# Deliverable 7-B: Performance Evaluation of Recommended Remote Sensing Systems in Unpaved Road Type Condition Characterization

## Michigan Technological University

## Characterization of Unpaved Road Condition Through the Use of Remote Sensing Project

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**Table of Contents**

**List of Tables and Figures**

## Section I: Introduction and Executive Summary

The ultimate goals of this program were to design, build, and test a prototype remote sensing-based unpaved road condition assessment system that can compete with manual methods, and to incorporate these measurements into a decision support system (DSS) to aid in managing unpaved road networks. A number of requirements were established for the performance of this system; previously established requirements are reviewed and the performance our assessment system are reported in this document. The criteria for such a system consists of a flight-worthy sensor for collecting data, a software suite to process these data to extract road distresses, and RoadSoft® GIS, a tool for road asset management decision support and data visualization. As described in our reports, Deliverables 1-A to 7-A, we have designed, built, and deployed such an integrated system, now named our Unsurfaced Road Condition Assessment System (URCAS). This report evaluates the performance of URCAS against the requirements established at the beginning of the project. Previous reports are available on our project website at www.mtri.org/unpaved under "Tasks and Deliverables."

This deliverable report, the most detailed of all our project reports so far, provides a summary of the measurement and sensor requirements originally described in the project's first report, Deliverable 1-A. Of the several requirements, the need to detect a 1" (2.5cm) elevation change in a 9' (2.7m) distance from road center to edge to measure cross section, so that presence of sufficient crown can be assessed, ended up being one of the most critical in defining needed resolution in the 3D data we were capable of producing. As we developed our system, the need to measure road features to a 1"/2.5 cm resolution was a requirement we were always keeping in mind.

To start the main Performance Review section, we thoroughly review each of the eight main unpaved road sites assessed in 2012 to 2013 (one site was repeated from the first assessment summer to the second). These were all rural, unpaved roads located in southeastern Michigan with a wide variety of representative road distresses that could be readily accessed by a field crew using the UAV and, when it could be arranged, by a manned fixed-wing aircraft operating from the Ann Arbor, MI airport. In addition, we collected data at two sites in Iowa and one in Nebraska in 2013 when a coincident data collection opportunity presented itself. This opportunity enabled us to demonstrate that our Unsurfaced Road Condition Assessment System could characterize results for other states' roads as well. For all these sites, we have been able to analyze data for 45 total road segments.

The Performance Review section then continues to describe the sensor system performance. The UAV-based system more than met the requirements to collect the type of overlapping imagery data needed to collect 1% crown measurement variations using readily available commercial hardware costing $9,000. However, even flying at the lowest safe elevation (about 500' or 150m), using the same single camera from the UAV-based system in a manned fixed wing aircraft could not meet resolution requirements due a lack of needed angular diversity. Without sufficient angular diversity, creating the needed 1" / 2.5cm resolution data is not possible with a 36 mp camera flying above 400' (120m). In the future, as technologies advance, a manned fixed-wing aircraft-based data collection system could eventually match the current capabilities of our UAV-based system.

The software suite used to extract road distresses from the measured data consists of a series of open-source packages focused on Structure from Motion (SfM) techniques, tied together with custom-written scripts. These were described in Deliverables 6-A and 6-C, but additional development would be needed to have a ready-to-install, simpler-to-operate commercial software suite. The Performance Review section continues with describing the performance of the URCAS analysis algorithms. The typical performance of the overall system in correctly estimating distresses is measured in two ways, by individual distresses, and by comparing Unpaved Road Condition Indices (URCIs). Overall, the analysis algorithms detected 93% of distresses measured manually, with the best performance for potholes. The overall false-alarm rate (detecting a distress when none was present) was 14%, reasonable in our opinion for maximizing detection of actual distresses. 95% of potholes were detected with a false alarm rate of only 4%. When compared to manual measurements, the requirement to measure crown with 2.5 cm (1") accuracy was met. Rut detection was more challenging with a 67% of probability of detection. Short ruts, essentially elongated potholes, were missed most often. While 100% of corrugations were detected, there was a relatively high level of false alarm, with the corrugation algorithm often identifying areas with significant 3D data reconstruction noise as corrugation. Tuning of this algorithm is continuing.

This report's final main section is a cost comparative analysis. There are a number of possible data-collection systems that can be fielded to perform necessary measurement functions; however the preferred system we tested is a heavy-lift multi-rotor UAV (we used a Bergen Hexacopter as our second-year platform), a high-resolution camera (Nikon D800 or equivalent), and good-quality lens (Nikkor 50mm f/1.4). This system, when operated 8 hours per day, 3 days per week, for a 21-week season to collect 300 road-miles of data segments, will cost $0.74/mile to operate to meet a representative set of unpaved road assessment needs (see the Comparative Cost Analysis section). This assumes a 3-year amortization of the initial hardware (aircraft and sensor). This preferred data-collection system satisfies all outlined performance requirements.

This preferred system was not suitable for manned, fixed-wing, collections without modifications that were beyond the scope of this effort, particularly affordability. However, it is possible that a system, built with current technology, could be fielded, with significantly more complicated processing required. Such a system, used to collect a similar amount of road data as described above, includes the following estimates: the plane costs $160/hr to fly, a one hour flight can cover up to 5 miles of roads needing assessment (because there are target areas for collection; not every mile of road in a flight path needs assessment), 300 road-miles need to be assessed over a season, and there is a 21-week data collection season. As described in the Comparative Cost Analysis section, this will cost $16,340 per season. For a system consisting of 3 cameras ($10k amortized over 3 years), this comes to $10.26/mile.

## Section II: Requirements Review

Deliverable Report 1-A (Brooks et al. 2011a) provided a thorough description of the requirements that would need to be met to develop a remote sensing system capable of collecting inventory and distress data for unpaved roads that would be useful to road managers, with the goal of developing a working prototype of a commercially viable unpaved road data collection and asset management system. The "Requirements for Remote Sensing Assessments of Unpaved Roads Conditions Report" has been available on the project website (www.mtri.org/unpaved) since early in this project and can be found directly at http://geodjango.mtri.org/unpaved/media/doc/deliverable_Del1-A_RequirementsDocument_MichiganTechUnpavedRoadsr1.pdf. In it, several critical indicators were defined for unpaved road condition assessment; these were the distresses that would be measured to indicate condition:

Critical leading indicator:

* Cross section (loss of crown)

Trailing indicators:

* Loose aggregate
* Corrugations
* Potholes
* Ruts

Desirable but optional:

* Road-side drainage
* Dust

The first table in Deliverable 1-A provided the most effective summary of measurement requirements, and is repeated here:

**Table 1: Summary of requirements for a successful unpaved road data collection and asset management system as described in Deliverable 1-A.**

| Number | Name | Type | Definition |
|---|---|---|---|
| 1 | Data Collection Rate | Sensor | The systems must collect data at a rate that is competitive with current practice (to be determined, TBD) |
| 2 | Data Output Rate | System | Processed outputs from the system will be available no later than 5 days after collection |
| 3 | Sensor Operation | Sensor | "Easy", little training required |
| 4 | Platform Operation | Platform | Training needed TBD, based on platform choice |
| 5 | Reporting Segment | System | <100ft x 70ft, with location precision of 10ft. Map position accuracy +/- 40ft |
| 6 | Sample locations | System | Specified by the user a map waypoints |
| 7 | Inventory | System | A classified inventory of road types is required prior to system operation. This will consist of 3 classes: Paved, Gravel, Unimproved Earth |
| 8 | Surface Width | System | This is part of the inventory, and may also be estimated by the system measured every 10ft, precision of +/- 4" |
| 9 | Cross Section | Distress | Estimate every 10ft, able to detect 1" elevation change in 9', from center to edge. |
| 10 | Potholes | Distress | Detect hole width >6", precision +/-4", hole depth >4", precision +/-2". Report in 4 classes: <1', 1'-2', 2'-3', >3' |
| 11 | Ruts | Distress | Detect >5" wide x 10' long, precision +/-2" |

| Number | Name | Type | Definition |
|---|---|---|---|
| 12 | Corrugations | Distress | Detect spacing perpendicular to direction of travel >8” - <40”, amplitude >1”. Report 3 classes: <1”, 1”-3”, >3”. Report total surface area of the reporting segment exhibiting these features |
| 13 | Roadside Drainage | Distress | Detect depth >6” from pavement bottom, precision +/-2”, every 10ft. Sense presence of standing water, elevation precision +/-2”, width precision +/-4” |
| 14 | Loose Aggregate | Distress | Detect berms in less-traveled part of lane, elevation precision +/-2”, width +/-4” |
| 15 | Dust | Distress | Optional – measure opacity and settling time of plume generated by pilot vehicle |
| 16 | Flight Altitude | Platform | ~400’ |
| 17 | Field-of- View | Sensor | 11 degrees |
| 18 | Resolution | Sensor | 0.5”, (4M pixels for this geometry) |
| 19 | Image Capture Speed | Sensor | 2.25 frames per second |

Deliverable 1-A also summarized as the sensor system as needing at least the following properties:

1. Flight altitude ~400ft (~122 m)
2. 11º FOV at that altitude -> 75mm lens
3. >4MP sensor
4. >2.25 fps imaging rate

The report also provided an initial description of the Unsurfaced Road Condition Index (URCI), (Department of the Army 1995; Eaton 1987) that was further detailed in Deliverable 2-A, the State of the Practice of Unpaved Road Condition Assessment (Brooks et al. 2011b; available at http://geodjango.mtri.org/unpaved/media/doc/deliverable_Del2-A_State_of_the_Practice_for_Unpaved_Roads_MichiganTech.pdf). Selection of the URCI was based on its ability to integrate information on unpaved road distresses into management and cost information needed by road managers. Distress information on improper cross section, corrugation (washboarding), potholes, ruts, and loose aggregate (berms) are scored based on the density and severity and compiled for a 0-100 score based on deduct values from a look-up table. Table 2 shows an example of the URCI data being tied to cost codes and management options (from Eaton, 1987; Eaton 1987a; Department of the Army, 1995) for a collection of information necessary to make the severity assessments that helped shape the project requirements.

**Table 2: Maintenance alternatives and corresponding distress categories, severity codes determined from UCRI, and cost codes adapted from the Unsurfaced Road Maintenance Management method.**

| Distress Number | Distress | Severity code | Cost code* | Description |
|---|---|---|---|---|
| 81 | Improper cross section | L | B | Grade only. |
| | | M | B/C | Grade only/grade and add material (water or both), and compact. Bank curve. Adjust transitions. |
| | | H | C | Cut to base, add aggregate, shape, water, and compact. |
| 82 | Improper roadside drainage | L | B | Clear ditches every 1-2 years. |
| | | M | A | Clean out culverts. |
| | | | B | Reshape, construct, compact or flare out ditch. |
| | | H | C | Install underdrain, larger culvert, ditch dam, rip rap, or geotextiles. |
| 83 | Corrugations | L | B | Grade only. |
| | | M | B/C | Grade only/grade and add material (water or aggregate or both), and compact. |
| | | H | C | Cut to base, add aggregate, shape, water, and compact. |
| 84 | Dust stabilization | L | C | Add water. |
| | | M | C | Add stabilizer. |
| | | H | C | Increase stabilizer use. Cut to base, add stabilizer, water, and compact. Cut to base, add aggregate and stabilizer, shape, water, and compact. |
| 85 | Potholes | L | B | Grade only. |
| | | M | B/C | Grade only/grade and add material (water, aggregate, or 50/50 mix of calcium chloride and crushed gravel), and compact. |
| | | H | C | Cut to base, add aggregate, shape, water, and compact. |
| 86 | Ruts | L | B | Grade only. |
| | | M | B/C | Grade only/grade and add material, and compact. |
| | | H | C | Cut to base, add aggregate, shape, water, and compact. |
| 87 | Loose aggregate | L | B | Grade only. |
| | | M | B/C | Grade only/grade and add material, and compact. |
| | | H | C | Cut to base, add aggregate, shape, water, and compact. |
| *Cost code guide: A = labor, overhead; B = labor, equipment, overhead, C = labor, equipment, materials, overhead. | | | | |

As noted in Deliverable 2-A, the project team found the Department of the Army's URCI method to be a good candidate method to focus on for this project because it offered a clear set of measurement requirements, the realistic possibility of collecting most of the condition indicator parameters, and the potential applicability to a wide variety of U.S. unpaved roads. The manned and unmanned systems used in this project were selected and developed so that they could collect the necessary URCI data with the required resolutions shown in Table 1. The performance review, concept of operations, and cost analysis all stem from the URCI system and related measurement requirements.

## Section III: Performance Review

### Description of Assessed Sites and Data Collections – Unmanned and Manned Flights

The MTRI team collected data at five sites in 2012 - Petersburg Road in Monroe County and Welch Road, Mills Macon Road, Garno Road and Piotter Hwy in eastern Lenawee County Michigan (see Figure 1). Four sites were in assessed in 2013 as well: Marsh Road and Fleming Road in northwestern Livingston County. Palmer Hwy and Piotter Hwy in eastern Lenawee County were also evaluated (also shown in Figure 1). For the purposes of this project, up to four people were sent so that ground truth data could also be collected, but the imagery needed for unpaved road assessment could be collected with just a single data collector. No single study site had all the distresses for ground truth assessments. As we eventually determined, our analysis software for locating unpaved road distresses was able to find and categorize more distresses than manual ground truth was able to do, so our "ground truth" data is better described as spot-checking reference data useful for evaluating part of the imagery analysis results. We selected roads for assessments, with the project UAVs (hexacopter/ single-rotor helicopter) and manned fixed wing aircraft based on communication with local county Road Commissions and extensive driving surveys by MTRI personnel. Often, county road commissions were unable to provide guidance on current unpaved road conditions within their counties (with the goal of narrowing the search for distressed unpaved road segments). Jay Carter of the Road Commission for Oakland County (RCOC), a partner in this project, was able to guide us to townships within the county with roads that had not been recently graded. However, it was up to the field crews to locate roads that met the data collection criteria.

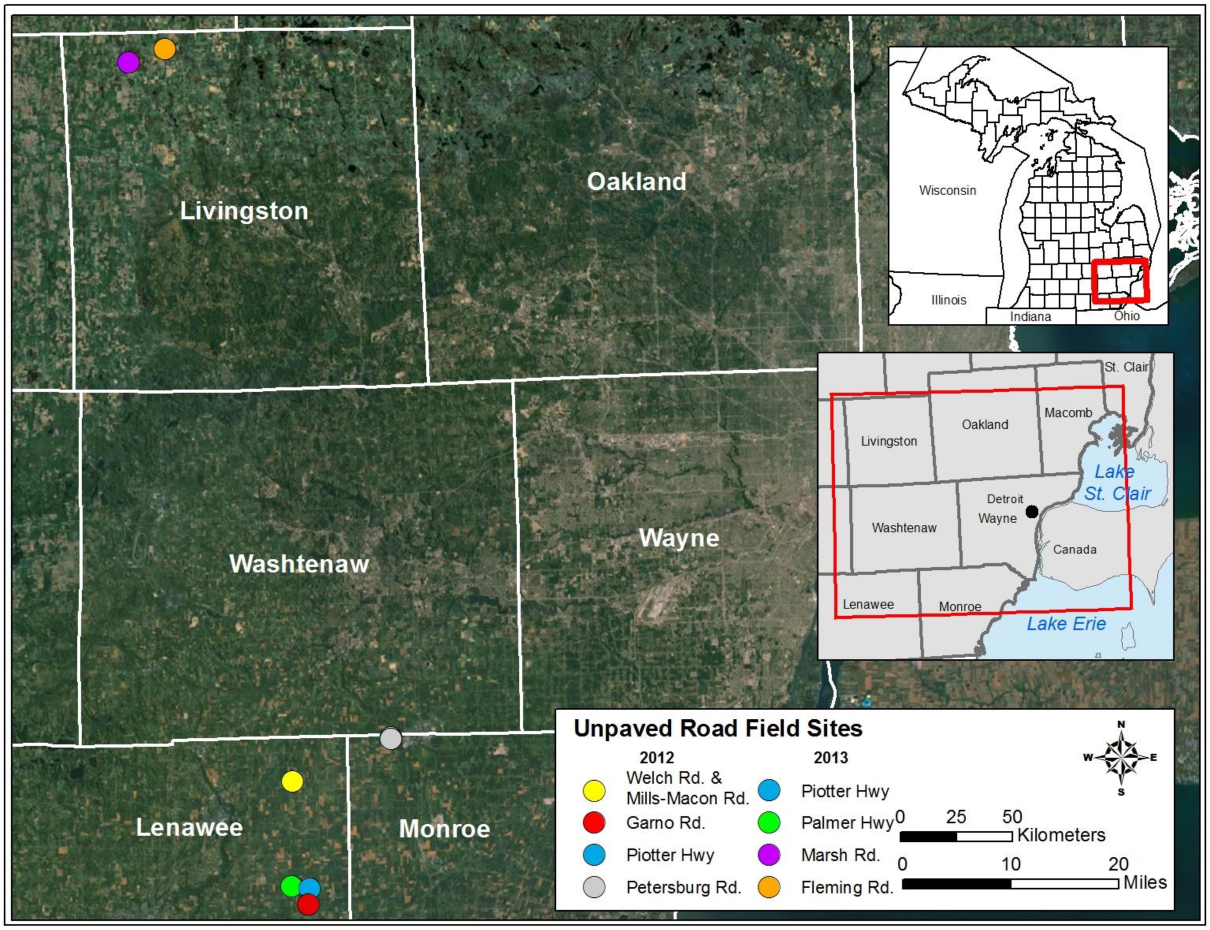
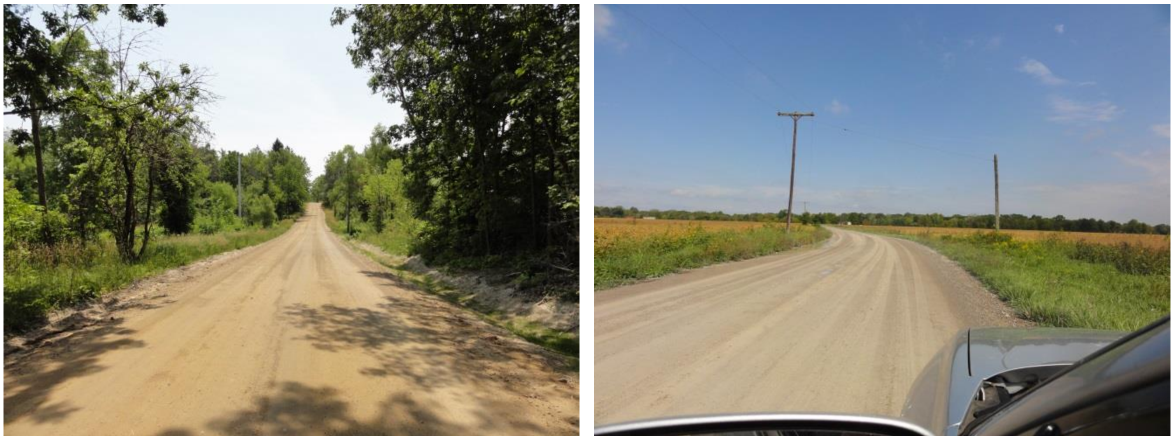
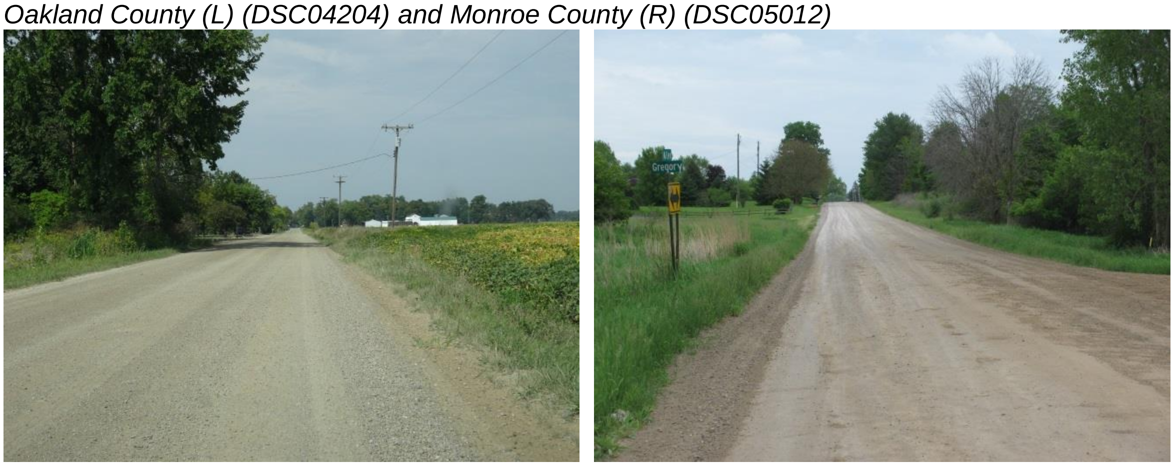



**Figure 1: Locations of the eight sites were unpaved road imagery were collected in 2012-2013 for calculating road distresses and the Unsurfaced Road Condition Index.**

As a result, to select unpaved roads for evaluation, we sent out field teams on driving surveys to look for distressed unpaved roads that met the conditions set for evaluation: they needed to be clearly visible from the air, had no trees or wires/poles close to the road, were lightly populated and lightly trafficked. Figure 2 shows some examples of road conditions and near-road landscapes found in unpaved road areas of southeastern Michigan.



*Oakland County (L) (DSC04204) and Monroe County (R) (DSC05012)*




*DSC00684 Macomb County (L) DSC_4855 Livingston County (R)*

**Figure 2: Sample road conditions and landscapes in several counties within SEMCOG.**

While the search for distressed unpaved roads included most of the member counties of the South Eastern Michigan Council of Governments (SEMCOG), suitable areas for aerial data collection were found in northwestern Livingston County, Monroe County and eastern Lenawee County in southeastern Michigan. The appropriate locations for data collection were generally in agricultural areas with open fields and few trees along the roads. The population density in the rural parts of these counties is low, the landscape is open and unpaved roads are common, making it easier to locate unpaved roads that are suitably remote and have quantifiable distresses of useful severity.

A challenge faced by the field team was staying ahead of graders once suitably distressed unpaved roads were located (see Figure 3). Often, the grader would pass over distressed unpaved roads between the time the field team identified the distresses and when the data collection team could get out to the site. This delay may have been only a day or two, but graders beat the data collection team to the distressed unpaved roads several times.

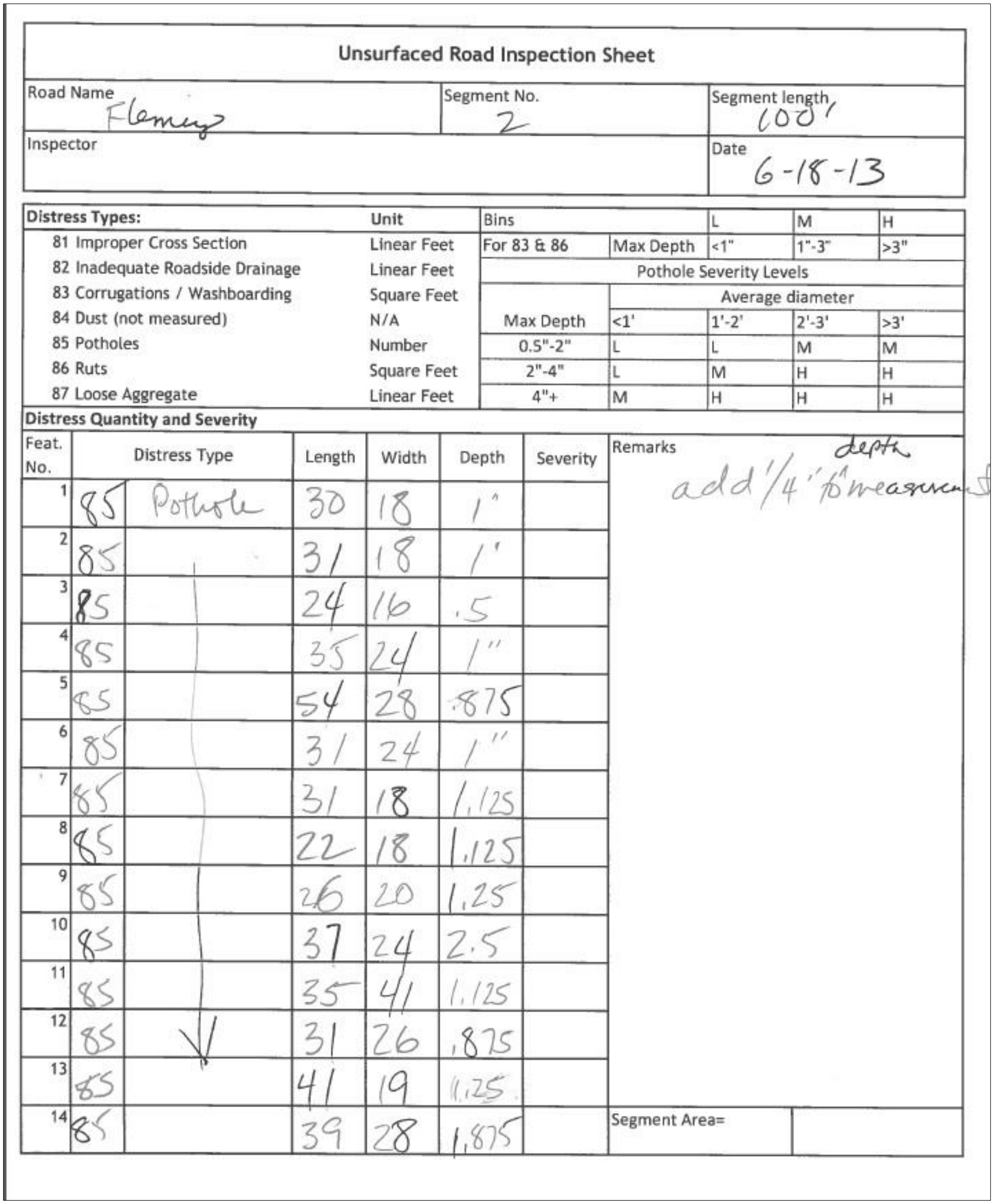

**Figure 3: A road grader working on a rural road in Livingston County, MI, as seen by data collection team while looking for distressed unpaved roads.**

In addition, there were two collections of opportunity in Iowa and one in Nebraska, made in late August 2013 (Figure 4). The purpose of this collection was to verify that roads maintained in other states, using potentially different materials and methods, could be characterized with the same processing suite as Michigan roads. These sites were chosen from reviews of Google Earth imagery, within several miles of I-80, to minimize transit time to the site. All three sites were judged to be undamaged, and typical of the surrounding rural roads. Examination of the results indicated that there were no problems in assessing road conditions on these other types of roads.

**Figure 4: Overflight of an Iowa road, also assessed for condition.**

### *Ground Truth Data Collection*

When a study site had been identified, a "ground truth" team followed to break the road down into short (typically 100 feet/~30 meters) segments for analysis. This was needed for verification and spot-checking of image analysis results and would not typically be required as part of an operational unpaved roads assessment system. The road is marked with pavement marking paint and each segment numbered. Distresses present in each segment are measured (length, width, depth and any other attributes that may be required) and recorded on a field data sheet (see Figure 5).



**Unsurfaced Road Inspection Sheet**

| Road Name | Segment No. | Segment length |
|---|---|---|
| Fleming | 2 | 100' |

| Inspector | Date |
|---|---|
| | 6-18-13 |

| Distress Types: | Unit | Bins | | L | M | H |
|---|---|---|---|---|---|---|
| 81 Improper Cross Section | Linear Feet | For 83 & 86 | Max Depth | <1" | 1"-3" | >3" |
| 82 Inadequate Roadside Drainage | Linear Feet | Pothole Severity Levels | | | | |
| 83 Corrugations / Washboarding | Square Feet | | Average diameter | | | |
| 84 Dust (not measured) | N/A | Max Depth | <1' | 1'-2' | 2'-3' | >3' |
| 85 Potholes | Number | 0.5"-2" | L | L | M | M |
| 86 Ruts | Square Feet | 2"-4" | L | M | H | H |
| 87 Loose Aggregate | Linear Feet | 4"+ | M | H | H | H |

**Distress Quantity and Severity**

| Feat. No. | Distress Type | Length | Width | Depth | Severity |
|---|---|---|---|---|---|
| 1 | 85 Pothole | 30 | 18 | 1" | |
| 2 | 85 | 31 | 18 | 1" | |
| 3 | 85 | 24 | 16 | .5 | |
| 4 | 85 | 35 | 24 | 1" | |
| 5 | 85 | 54 | 28 | .875 | |
| 6 | 85 | 31 | 24 | 1" | |
| 7 | 85 | 31 | 18 | 1.125 | |
| 8 | 85 | 22 | 18 | 1.125 | |
| 9 | 85 | 26 | 20 | 1.25 | |
| 10 | 85 | 37 | 24 | 2.5 | |
| 11 | 85 | 35 | 41 | 1.125 | |
| 12 | 85 | 31 | 26 | .875 | |
| 13 | 85 | 41 | 19 | 1.25 | |
| 14 | 85 | 39 | 28 | 1.875 | |

Remarks: add 1/4" to measured depth

Segment Area=

**Figure 5: A completed field data collection sheet for segment 2 of Fleming Road, Livingston County. Values on this form were entered into the MS Excel version of this inspection sheet where severity calculations were performed. Note that some units of measure conversions were necessary.**

Road condition attributes recorded on the field sheets are standard Army Corps of Engineers Unpaved Roads Condition Index attributes – cross section, roadside drainage, corrugations (washboarding), potholes, ruts and loose (float) aggregate. Dust is part of the URCI but was not measured as a practical part of this project. Road width was measured at each end of the segment; it was measured more often if road width varied significantly within a segment.

Each road segment to be measured was numbered and distresses present marked and numbered. It was not necessary for segments to be immediately adjacent to each other. Distresses present within the segment are mapped, measured and the values recorded on the field data collection sheet. A second page of the data collection form allowed for the mapping of distress location as well as entering data on road width, cross section (crown) drainage and float aggregate measurements.

The data recorded on the field data sheet are entered into an Excel spreadsheet that is identical to (and the source of) the field data sheets (see Figure 5). This field data sheet is an evolution of a manual system developed to capture ground conditions when the data were collected. Calculations are built into the spreadsheet to classify the distresses present into the appropriate "bin" (seen at the top of the data sheet) and produce a URCI index number. While out in the field, the ground truth team also made sketch maps of the sections to help interpret locations and types of distresses (Figure 6). To help understand how these data fed into the complete end-to-end system, three additional figures are included: Figure 7 shows a photo of the Fleming Road segment 2 data collection site (one of our representative segments needed for URCI evaluation of distress condition); Figure 8 shows the UAV-collected imagery after it has been converted into a 3-D point cloud using the project's remote sensing processing system analysis software, and Figure 9 shows a "height map" indicating that potholes could be mapped using the project's analysis software.

**Unsurfaced Road Inspection Sheet**

| | | | | | |
|---|---|---|---|---|---|
| Road Name | Fleming Road | Segment No. | 2 | Segment length | 100 |
| Inspector | | Page: 1 | of 2 | Date | 6/18/2013 |

| Distress Types: | | Unit | Bins | | L | M | H |
|---|---|---|---|---|---|---|---|
| 81 | Improper Cross Section | Linear Feet | For 83 & 86 | Max Depth | <1" | 1"-3" | >3" |
| 82 | Inadequate Roadside Drainage | Linear Feet | Pothole Severity Levels | | | | |
| 83 | Corrugations / Washboarding | Square Feet | | Average diameter | | | |
| 84 | Dust (not measured) | N/A | Max Depth | <1' | 1'-2' | 2'-3' | >3' |
| 85 | Potholes | Number | 0.5"-2" | L | L | M | M |
| 86 | Ruts | Square Feet | 2"-4" | L | M | H | H |
| 87 | Loose Aggregate | Linear Feet | 4"+ | M | H | H | H |

**Distress Quantity and Severity**

| Feat. No. | Distress Type | | Length (in) | Width (in) | Depth | Severity | Remarks | |
|---|---|---|---|---|---|---|---|---|
| 1 | 85 | Pothole | 30.0 | 18.0 | 1.250 in. | M | | |
| 2 | 85 | Pothole | 31.0 | 18.0 | 1.250 in. | M | | |
| 3 | 85 | Pothole | 24.0 | 16.0 | 0.750 in. | L | | |
| 4 | 85 | Pothole | 35.0 | 24.0 | 1.250 in. | M | | |
| 5 | 85 | Pothole | 54.0 | 28.0 | 1.125 in. | M | | |
| 6 | 85 | Pothole | 31.0 | 24.0 | 1.250 in. | M | | |
| 7 | 85 | Pothole | 31.0 | 18.0 | 1.375 in. | M | | |
| 8 | 85 | Pothole | 22.0 | 18.0 | 1.375 in. | L | | |
| 9 | 85 | Pothole | 26.0 | 20.0 | 1.500 in. | L | | |
| 10 | 85 | Pothole | 37.0 | 24.0 | 2.750 in. | H | | |
| 11 | 85 | Pothole | 35.0 | 41.0 | 1.375 in. | M | | |
| 12 | 85 | Pothole | 31.0 | 26.0 | 1.125 in. | M | | |
| 13 | 85 | Pothole | 41.0 | 19.0 | 1.500 in. | M | | |
| 14 | 85 | Pothole | 39.0 | 28.0 | 2.125 in. | H | Segment Area= | 3017.5 |

**Figure 6: A completed Unsurfaced Road Inspection Sheet, transcribed from the field data sheet above. The values on this sheet were collected from segment 2 on Fleming Road, Livingston County, MI and are actual attribute data. Values in the "Severity" column are calculated based on data entered for that particular feature.**

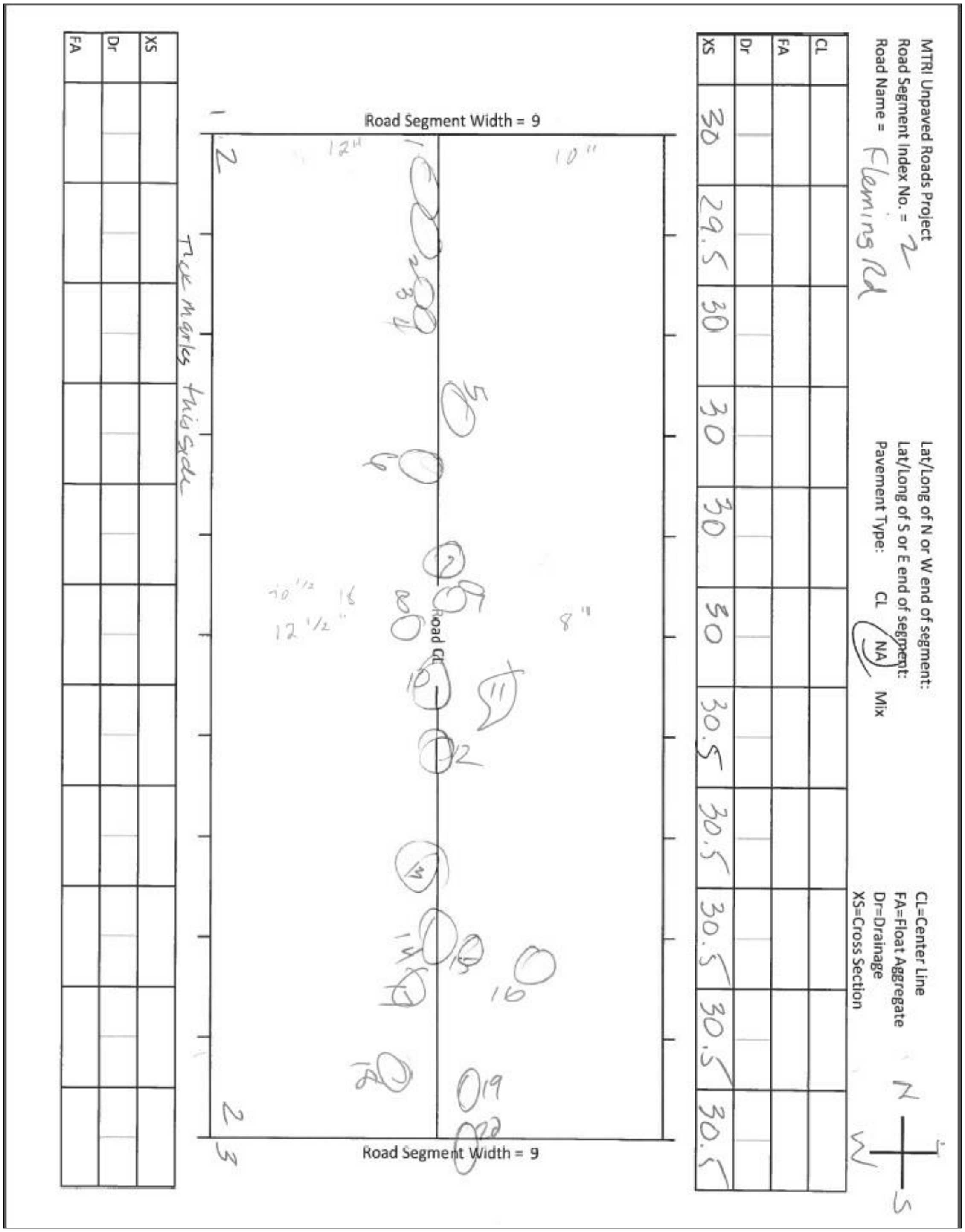



**Figure 7: Distress map from segment 2 of Fleming Road. The compass rose allows orientation of the map. In this case, the distresses are mapped and numbered, correlating to numbers painted on the road next to the corresponding feature. Road width is captured every ten feet in the XS field. All twenty distresses found on this segment were mapped on this sheet although documenting them required a second field data sheet.**

**Figure 8: Fleming Road segment 2 looking north. Distresses have been marked, measured, mapped and numbered prior to overflight. This image correlates to the south end of the distress map above.**

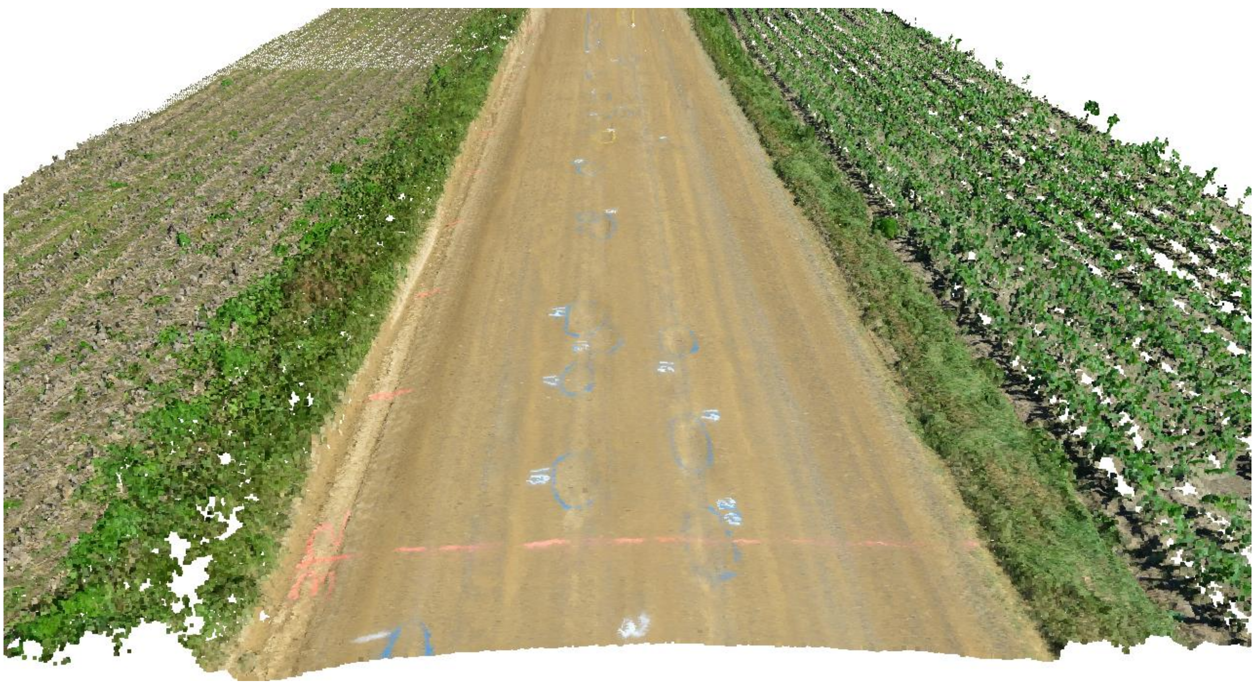


**Figure 9: A 3-D point cloud generated through the project's structure-from-motion based remote sensing processing system software using overlapping UAV-collected imagery, of the same location shown in the ground photo in Figure 7.**

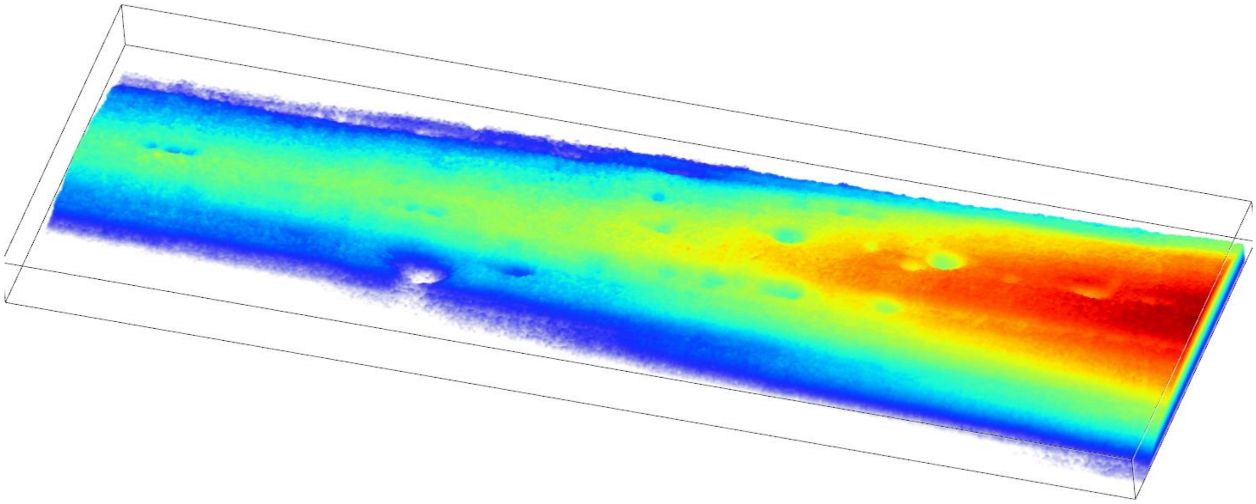


**Figure 10: Part of the Fleming Road segment 2 as shown in Figure 7 and Figure 8, displaying a height map where potholes and their depths can be seen.**

### *2012 Field Season*

Figure 11 shows the five main locations evaluated during the project's initial 2012 field season: Petersburg Road, Welch Road, Mills-Macon Road, Piotter Highway, and Garno Road (see Figure 1 for their context in the rest of southeastern Michigan). Descriptions of each of the evaluated sites follow.

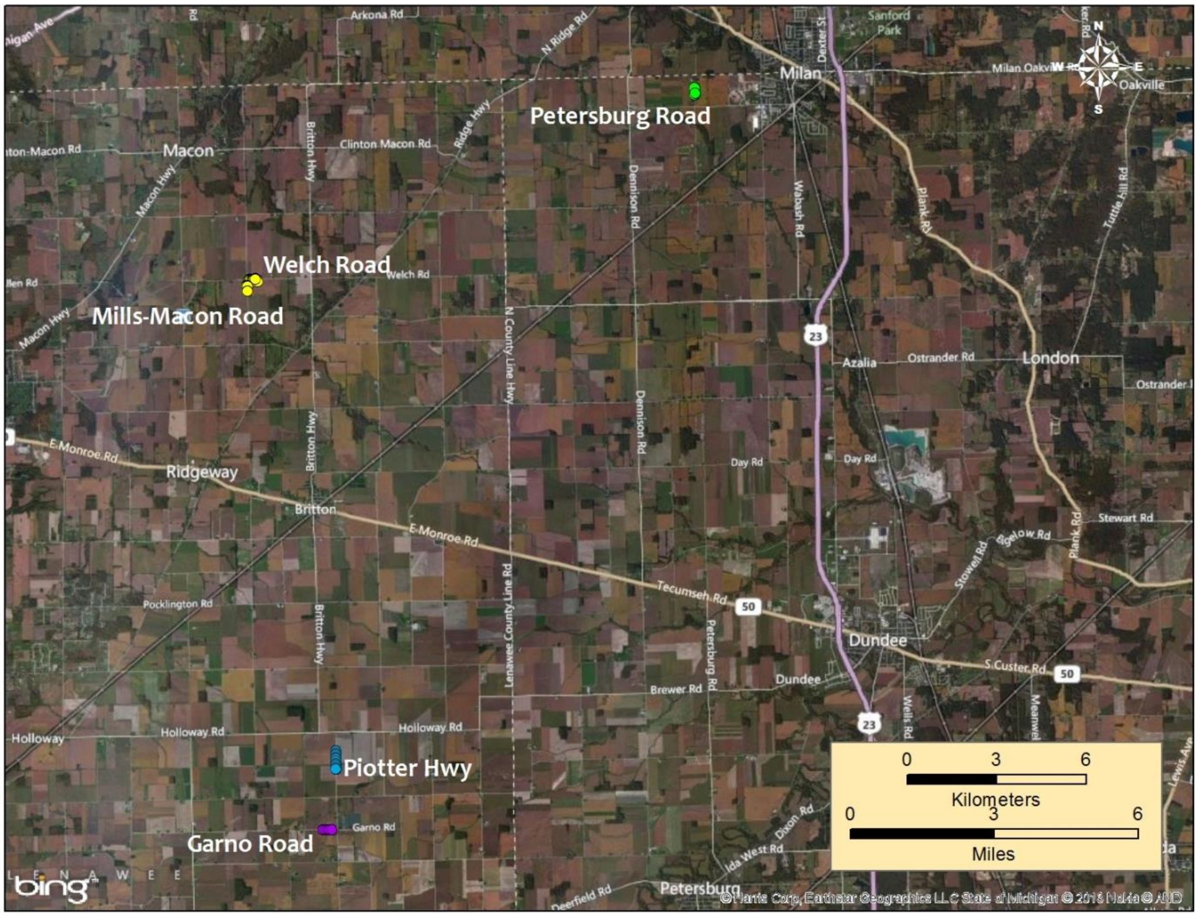



**Figure 11: Focus map of the 2012 unpaved roads project field study sites.**

***Petersburg Road***

The first flight and data collection tests were completed on Petersburg Road near Milan, Monroe County, MI on October 16 2012. This road met the conditions set for a data collect – distresses present, away from airports, no trees or poles near the road, light traffic and no buildings in the segment of the road to be flown. The road surface is crushed limestone.

The road was broken down into 100 foot / 30.5 meter segments and the segments were marked with fluorescent orange marking paint (Figure 12). The URCI method is based on taking one or two 100 foot samples to represent approximately a one mile stretch of road (Department of the Army 1995). The road width was measured and recorded, then distresses were measured and values recorded (Figure 13). While the road was marked and measured, the Bergen Tazer 800 helicopter was prepared and programmed for flight. When the helicopter was ready, the road was briefly closed for safety and to keep vehicles from passing under the helicopter during a data collection.

**Figure 12: Petersburg Road near Milan MI looking north. Note visible distresses (potholes).**

**Figure 13: Location and attribute data about distresses found in each road segment were measured and recorded for comparison to image processing results. (three photos above): (DSC1285, DSC1295, DSC1297)**

### *Welch Road*

The surface of Welch Road consists of natural aggregate or river sand and gravel (Figure 14). This material, unlike crushed limestone, does not 'lock' into a hard, impermeable surface as it is compacted and is prone to plastic deformation as the road and roadbed become saturated with water and vehicles (particularly trucks) pass over the road. Welch Road runs east-west; distresses identified on the road are washboarding and potholes, with a small accumulation of float aggregate primarily along the north shoulder of the road. Figure 15 shows a single image, as collected by the single-rotor Bergen Tazer 800 UAV (in 2013, the project team switched to a simpler-to-fly Bergen hexacopter for its data collection). Figure 16 is an example of the 3-D point cloud created by our remote sensing processing system as an intermediate step in being able to locate and categorize road distresses. Figure 17 is another example of a height map that helps demonstrate that we were able to generate the 3-D data needed for unpaved road condition assessment.

**Figure 14: Welch Road (facing west) near Mills-Macon Road, Lenawee County, MI. Road segmentation marks, potholes, washboarding (corrugation) and float aggregate are visible in this image. (DSC03546)**

**Figure 15: Aerial view of the same segment of Welch Road as Figure 14 above, seen from the MTRI remote control helicopter flying at 25 meters above the ground. Note the road segmentation marks, potholes, washboarding and float aggregate visible in both images. (DSC2865)**

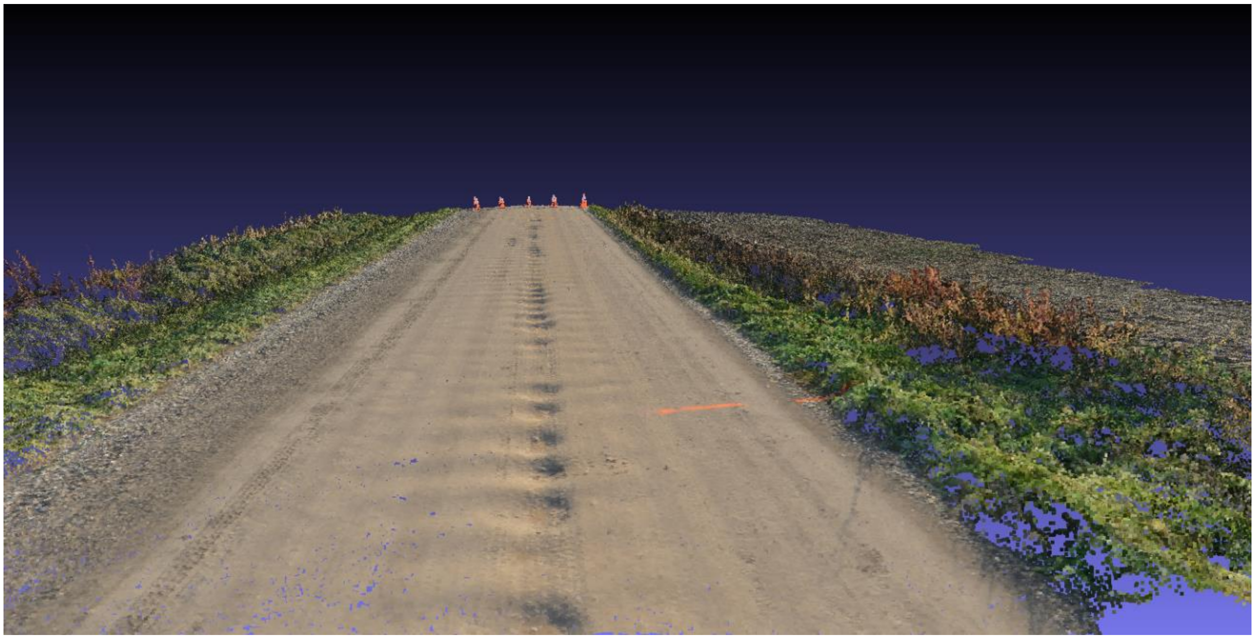


**Figure 16: Example of the 3-D point cloud generated by the remote sensing processing system for the same stretch of road shown in Figure 14 using the overlapping UAV-based imagery.**

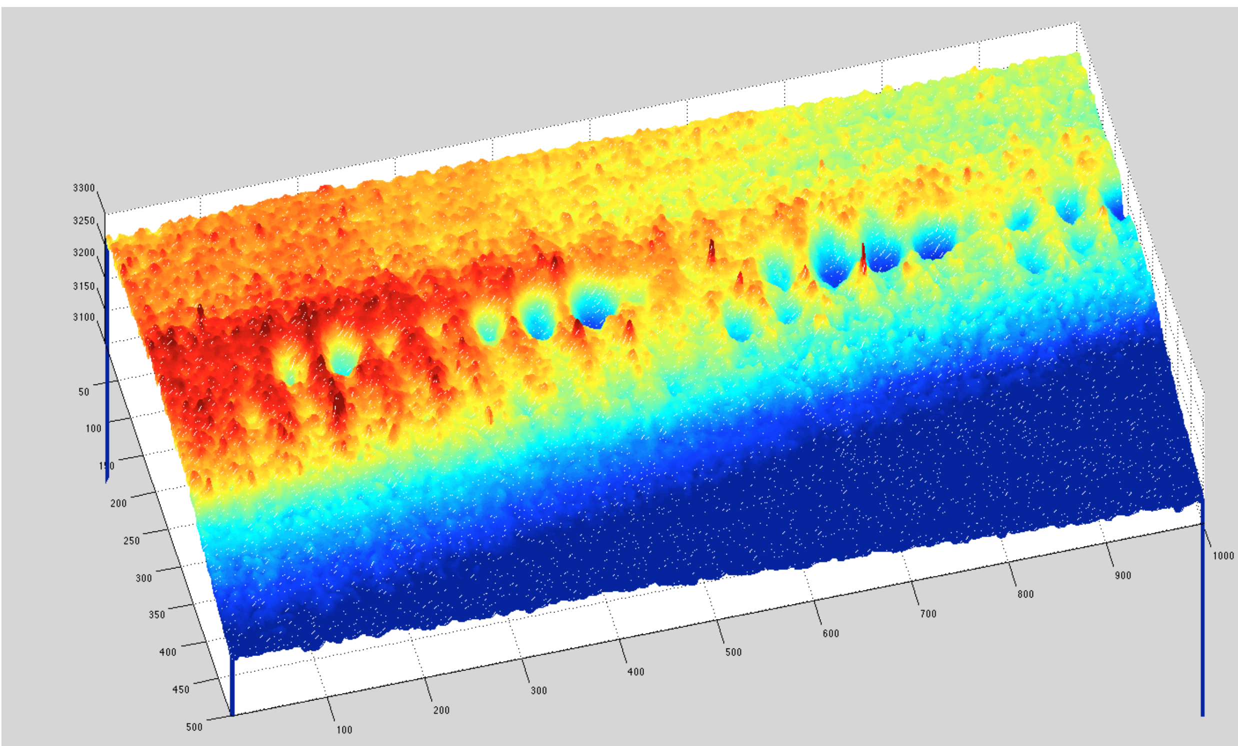



**Figure 17: 3-D height map showing pothole distresses on Welch Road, as derived using the project's remote sensing processing system.**

### *Mills Macon Road*

Mills-Macon Road is a north-south road that intersects Welch Road just west of the Welch Road study area. The study area on Mills-Macon Road starts ~120 meters south of the intersection with Welch Road.

The road surface as shown in Figure 18 (from the ground) and Figure 19 (from our UAV imagery) appears to be natural aggregate, with possibly some crushed limestone added when the road was last graded. Mills-Macon Road showed no significant distresses other than a minimal crown and some loose aggregate on the road. Mills Macon Road was used for prototype analysis; this sample output with few distresses was compared to known good road surfaces.

**Figure 18: Mills-Macon Road south of Welch Road looking north. Note thin layer of loose aggregate on the road surface and lack of other distresses on the road surface. (DSC03667)**

**Figure 19: Aerial view of same segment of Mills-Macon Road as Figure 18 above, seen from the MTRI remote control helicopter flying at 25 meters above the ground. Note the road segmentation marks and slight windrowing of the loose aggregate on the road surface. (DSC3440)**

### *Piotter Highway*

Piotter Highway is a north - south road located south of the town of Britton in eastern Lenawee County, MI. The study area is approximately midway between Laberdee and Holloway Roads. The road surface appeared, at the time of the survey, to be mostly natural aggregate although some crushed limestone may be present (Figure 20). Distresses found on Piotter Hwy in the fall of 2012 were generally potholes of various sizes irregularly scattered down the length of the study area along with a few ruts. The road was broken up into 100’ (30.5 meter) segments and marked with fluorescent orange marking paint. The location and size (length, width and depth) of distresses on the road were documented for later comparison to image processing results. Imagery was collected from the MTRI helicopter at 25 meters (about 82 feet; see Figure 21 and Figure 22) and 30 meters altitude (about 100 feet) as well as from a manned fixed wing aircraft (a Cessna 172) flying over the road at approximately 150 meters (about 500 feet) above ground level (Figure 23 and Figure 24). The helicopter captured overlapping aerial imagery at nadir, while the imagery taken from the Cessna 172 was taken out the passenger side window at an angle (Figure 25).

**Figure 20: A ground level view of part of segment 6 on Piotter Hwy, Lenawee County MI. View is to the north.**

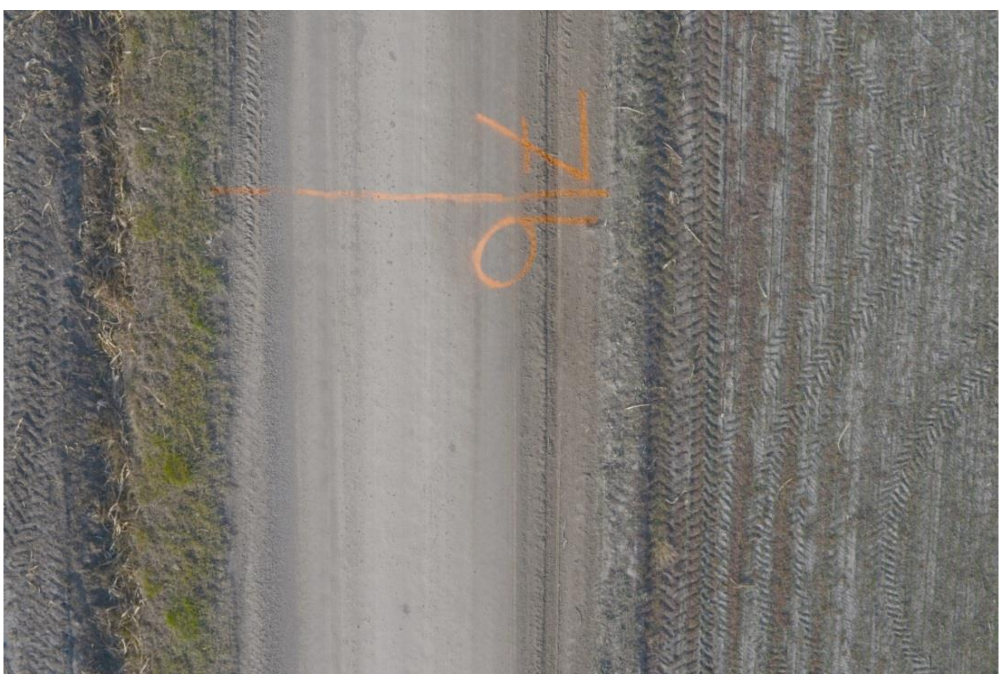


**Figure 21: The same segment of Piotter Hwy seen in Figure 20 above from the MTRI remote control helicopter flown at 25 meters. Few potholes are visible in this image but a long rut on the right side of the road is visible in both this image and the ground view of the same area. (DSC3449_gamma.jpg)**

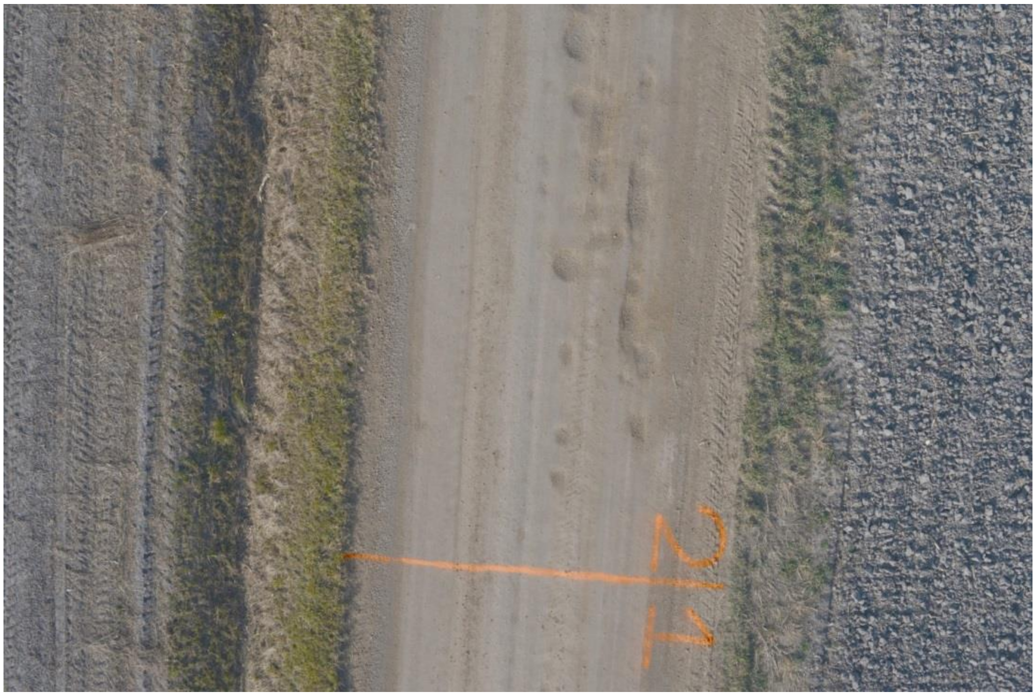


**Figure 22: Aerial view of Piotter Hwy from the MTRI hexacopter flown at 25 meters altitude. Note the segment markings and clearly visible distresses (potholes) in the road surface. (DSC3227_gamma.jpg)**

**Figure 23: An aerial view of segment 6 of Piotter Rd from a Cessna 172 flying at approximately 500 feet above ground level. The orange segment marks are clearly visible, but distresses are difficult to identify from this angle and altitude. (DSC5879)**

**Figure 24: Low oblique aerial photograph of Piotter Hwy segment 2 from the Cessna 172. Markings are clearly visible but distresses while visible are too small to be characterized into classes based on size. (DSC5855)**

**Figure 25: View from the Cessna 172 over Piotter Rd while taking aerial photographs of the Piotter Hwy study area.**

### *Garno Road*

Garno Road is an east-west road located about one mile south and a little west of Piotter Highway in Lenawee County MI. The study site consists of four 100 foot (30.48 meter) segments between Piotter Hwy and Sisson Hwy. The only distress noted by field crews on Garno Road in the fall of 2012 was float aggregate (see Figure 26 for a ground-based view).

Data were collected on Garno Road from the MTRI helicopter and fixed wing aircraft (a Cessna 172) on the same day. The data were collected with the helicopter in the morning (Figure 27) and Garno Road, along with Piotter Hwy, was overflown in the early afternoon (Figure 28).

**Figure 26: Garno Road looking east. Note the loose/float aggregate on the road shoulders and along the crown of the road.**

**Figure 27: Garno Road from the MTRI helicopter at 25 meters. Loose/float aggregate is the only distress present. Note the marks in the loose gravel from the tires of farm equipment.**

**Figure 28: Garno Road from a manned fixed wing aircraft at approximately 150 m / 500 feet agl (above ground level). The float aggregate distress is visible, but not easily characterized from this angle and altitude.**

*2013 Field Season*

Additional roads in southeastern Michigan were selected for evaluation in 2013 and a few roads evaluated in 2012 were revisited. A review of maps of paved vs. unpaved roads that we produced using semi-automated analysis of SEMCOG-provided color-infrared aerial imagery enabled field teams to focus their search to areas with a high proportion of unpaved roads that have minimal tree cover obscuring the road surface, allowing for both hexacopter and manned fixed wing aircraft operations (see Deliverables 6-A and 6-C, Roussi et al. 2012a and Roussi et al. 2012b for the descriptions of the aerial imagery analysis to inventory the locations of unpaved roads) . The roads evaluated during the 2012 field season were located in Monroe and Lenawee counties, south of Ann Arbor. We made a concerted effort to include unpaved roads in the northern SEMCOG counties. Reconnaissance trips for 2013 data collection efforts used maps of the locations of unpaved roads that we generated to find unpaved roads with suitable distresses for evaluation.

Again, the criteria for evaluation of the roads from the air made locating unpaved roads with current distresses challenging to find. In part, this reflects the very active management of unpaved roads in southeastern Michigan by local road maintenance agencies. Gravel roads are regularly graded, and County road commissions appear to rapidly attend to problems reported by local citizens. Field crews evaluated unpaved road condition in a large part of southeastern Michigan from northern Macomb County to southern Monroe County. Many distressed unpaved roads were located but few met the criteria for evaluation. Eventually, Marsh and Fleming roads in northern Livingston County (Figure 29) and Palmer Road in eastern Lenawee County were selected for evaluation. Piotter Road in eastern Lenawee County, originally assessed in 2012, was revisited to evaluate changes in road condition (see Figure 1 for its location).

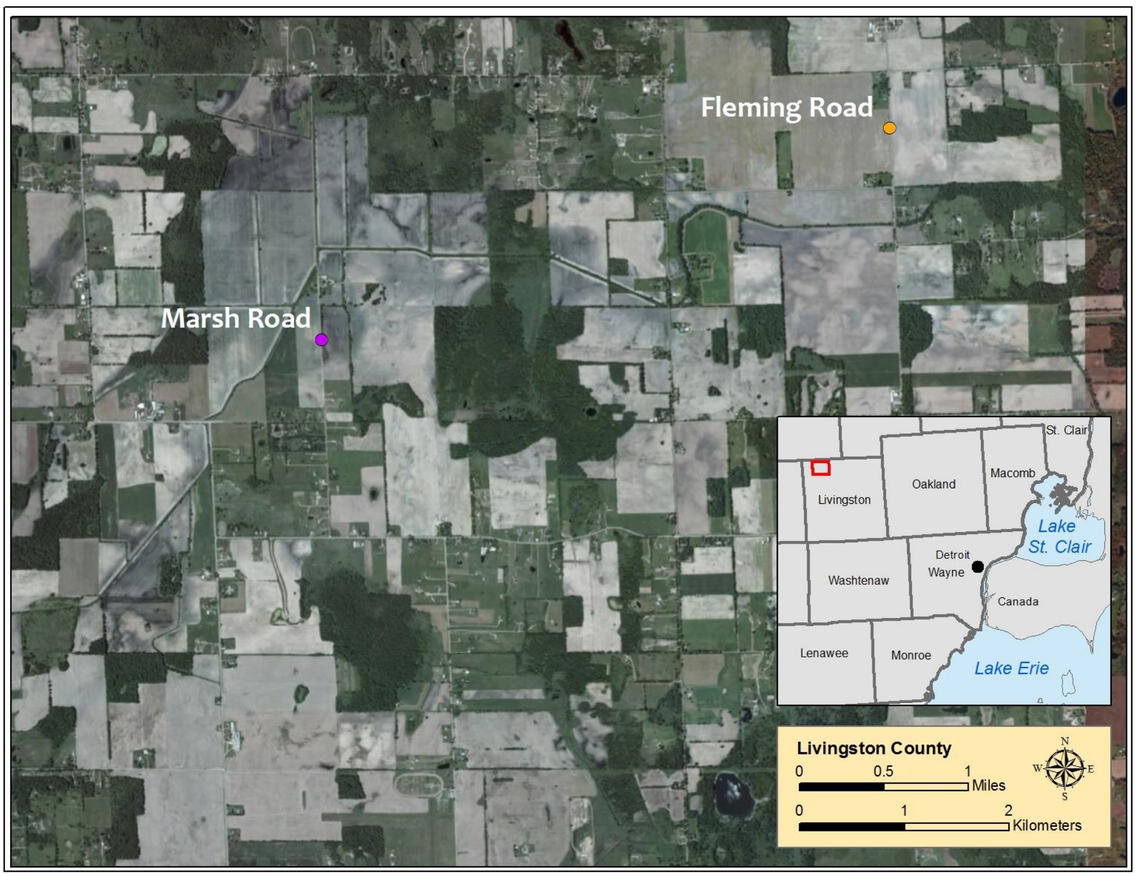



**Figure 29: 2013 unpaved roads project field study sites in Livingston County.**

### *Marsh Road*

Marsh Road in northwestern Livingston County (see Figure 29) was identified as a good candidate for evaluation in late May 2013 based on presence of visible distresses. The distresses were primarily potholes and extensive washboarding over a distance of approximately a half mile (800 m). When the field evaluation team arrived on site for an evaluation, it was found that the road had been recently graded and was in excellent condition (see Figure 30 for a ground view and Figure 31 for hexacopter imagery-based view). It was decided to use the recently graded road as an example of an unpaved road with no distresses; at least crown could be assessed, which is of strong interest to local road commissions. The road surface was measured and marked; attributes were collected using the same methodology as was applied during 2012 data collection activities. Additional data were collected at this location on crown as there was substantial crown present over most of the length of the sampled area of the road.

**Figure 30: Marsh Road, north of Fowlerville, Livingston County, MI looking south. Image on the left illustrates some of the distresses present on May 31, 2013; the image on the right was taken June 18, 2013. (IMG_4890 (L); IMGP0030 (R))**

**Figure 31: A segment of Marsh Road from the MTRI hexacopter. No significant distresses were present, however crown measurements were taken on Marsh Road for comparison to the results from image processing.**

### *Fleming Road*

Fleming Road (Figure 29) is located several miles east of Marsh road in northwestern Livingston County. Distresses present on Fleming Road were primarily potholes of varying sizes and some minor ruts. Distresses on Fleming Road were measured and mapped as had been done at other study sites (see Figure 32). However, on Fleming Road, the individual distresses were marked and numbered with different colored marking paint (blue for minor potholes, yellow for moderately sized potholes) in an effort to better differentiate and correlate distresses on the road with those seen in image processing output (Figure 33, a seen using UAV-based imagery). The numbering sequence restarted for each 100 foot (30.5 m) road segment that was evaluated.

**Figure 32: Distress markings on analysis segment 2, Fleming Road, Livingston County MI. Each distress feature was circled and numbered when it was mapped.**

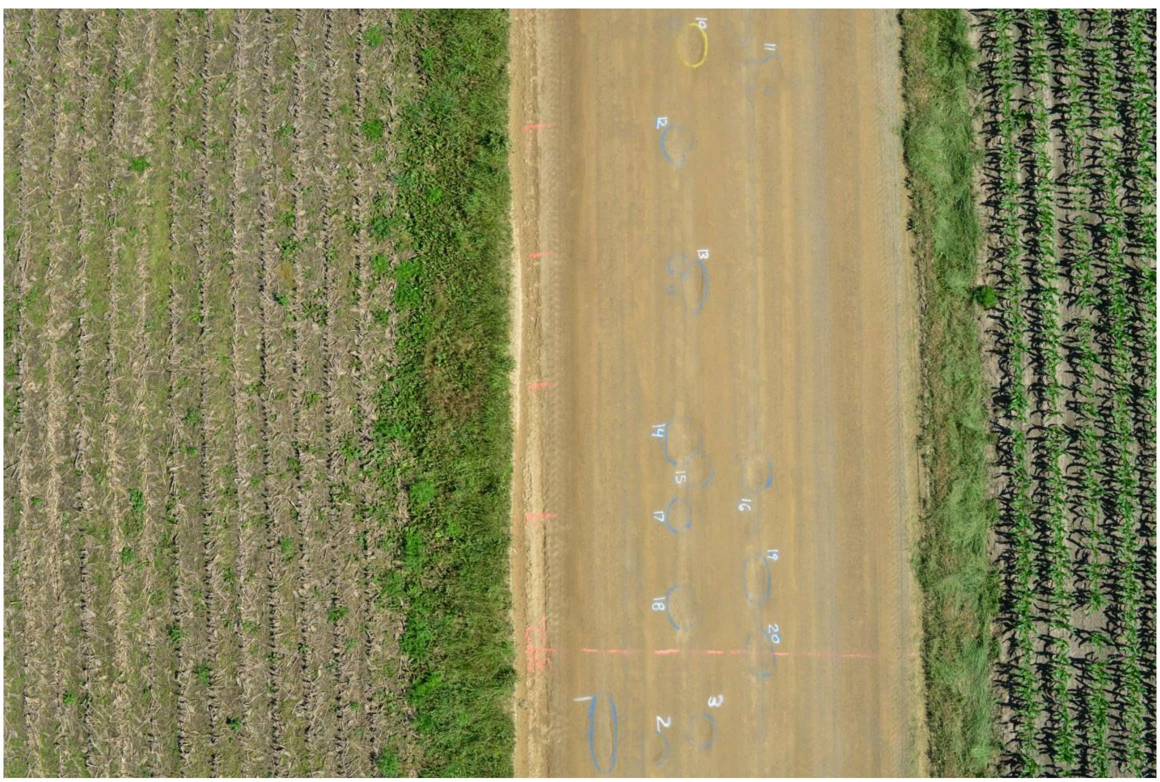


**Figure 33: Part of Fleming Road segment 2 with marked, numbered distresses as captured by the MTRI hexacopter flying the Nikon D800 DSLR camera. Data were collected the day after the road was marked. Note the blue distress feature markings have been worn by passing traffic. Feature numbers were refreshed with white marking paint.**

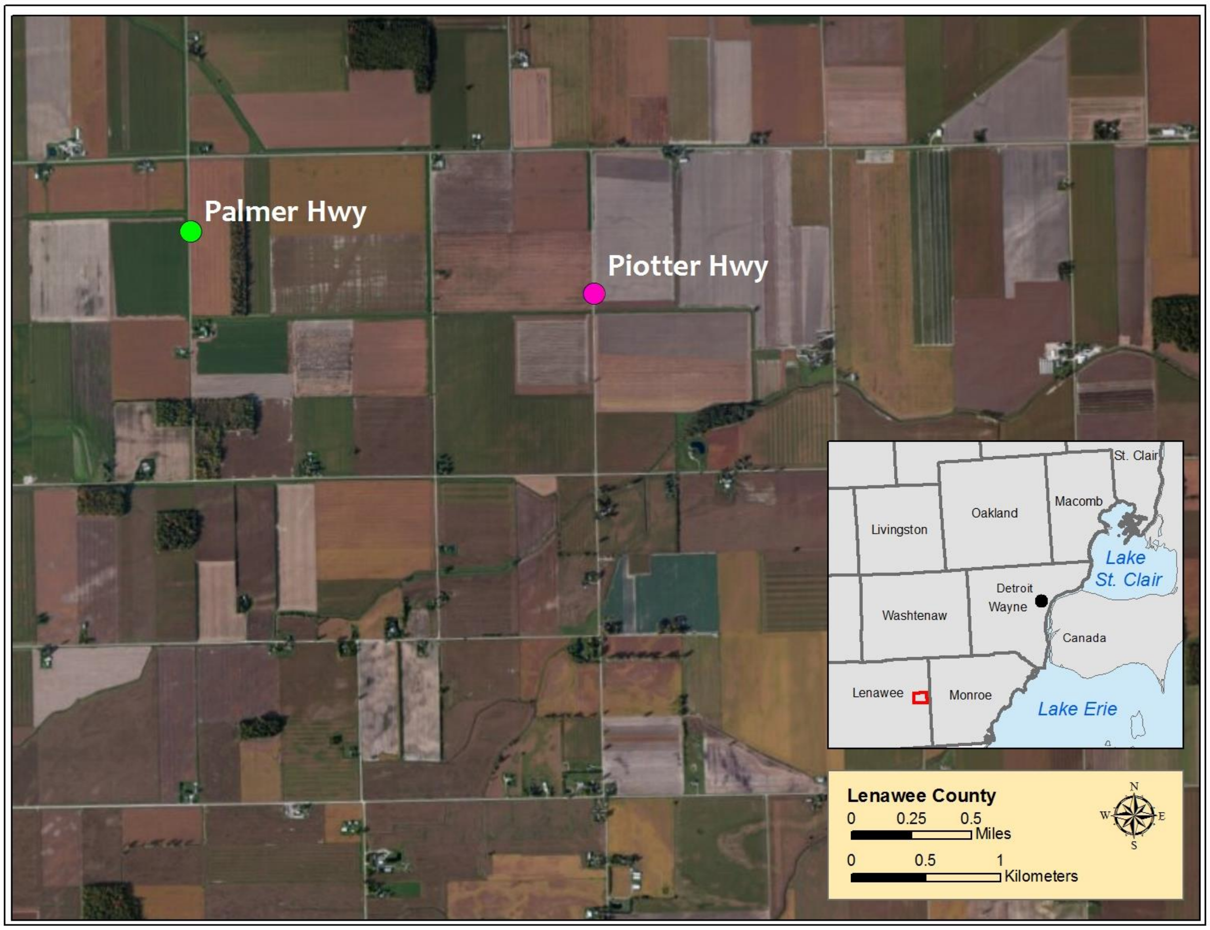



**Figure 34: 2013 unpaved roads project field study sites in Lenawee County.**

### *Piotter Highway 2013*

Piotter Highway in Lenawee County, MI, (see Figure 34) was evaluated again in 2013 as it had developed distresses in similar locations as well as in different locations from those found in the 2012 data collect. Distresses on Piotter Hwy in 2013 were found in clusters down the road rather than a continuous distribution of distresses spread down the road. Potholes and ruts were the dominant distresses found on the road (Figure 35). Figure 36 shows an UAV-based view of the distresses present during the sampling period in 2013. As was the case for Fleming Road, the distresses were numbered as they were marked and mapped. Unlike Fleming Road, Piotter Hwy was broken into two groups of segments and only the northern segments were marked and mapped. The southern segments were only broken into 100 foot sections. None of the distresses in those sections were identified.

**Figure 35: Piotter Hwy marked and measured during the 2013 data collection. Note the clustering of potholes at this particular location, which as a feature of the 2013 distress patterns (IMGP0262.jpg)**

**Figure 36: An image of Piotter Hwy from the hexacopter flight. This is approximately the same location as in the previous figure. Above, however the hexacopter flight was made before the distress features were numbered. (975-7916.jpg)**

***Palmer Highway***

Palmer Highway, also in Lenawee County, MI (Figure 34) is a north-south road slightly more than a mile west of Piotter Hwy. It had been identified as having significant distresses in a survey earlier in the summer of 2013; however it was graded before marking and overflights could be scheduled. However, by fall 2013, some distresses had returned and it was decided to collect data on some segments of the road using both manned fixed-wing aircraft (Figure 37) and the project's hexacopter UAV (Figure 38). Distresses present on Palmer Highway at the time of survey were predominantly ruts and potholes (Figure 39). The road appeared to have reasonable crown, however, some of the ruts along the shoulder of the road prevented water from properly draining from the road, saturating the roadbed and making the ruts worse in those areas over time.

Data were collected from the MTRI hexacopter using techniques described previously as well as from a Cessna 172, using the same Nikon D800 camera as was mounted on the hexacopter but with a longer (200 mm focal length) lens (Figure 37). Data collected form the Cessna 172 were collected at the minimum safe altitude (around 500 feet / 150 m above ground level) while flying parallel to the road (Figure 40, as taken by our ground truth crew). As a side note, we found that the aerial imagery of nearby corn field areas made our team interested in potential applications of our systems for agriculture assessment as well.

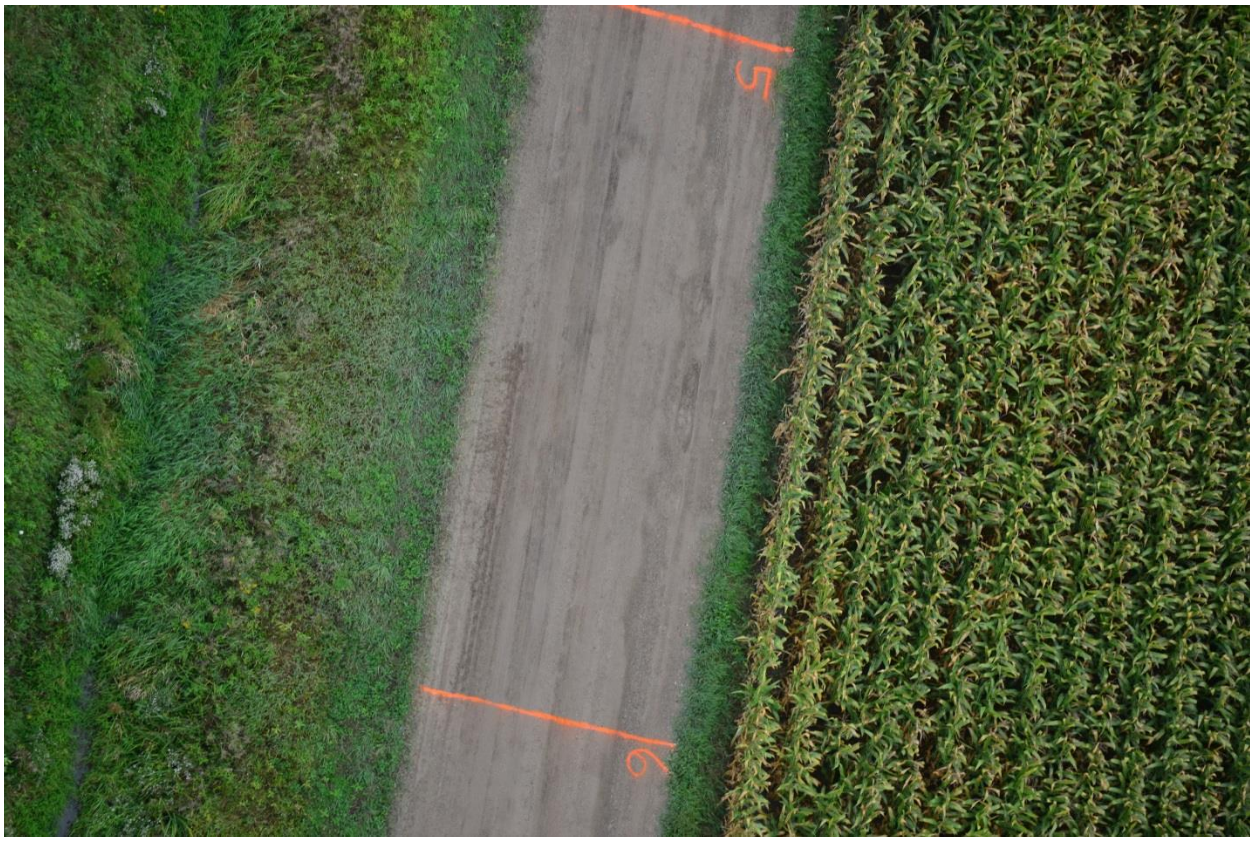



**Figure 37: An image of an approximately 50 foot / 15 meter section of Palmer Hwy taken with the Nikon D800 camera with a 200mm lens from the manned Cessna 172 flight. Altitude and airspeed can make it difficult to capture usable overlapping aerial imagery from a manned fixed wing aircraft at a reasonable cost. (CJR_4426.jpg)**


**Figure 38: Segment 3 of Palmer Road from the MTRI hexacopter from approximately 25 meters altitude. A rut is visible on the right side of the road just above the segment line.**

**Figure 39: Ruts and potholes on Palmer Road. Note deformation along edge of road in left hand image. DSC00691 (R) and DSC00717 (L)**

**Figure 40: Cessna 172 flying over Palmer Road collecting the unpaved roads assessment project imagery. (DSC00708.jpg)**

***Manned Fixed Wing Collects***

Data collection using a manned fixed wing aircraft has the potential to be able to collect overlapping aerial imagery of sufficient quality for extracting information on unpaved road condition. The cost of using a metric camera mounted inside a single or twin engine aircraft is beyond the cost limits for this project, so other approaches were evaluated to test the potential feasibility of using the same Nikon D800 sensor in the manned aircraft as we were using in the UAV. Part of the original challenge of this project was to see if we could use the same relatively inexpensive imaging sensor system in both our manned and unmanned platforms.

While we were able to acquire overlapping imagery from manned fixed wing flights, there were challenges acquiring the imagery easily without a metric camera. MTRI field crews made three flights to acquire aerial imagery from a manned aircraft (Figure 41). The Federal Aviation Regulations require that aircraft stay above 500 feet above ground level. In order to have enough “pixels on the road” so to speak to be able to meet resolution requirements, the road needed to fill at least a quarter of the frame. We calculated that a 200mm focal length lens should get enough of the road in the frame from 500 feet to extract road condition information. The technique we used involved flying a Cessna 172 parallel to the road but slightly to the left to allow the passenger to open the window and point the camera as close to straight down as possible. The Nikon D800 camera is triggered at approximately 2 frames per second by an intervalometer plugged into the camera. The photographer then has to keep as much of the road in the frame as much as possible while passing over the study area. A longer lens (up to 300mm focal length) would improve the ability of the photographer to keep enough of the road in the frame. It would also give some altitude flexibility to the pilot as they overfly the roads. However, such lenses are expensive and beyond the cost limitations of this project.

Challenges to this approach are many. The aircraft, in this case a Cessna 172, is typically flying at 60 - 65 knots (69 – 75 mph) even in slow flight. Depending on wind speed and direction, managing the ground speed of the aircraft may become an issue. The slipstream is strong, making it difficult to keep the camera pointed at the intended target, particularly when it fills a large portion of the frame. For best performance of the algorithm that identified and quantifies distresses on an unpaved road, the unpaved road should fill a quarter to a third of the frame. The photos should also have sufficient angular diversity to enable complete imaging of distresses such as potholes at a wide variety of angles. The relatively high speed and altitude makes this difficult. Low clouds or poor visibility can also preclude flying aerial photography missions in a manned aircraft. A UAV may be able to collect data under conditions that preclude operation of manned aircraft because of ceiling or visibility restrictions.

Cost and aircraft/pilot availability is another factor, since the aircraft must fly from the nearest airport to the study site, fly the mission and return to the airport. The study area could be a substantial distance from an airport with available aircraft and pilots. Rental for a Cessna 172 and experienced pilot recommended through the Professional Aerial Photographers Association (PAPA) in the Ann Arbor, MI area was approximately $160 to $175 per hour as of summer, 2013.

**Figure 41: A first pass at determining whether good data could be collected from a manned fixed wing aircraft. At 500 feet agl over Garno Road, Lenawee County, October 2012.**

A modified approach to data collection from a manned fixed wing aircraft was tried in 2013. MTRI was able to acquire a door for a Cessna 152 that had space for camera mount inside (Figure 42, Figure 43, and Figure 44). A camera mounting assembly for the Nikon D800 was designed and built by MTRI staff then mounted on a Cessna 152 and flown over Piotter Road. The concept was to fly down a study road at a low ground speed and remotely trigger the camera as the aircraft passed over the study area. When an aircraft is in slow flight, the nose is usually up, making it difficult to see and align the aircraft with the road to be photographed. A product called CamRanger allowed the pilot and photographer to view the camera perspective. The CamRanger proved a useful tool and was used as an aid to lining the aircraft up correctly over the road. However, we learned through practical testing that because the camera was not mounted on a gimbal that allowed it to move so that it would always point straight down, any change in the aircraft in pitch (nose up/down) or roll (wing up or down) of the aircraft changed where the camera was pointed making it difficult to keep the camera pointed at its subject.

Gyrostabilized camera mounts for aircraft are available but they are expensive, generally mounted on helicopters and geared toward larger cameras used for film production. A quick search did not locate any appropriately sized stabilized camera mounts usable in our small manned fixed-wing aircraft concept.


**Figure 42: The door of a Cessna 152 with a fairing allowing the mounting of a camera pointed straight down (nadir).**

**Figure 43: The Nikon D800 camera mounted on the door of a Cessna 152. The protective shade at the end of the camera lens can be seen at the bottom of the door.**

**Figure 44: Preparing to fly the D800 in the door of the Cessna 152. The camera can be seen in the door, the camera trigger mechanism can be seen on the pilot seat.**

## Performance Evaluation Main Analysis

### *Sensor System Performance Evaluation*

The basis for all derived distresses is the depth map created from the sensor data. This, in turn, is derived from the 3D point-cloud reconstruction which is obtained from the Structure From Motion (SFM) algorithm. A series of 2D, overlapping, images is used to extract the complete 3D information. However, the overlap must be carefully managed to obtain a consistently good reconstruction without manual intervention.

One "rule-of-thumb" is that the same object must appear in no less than 5 different images. These images may be at different distances and orientations, but they must span several degrees of angular extent. The closer to the scene the sensor, the more angular diversity is present in the overlapping images. This would imply that there is some maximum altitude, beyond which reconstruction is not possible. Although this is true, the ground sample spacing of the image pixels is actually the limiting factor at this point.

For good reconstruction, the requirement of 5 overlapping images translates into time and speed requirements. The requirements on accuracy of crown measurement (<1% variation, or about 2cm resolution), combined with the requirement that we measure both lanes and adjacent drainage, influence the sensor distance and lens specifications. A functional system that meets (or exceeds) all these requirements is a 36M-pixel sensor with a 50mm lens, firing at 2 frames-per-second, flying at an altitude of 25m at 2m/s forward speed. All of these parameters are achieved easily using readily available, inexpensive, commercial equipment. Such a system collects about 20GB of data per kilometer of road inspected.

There are three camera parameters that can be varied to obtain "correct" exposures, the ISO (the "speed" of the sensor), the aperture, and the exposure time (or shutter speed). However, there are other requirements that must be met, so not all combinations of these parameters are useful, although they will result in a properly exposed image. For example, it is important that all images be in focus, with no motion-blur. This requires a short exposure time, implying that the aperture is fully open, letting in as much light as possible. But many lenses do not have a flat focal plane when at full aperture (that is, there are distortions present at the image edges). This can be avoided by closing the aperture down 2 stops. This also has the effect of increasing the depth-of-field (although in most cases, we will be operating beyond the 10m hyperfocal distance, at which everything is in focus). It also will cause the shutter speed to be 4x slower, which can lead to motion-blur at lower light levels. To avoid this, one needs to change the ISO setting, to obtain a properly-exposed image at a shutter speed of at least 1/250s with an aperture of f/2.8.

In summary, the following data collection parameters will meet all system performance requirements:

- 24M-36M-pixel sensor
- 50mm, f/1.4 lens set at f/2.8
- 1/250s (maximum) shutter speed (shorter is better)
- ISO set as needed for proper exposure given ambient lighting
- Distance of 20m-30m from surface
- 2m/s (maximum) forward speed
- 2fps (minimum) image capture rate (obtained with a simple intervalometer)
- 64GB high-speed storage medium

It is important to note that the algorithm performance, and the ability to meet the stringent requirements on resolution, depends on the ability to collect data that has enough angular diversity to be able to reconstruct three dimensions from two dimensions. This means that enough (and sufficiently different) views of the same ground location must be taken. As the distance from the ground increases, the solid angle that any object subtends decreases, and at some point, becomes too small for high-resolution reconstruction. Experimental results, discussed in detail in the next section, shows that data taken from a an altitude of 500 feet do not meet the system requirements in resolution. That is, the reconstructed pixels have been found to be "too large". This is due to the lack of sufficient angular diversity.

There are three possible solutions to this problem of angular diversity.

1. More data are collected with the camera points at the same point on the ground, but at oblique (as well as nadir) views. This could be done either with multiple cameras on the same platform (e.g. one pointed forward, one downward, and one rearward). This would require longer focal-length lenses, and much more accurate pointing, on the non-nadir-looking camera. The pointing system could be quite complex (and expensive).
2. Several passes over the same location can be made, with the camera at different angles. Again, focal-length changes might be needed during oblique measurements, along with accurate pointing. This would also take more time, since lining up for multiple passes is not trivial.
3. Much higher resolution sensors, with a wider-angle lens than the 200mm currently used, would allow data to be taken in a single pass. Preliminary calculations indicate that a sensor with 4-5

times the current resolution (i.e. a sensor with 140M-180M pixels) with a 100mm lens would likely provide the needed resolution. No such sensor is readily available today.

We conclude that the use of a sensor at altitudes above 400 feet is not practical at this time, with the choice of SFM as the reconstruction technique. It may be that some other reconstruction method would yield the desired resolution, but we are not aware of a method that can be used with a sensor that would be competitive in cost with manual inspection methods. At this time, only sensors flown at altitudes below 100m will meet all the performance (i.e. resolution) and cost-effectiveness requirements.

***Algorithm Performance Process Overview***

During the process of assembling the performance results, we began to notice that the algorithm outputs were much different than the scoring done manually. Not wrong, since we could see it was finding the distresses, but different from what the raters were reporting. It turns out that the humans measuring the road were not reporting some distresses, either because they didn't see them, or they thought that they were not sufficiently bad to report. But the algorithm finds everything, and while one might think this is a good thing, it's not, as far as the final score is concerned. It turns out that the final step in creating the URCI is to transform the deduct values (using a non-linear set of curves) to make the road score "better" if the distresses are more evenly distributed by type. That is, a road with just one, very large, distress is scored lower than a road with many small distresses that add up to the same area. Since the human raters tended to only report large damages, our automated outputs (which report everything), were routinely finding the roads less damaged than reported. This might lead one to believe the software was somehow defective. However, when a human, aided by the (very accurate) depth map, counts all the damages, we report more similar score to the algorithm outputs.

This led us to the following conclusion; we can't call the manual measurements made with rulers and levels the "ground truth"; it is nothing of the sort. It is useful to verify that, when the algorithm says the pothole is 3" deep, that we can show that it was, in fact, 3" deep. But in terms of scoring the roads, we can't use the on-the-ground measurements to create a (valid) URCI score.

The process we adopted to assess algorithm performance is to visually inspect the reconstructed height map (which is verified correct by the spot-sampling done on the ground), extract the distresses one-at-a-time using the mouse cursor and data-ruler, and then use those to (manually) form damage classifications based on the Army manual. It turns out that, while tedious, it is not as onerous as walking along a road in 98-degree heat, trying to locate, and measure, many small distresses.

The process implemented to find and characterize distresses was:

1. Use filters matched to the distress characteristics to detect possible distresses.
2. Assess filter outputs, and reject objects not matching distress characteristics.
3. Classify the resulting detected features according to rules specified in the Army manual.

***Algorithm Performance Evaluation***

Algorithm performance was determined by comparing a manual scoring of the distresses (as determined by careful measurements in the field of select distresses) with the automated outputs of the detection algorithms. It was extremely difficult to measure, by hand, every distress present; it was time-consuming, and error-prone. The algorithm, however, finds even the smallest variations, including ones that human testers would either ignore, or overlook. We saw that humans tended to locate, and measure, only the worst damage. As a result, the manual measurements were used only to verify that the height maps were correct. Locating distresses from the height map visually became the "ground truth" scoring of the road. This was then compared to the performance of the human observer to the algorithm outputs.

The process starts with a data collection by one of the platforms under evaluation. Data were collected from three different collection platforms, single-rotor helicopter UAV, multi-rotor helicopter UAV, and manned fixed-wing aircraft. Locations of interest were selected based on the type of damage present with an unobstructed road surface view. Each section of road was divided into sections of equal length and the select damages noted. Data were then collected using the airborne system. For a detailed description of the road segments and field measurements see the previous part of this section.

Following collection of the airborne data, the imagery was processed and a road score was generated. In the first step of the process the photographs were divided into groupings corresponding to the different measurements collected. Data were grouped according to the road segment, then based on collection platform, then separated by collection altitude and/or collection pass, and finally by sections corresponding to the marked segments for which ground measurements were made. Images not from sections of interest or images collected during takeoff and landing were excluded from analysis.

Following the grouping of the images, each group was processed through the structure from motion (SFM) algorithm. To automate this, a script was written to execute the sequence of algorithms leading to a distress characterization, resulting in an output XML file containing the report of the damages for that section of road.

To properly perform the evaluation of the algorithm, each intermediate step in the process must be checked to verify a valid output. Overall performance depends entirely on the correctness of each step. In particular, the absolute correctness of the reconstructed 3D surface is essential. For evaluation purposes here, intermediate outputs from the algorithm not usually displayed to the user will be presented. This will demonstrate the accuracy of the process, as well as provide indicators of potential problems.

Before running the algorithm, it is necessary to have collected good imagery. Photographs of the road must have sufficient angular diversity and ground resolution for construction of an accurate 3D height map. Unfocused images, or ones with motion blur, will not result in an accurate 3D surface. Shown in Figure 45 is a point cloud generated from good images. Figure 46 shows a point cloud generated from images that possessed too little angular diversity. This manifests itself as “noise” (large variations) in the locations of the point cloud not associated with “real” height variations. These will result in poor estimations of road surface conditions. It should be noted, at this point, that good reconstructions are always assured if the system is configured as recommended, and the ConOps are followed.

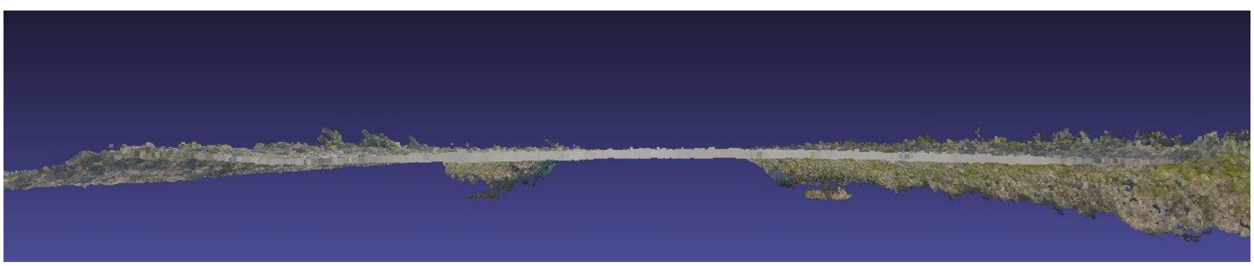


**Figure 45: Good point cloud**

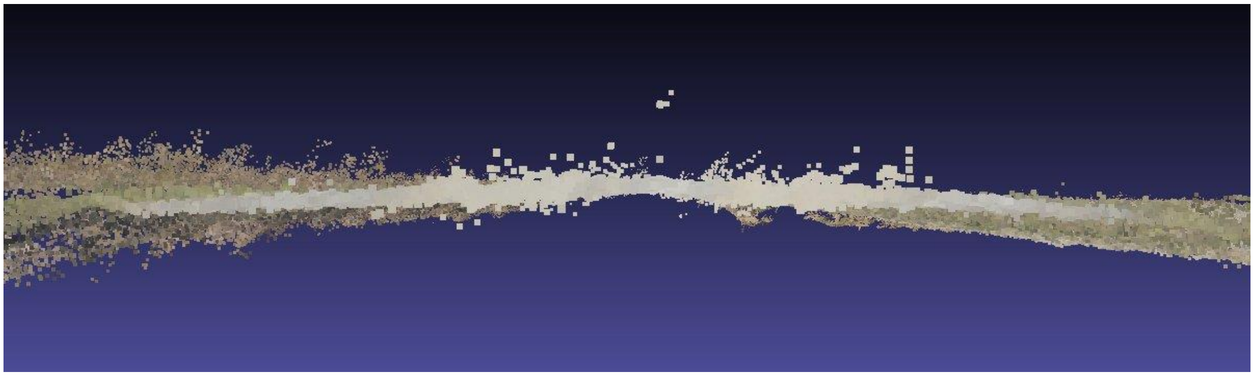


**Figure 46: Noisy point cloud**

Since the height map derived from the point cloud is the 3D reconstruction on which all subsequent evaluations are based, this height map must correspond to actual depths on the road to determine accurate classifications of damage. Height maps from sections of road with good reconstruction were compared against known measurements from those roads (taken manually). The depth values in the height maps have been verified to be within the required measurement error (1 inch).

Once the height map was verified to be accurate, it was used to generate damage scores in the same manner as described in the URCI Manual. A two dimensional version of the height map was displayed with colors representing the z-values (heights). The following performance discussion is based on the evaluation of 45 road segments at 7 different sites. Roads and segments with insufficient imagery resulting in poor reconstruction were excluded from analysis. Analysis was performed for sections from Palmer Rd., Piotter Rd., Welch Rd., Marsh Rd., Fleming Rd., and two roads in Iowa with no damage. Piotter Rd. was visited twice in two different years. Piotter Rd., Welch Rd., and Marsh Rd. each have more than one measurement per visit.

***Potholes:***

Potholes were visually identified and their sizes estimated. This was done by first getting an average z-value from around the top of the pothole. These points were also used to calculate the average diameter of the pothole. Then the z-value from the bottom of the pothole was used to calculate the depth. The potholes were then classed according to standard procedure. Shown in Figure 47 is a color coded height map with potholes numbered. Table 3 contains the manual score for those potholes.

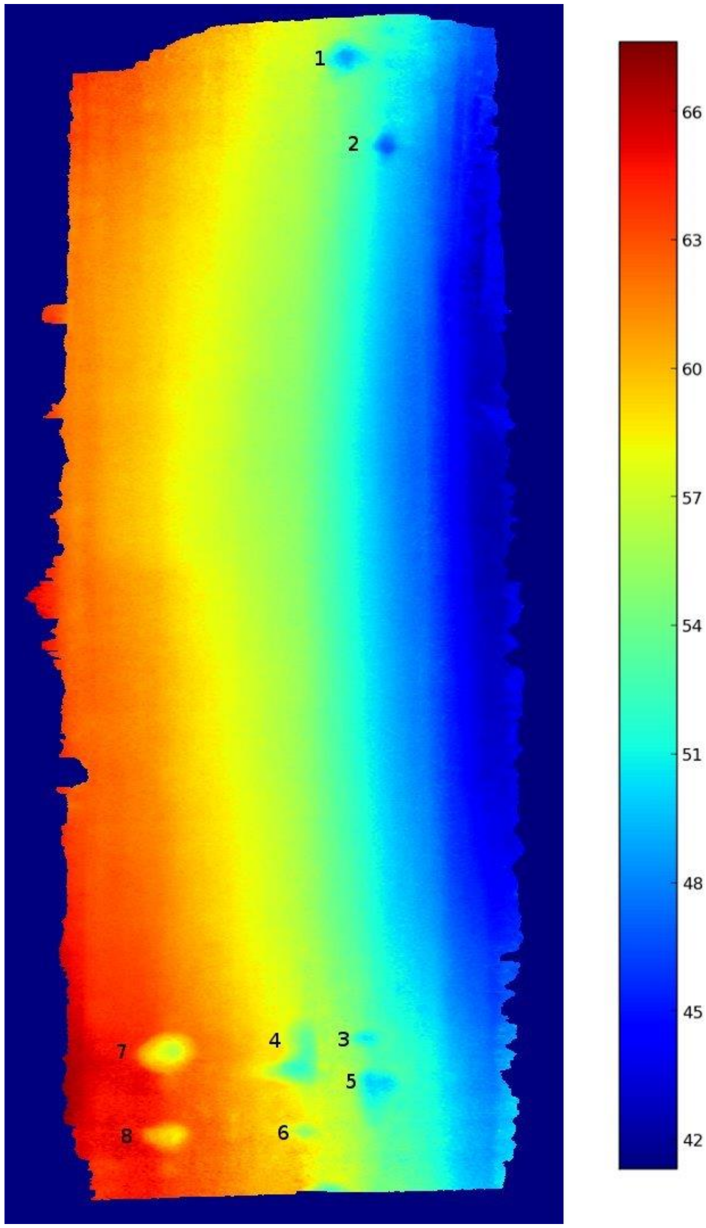



**Figure 47: Height map of a 30m road segment with potholes. Values in cm.**

**Table 3: Manual Score of potholes**

| Pothole | Manual Classification |
|---|---|
| 1 | M |
| 2 | L |
| 3 | L |
| 4 | H |
| 5 | M |
| 6 | L |
| 7 | H |
| 8 | H |

When measuring and classifying potholes, it is important to note that determining the extent of a pothole is highly subjective. Since potholes do not have uniform shapes or slope between the edge of the top of the pothole and the bottom, determining where the pothole begins and ends is dependent on the human making the assessment. Variations in depth also arise if the road surface around the pothole is not flat. For example, a large pothole in a road with a sloped surface would have different depth measurements referenced to the middle and edge of the road sides of the pothole. In manual evaluations of pothole depths and areas, a single point in the pothole is estimated. The algorithm is able to look at the entire region containing the pothole to make its assessment.

A comparison was made between the manual damage classifications and the algorithm. Several road sections representing different roads or measurements on the same section were randomly selected for analysis. Road segments having poor reconstruction were excluded from analysis. Table 4 shows the comparison of manually detected potholes to potholes detected by the algorithm. The probability of detection is the number of potholes the algorithms finds divided by the “true” number of potholes, as determined by visual inspection. The probability of false alarm is the number of falsely declared potholes divided by the true number of potholes.

**Table 4: Pothole detection comparison**

| Potholes | Detected Potholes | Potholes misidentified | Probability of Detection | Probability of False Alarm | Probability of Correct Classification |
|---|---|---|---|---|---|
| 101 | 96 | 4 | 95% | 4% | 96% |

***Loss of Crown:***

The height map was also used to generate damage values for the crown. The segment cross section was measured visually at ten points (approximately every 10 feet) and heights at the edges and middle of the road were measured to determine the difference. The width of the road at those points was used to calculate a slope for each side of the road. The side of the road with the worst damage was used to classify the segment. The slope value was then used to classify the severity of the damage. Table 5 shows the metrics used to classify crown damage. Negative grades represent a road edge higher than the middle. Crown damages for this section of road are shown in Table 6. The total segment length was divided by the number of cross sections and this number was multiplied by the number of cross sections having the same score. This gives a linear distance along the road of a specific damage level.

**Table 5: Crown Damage Metrics**

| Damage Class | Surface Grade |
|---|---|
| None | 3% < Grade |
| Light | 0% < Grade < 3% |
| Medium | -2% < Grade < 0% |
| High | Grade < 2% |

**Table 6: Crown damages measured manually**

| | Width (cm) | Crown A (cm) | Crown B (cm) | Grade A | Grade B | Min Grade | Damage |
|---|---|---|---|---|---|---|---|
| 1 | 535 | -8.1 | 10.9 | -0.0302803 (-3.02%) | 0.0407476 (4.07%) | -0.0302803 (-3.02%) | H |
| 2 | 537 | -7.4 | 11.5 | -0.0275605 | 0.042830 | -0.0275605 | H |
| 3 | 545 | -7.5 | 12 | -0.0275229 | 0.0440366 | -0.0275229 | H |
| 4 | 519 | -7.1 | 13.1 | -0.0273603 | 0.0504816 | -0.0273603 | H |
| 5 | 550 | -7.3 | 12.9 | -0.0265454 | 0.0469090 | -0.0265454 | H |
| 6 | 539 | -7.5 | 13 | -0.0278293 | 0.0482374 | -0.0278293 | H |
| 7 | 537 | -6.4 | 13 | -0.0238361 | 0.0484171 | -0.0238361 | H |
| 8 | 530 | -6.1 | 12.6 | -0.0230188 | 0.047547 | -0.0230188 | H |
| 9 | 525 | -5.2 | 12.6 | -0.0198095 | 0.048 | -0.0198095 | M |
| 10 | 520 | -7.2 | 11.7 | -0.0276923 | 0.045 | -0.0276923 | H |

In evaluation of crown measurement performance, it is important to note that the manual crown measurements were taken only a few times in a segment, and without regard to where the crown may have looked better or worse (they were evenly spaced). The process involved a water-level, two people (one in the road center, and one at the edge), and a tape-measure. The team would move to the measurement spot, and record only the crown at this point. Thus, it is likely that much of the crown variability went unmeasured. The automated detection, in contrast, takes a crown estimate at 1-inch intervals, averages them, and then produces a classification. This results in a much more accurate output in all cases than the manual estimates. Table 7 compares the crown values.

**Table 7: Comparison of crown values.**

| Damage Class | Manual Score (meters) | Algorithm Score (meters) |
|---|---|---|
| L | 0 | 13.67 |
| M | 2.7 | 12 |
| H | 24.3 | 0 |

***Ruts:***

To evaluate algorithm performance on ruts, ruts were identified from the height map visually and then area and severity measured. Shown in Figure 48 is the height map from a road segment with a large rut along the side. This rut was visually estimated to be of low severity and 34.4 square meters.

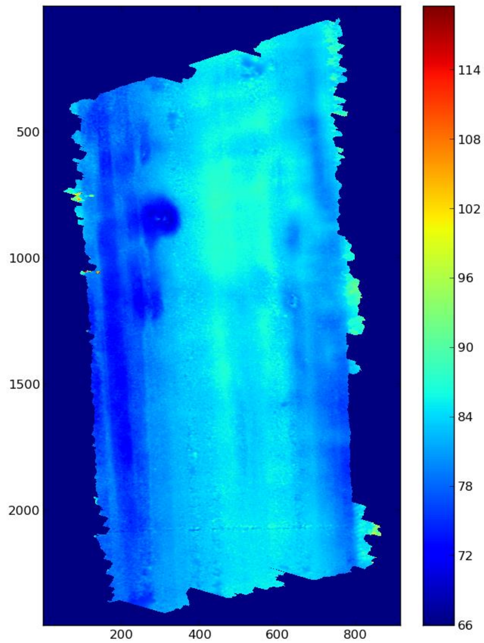



**Figure 48: Height map of a 15m road segment with a rut. Values in cm.**

Rut classifications were first evaluated on correct identification of areas with ruts. Road segments were visually assessed on the presence of ruts. The algorithm's detection of ruts was then compared against this manual score. The algorithm found most areas where ruts were visually detected. Missed detections occurred with very short ruts, essentially elongated potholes. False alarms occurred in areas where corrugations were present. Shown in Table 8 is the probability of detection and false alarms with rut detection.

**Table 8: Rut Detection**

| Probability of Detection | Probability of False Alarm |
|---|---|
| 67% | 19% |

We attribute the difference in visual and automatic performance to the fact that the algorithm parameters controlling the detections were not "tuned" to match how the rater was identifying the features. We discuss this later.  But much like potholes, ruts have irregular shapes and their size estimates must be visually classified. In the field, ruts were often seen to have small ridges along the edges caused by displaced material. Depth measurements referenced between this ridge and the ground would be higher than measurements referenced to the road surface. In addition, rut depth was only manually measured at one or two locations along the rut. The algorithm is able to classify the rut along its entire length to generate a score. We have observed that the algorithm classifies approximately 30% of detected ruts into a lower rating than the manual rating.

***Corrugations:***

Corrugations (washboarding) were also scored in the same manner as ruts. Shown in Figure 49 is an example of a road segment exhibiting corrugation. Since this segment contains corrugations along most of the length, manual measurements were made at 6 arbitrarily selected points along the length. The measurement used to rate the distress was taken at the most severe point of damage. The width was measured and the corrugations assumed constant over the length of the 6 sections. In this segment the road was manually scored to have 40 square meters of medium damage.

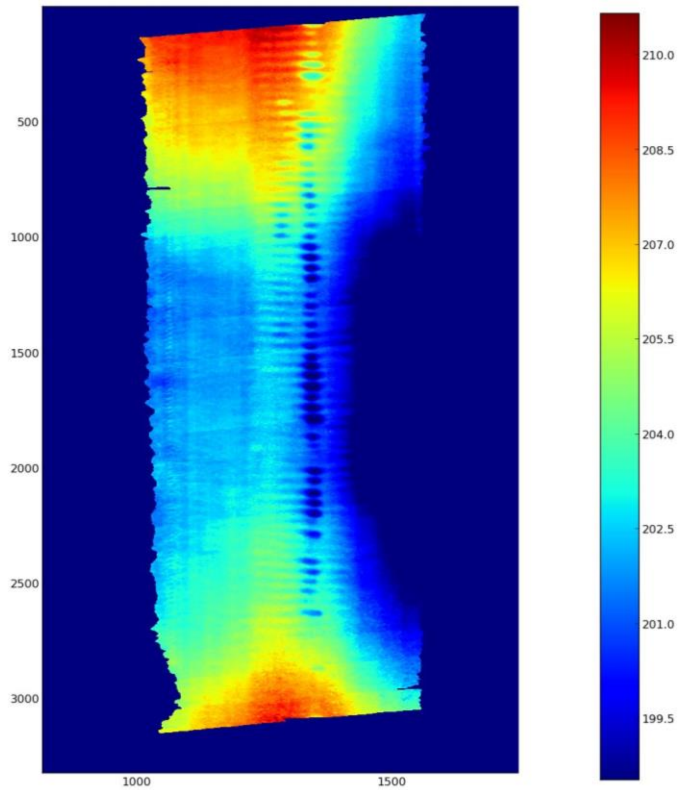



**Figure 49: Height map of a 30m road segment with corrugation.**

Road segments were visually assessed to see if corrugation was present anywhere on the road. The algorithm was then compared with the manual detection. The algorithm correctly identified all areas where corrugation was visually assessed to be present. The algorithm found other areas with features similar to corrugations in areas where reconstruction noise was present, and declared them as corrugations (i.e. false alarms). The probability of detection and the probability of false alarm are shown in Table 9.

**Table 9: Corrugation Detection.**

| Probability of Detection | Probability of False Alarm |
|---|---|
| 100% | 38.5% |

When manually scoring corrugations, it is not practical to measure all the variations. However, the algorithm assesses the corrugations at a much finer detail. This means that in a manual measurement, the entire area will be scored according to the worst damage present. The algorithm identifies 58% of the area of corrugation that was manually scored. Shown in Table 10 is a comparison of the algorithm performance compared to a manual classification. Our assessment so far is that corrugation classification needs further development for ready usage.

**Table 10: Percent Total Area of Corrugation Damage Classification.**

| Classification | Manual Classification | Algorithm Classification |
|---|---|---|
| L | 25% | 0% |
| M | 75% | 30% |
| H | 0% | 70% |

***Loose Aggregate:***

There were no roads found with excessive loose aggregate. But the "loose aggregate finder" is just the rut algorithm, locating "inverted ruts". The performance should be comparable to the rut performance. This process is unable to differentiate a road surface completely covered in loose gravel from one without loose gravel.

***Discussion of Performance Evaluation***

Although we attempted to remotely sense the road conditions from a fixed-wing aircraft, the combination of pointing inaccuracies, and the lack of angular diversity (due to altitude effects), led to poor 3D reconstructions. These were not of sufficient quality to make road distress measurements. The following discussion applies only to UAS-based measurements.

The algorithms' performance was evaluated by comparing the result of manual scoring of the height map. The measurements made on the ground served to verify the accuracy of the height map. We are not using those measurements as "ground truth" because we have seen that the manual distress characterization is very dependent on the skill and experience of the rater. Two raters may get different assessments of road condition in cases where the distresses are generally mild. This variability is eliminated by automating the process, which can lead to greater confidence in the overall assessment of network conditions.

The software performs well at correctly forming the height map of the road surfaces (for data collected with the UAS/UAV). In all cases where the image quality was within specifications, the height maps were noise-free, and within required resolutions. Since this map forms the basis of all subsequent distress characterizations, it must be as accurate as possible.

There are some things to note about the current implementation:

1. Sometimes ruts that have deep sections will be identified both as potholes, and ruts (Figure 50). The algorithm could be modified to detect ruts first, then exclude that section of the road from further distress detections.
2. Strings of potholes along the driving direction can be characterized as corrugation (see Figure 51 for an example of this). Again, the algorithm could be modified to prevent this.
3. Roads with a strip of grass in the road surface have poor reconstructions in that region. This causes false alarms (see Figure 52). The algorithm could be modified to handle these situations.

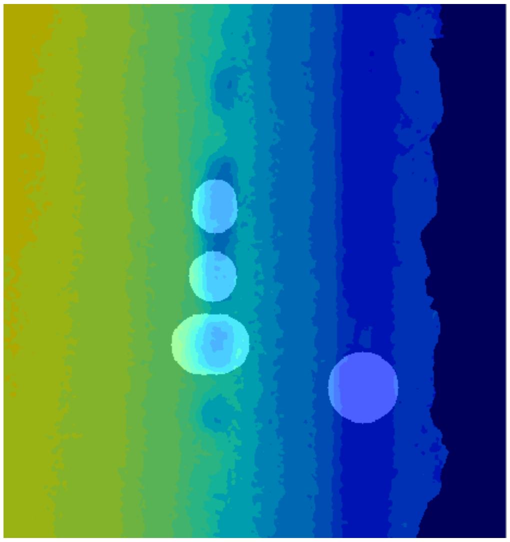


**Figure 50: Pothole Detection in Rut.**

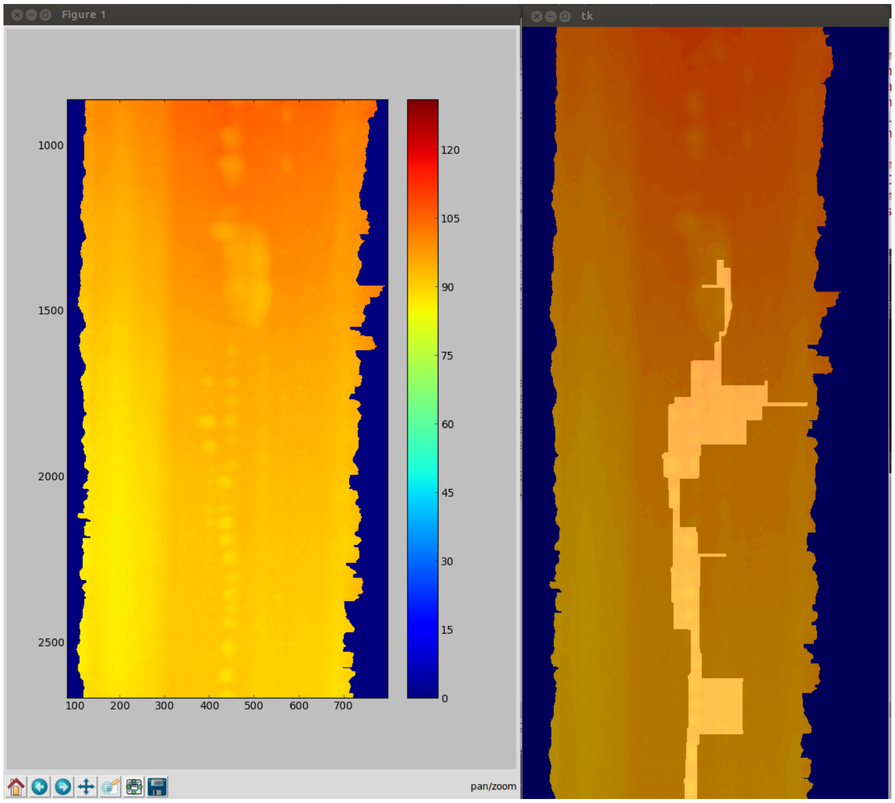



**Figure 51: On left is the original image, showing potholes in a line. On the right is a mask showing the detected corrugations.**

**Figure 52: Road surface with grass strip that causes noisy reconstruction and false pothole detection.**

We have shown that the detection of distresses is above 93%, and tends to be better for potholes. The false-alarm rate (i.e., declaring a distress when there is none) is less than 14%, and many of these were potholes found at the very edges of the road; the number could be improved, if necessary, by reducing the size of the mask used to evaluate the distresses. Once a distress is declared 96% for potholes and 70% for ruts are classified into their distress severity categories correctly. Correct classification of corrugation is 23%. The variability inherent in manual measurements due to experience and visual estimation results in measurements much coarser than the algorithms' and it extrapolates damage severity levels to larger areas than the algorithm.

There is, however, a process to make the algorithms' output closer to a human rater, called "supervised training". One would first have an experienced rater (which we lacked) score a number of road segments. One then performs a process to adjust the parameters that control the algorithm detection and classification to produce results close to the human rater. This process was not performed on the current parameters.

Although dust was not one of the distresses that we needed to measure, we noticed that, in cases where the road had very fine-grained material, we could detect and measure tire-tread patterns. In fact, they were sometime detected as corrugations, although would be excluded because they did not meet the height requirements. It may be that the existence of the tread-marks could serve as an indirect measure of fines (although their absence would not imply the lack of fines).

It should be noted that these algorithms all have multiple parameters on which their performance depends, sometimes in a complicated way. We have attempted to choose an operating point for all algorithms that balances detection and classification accuracies with acceptable false-alarm rates. However, different users may find that they must have more (or can accept less) accuracy; the algorithms can be adjusted for better detection rates, at the expense of increased false alarm rates on an application-by-application basis.

In some cases, there may be a need to assess, for example, the accuracy or consistency of a repair. In this case, it is easy to examine the height maps visually, and "measure" the crown, etc. from the displayed height map. Similarly, one can quickly score a road just by looking at the height map; the distresses are visible clearly when the map is displayed on an exaggerated height scale. This could serve as a "quick-look" capability when a complete characterization is not needed, or when the DSS need not be invoked.

***Cost Performance Notes about Performance Evaluation:***

We recommend being careful in making cost comparisons between remote sensing and manual characterization of road conditions. That is because the remote sensing output (which is abstracted for reporting purposes) is a centimeter-by-centimeter characterization of every part of the road segment. The manual output (compared to the automated output) is, at best, an overview of the road condition. In cases where details are important, these comparisons do not make real sense; getting the same level of detail manually is not only cost prohibitive, it is essentially impossible.

It has been shown that the UAS-based system has a per-mile cost of $0.74 (see the comparative cost section). This would be in addition to the cost of the use of a vehicle ($0.55/mi) to transport the UAS to the measurement site (which is the same cost as driving to the site to perform a manual measurement). The UAS system is actually more cost effective than purely manual rating that tried to gather the same amount and precision of data, while also providing the benefits of vastly more detailed, consistent, and accurate characterizations.

In contrast, we estimate that the manned, fixed-wing solution would cost, under reasonably generous assumptions, to cost $10.26 per mile (or worse). The advantage of such a system is a great reduction in time spent per mile, at an increase in cost. The fixed-wing system is significantly more complicated in practice than the UAS-based system, guiding us towards our hexacopter-based system to be more ready for practical deployment for unpaved road condition assessment.

## Section IV: Concept of Operations Description (ConOps)

We have been developing the detailed description of the process of collecting and processing data. This is the so-called "Concept of Operations" (ConOps). The ConOps includes instructions for selecting sites, developing flight plans, pre-flight checks, sensor setup, flight operations, data quality checks, and data selection. Once data are selected, the processing is generally automated up to the point of handing the results to the RoadSoft GIS decision support package.

### *Background*

The first step in assessing unpaved roads is to collect the data that will be used to extract road distresses. Since we evaluated two different collection platforms (manned and unmanned), there will be slightly different ConOps for each. In the discussion to follow, the more detailed unmanned ConOps will be described, with comments about the manned platform in cases where they differ.

There are two possible ways in which a system may be used for data gathering. There is an "in-house" option, where the organization dealing with roads also owns and operates the sensor, and as a contracted service from a company specializing in the data collection (and possibly processing). In the case of a manned platform, in-house ownership and operation are a significant expense, both initially to purchase the aircraft and pilot, and ongoing, for maintenance and operation. We assume that this is unlikely. However, owning and operating a small UAV (also called an Unmanned Aircraft System or UAS) is well within most county agency budgets. For the purposes of this document, we will assume the in-house, unmanned model, and describe those ConOps; the contracted service option would be significantly simpler from the point of view of the customer, since the service organization would be performing the ConOps internally.

### *System Preparation*

The process begins compiling the system and accessories needed to perform a data collection. These include:

1. Platform parts, including the aircraft, batteries, controllers, downlink (if used), and tools for adjusting and mounting things.
2. The sensor, including the camera, lenses, batteries, memory, and intervalometer (used to set the frame rate at which photos are taken).
3. The mission-planning/ground-control system.
4. Support items such as traffic-cones, safety equipment such as vests and goggles, and survey tools, such as tape-measures, marking paint, etc.

As in many processes, a checklist can assist the user in making sure that key steps are not overlooked. As an example, consider the list below as a start for a multi-rotor system preparation checklist:

- Charge all flight batteries
- Charge avionic support batteries (radio, camera, intervalometer, on-screen-display (OSD), etc.)
- Spare rotors (both left and right pitch)
- Tools-kit for platform maintenance and site observations
- Video monitor for OSD
- Tripod
- Battery charger(s)
- Mission-planning system
- Radio controller
- Camera, including lenses, memory cards

- Spare Velcro, zip-ties, and duct-tape
- Road-cones
- Safety glasses
- Safety vests

Once the system components are ready, one needs to select a mission.

### *Site Selection and Mission Planning*

The user needs to select a site to collect. If multiple sites are chosen, their locations should be chosen to minimize flight times and transport between sites. For the unmanned systems we tested, there is a tool that allows one to look at a site from an overhead view (using Google Earth), evaluate obstructions, choose flight lines and site access, and load a flight-path, as first described for this project in Roussi et al. 2012a – Deliverable 6-A (see http://geodjango.mtri.org/unpaved/media/doc/deliverable_Del6A_MissionPlanningSystemReport.pdf). The platform may be programmed either during this process, or on-site, depending on the users' preferences. If fully autonomous flight is not being planned, then the programming step can be skipped.

The mission planning should include at least the following:

1. Launch and recovery locations, with an estimate of needed flight-time and distance traveled. (For a manned mission, it may be necessary to file a flight-plan if the roads are within certain classes of airspace. It is up to the pilot to determine this during mission planning.) Care should be taken to estimate the battery use based on these factors, as well as temperature and wind conditions (since hot, dry weather or high winds will reduce effective flight times). At no time, should usage exceed 75% of battery capacity, to allow for unexpected on-site maneuvers.
2. Verification that the flight path is unobstructed. This includes visual obstructions of the surface, as well as objects in the flight-path, such as power-lines, towers, etc.

Verification that the "fail-safe" return path (taken in the event of radio loss) remains unobstructed throughout the flight-path

### *System Deployment and Pre-Flight Checks*

Once on-site, the system must be deployed in an orderly fashion. A small area to one side of the road is needed for system checks. Again, a checklist can be useful. Consider this example hexacopter checklist:

Hexacopter Pre-Flight Checklist

[ ] Arms deployed and secure
[ ] Props secure and shafts vertical
[ ] Wiring harnesses secure
[ ] All chassis screws/connectors tight
[ ] TX in GPS Mode
[ ] TX Failsafe OFF
[ ] TX Throttle Trim LOW
[ ] TX Rudder, Aileron and Elevator Trims NEUTRAL
[ ] AUX4 - NEUTRAL (not in POI or HOME mode)
[ ] TX Throttle LOW
[ ] Camera platform horizontal
[ ] Power-ON TX
[ ] Power-ON Aircraft (26,000mAh)
[ ] Power ON Video Downlink

[ ] Power ON DVR
[ ] Camera lens-cap OFF
[ ] New card inserted in camera
[ ] Power-ON camera and set mode, exposure, aperture
[ ] Power-ON Camera Controller
[ ] DVR to REC
[ ] Test camera platform
[ ] Aircraft HOT Verify Adequate Satellite Link (no red flashes)
[ ] Aircraft HOT Test Spool-up
[ ] Aircraft HOT ……ready for launch

This particular checklist is detailed and specific to the radio controller and autopilot being used. It is important that all switches on the controller be checked; if something is in the wrong position, unexpected behaviors can result, with possibly dangerous outcomes.

For a manned mission, the checklist for the pilot would include the normal checks of aircraft flight-readiness, and include the checks for the camera and controller.

### *Flight and Data Collection*

At this point, the road should be closed to through traffic for several reasons. Vehicles moving through the scene may obstruct features, preventing their reconstruction. Also, if there is a failure in flight, this ensures that the aircraft is not run over (should it have to land quickly) and that vehicles are not hit with falling debris, which can cause direct damage, or loss of control by the driver, causing secondary damage. For a manned mission, this is not necessary, although traffic on the road can prevent full reconstruction. As technologies advance, we would anticipate the ability to not close roads for UAV-based collections, but we recommend caution for the time being to ensure safety.

Once the road is secure, flight operations can begin. Although fully autonomous launch is possible, it is preferred to take off manually, verify that the aircraft is behaving normally at a low hover, point the camera platform at the ground, take it to altitude, and then commence autonomous flight. This gives one extra confidence that preparations were complete.

During the data collection, there should be a trained pilot either in control, or ready to assume control, at all times. It is also desirable to have a second “spotter” keeping track of the OSD outputs (such as battery voltage, speed, and altitude), while the pilot keeps track of the aircraft attitude and flightpath. This is especially important if flight conditions are severe, since the pilot should not be distracted.

The typical unmanned flight parameters used during this program are listed below.

- Altitude 20m-30m (with a 50mm prime lens) – this ensures that the road and ditches are fully imaged. Lower altitudes provide better resolution, while higher altitudes provide more overlap between images.
- Forward velocity: 2m/s – this reduces motion blur, while providing a reasonable speed.
- Camera controller set at 2 frames/sec – this gives enough overlap in adjacent images to obtain high-resolution 3D reconstruction.
- Camera in manual exposure mode with shutter speed <= 1/500s, aperture 2 stops from full open, and ISO adjusted for proper exposure – this ensures that there is no motion blur, images are crisp across the entire field-of-view, and that they are properly exposed.

The typical manned parameters are somewhat different:

- Altitude ~200m (with a 200mm lens)
- ~60kn airspeed (ground speed should not exceed ~75kn)

- Camera controller set at 2fps
- Camera in manual exposure mode, with settings as listed above

At the end of the unmanned flight, although auto-landing is possible, this is time-consuming, and it is preferred that the pilot take over and land the aircraft manually. This is particularly important when the mission is approaching the maximum time-limit.

### *Post-flight Checks*

Once the UAS has landed, there are some steps to end the process.

[ ] Throttle to LOW
[ ] Power-OFF camera
[ ] Camera lens-cap ON
[ ] Power-OFF camera controller
[ ] DVR to STOP
[ ] Power-OFF Aircraft
[ ] Power-OFF TX
[ ] Power-OFF Video Downlink
[ ] Power-OFF DVR
[ ] Stow hexacopter and gear for transport

At this point, it is likely to be worthwhile to verify that the data that were collected are acceptable in terms of focus, exposure, and overlap. A typical collection will consist of 1 image per meter of road imaged. This corresponds to 20GB of data per kilometer for this sensor.

### *Administrative Issues*

It should be noted that current (as of October 2013) FAA regulations do not adequately address UAS operations for private entities. At this time, establishing a commercial service to perform these measurements is prohibited by 2007 FAA guidelines. The FAA document 14 CFR Part 91 (http://www.faa.gov/about/initiatives/uas/reg/media/frnotice_uas.pdf) specifically excludes individuals or companies flying model aircraft for business (commercial) purposes. This may change by 2015, when the FAA has to have established regulations dealing with Unmanned Aerial Systems (UASs) in the National Airspace System (NAS). The same document also prohibits UAS flights within the NAS without prior approval. For public entities (such as the USDOT), the process of operating a UAS involves obtaining a Certificate of Authorization (COA) for a particular mission. Each mission must have its own COA, which effectively prevents the current use of UASs for arbitrary unpaved road assessment. Thus, under current FAA guidelines, there is no way to deploy an unmanned system for this purpose. However, some agencies with COAs have been able to get them reapproved within relatively short time periods (< 1 month), thus allowing some practical current usage. The FAA has stated that it expects to have small UAS (sUAS) regulations formulated by 2015 and we expect these will significantly increase the practical usage of UASs for unpaved road assessment.

In November, 2013, the FAA released their “roadmap” for integration of civil UAS in the NAS[1]. It says, in part, “Ultimately, UAS must be integrated into the NAS without reducing existing capacity, decreasing safety, negatively impacting current operators, or increasing the risk to airspace users or persons and property on the ground any more than the integration of comparable new and novel technologies.” They recognize that the rules and regulations that have been established (and which been very effective at ensuring safe operations) for manned aircraft do not map well onto UAS operations. In particular small UAS (sUAS) are called out as exceptions to most of the expected regulations (e.g. design and airworthiness certifications, filing IFR flight plans, etc.). The FAA UAS Comprehensive Plan[2] states “A Notice of Proposed Rulemaking (NPRM) on small UAS is under development with the intent to provide safe small UAS access to the NAS. The NPRM for small UAS is being drafted and is targeted for release in 2014.” The first two stated goals are to allow both public and civil sUAS VLOS operations in the NAS without special authorizations (i.e. COAs or Special Airworthiness Certificates). Based on these documents, it seems likely that regulations allowing sUAS operations in line-of-sight (LOS) without prior certification or approval will be in place within the next several years. This is what we expect will make deployment of small Unmanned Aerial Systems much more practical for transportation infrastructure assessment, including unpaved roads.

In contrast to sUAS operations, deploying a manned system is quite easy at this time, although if any of the sites lie under anything but Class G (uncontrolled) airspace, the procedures can become more complicated for the pilot (especially if any of the sites lie under Class B airspace, around major metropolitan areas).

[1] http://www.faa.gov/about/initiatives/uas/media/UAS_Roadmap_2013.pdf

[2] http://www.faa.gov/about/office_org/headquarters_offices/agi/reports/media/UAS_Comprehensive_Plan.pdf

## Section V: Comparative Cost Analysis

### Background Considerations for Data Collection Costs

Data collection is usually the single largest cost in an asset management program, so effective management systems need a source of reliable, low cost data. Challenges when comparing the costs of distress data collection for unpaved roads include the comparison of equipment versus labor requirements across methods, the differences in labor requirements, and unavailability of reliable sources of cost information.

Most distress data collection methods are labor intensive and have few capital equipment requirements (Department of the Army 1995, Huntington G. 2011a, Cline 2003, UNH TTC 2011, Goodspeed 1994, WTTC 2010, Walker 2002 2011) so they can be easily compared to each other. Remote sensing methods can require significant capital investment; in this project's primary example platform, this includes the purchase of a UAV, the sensor, and associated software for image analysis. Automated methods that rely on equipment are difficult to compare to labor intensive methods because of these large capital investment costs for equipment and accompanying amortization assumptions which can greatly influence the outcome of the cost comparison.

Reliable cost information for unpaved road distress data collection is largely unavailable in published literature; very few studies that consider data collection efficiency or costs exist. Most cost information that is available for unpaved road data collection is from practitioners who have a history of collecting data with a specific method. In most cases this cost data is only available in the form of production rate estimates rather than formal studies. In some cases, cost information for collection of distress data for paved roads can be used to estimate costs for unpaved road collection due to the similarity of the methods, but it should be noted that when this is done, it is not an exact comparison (Huntington 2011 2013, Cline et al. 2003, Goodspeed 2011 2013, CRAM MDOT n.d.).

This cost analysis compares the costs derived from available information from several methods of unpaved road assessment and remote sensing data collection. Only methods that collect the Unsurfaced Road Condition Index (URCI) data are a direct comparison with the level of data that is produced by the remote sensing system developed for this project because the remote sensing system reported here was developed to collect URCI input data, such as the amount and severity of potholes, washboarding/corrugation, and ruts along with crown levels. Other data collection costs reported here were estimated for rating methods such as PASER and RSMS. However, it should be noted that the URCI, RSMS, and PASER method vary in terms of labor, with PASER being the least intensive, URCI the most intensive, and RSMS method falling somewhere in the between. It should also be noted that PASER and RSMS condition assessment methods produce different types of data than the URCI method, so they should not be directly compared to the remote sensing system.

### Cost Basis Assumptions

Total costs for a particular rating method can be greatly influenced by assumptions made in the analysis. To compare costs across methods, assumptions were made by the research team to illustrate conditions that a transportation agency would likely encounter during data collection and for arriving at a total cost. In this cost comparison the following general assumptions are made:

- Only drive time of actual collection is included, it is assumed that the URCI method will require the same amount of transit between locations regardless if it is UAV collected or manually collected with an observer, because in both cases the representative analysis segments have to be visited..
- The majority of the roads are moderately distressed sections with multiple distresses and severities.

- Trained/experienced raters are rating efficiently (no training time or learning curve).
- Labor costs are similar for all staff completing activities: $40 per hour for trained technician or engineer.
- Capital costs for significant, specialized equipment (single use equipment or software not likely to be normally present at a transportation agency) will be amortized over its assumed useful life. Standard equipment like handheld GPS or office computers are assumed to be available at no cost as agencies are most likely to already own these.
- Cost data that is more than a year or two old will be equated to 2013 costs using a consumer price index calculator.

Calculations are provided here for each method. Assumptions should be modified as agencies deem necessary for their own priorities.

**Manual Unsurfaced Road Condition Index (URCI): Wyoming, Ground Truth**

The URCI method was originally developed as a manual data collection method using simple measuring devices and paper collection forms (Department of the Army 1995). The process is relatively labor intensive because each distress type and severity must be field measured and recorded by hand; however, it provides a relatively complete picture of the severity of unpaved roar distress. Samples are collected that each represent larger parts of the road network. Typically two-100 foot long sample segments can represent up to one mile of road. The identification of sample segment locations from year to year can be difficult since they are usually manually marked with stakes which may be removed or damaged from year to year (Department of the Army 1995).

Two sources of data were available for production rates and cost estimates for URCI manual collection. Phone interviews were conducted with George Huntington, P.E. from the University of Wyoming – a source familiar with all types of unsurfaced road condition assessments – (Huntington G. 2011a) and ground truth collection efforts completed during this project – to verify remote sensing efforts and to determine a production rate for URCI standard data collection.

Huntington conducted extensive unpaved road assessments using multiple road distress identification methods over the last several years in an effort to assist local and state road agencies management of increases in unpaved road distress in the state of Wyoming (Huntington G. 2011a). According to estimates from Huntington, a team of two trained people can collect URCI data on a road sampling segment in approximately 30 to 45 minutes once they have identified the sample site (Huntington G. 2011a). An additional 30 minutes (one person) was necessary to calculate deduct points and tally the final URCI rating using the manual curve graphs for each sampling location.

***Cost estimate for Wyoming Manual Unsurfaced Road Condition Index (URCI)***

- Assessment – 2 staff x $40/hr x 0.75hr + 1 staff x $40/hr x 0.5 hr = $80 per segment
- Assume 2 sample segments per mile of road represented = $80 x 2 = $160 per mile of unpaved road in the network

The purpose of ground truth verification was to collect data from the sample locations to compare it to the data acquired by the remote sensing system for at least spot-checking of analyzed results. Two person teams evaluated the distress extent and severity using basic measuring devices (hand tapes and wheel tapes) for ground truth verification. For distress quantification of the cross section and drainage condition a rapid and accurate measurement system using a water level and tape measure was applied. Ground truth collections were more intensive than standard production data collection as indicated by the increased time of collection, thus these measurements most likely provided more accurate data, but also lead to higher cost per mile. The amount of time to collect the data also depended on the severity of the distresses; we found that sites with dense distresses could take up to 1.5 hours.

***Cost estimate for Manual URCI Ground Truth Collection:***

- Assessment moderate distress– 2 staff x $40/hr x  1.0hr + 1 staff x $40/hr x  0.5 hr = $100 per segment.
- Assessment high distress 2 staff x $40/hr x 1.5hr + 1 staff x $40/hr x 0.5 hr = $140 per segment.
- $Assuming a  2 sample segments per mile of road represented  = $100 X 2 = $200 per mile of road represented for  moderate  distress
- Assuming a  2 sample segments per mile of road represented = $140 X 2 = $280 per mile of road represented for  high  distress

**Automated and Manual Pavement Condition Index (PCI): Army Cold Region Laboratory**

The Pavement Condition Index (PCI) distress assessment method for paved roads was originally pioneered by Mohamed Y.  Shahin at the Army Cold Region Laboratory (Cline et al. 2003).  The PCI method assesses sample segments for severity and extent of several classifications of distresses.  Field measurements of distresses are used to calculate deduct points which in turn are used to create an overall quality index. The URCI method for unsurfaced roads is a modification of the PCI method (Department of the Army 1995).  The PCI method and the URCI method are very similar in application and assessment.

A 2003 study from Naval Pavement Center of Expertise assessed the cost of PCI data collected by automated and manual means (Cline et al. 2003, see Figure 53).  The study concluded that the cost for either manual or automated collection was approximately the same at approximately $\$0.10/yd^2$ of pavement data collected for areas greater than 100,000 $yd^2$ (Cline et al. 2003).  Since the PCI and URCI methods are very similar, it is likely that PCI assessments can be used to estimate URCI measurements.

***Cost estimate for Pavement Condition Index (PCI) Automated collection***

- Assume a standard road segment with two **-** 12 foot wide lanes by 100 feet long sampling segment.
- Assume $\$0.10/yd^2$ (2003 cost index) for collection costs (Cline et al. 2003).
- $\$0.1\ yd^2$ x 100’ x 24’ /9 $ft^2$/ $yd^2$ = $27 per segment (2003 cost index).
- Assume 2 sample segments per mile of road are represented = $27 x 2 =  $54 per mile of road represented.
- Using a consumer price index calculator from 2003 to 2013 yields costs of $34.23 / segment and $66.10 per mile respectively in 2013 dollars.

The Cline study also concluded that manual data collection costs per yard were significantly higher for smaller areas of collection.  Figure 53 below illustrates the change in cost per square yard for varying areas of assessment.  It is likely that a typical local agency using manual collection would have between 50,000 and 100,000 $ft^2$ of surveyed area each year, which would produce a cost of approximately $\$0.15 / yd^2$ for manual collection (Cline et al. 2003).

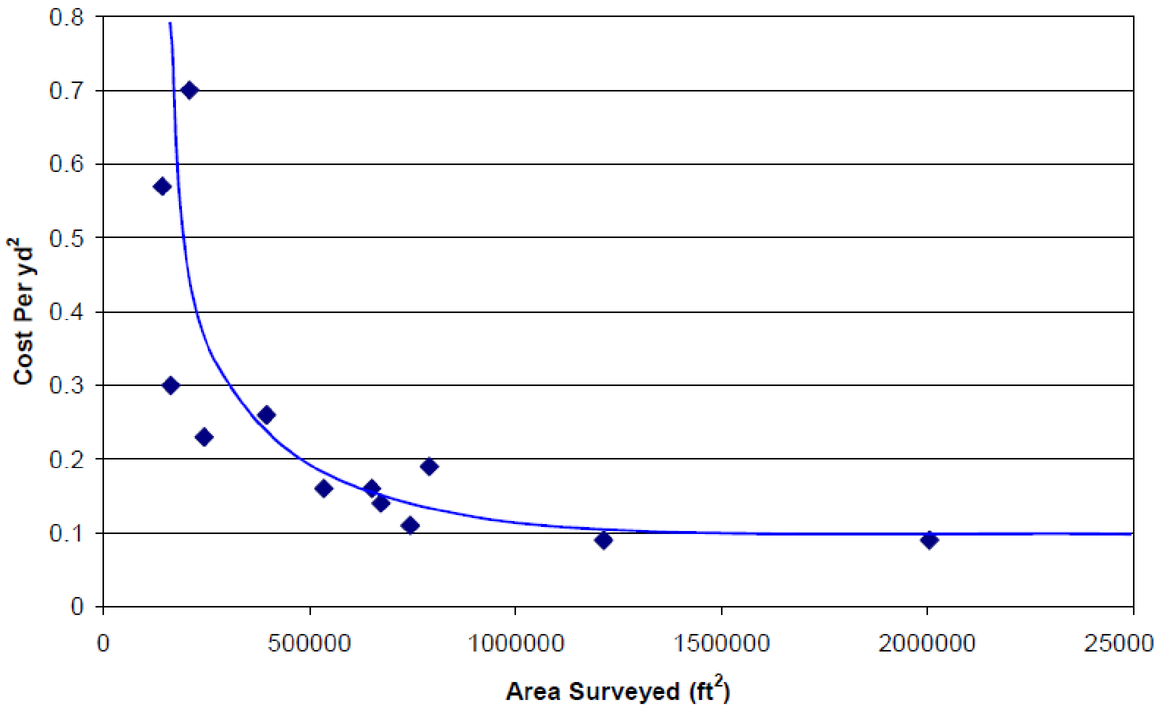



**Figure 53: Manual PCI data collection costs (Cline et al. 2003).**

***Cost estimate for Manual Pavement Condition Index (PCI) collection***

- Assume a standard road segment with two - 12 foot wide lanes x 100 feet long sampling segment.
- Assume \$0.15/yd$^2$ (2003 cost index) for collection costs (Cline et al. 2003).
- \$0.15 yd$^2$ x 100' x 24' /9 ft$^2$/ yd$^2$ = \$40 per segment.
- Assume 2 sample segments per mile of road = \$40 x 2 = \$80 per mile of road.
- Using a consumer price index calculator, costs converted from 2003 to 2013 yields costs of \$50.84 / segment and \$101.68 per mile respectively in 2013 dollars.

**Road Surface Management System (RSMS): University of New Hampshire (UNH)/FHWA**

The Road Surface Management System (RSMS) is a data collection method that generates distress data with a similar level of complexity as the URCI method. The main difference between RSMS and URCI is that RSMS uses visual assessment (Goodspeed et al. 1994) to estimate the extent of distresses while the URCI method relies on physical measurement. Because RSMS relies on visual assessment, it can be completed quickly. However it requires that every mile of road must be driven, inspected and rated during a rating event, as opposed to the URCI method that only requires two 100-foot segments to be measured per road mile. More information on the RSMS method is included in project deliverable 2A – State of The Practice for Unpaved Road Condition Assessment (Brooks et al. 2011b).

According to the University of New Hampshire, a trained rating team using hand held GIS devices can collect rating data for a town of approximately 50 road miles in approximately two days (Goodspeed 2011). Goodspeed (2011) recommended that two people are necessary for data collection, one to driver and one observer. Three passes of road segment are recommended depending on the road segment.

- First pass: This pass determines the length of road segment has and that uniform cross sectional properties exist. This is normally not needed in residential or urbanized areas as a road section is typically defined from one intersection to another.
- Second pass: The observer records the 9 stress characteristics of the road as defined in the RSMS system. Each distress is rated for severity and extent of the severity.
- Third pass: This pass is driven at the posted speed so the roughness of the road can be judged.

According to Goodspeed (2013), 10 to 20 miles a day can be rated depending on the locations of the roads to be rated. More roads can be rated if the roads are densely located. Analysis of the data to develop a maintenance schedule to correct the deterioration takes one or two days (Goodspeed 2013).

***Cost estimate for RSMS (manual)***

- Low productivity estimate: 2 staff x $40/hr x 8 hr/day / 10 miles per day rated + $0.55 per mile for vehicle x 3 passes = $65.65 per mile rated.
- High productivity estimate 2 staff x $40/hr x 8 hr day / 20 miles per day rated + $0.55 per mile for vehicle x 3 passes = $33.65 per mile rated.
- These costs do not include cost of the GPS equipment or software which is assumed to be available at the local agency.

**Wyoming Modifications of the PASER System**

The PASER rating system is a visual distress rating system that uses the presence and extent of road distresses to characterize unpaved roads into one of four or five rating categories for an overall characteristic of the road in question (WTTC 2010). The level of data that is produced by PASER is much less detailed than the URCI method, because each sample is only represented by the rating category it is placed in; no intermediate measures are recorded for specific distresses. Fewer visual rating categories allows for rapid data collection for PASER compared to the higher investment of time required to collect quantitative data in the URCI method.

Staff from the University of Wyoming modified the PASER system to include additional criteria for rating that included an assessment of comfortable riding speed (WTTC 2010). More information on the Wyoming Modified PASER method is included in project deliverable 2A – State of The Practice for Unpaved Road Condition Assessment (Brooks et al. 2011b).

Huntington from the University of Wyoming summarized the use of the modified PASER rating system on local agency roads. The University of Wyoming team concluded the most efficient team consisted of two raters in a vehicle with one rating and recording while the other drives the vehicle. The two person team rated approximately 10 miles per hour rated for a team of two collecting both PASER distress data and ride data (Huntington 2011).

***Cost estimate for Wyoming Modified PASER***

- (8 hours x 2 staff x $40/ hour )/80 miles per day + $0.55/mile = $ 8.55 / mile

**Michigan PASER Study**

Transportation agencies in Michigan extensively use the PASER rating system to collect paved road data on an annual basis (Cambridge Systematics, Inc. 2007). PASER is different from URCI in that every mile of road must be driven, inspected and rated during a rating event. During a pilot rating study, the County Road Association of Michigan and the Michigan Department of Transportation extensively evaluated the cost to collect PASER data on a mix of paved and unpaved roads through a series of benchmarking tests in a number of different counties (CRAM MDOT n.d). The report concluded that teams of three (one driver, one data recorder, and one rater) could collect PASER data at an overall average speed of 16 mph for a mix of urban and rural agencies (CRAM MDOT n.d.).

***Cost estimate for Michigan PASER***

- 16 mph collection speed average
- 8 hours x 3 staff x $40 hours/128 miles + 128 miles * $0.55 / mile / 128 miles per day = $ 8.05 / Mile

Table 11 summarizes the costs of the various manual distress identification methods. Further comments are made when comparing these results to the UAV-based system and manned fixed-wing aircraft-based system.

**Table 11: Data collection costs for selected distress identification methods.**

| Rating Method | $/sample segment | $/Mile |
|---|---|---|
| Wyoming Manual URCI (Huntington 2013) | $80 | $160* |
| Manual URCI Ground Truth Collection moderate distress | $100 | $200* |
| Manual URCI Ground Truth Collection high distress | $140 | $280* |
| Army Cold Regions Automated PCI (Cline et al. 2003) | $34.23 | $66.10 |
| Army Cold Regions Manual PCI – low total area (Cline et al. 2003) | $50.84 | $101.68 |
| UNH/FHWA: RSMS – high productivity estimate (Goodspeed 2011 2013) | NA | $33.65 |
| UNH/FHWA: RSMS – low productivity estimate (Goodspeed 2011 2013) | NA | $65.65 |
| Wyoming Modifications of the PASER Method (Huntington 2011 2013) | NA | $8.55 |
| Michigan PASER Method (CRAM MDOT n.d.) | NA | $8.05 |

** Note that this is cost per mile of road rated; with the URCI, a pair of 100-foot segments represents approximately a mile of assessed road; these costs should be divided by 26.4 (5280 feet or 1 mile divided by 200 feet) to directly compare them to rating methods that require every mile of the road to be assessed (see below in the UAV data collection rate explanation for more on this)*

**Data Collection Rate for UAV System**

The remote sensing system requires a moderate capital investment to purchase the UAV, the sensor and the associated software for data reduction. Most traditional data collection methods discussed in this study do not require a similar level of capital investment, but rather are labor intensive. The capital cost for the UAV system, while not excessive, must be considered in the cost analysis since road agencies do not typically own this type of equipment. For example, the Bergen Hexacopter used in the second field season cost $5400 including spare batteries (this included mission planning software), the Nikon D800 camera cost $3,000 (without lens), the intervalometer (to set photo frame rates) cost us $100, and the Nikon 50mm f/1.4 lens cost $500. The capital cost of this type of equipment must also be amortized over its useful life including the number of miles of data collected during its useful life. Two cost scenarios are presented here with differing capital cost amortization assumptions:

- Operation of the UAV system as a stand-alone or add on commercial service for firms engaged in aerial survey activity (Scenario 1).
- Operation of the UAV by a road owning agency collecting data once a year for its own purposes (Scenario 2).

*UAV Cost Amortization of Capital Equipment – Scenario 1*

- Assume the UAV unit is purchased and operates as a commercial service.
- Assume the UAV unit operates continuously during snow free months (April to October).
- Assume data is collected 3 days a week for 8 hours a day (60% use).
- Assume the units will last 3 years with modest maintenance
- Amortize costs based on the production rate (miles or segments) per hour x 10 hr a day x 3 days/ wk x 21 weeks.

*UAV Cost Amortization of Capital Equipment – Scenario 2*

- Assume the UAV unit is purchased and is operated by an agency.
- Assume unit operates only on agency owned roads or neighboring agency roads once per year (per road)
- Assume the units with last up to 3 years with modest maintenance
- Assume the agency collects data for 300 miles of gravel road each year; two sample locations per mile.
- Amortize costs based on up to 600 sample locations per year.

*UAV Operation and Maintenance Costs – Scenario 1*

- Batteries will need to be replaced every 300 charge-cycles (3000 flights - one flight per segment, 90 seconds each, for a total of 10 segments per charge) at a cost of $250. For the assumed 2 segments per mile, then battery replacement will be needed every 1500 miles of roads sampled.
- Assuming one typical hard landing (free fall from 5m) per year, $300 in mechanical repairs.
- Assume replacing two motors per year, for a total cost of $160.
- Production rate while at the site for continuous measurement is approximately 350' road-feet per flight-minute (106 road-meters per flight minute, or slightly under our normal 2 m/s flight speed). This translates into about 1 mile of measured road before batteries must be charged (or swapped). This is approximately 3 miles per hour, about 75 miles per week. For 2 samples per mile, the rate is 6 miles per hour, or 144 miles per work week.
- Processing of the data requires 2 hours per segment, or 576 CPU hours per week (for 144 miles). For a typical 4-core, dedicated, system, this would be 144 elapsed hours per week (essentially 1 hour of elapsed time for every mile of sampled road data).

Yearly production 21 weeks X 75 miles per week = 1,575 miles per year

It should be recalled, though, that one mile of physically measured road with URCIs represents a road network approximately 26.4 times larger, using the idea of two 100-foot segments representing one mile of road; 5280 feet (one mile) divided by 200 feet (the two representative segments) equals 26.4. So 1,575 miles of physically measured miles represents a road network of up to 41,580 miles in length.

- Yearly maintenance cost: $300 (to cover repairs after hard landing) + $160 (replacement of motors) + $250 (one set of batteries) = $710/ yr
- Capital cost for hexacoptor, sensor and controls $9000 / 3 years of service = $3000 / yr
- Labor cost for collection: 24 hours / week collection X 1 staff X $40 / hr X 21 Wk= $20,160 / yr

- Data post processing time 8 hr / wk X 21 wk/yr X $40/hr = $6,720 / yr
- Total yearly cost = $30,590

Cost per mile rated $30,590/yr/1575 mi/yr = $19.42/mi rated. To put this in terms of represented road network rather than physically measured amount of road, the cost for UAV scenario 1 (stand alone/commercial service) drops all the way to $30,590/year divided by 41,580 mi/year or $0.74/mile.

Applying same assumptions to manual URCI data collection costs of $160 per mile (Wyoming URCI data) to $280 per mile (our heavy distress manual URCI scenario), which are the most comparable to our UAV based methods and results, this gives a cost of $6.06 per mile assessed up to $10.61 per mile assessed (and $7.58 per mile assessed for our moderate distress manual URCI scenario. The importance of the URCI segment-based data collections representing a larger road network should not be under-emphasized when comparing costs.

### Operation and Maintenance Costs – Scenario 2

Yearly production: 300 mi/year / X 75 miles per week = 4 weeks of collection per year

- Yearly maintenance cost: $300 (hard landing) + $160 (motors) + $250/3 (one set of batteries every three years) = $540/ yr
- Capital cost for hexicoptor sensor and controls $9000 / 3 years of service = $3000 / yr
- Labor cost for collection: 24 hours / Wk collection X 1 staff X $40 / hr X 4 Wk= $3,840 / yr
- Data post processing time 8 hr / wk X 4 wk/yr X $40/hr = $1,280 / yr
- Total yearly cost = $8,660

Cost per mile rated $8,660/ yr/300 mi/yr = $28.86/mi rated

Again, converting this to miles per year assessed, because two 100-foot rated segments represent approximately a mile of road with the URCI method, this gives a cost of $1.09 per mile of road assessed.

### Cost of Fixed Wing Aircraft Collection

The cost of fixed-wing aircraft unpaved road assessment is not directly comparable to the UAV based methods, because the low-cost Nikon D800 sensor ($3500 including lens) does not produce the needed ground sample resolution for reconstructed 3D data, even when flown as low as possible (500' / 150 m). However, here we assume a more advanced, more expensive three-camera system would be capable of collecting the needed data, at a sensor system cost of approximately $10,000. Assume collecting one agency per day with 300 miles of road to collect.

We also explicitly assume here: Flight time 0.25 hr for actual collection time at 75 mph, assume 1 hour total time collection to assess several pairs of URCI segments. The total cost is very sensitive to the number of URCI segment pairs that can be assessed in an hour of flight time. In our southeast Michigan experience, our 5 sites in Lenawee County, Michigan could have been flown over with one hour of flight time starting in Ann Arbor, MI, and each site represents one mile of assessed road with two segments per site. This means 1000 feet (5 sites X 200 feet per site) of road are collected per mile flown. 300 miles of road needing to be collected divided by 5 sites assessed per flight equals 60 flights.

- Plane costs $160/hr X 1 hr = $160 / assessment flight
- Total plane costs = $160/hour X 60 one-hour flights = $9600
- Cost of Sensor $10000 / 3yr = $3500 / yr
- Staff time for collection = $40/hr X 1 hr = $40 / agency X 60 flights = $2,400 (to fly in the airplane to operate the equipment)

- Data post processing time 21 hr (for a 21-week data collection season, assuming 1 hour to cover process time per week of collection) X $40/hr =  $840 / agency
- Total cost assuming 1 agency collected: $16,340 / agency

Cost per mile assessed $16,340/year for 300 mi/yr = $54.47/mi assessed (it is noteworthy that these costs are already in cost per mile of assessed road).

If we instead assume that every mile flown includes data constantly being collected for assessment, then instead of getting 1000 feet of road per mile flown we would get 5280 feet per mile flown (1:1); this drops the cost by a factor of 5.3X, yielding a cost of $10.26/mi assessed. While competitive with some manual methods, this is still significantly more expensive than our UAV-based methods, largely because of flight time costs and staff time to ensure sensor operation while in flight.

## Section VI: Concluding Discussion

During the process of evaluation the performance of the system, and the associated software, several important issues arose. The successful operation of the system depends on certain key factors:

1. The quality of the 3D reconstruction is the key to a good characterization. All measurements of the road are derived from this reconstruction, and for those measurements to be accurate, the reconstruction must meet certain minimum standards, influenced by the collection:
    a. The camera MUST be set up to avoid blurring of the images, either from motion artifacts, or lens misfocus. That means careful preparation of the sensor before flight is essential, with a clear understanding of the causes of blurring.
    b. The combination of field-of-view of the sensor, and ground sample spacing of image pixels, must be such that at least 10 degrees of angular diversity are seen between images, and the samples be no larger than 1cm. In practice, this means that, for current sensors, one must not fly at an altitude of no more than 100'-150' (30 m to 45 m).
    c. To avoid having to tune software parameters, it is important that images be properly exposed; over- or under-exposure will result in either lack or surface detail, or poor camera location estimation (resulting in poor reconstruction).

In short, understanding the interplay of aperture, shutter-speed, and ISO settings is key to be able to set up the sensor for a high-quality collection. Fortunately, this can be provided in a table, to allow non-experts to be able to be assured of useful measurements.

2. The formation of the "watertight" surface from the 3D reconstructed point cloud MUST NOT perform too much smoothing. It is important that rapid changes in surface profile be preserved when forming the surface, in order to be able to find those distresses that are characterized by local height changes (e.g. potholes and ruts).

Fixed-wing collections, using the sensor system appropriate for small UASs, had several issues:

1. Pointing accuracy – because the lens needed to obtain sufficient resolution was imaging a relatively small area on the ground, it was difficult for the pilot to keep the aircraft stable enough to keep the road in the field-of-view of the camera. Any slight attitude adjustments led to slewing of the images. A gimbaled, stabilized camera mount would be needed, and this was outside the scope of this effort.
2. At the minimum possible altitude for safe flight (500' / 150 m), the angular diversity of a nadir-looking camera was insufficient to reconstruct accurate 3D surfaces. This could be corrected in three ways (all outside the scope of this effort):
    a. Using three cameras, one pointing forward, one nadir, and one astern, and combining the images to obtain enough angular extent.
    b. Multiple passes over the same road, using a single camera, but changing the angle from oblique to nadir between passes.
    c. Combining a wider-angle lens with a much larger sensor (4-5 times the number of pixels).
3. Under overcast conditions, or windy conditions, the camera could not be adjusted to obtain crisp images. Using a much higher-quality lens (on the order of $10,000 per lens) would be needed.

We plan to conclude the discussion of optimal 3D data reconstruction, tuned algorithms, assessment costs and their associated assumptions, and our comparison between small UAS and fixed-wing based collections in the project report. Based on the results detailed in this performance evaluation report, the time appears to be right for a more intensive outreach period to communicate project successes, challenges, and detailed findings to the transportation community concerned with effective and timely assessment of unpaved road condition.

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