Research Project Work Plan

for

EYES IN THE SKY: BRIDGE INSPECTIONS WITH UNMANNED AERIAL VEHICLES

SPR 787

Submitted by

Daniel T. Gillins, Assistant Professor
Christopher Parrish, Associate Professor

Oregon State University
311 Kearney Hall
Corvallis, OR 97331

for

Oregon Department of Transportation
Research Section
555 13th St. NE, Ste 2
Salem, OR 97301-6867

June 2015

Research Project Work Plan
for

EYES IN THE SKY: BRIDGE INSPECTIONS WITH UNMANNED AERIAL VEHICLES

1.0 Identification

1.1 Organizations Sponsoring Research

Oregon Department of Transportation (ODOT)
Research Section
555 13th Street NE
Salem, OR 97301 Phone: (503) 986-2700

Federal Highway Administration (FHWA)
Washington, D.C. 20590

1.2 Principal Investigator (ODOT requests only one per institution or firm)

Daniel T. Gillins, Assistant Professor
School of Civil and Construction Engineering
Oregon State University
311 Kearney Hall
Corvallis, OR 97331 Phone: 541-737-4865

1.3 Associate Investigator(s)

Christopher Parrish (Co-PI)
School of Civil and Construction Engineering
Oregon State University

1.4 Technical Advisory Committee (TAC) Members

Erick Cain, ODOT Bridge Section
Michael Goff, ODOT Region Bridge Inspector
Xiugang (Joe) Li, ODOT Research Section
Tim Rogers, FHWA Oregon Division
Ron Singh, ODOT Geometronics
Mitch Swecker, Oregon Department of Aviation

1.5 Friends of the Committee (if any)

Bert Hartman, ODOT Bridge section
Bruce Johnson, ODOT Bridge section
Paul Panzica, ODOT Wireless communication section
Craig Shike, ODOT Bridge section

Jeff Swanstrom, ODOT Bridge section
Corey Withroe, ODOT Bridge section

1.6 Research Coordinator

Xiugang (Joe) Li, ODOT Research Section Phone: 503-986-4115

1.7 Project Champion

Ron Singh, Manager, ODOT Geometronics

2.0 Problem Statement

The Federal Highway Administration (FHWA) requires states to inspect and inventory federal-aid highway system bridges every two years. These bridge inspections are important for assessing the safety of a bridge and are done by qualified structural inspectors, typically at an arm's length from the inspection point(s). However, as stated in the FHWA Bridge Inspector's Reference Manual, "[b]ridge inspection is inherently dangerous." In order to access and view necessary bridge elements, inspectors are often required to stand in vehicles that are costly to mobilize and at times dangerous, including platform trucks, bucket trucks, or under-bridge inspection vehicles. Some inspections require extensive climbing or use of rescue boats. In addition to the danger to the inspector and vehicle operator, road users also face danger as traffic lanes on bridges are closed or reduced during inspections. The purpose of this research is to evaluate the capabilities and limitations of Unmanned Aerial Vehicle (UAV) technology for use in visual structural inspections. This research addresses ODOT's core values: enhancing transportation and employee safety, and improving the reliability of Oregon's transportation system. UAV technology has great potential to provide a cost-effective and safe method for remotely performing preliminary visual inspections.

2.1 Background and Significance of Work

UAVs are capable of flying a pre-loaded path and can carry digital cameras and other sensors. They are excellent for accessing spots that are dangerous or hard to reach by humans without the use of specialized climbing equipment. During flights, operators can view live video from the camera to determine areas that may need detailed inspection. Digital photographs from onboard cameras can be processed, mosaicked, georeferenced, and converted into 3D point clouds for analyses.

Because of the rapid emergence of UAV-related technology in recent years, there is growing interest in the feasibility of inspecting structures with UAVs. For example, Hallerman and Morgenthal (2013) concluded that UAVs can be effective for inspecting industrial chimneys and historical buildings. Sa et al. (2015) investigated the use of a UAV for inspecting poles. Ellenberg et al. (2014), and Eschmann et al. (2013) showed that UAV imagery can be used to detect cracks and other defects in structural elements.

Because of low flight costs, UAVs can also be flown regularly to monitor ground and structural changes. For instance, Hallerman et al. (2014) showed that imagery from a UAV can be used to monitor deformations along dams and earth retaining walls.

Although some very recent work has been published on the feasibility of using UAVs for some structural inspections, much more work is needed if DOTs intend to implement UAVs in their bridge inspection programs. First, this project aims to test and evaluate the effectiveness of inspecting bridges (and, as discussed below, wireless communication towers) with UAVs. To date, no peer-reviewed papers have

been found on inspecting these types of structures with UAVs. Second, a cost-benefit analysis will be provided on using UAVs for inspecting these structures as compared with conventional inspection methods. Third, this project will give practical recommendations on how to best and safely perform UAV inspections. Recommendations will include how to best plan a flight mission and set the camera acquisition parameters.

3.0 Objectives of the Study

The overall goal of this research is to determine the capabilities and limitations of performing structural inspections with UAVs. In addition to investigating bridges, the research team will also evaluate the performance of UAVs in inspecting wireless communication towers. Similar to bridges, communication towers also need to be routinely inspected, requiring extensive climbing, bucket trucks, and ropes and harnesses. Because the inspection of bridges and communication towers present similar safety concerns, and because UAVs could potentially reduce their inspection dangers and costs, both types of structures will be investigated. This research seeks to:

- Evaluate the performance of UAV-based methods for inspecting bridges and communication towers
- Identify which ODOT inspection requirements can and cannot be satisfied with a UAV inspection.
- Provide a cost-benefit analysis of performing UAV inspections for communication towers and bridges.
- Develop procedures/guidelines for how to safely and effectively perform UAV inspections of bridges and communication towers. These guidelines will include recommendations on any necessary UAV-related equipment and image processing software.

3.1 Benefits

This project will evaluate the potential use of UAVs for enhancing safety in structural inspections. If successful, remote structural inspections will reduce the need for extensive climbing, use of bucket trucks, under-bridge inspection vehicles, and temporary scaffolding. Furthermore, UAV technology may provide a method for performing visual inspections at a lower cost than traditional inspection methods. The proposed project is anticipated to provide practical lessons-learned, and recommended procedures for safely and effectively implementing UAVs in a structural inspection program. ODOT will be able to use the results of this research to develop UAV structural inspection specifications. Furthermore, this research can be shared widely and will potentially benefit other U.S. DOTs, as few (if any) have performed a detailed study on the use of UAVs for structural inspections. Because of the potential reduction in inspection cost and enhancement in inspection safety, DOTs across the nation will likely be interested in the results of this research project.

4.0 Implementation

The research findings will allow ODOT to develop specifications for how to safely and effectively perform UAV structural inspections. These specifications can be shared with ODOT Geometronics, which is responsible for ODOT's UAV operations. ODOT will also be able to distribute these specifications to internal UAV structural inspectors, or to external companies who may be contracted by ODOT for inspecting structures with UAVs. The results of this project are also expected to assist ODOT in evaluating the capabilities, equipment and procedures of external companies who propose to use UAVs in contracted work.

The research team will write a final ODOT technical report that details the two-year research effort. In addition, the team will write an ODOT Research Note that summarizes the results of the study. They will also give presentations on their work for 4 ODOT meetings, as discussed below, and will provide ODOT with the presentation slides. ODOT will then be able to share the results of this study with industry through regional and/or national structural inspection conferences.

The research team may publish key findings in scholarly structural engineering journals and/or national conferences.

5.0 Research Tasks

The project is estimated to be 24 months in duration. The project will consist of the tasks listed below.

5.1 Expected tasks:

Task 1: TAC Meeting #1; Project kick off meeting.

As early as possible, hold a meeting with TAC. The purpose of this meeting is to discuss the scope and purpose of the research, the tasks proposed in this work plan, the schedule, and the representative types and sizes of bridges and communication towers that ODOT would like to inspect with a UAV.

Time Frame:
Responsible Party: PI, ODOT Research Coordinator, and TAC
Cost: $500
Deliverable: TAC meeting attendance, TAC meeting presentation, TAC Meeting Minutes
TAC Action: Review and understand the project research problem statement, research question, the limits of the research, and the project schedule. Advise ODOT Research Coordinator regarding any critical issues with the project's scope or schedule. Advise PI regarding related professional practices, standards, methods and context for the project.

ODOT Action or Decision: Review TAC advice, discuss with PI, and if necessary direct PI to make changes to project documents.

Task 2: Draft Literature Review

During this task, review technical information and important lessons learned by other state DOTs and countries that have used UAVs for structural inspections. Since there may be a lack of published literature to date, this task will also involve contacting transportation agencies directly to determine their experiences with using UAVs for inspections and other applications. Feedback and related activities from these agencies will be summarized. All citations will be given in the prescribed ODOT format.

In addition to reviewing material related to structural inspections with UAVs, also review the ODOT Bridge Inspection Manual, relevant FHWA bridge inspection manuals, and relevant manuals on the inspection of wireless communication towers. After reviewing these manuals, provide a preliminary identification of which structural inspection requirements likely can and cannot be satisfied with a UAV.

Time Frame: October 2015 – December 2015.
Responsible Party: PI
Cost: $10,300
Deliverable: Draft Literature Review
TAC Action: Read Draft Literature Review and advise ODOT Research Coordinator regarding any gaps in the literature.
ODOT Action or Decision: Review TAC advice, discuss with PI, and if necessary direct PI to make changes to project documents.

Task 3: Preliminary Test Flights

During this task, fly a UAV along nearby structures with known defects (with ODOT's inspectors input) including cracks, missing bolts, etc. Systematically vary the standoff distance and flying speed in order to quantify the effects on image quality as well as the tradeoff with GPS signal quality. Conduct UAV flights in varying weather conditions (fog, rain, day/night) to evaluate the UAV's ability for in-field inspections. Collect video and imagery using 3 different types of cameras (i.e., full-frame digital, mirrorless interchangeable lens, and HD camcorder) mounted on a UAV. Systematically vary the acquisition parameters, including camera pointing angle, endlap and sidelap, focal length, shutter speed, backlight, and GPS geometry. Afterwards, evaluate the imagery and video to determine which method(s) best identify the known structural defects (e.g. corrosion, cracks, missing bolts, etc). Based on these experiments, document the optimal flight variables, camera acquisition parameters, and camera type for identifying defects while ensuring safe and efficient operations. Using these results, draft an approach for the test inspections of the wireless communication towers and bridges.

Time Frame: January to April 2016
Responsible Party: PI
Cost: $18,700
Deliverable: Draft an approach for UAV inspection of communication towers and bridges
TAC Action: Read draft approach in preparation for TAC Meeting # 2. Identify possible communication towers and bridges for test inspections in preparation for TAC Meeting #2.
ODOT Action or Decision: Schedule TAC Meeting #2

Task 4: TAC Meeting #2

The purpose of this meeting is to discuss the results of the preliminary test flights, and to review the draft approach for performing the UAV test inspections of the communication towers and bridges. In addition, during this meeting, we will identify the towers and bridges that will be test inspected with a UAV, and will begin coordinating the test inspection schedule. Ideally, test inspections will be performed slightly before or after a regular structural inspection. Hence, the test inspections will require careful coordination with ongoing ODOT inspection programs.

Time Frame: April 2016
Responsible Party: PI, ODOT Research Coordinator, TAC
Cost: $500
Deliverable: TAC meeting attendance, TAC meeting presentation, TAC Meeting Minutes, meeting agenda
TAC Action: TAC review of the approach for conducting UAV test inspections. Coordinate the test inspections with relevant ODOT inspection programs. Advise ODOT Research Coordinator regarding any critical issues with the project's research design. If possible reach consensus regarding the content and methods contained in the draft test inspection design. Advise ODOT Research Coordinator regarding project next steps.
ODOT Action or Decision: Review TAC advice. Assess project potential for successful completion. If necessary direct PI to make changes to project documents. Provide formal acceptance of the UAV test inspection approach. Authorize PI to proceed with subsequent steps, notify by memo or email.

Task 5: Test Inspections of Wireless Communication Towers

During this task, use the draft approach developed after TAC Meeting #2 to perform a test inspection of two wireless communication towers. These inspections will be performed with inspectors present who can recommend the inspection of key structural elements at each tower. As wind may have an impact, measure the wind speed during each flight and evaluate its influence on the quality of the data. Some elements of the structure will likely have poor lighting. For low-illumination

conditions, test the use of a high-beam headlamp on the UAV. (In the office, investigate and recommend digital image processing techniques for enhancing underexposed, low-contrast images collected in poor illumination.)

After test inspections on 2 towers, draft a memo documenting lessons learned, and the quality of the collected data. Submit this letter to TAC in preparation for TAC Meeting #3, described below.

After receiving feedback from TAC, and after adjusting the test inspection methodology (as necessary), collect data at up to 3 more wireless communication towers. Coordinate flights with ODOT's tower inspection program. Ideally, flights will be conducted slightly before or after a conventional (human) tower inspection. ODOT will ensure that the data from a human tower inspection is shared, so that the results can be compared with the UAV inspection. Compare inspection results and identify which defects identified by the human inspectors were and were not shown in the UAV imagery.

All UAV data will be collected, stored and delivered to ODOT in compliance with Institutional Review Board approvals and Federal requirements. The PI will be responsible for documentation of any departures from the Draft Research Methodology.

Time Frame: May to September, 2016
Responsible Party: PI
Cost: $25,000
Deliverable: After the first 2 inspections, provide a draft memo documenting where and what data was collected. In this memo, note any problems with the test inspection approach in preparation for TAC Meeting #3. Upon completion of all inspections, provide a final memo documenting where and what data was collected, and any specialized data collection tools or algorithms. Also, provide documentation that the raw data is securely stored and protected from data corruption. (Federal projects may require delivery of raw data to the Agency)
TAC Action: Review the draft memo in preparation for TAC Meeting #3.
ODOT Action or Decision: Review

Task 6: Test Inspections of Bridges

During this task, use the draft approach developed after TAC Meeting #2 to perform a test inspection of one to two bridges. These inspections will be performed with inspectors present who can recommend the inspection of key structural elements along each bridge. Similar with the test inspection of the communication towers, document the wind speed during each flight, and test the use of a high-beam headlamp mounted on the UAV. Before and during flights, video-record the traffic from with a camcorder on a tripod in order to assess any impacts during a UAV inspection. If the structure is instrumented with traffic monitoring equipment, request data before and during the flight from ODOT to assess traffic impact during a

conventional bridge inspection as compared to a bridge inspection with a UAV. If rural bridges are not instrumented, the research team will coordinate with the ODOT bridge crew and traffic control crew in order to efficiently install temporary monitoring devices for collecting data before and during inspections with and without UAV flights.

After the first one to two test inspections and similar to the tower inspection program, draft a memo documenting lessons learned, and the quality of the collected data. Submit this memo to TAC in preparation for TAC Meeting #3, described below.

After receiving feedback from TAC, and after adjusting the test inspection methodology (as necessary), collect data at up to 6 to 8 additional representative bridges. Coordinate flights with ODOT's bridge inspection program. Again, ideally flights will be conducted slightly before or after a conventional (human) bridge inspection. Results will then be compared to evaluate the effectiveness of performing UAV bridge inspections versus conventional inspections.

All UAV data will be collected, stored and delivered to ODOT in compliance with Institutional Review Board approvals and Federal requirements. The PI will be responsible for documentation of any departures from the Draft Research Methodology.

Time Frame: July to December, 2016
Responsible Party: PI
Cost: $84,000
Deliverable: After the first 1-2 inspections, provide a draft memo documenting where and what data was collected. In this memo, note any problems with the test inspection approach in preparation for TAC Meeting #3. Upon completion of all inspections, provide a final memo documenting where and what data was collected, and any specialized data collection tools or algorithms. Also, provide documentation that the raw data is securely stored and protected from data corruption. (Federal projects may require delivery of raw data to the Agency)
TAC Action: Review the draft memo in preparation for TAC Meeting #3.
ODOT Action or Decision: Review

Task 7: TAC Meeting #3

This meeting will be held in the middle of the test inspection schedule, after completing tests on 2 communication towers and 1 to 2 bridges. The purpose of this meeting is to discuss the results of the first set of tests, and to decide if any modifications are necessary to the test inspection approach. After reaching a consensus, the PI will modify the approach for the remaining test inspections.

Time Frame: August, 2016
Responsible Party: PI, ODOT Research Coordinator, TAC

Cost: $500
Deliverable: TAC meeting attendance, TAC meeting presentation, TAC Meeting Minutes, meeting agenda. Provide memo explaining any modifications to the test inspection approach, as decided upon during the meeting.
TAC Action: TAC review of the memo explaining any modifications to the test inspection approach. Advise ODOT Research Coordinator regarding any critical issues with the test inspection approach.
ODOT Action or Decision: Review TAC advice. Assess project potential for successful completion. If necessary direct PI to make changes to project documents.

Task 8: Data Analysis

Analyze the data collected during the test inspections and determine the optimal flight pattern, flying speed, pointing angle, camera, camera acquisition parameters, and wind speed for inspecting the various types of structures with UAVs. Document any impacts to traffic during the flights. Afterwards, perform a cost/benefit analysis of using UAVs for structural inspections. Based on ODOT structural inspection manuals and the collected data, determine which inspection requirements are efficiently and/or safely satisfied by using a UAV. Document the associated cost savings, and the reduction of time an inspector would physically spend on the bridge. Further, determine the cost and safety benefits of reducing or even eliminating the use of temporary scaffolding, extensive climbing equipment, ladders, bucket trucks, under-bridge inspection vehicles, rescue boats, etc.

Document any deviations to the test inspection methodologies, and update the Draft Literature Review to support any methods of analysis not previously included in the literature review.

Time Frame: October 2016 to March 2017
Responsible Party: PI
Cost: $22,500
Deliverable: Write a draft paper on the analysis of the collected data
TAC Action: Review and comment
ODOT Action or Decision: Review

Task 9: Draft Final Report

Write and submit a Draft Final Report documenting findings of this research to ODOT for review. The Draft Final Report will be publication-ready, written in the prescribed ODOT report format (i.e., including correct fonts, spacing, citations, and graphics). The content of the Draft Final Report will include: an updated abstract, acknowledgements, disclaimer, introduction, and an updated literature review, explanation of the UAV test inspections, an analysis of the collected data, and discussion of results, conclusions, and identification of future research potential.

Time Frame: April to June, 2017
Responsible Party: PI
Cost: $11,000
Deliverable: Draft Final Report using ODOT's report template
TAC Action: TAC review and feedback to the ODOT Research Coordinator
ODOT Action or Decision: Review and counsel prior to TAC meeting

Task 10: Draft ODOT Research Note

Write 1000 to 1500 word executive summary of the research project, using ODOT's Research Note template. The summary will concisely document the research findings, value of the research to the agency, science and society, and any limitations on the use of the findings. The Draft ODOT Research Note will be submitted for review along with the Draft Final Report.

Time Frame: June, 2017
Responsible Party: PI
Cost: $1,000
Deliverable: Draft ODOT Research Note using ODOT's template
TAC Action: Review Draft Research Note in preparation for TAC Meeting #4.
ODOT Action or Decision: Review and advise

Task 11: TAC Meeting #4.

The purpose of this meeting is to review the material presented in the Draft Final Report, and Draft Research Note. TAC will offer advice on the content and clarity of these work products. TAC will also advise on post research implementation.

Time Frame: July, 2017 (or starting 2 to 4 weeks after submission of the Draft Final Report and Draft ODOT Research Note)
Responsible Party: PI, assisted by the ODOT Research Coordinator, TAC
Cost: $500
Deliverable: TAC meeting attendance, meeting presentation, TAC Meeting Minutes
TAC Action: TAC review of Draft Final Report, and Draft Research Note. Advise ODOT Research Coordinator regarding any critical issues with these documents. Advise ODOT Research Coordinator regarding any required final edits to the Draft Final Report, and Draft Research Note.
ODOT Action or Decision: Review TAC advice. If necessary direct PI to make changes to project documents.

Task 12: Final Report

Finalize the Final Report by addressing any edits or comments identified by the ODOT research coordinator after TAC meeting #4. The Final Report will be completed by the end of the funding cycle and will be delivered to ODOT along with supporting data files.

Key findings from this research will also be published in graduate student theses and in peer-reviewed journal and conference papers. However, it is anticipated that these other publications will require additional time beyond the project cycle.

Time Frame: July to September, 2017 (or starting 3 months after receiving review comments)
Responsible Party: PI
Cost: $5,000
Deliverable: Final Report
TAC Action: None
ODOT Action or Decision: Review. Provide formal acceptance of Final Report. Publish Final Report on ODOT's research website

Task 13: Final Research Note

The Draft Research Note will be edited to address any review comments by the ODOT research coordinator after the final TAC meeting. The Final Research Note will be submitted along with the Final Report.

Time Frame: September, 2017 (or starting 3 months after receiving review comments)
Responsible Party: PI
Cost: $500
Deliverable: Final Research Note
TAC Action: None
ODOT Action or Decision: Review. Provide formal acceptance of Research Note. Publish Final Research Note on ODOT's research website

5.2 Reporting

All reports shall be produced in the standard ODOT Research Section report format provided to the Project Investigator by the Research Coordinator unless some other format is deemed to be more appropriate. The Project Investigator shall be responsible for submitting deliverables as professional-level written composition equivalent to the writing standards of peer-reviewed journals. These writing considerations include grammar, spelling, syntax, organization, and conciseness.

The Project Investigator, in consultation with the TAC and Research Coordinator, shall deliver to ODOT in electronic format the data produced during the project. The Project Investigator shall ensure the data is labeled and organized to facilitate future access. ODOT shall warehouse the data.

5.3 Safety and Related Training

Prior to accessing ODOT right-of-way (ROW), all personnel who will work on ODOT ROW shall complete safety training appropriate to the work to be performed within the ROW. The Project Investigator shall notify Project Coordinator in writing (email accepted) prior to the first day of work within the ROW that all project personnel who will access ODOT ROW have been trained. Until all ROW work is completed, the Project Investigator shall notify Project Coordinator in writing (email accepted) annually that an active safety training appropriate to the work to be performed within the ROW has been completed by all personnel who will work on ODOT ROW. OSU students should not climb bridges or towers to do inspection work unless approved by ODOT.

6.0 Time Schedule

The time line for the project is given in the matrix below. The matrix also shows interim and final deliverables for each of the tasks.

Task	2015	2016												2017								
	FY2016									FY2017										FY18		
	Oct - Dec			Jan - Mar			Apr - Jun			Jul - Sep			Oct - Dec			Jan - Mar			Apr - Jun			Jul - Sep		
1: TAC Meeting #1	*																							
2: Literature Review			*																					
3: Preliminary Test Flights							*																	
4: TAC Meeting #2							*																	
5: Inspection of Comm. Towers											*													
6: Test Inspection of Bridges											*													
7: TAC Meeting #3											*													
8: Data analysis; cost-benefits																		*						
9: Draft Final Report																					R			
10: Draft ODOT Research Note																					R			
11: TAC Meeting #4																						*		
12: Final Report																								F
13: Final ODOT Research Note																								F

*Deliverables

R - Draft report submitted for ODOT review.

F - Revised report submitted to ODOT for publication. End of contract.

7.0 Budget Estimate

An itemized budget, showing expenditures for each task by fiscal year is given below.

Task	FY16	FY17	FY18	Total
1: TAC Meeting #1	$500			$500
2: Literature Review	$10,300			$10,300
3: Preliminary Test Flights	$18,700			$18,700
4: TAC Meeting #2	$500			$500
5: Inspection of Comm. Towers	$10,000	$15,000		$25,000
6: Test Inspection of Bridges		$84,000		$84,000
7: TAC Meeting #3		$500		$500
8: Data analysis; cost-benefits		$22,500		$22,500
9: Draft Report		$11,000		$11,000
10: Draft ODOT Research Note		$1,000		$1,000
11: TAC Meeting #4			$500	$500
12: Final Report			$5,000	$5,000
13: Final ODOT Research Note			$500	$5,00
Total for tasks (Contract amount)	**$40,000**	**$134,000**	**$6,000**	**$180,000**