</tr>
<tr>
<td>5</td>
<td>Rafts</td>
</tr>
<tr>
<td>6</td>
<td>Submarines</td>
</tr>
<tr>
<td>7</td>
<td>Hybrids (any combination of above)</td>
</tr>
<tr>
<td>8</td>
<td>Others (something totally different – ex. LiDAR surveying system)</td>
</tr>
</tbody>
</table>
Inspection System/Tool Options

- **Zoom Cameras**

- Great for inspecting small diameter pipes (6” to 24” typ.), through a manhole/ catch basin opening

- Typically mounted on a pole and maybe supported on a tripod

- Zoom camera capable of seeing 20-40 ft in small dia. pipes and up to 400 ft in larger dia. (36”-48”) pipes. Distance more limited inside pipes made of reflected materials (ex. PVC).
• **Snake Cameras**

• Great for inspecting small diameter pipes (6” to 18” typ.), accessing drainage structures with a limited entrance opening

• Typically provides only visual data

• Camera may hang up at joints (due to gaps, offsets)

• Special tip attachments are available to overcome the problem
Inspection System/Tool Options

- **Crawlers**

  - Great for inspecting pipes that are medium in size (24” to 120”), relatively free of sediment/debris, and free of water.
  
  - Most are wheel-powered and come with a fairly long endurance time (ex. 1 to 2 hours); Speed 30 to 50 fpm
  
  - Most come with LED lights and a camera
  
  - Some are waterproof.
  
  - Some vehicles accept a laser ring profiler or a laser profile-meter
  
  - Some are remote-controlled. Need to be tethered for manual recovery in case it gets stuck
Inspection System/Tool Options

- Crawlers
Inspection System/Tool Options

- Crawlers

- Some are provided as a flexible kit so that the crawler can be reconfigured to fit varied pipe sizes, with different size wheels and a lift arm.
Inspection System/Tool Options

- **Crawlers**
- Tracked version as an all-terrain vehicle, More expensive
- Can climb over debris and have more traction (less chance of getting stuck on wet sediment); Heavy, Speed 20-30 fpm
- Not suitable for inspecting small size (< 30”) pipes
- Most are tethered. Some allow flexible customization
Inspection System/Tool Options

- Crawlers
- Advanced multi-sensor vehicles available for sale or rental
- Time-consuming data processing

Camera
Laser
Sonar
Temp. sensor
GPR
Robotic arm
Inspection System/Tool Options

- Crawlers
- Another variation (robotic)
- Stay elevated above pipe bottom
- Can expand/contract to fit a range of pipe size (18” to 70”)
- Speed 20 to 30 fpm
- Flexible for adapting a few different devices/sensors
Inspection System/Tool Options

- Aerial Drones or UAVs
- Most come with only a camera
- A long range; Flight endurance (15 to 50 minutes; 20-30 minutes ave.)
- Potentially useful for inspecting pipes that are relatively large (> 60”), not too long (< 100’), and largely free of water and sediment
- Pipe entrance area should be accessible and visible (located within 400’) from the launch area
- Some come with basic collision avoidance system
- A few water-proof systems out in the market
Literature Review

• UAVs or Aerial Drones
Literature Review

• UAVs or Aerial Drones
Literature Review

- UAVs or Aerial Drones
- A military-grade nano drone ‘Black Hornet’
- Roter span 5”, Speed 16 fps max., 15 min. endurance
- GPS navigation or visual navigation through video
- Live video & snapshot feed
Literature Review

- UAVs or Aerial Drones
- A home security drone
- Soft fabric cylinder body (14”H, 12” Dia., 3-lb W)
- 3-D 4k camera w/ night vision & 4 sonar sensors
Literature Review

- UAVs or Aerial Drones
- Passive collision-prevention cage
Literature Review

- UAVs or Aerial Drones
- Air-Water Surface-Under Water Drone
- Loon Copter (developed by Oakland University)

https://youtu.be/K_wiVdY5BWU
Literature Review

- Recent Developments
- Submarine Drone (or Underwater Air Drone)

https://youtu.be/l4sT-RpazRw
Literature Review

• **Recent Developments**

• Extreme Access Pocket Flyer

• A compact UAV (7” dia.), equipped w/ 360° view camera, developed for US Airforce by CyPhy Works

• Power can be supplied via a chord, for a long endurance
Underwater Drones

Great for inspecting pipes (> 12” dia.) full of water

Most have a battery inside to underwater navigation and are tethered (up to 500’)

Most equipped with just lights and a video camera for visual inspection

Works best if water is clear and flow velocity is not too fast
Literature Review
Literature Review
Inspection System/Tool Options

• **Rafts**

• Great for inspecting pipes that have at least of 12” of water

• Some are just a floating video camera system. Others have multi-sensors (camera, laser profiler, sonar) to provide more comprehensive data

• Water must be flowing steadily to carry the raft downstream

• Sonar may not work well if water turbidity is relatively high

• Sonar cannot provide the pipe shape if sediment is present
Literature Review
Inspection System/Tool Options

- **Submarines**
- Great for inspecting pipes that are submerged in water
- More expensive than rafts and underwater drones
- Most equipped with at least a camera, lights & a sonar
- Unlike the rafts, these may come with self-propelling capability
- Limitations of rafts also apply
Literature Review
Inspection System/Tool Options

- Hybrids
- Any combination of the remote inspection systems just mentioned.
- Presently the available models are limited and of low quality (toy like quality)
Literature Review

- Hybrids
- Hex Drone/Multi-Leg-Robot Hybrid (Mad-Lab Industries)

https://youtu.be/0sOvP9PhDQU
• Others

• Systems/tools that do not belong to any of the categories mentioned.
Literature Review

- **Others**
- **Robot w/ Walking Legs; Currently not water-proof**
  - https://www.youtube.com/watch?v=37Q6X5ZJw-E
- **Legs may get stuck in soft sediment**
Inspection System/Tool Options

- **Others**
- **3-D Laser Survey Scanning ➔ AutoCAD Civil 3D Model**
- Quick mobilization & deployment
- No light issues; Accuracy 2-3 mm & Long range
Inspection System/Tool Options

• **Initial Drone Testing @ OU**

• MTRI Blackout Mini H Quadcopter (a small UAV assembly kit; dimensions 11” x 13” x 3”)
  
  • Cost = less than $500
  
  • Weight = 1.5 lbs
  
  • Flight endurance = 15 mins max.
  
  • Equipped with a flight controller, a GPS module, radar scanners (x 2), LED lights, and a camera

• FatShark – Allows FPV

• Note – Drone not waterproof
Inspection System/Tool Options

- Initial Drone Testing @ OU
- Flight through a 60” dia. pipe
Inspection System/Tool Options

• **Initial Drone Testing @ OU**

  • The drone created some ground effect (uplifting air pressure coming from the pipe 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.

  • Whenever the drone’s position shifted off center, 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 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.
Inspection System/Tool Options

- Initial Drone Testing @ OU
### Remote Inspection Systems for Varied Culvert Conditions

<table>
<thead>
<tr>
<th>Culvert Size (in)</th>
<th>Culvert Interior Conditions</th>
<th>Remote Inspection Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water Level</td>
<td>Sediment Level</td>
</tr>
<tr>
<td>Small (12 to 48)</td>
<td>None to low</td>
<td>None to very shallow</td>
</tr>
<tr>
<td></td>
<td>Up to springlines or higher</td>
<td>None to very shallow</td>
</tr>
<tr>
<td></td>
<td>None to low</td>
<td>Up to haunch or springline</td>
</tr>
<tr>
<td>Large (60 to 120)</td>
<td>None to low</td>
<td>None to very shallow</td>
</tr>
<tr>
<td></td>
<td>Up to springlines or higher</td>
<td>None to very shallow</td>
</tr>
<tr>
<td></td>
<td>None to low</td>
<td>Up to haunch or springline</td>
</tr>
</tbody>
</table>
• **Crawlers vs. Drones**

  **Crawlers**: Less agile, slower speed, a longer battery life, can employ multiple sensors, can be modified easily, higher costs, can be fully water-resistant, less training before initial trial, no regulatory issues, easier to recover a crawler

  **Drones**: More agile, faster speed, much shorter battery life, limited pay load (cannot support multi-sensors), lower costs, may not be fully water-resistant, more training before initial trial, regulatory issues, difficult to recover a downed drone
Questions

• Commercial vs. Custom-Built

• Commercial Systems: Readily available, Price fixed, Already tested, Specifications, performance & limitations known, Software already developed, Not unique, May be difficult to enhance/modify

• Custom Systems: Not readily available, Price may be unknown initially, Not tested in the field, Software must be developed, Can be designed & built to any specifications, Unique, Can be enhanced/modified more easily
Questions

- **Rigid vs. Flexible**

- **Rigid Systems**: Already assembled, Ready to be used for specific field conditions, Cannot be modified, Cannot be employed for a variety of different field conditions

- **Flexible Systems**: Needs to be assembled, Can be modified to adjust to varied conditions in the field, Can incorporate different devices & sensors
Questions

• **Single-Sensor vs. Multi-Sensor**

  • **Single-Sensor Systems**: Simple, Light-weight, Less expensive; Less data processing time; Data limited to only one type (usually vision), Provide no additional measurements

  • **Multi-Sensor Systems**: More complicated, Bulky/heavy, More expensive; Much more data processing time, Provide additional measurements
Recommendations

• **Essential Features of Culvert-Inspection Aerial Drones**

  • Auto Vertical Launch to Hover & Auto Gentle Vertical Landing
  • Relatively Long Battery Life (min. 30 mins)
  • LED Lights
  • 120°-angle 4K HD Camera with Zoom
  • Memory Card
  • Live Video Feed
  • Water-Proof & Floatation
  • Laser Measurement System
  • Collision Avoidance
Recommendations

- **Risk Assessment of Aerial Drones**

  - Risks for crashing exist whenever a drone is flown
  - No detailed historical data on drone crashes by FAA; FAA does not allow drone flying over non-participating people
  - Difficult to recover a downed drone. Crawlers are not failure-proof
  - Visual Line of Sight (VLOS) can be lost momentarily but must be regained quickly
  - FAA sponsored a UAS Ground Collision Severity study (2016). UAS types consisting of one continuous body are safer to humans, compared to those with modular construction (having multi-parts). Lower chances to penetration & laceration injuries to head and arms
  - New collision –tolerant type is effective in preventing injuries.
Recommendations

- **Essential Features of Culvert-Inspection Crawlers**
- Locomotion – Large Wheels or Multi-Tracks
- Tether (thin, light-weight, strong, 5’ interval markings)
- Modular Kit to Vary Rover Size from Very small to relatively big
- Long Battery Life (min. 60 mins.)
- LED Lights
- Water-Proof Construction
- 360°-rotation 4K Camera with Zoom
- (Laser Profile-meter and Sonar) or Laser Scanner
Recommendations

• **Essential Features of Culvert-Inspection Rafts**

• Tether (strong, thin, distance marked)

• Modular Kit to Vary Rover Size from Very small to ...

• Long Battery Life (min. 60 mins)

• LED Lights

• Water-Proof construction

• 360°-rotating 4K Camera with Zoom

• Laser Profile-meter and Sonar or Laser Scanner
Recommendations

• **Essential Features of Culvert-Inspection Underwater Drones**

• Tether (strong, thin, distance marked, resist entanglement)

• Long battery life (min. 60 mins.)

• LED Lights

• Water-proof construction

• 120°-angle 4K Camera with Zoom
Recommendation

- **Ideas for Future Development**
  - Develop a crawler that can perform guided wave acoustic test.
  - Develop a drone that can carry a crawler and insert it into a culvert.
  - Develop a crawler that can also fly.
  - Develop a drone that has autonomous flight capability inside culverts.
  - Develop a crawler that can turn into a raft. Such a system is needed for inspecting culverts that have a shallow water at inlet but are half full of water at outlet.
• PureRobotics (a robotic pipe inspection crawler)
  https://www.youtube.com/watch?v=p_g4phx5CbA
• Flyability ELIOS (a collision-tolerant industrial inspection drone)
  https://www.youtube.com/watch?v=4aBVETEfY6w
• In the not-so-distant future, I envision that we will have an totally autonomous inspection system which can crawl, fly, float, and/or submerge. And, it will be carrying a host of sensors/devices that are useful for culvert inspection work.
In the not-so-distant future, we may also have either smart pipes (which can provide us structural health information remotely via sensors and thus can eliminate our needs for traditional inspection work entirely) or small humanoid robots (which can simulate man-entry inspections).
Thank You 😊

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