



Bridge Inspecting with Unmanned Aerial Vehicles R&D

Project No. 17STLSU11

Lead University: University of Louisiana at Lafayette

Collaborative Universities: Louisiana State University



Preserving Existing Transportation Systems

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16. Abstract The project achieves through research including literature, on site interviews, and experimentation: 1) a recommendation for a UAV-based system to practically assist in routine bridge inspection work in the State of Louisiana, 2) the identification and description of advantages, disadvantages, and limitations in the use of UAVs for routine bridge inspection work in Louisiana, and 3) provided recommendations for future work. The Yuneec H520 aircraft and its E90 camera are recommended, as is the need for a boat to be included as part of the system. The recommended system has advantages in reaching portions of the bridge that are difficult to reach by human inspectors and includes sufficient image resolution to assist the bridge inspection process. A disadvantage though, is that of the overburden of regulations both from the FAA and for getting permission to inspect a bridge using a UAV. These regulations may render negligible, any gains in efficiency perceived in the use of UAVs for bridge inspection. Also, the UAV is described by the project as an assistance tool for the manual bridge inspection process and cannot replace the needed work of bridge inspectors, as it has limitations. For example, the UAV cannot perform inspections beneath the bridge deck since it may lose its GPS navigation reference. Likewise, it cannot see beneath the surface to tell if concrete components have subsurface cracks or timbers might be hollow. These tests are still the domain of manual bridge inspection. The project provided recommendations with respect to changes in how inspections should be done using the UAV, i.e. in the pre-inspection phase, needed field studies using the UAV, needed economics alternative-tradeoffs studies, and recommendations for augmenting the aircraft and its instruments. The Second phase, i.e. the Implementation Phase, will utilize the information and educational fruits of the technical research phase for tutorials, seminars and to facilitate feedback surveys with engineering firms, the LADOTD, engineering societies, and students.			
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

COTS	Commercial-Off-the-Shelf
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FPV	First Person View
GPS	Global Positioning System
LADOTD	Louisiana Department of Transportation and Development
MnDOT	Minnesota Department of Transportation
UAV	Unmanned Aerial Vehicle

EXECUTIVE SUMMARY

Through secondary and primary research including literature, interviews, and experimentation respectively, the project achieved: 1) a recommendation for a UAV-based system to assist practically in routine bridge inspection work in the State of Louisiana, 2) the identification and description of advantages, disadvantages, and limitations in the use of UAVs for routine bridge inspection work in Louisiana, and 3) provided recommendations for future work.

Specifically the project resulted in the following:

1. UAV-based System Recommendation: An aircraft, i.e. the Yuneec H520, including its gyroscopically stabilized camera, i.e. the E90 4K UHD, for a bundled cost of approximately \$4,200 is recommended for use in bridge inspection due to its stability, relatively superior performance as compared to other aircraft in the prosumer class, and for its ability to adapt software for automatic flight waypoints and 3D mapping of objects, a very useful set of functions in bridge inspection. Along with the aircraft, the use of a watercraft was recommended to serve as a mobile intermediate staging platform for aircraft takeoffs and landing, enabling onsite freshly charged batteries, ferrying the aircraft to focal points along the bridge to save on aircraft battery life, and to serve as a rescue vessel, should the aircraft impact the water.
2. Identified and Described Advantages, Disadvantages, and Limitations associated with the use of a UAV-based system in Louisiana:
 - Advantages: Experiments and analysis proved the UAV could provide assistance to bridge inspectors in the field since it is capable of reaching places on the bridge superstructure not easily accessible to human inspectors, even where lifting booms are used. The UAV is considered especially useful where the frequency of necessary repeated visits is relatively high, since use of the UAV is associated with less need for support equipment and hence, no time delay or costs and labor to obtain and set up that equipment for use. The photos and videos captured by the camera were more than adequate in quality and resolution to capture imagery useful to bridge inspectors even at considerable distances (i.e. 10 meters).
 - Disadvantages: The perceived advantages, i.e. the potential cost reduction, time reduction, and safety improvement of UAV-based bridge inspection as compared to traditional manual methods, may be rendered insignificant due to the overburden of regulation that comes with UAV-based inspection that will tend to slow the work and complicate the inspection process. FAA regulations, the time to do paperwork for permission from state agencies to flight-inspect the bridge, and the assumed liability of the UAV in the presence of motorists are seen as a disadvantage.
 - Finally, limitations of the UAV-based approach for routine bridge inspection in Louisiana are identified: These limitations include portions of the bridge not accessible to the UAV including the areas beneath the bridge deck, and of course the obvious portions beneath the waterline. But more subtly, the limitations include areas beneath the surface of bridge timbers and concrete members where hollow sections and subsurface cracks respectively may reside. These areas are still in the manual inspector's domain in the current state of the art.

3. Recommendations were provided with respect to 1) how inspections are done using UAVs, i.e. pertaining to what's done prior to the inspection and where the UAV should focus its efforts, 2) field studies that need to be done with the UAV working in the field alongside inspectors, 3) a needed economics alternatives-tradeoffs study, 4) augmenting the aircraft and instrument functionality, and 4) imaging analysis software.

IMPLEMENTATION STATEMENT

The Second phase, i.e. the Implementation Phase, will utilize the informational and educational fruits of the technical research phase for Workforce Development, Outreach Activities, and Education.

1. **Workforce Development:** will include the dissemination of results through short presentation meetings and workshops to engineering firms, and/or to the bridge inspectors at the Louisiana Department of Transportation and Development (LADOTD).
2. **Outreach Activities:** will include presentations to high schools where STEM students can be reached.
3. **Education:** will be realized in a university setting where seminars will be conducted for classes of engineering students, including both electrical and civil engineering students where possible.

Specific planned activities during the Implementation Phase include:

- A presentation of findings, recommendations, and potential development to Pelican Engineering (engineering firm) and Techneaux.
- A seminar presentation to IEEE electrical engineers society (professionals, potential students, and students) and undergraduate students seminar at the University of Louisiana at Lafayette.

1. INTRODUCTION

1.1 Background

There are more than 1,600 bridges just in the Acadiana area of Louisiana that LADOTD bridge inspectors must inspect and report on annually, drawing from resources that include only 6 bridge inspectors. A wide variety of bridge types must be inspected, including pipe bridges, box culverts, truss bridges, fixed bridges, and timber bridges. The bridge inspector's main duty is to collect all data required by the Federal Highways Administration (FHWA) for each bridge and to keep it in a database for use by state, parish, and federal government. Bridge inspectors look for potholes, ravels, cracking, spalling, and exposed rebars. They also look for bent members, cracked members, and hollow members, examining the condition of members, paint, abutments, fender systems, guardrails, and every other piece of the bridge for damage, corrosion and section loss.

Sometimes initial inspections find conditions that warrant repeat inspection and hence, repeated periodic visits to the bridge to check on the progression of initial deficiencies, such as cracks or corrosion. This process is time consuming and costly, especially where inspections must be carried out beneath the bridge deck, i.e., where special equipment with a boom would need to be obtained so as to gain visual access for inspection. Moreover, portions of the bridge superstructure are often located at heights that are difficult to reach and potentially hazardous for bridge inspectors to go. Furthermore, often hundreds or thousands of photographs and instrument readings must be scanned and analyzed by bridge inspectors for indications of potential problems that may warrant further analysis. This is also a time intensive process. Can technology in the context of UAVs be practically and effectively applied to assist the bridge inspector in his/her job?

The question is an interesting one, and at first glance it appears to have merit. However, a solution involving UAVs to assist bridge inspectors comes with a number of hurdles, requiring necessary augmentations if it is to be viable, effective, and useful practically. No commercially available UAV, in and of itself is ideal for the job at hand, and so UAV systems must be devised comprised of customized, modified or augmented UAVs and instrumentation systems, suitable for use near and around bridges for bridge inspection. Moreover, the requirement to follow Federal Aviation Administration (FAA) regulations and other legal and liability considerations have the potential to dampen the effectiveness and efficiency of any proposed technologically-based solution.

1.2. Purpose

The purpose of this project is to evaluate through research and analysis and to provide recommendations for instrumented UAV systems for demonstration so as to determine their application, feasibility, suitability, practicality and effectiveness according to a defined rubric centered around routine bridge inspection activities. It is not the intent of the project to seek UAV systems that will replace the bridge inspector's work, but instead, to only assess whether or not and to the degree practical whether UAV systems can assist and/or augment the bridge inspector's work and its effectiveness, so that it is fundamentally more economical, efficient, or even safer. The report herein contains findings produced through this demonstration project

that identifying the advantages, disadvantages, and limitations in the use of UAVs for routine bridge inspection work in Louisiana.

2. OBJECTIVES

The goals of the research study are to 1) to provide recommendations for a UAV system to practically assist in routine bridge inspection work in the State of Louisiana, and 2) to identify the advantages, disadvantage, and limitations of the use of UAVs for routine bridge inspection in Louisiana.

3. SCOPE

The research included an investigation into the pertinent technologies, sciences, and areas of the project's intersecting requirements, i.e. bridge inspection, others doing UAV-based bridge inspection, appropriate instrumentation for bridge inspection with UAVs, and the performance qualities of the UAVs themselves as they relate to the performance of bridge inspection, as well as an investigation of FAA regulatory requirements having bearing on this topic. It included surveys, interviews and input from knowledgeable parties, student involvement and investigation, data gathering, experimentation, tabulation and analysis of data, and equipment selection along with the purchase of a UAV and its configuration and modification for application to bridge inspection, as well as a field-test demonstration-experiment using the purchased UAV to capture bridge images, while getting feedback about the results from bridge inspectors at LADOTD, so as to provide an experienced recommendation for a UAV system capable of practically assisting in bridge inspection in the State of Louisiana.

A report on the demonstration is provided along with findings and recommendations for a long-term UAV-based system approach, including an identification of the advantages, disadvantages, and limitations in the use of UAVs for routine bridge inspection work in Louisiana. The scope does not provide a perfected UAV-based system ready for all facets of bridge inspection, nor does it provide significant research to implement the development of such a system, in either the areas of instruments or UAVs; instead, it provides only a system recommendation and findings, as well as suggestions and insights for further research that may lead to the development of practical UAV-based systems for bridge inspection. Further, projects of this type may be considered to be of "high risk," since a number of factors may act to prevent project completion to a satisfactory level of demonstration, with sufficient testing to be useful practically, including 1) regulations in that the UAV must be flown by a licensed UAV pilot, where the availability of that pilot must be acquired and scheduled, 2) a purchase of UAV equipment is required which historically has a long "paperwork" lead time at the university, 3) bridges must be carefully selected such that they are not within five (5) miles of an airport due to FAA regulations, 4) the weather is a factor, i.e. "Force Majeure," i.e. wind, rain, and lightning, especially in Louisiana, which can prevent necessary outdoor experimentation and demo with the UAV, 5) liability is a concern, and hence bridges must be carefully selected such that they have low traffic levels, and so permission paperwork can be completed to fly them, in a timely manner, or private or semi-private bridges must be selected, 6) a rescue team of volunteers must be organized, having both a boat and nets, and the aircraft must be equipped with floatation devices, such that if the craft were to crash into the water, the team can retrieve it from the river, bayou, etc. so that some part of the craft is reusable (not a total loss), and more importantly so that the craft's Lithium Polymer battery does not contribute to an environmental incident in the river, bayou, etc. All of these contributed to, complicated and added time and a high degree of risk to the project.

4. METHODOLOGY

The research methodology included 1) surveys to gain understanding into bodies of knowledge pertinent to the project at hand, i.e. “Bridge Inspecting with Unmanned Aerial Vehicles,” 2) an investigation of FAA regulations affecting UAVs in Louisiana, 3) alternatives and tradeoffs to facilitate selection of a UAV and instrumentation system, applicable to bridge inspection and demonstration, and 4) field test demonstration with UAV on selected actual bridge. Method details are described below.

4.1. Task 1: Activity and Methods – Surveys

Firstly, surveys were conducted by the project team, i.e. PI and students, to understand pertinent technologies, sciences, and areas, of the project’s intersecting requirements as follows:

- **Survey 1:** A general survey of the science and methods of conventional bridge inspection. This was facilitated through a web-based literature search, and direct on-site interviews with the LADOTD district bridge inspection engineers in the Lafayette District office.
- **Survey 2:** A survey of projects similar to this UAV bridge inspection project. This was facilitated through web-based search and an email-interview with the Minnesota Department of Transportation (MnDOT).
- **Survey 3:** A survey of available instrumentation potentially suitable for bridge inspection using UAVs. This was facilitated through a review of web-based information and scholarly paper.
- **Survey 4:** A survey of available UAVs and their characteristic performances. This was facilitated through review of UAV hobbyist’s books, and online web information and reviews. See Appendix A0 for details.

Note: The surveys included both literature reviews as well as interviews with persons having pertinent knowledge in the subject at hand.

4.2. Task 2: Activity and Methods – FAA Regulations Affecting UAVs in Louisiana

Secondly, the methodology proceeded with an investigation of the FAA regulations affecting the use of UAVs in Louisiana Airspace. Data collection was facilitated through direct on-site interview with the FAA field office in Baton Rouge, Louisiana.

4.3. Task 3: Activity and Methods – Alternatives, Tradeoffs, Selection of UAV and Instrumentation

Thirdly, at this stage, a team of volunteer students, UAV hobbyists and enthusiasts, and a licensed UAV pilot, was formed by the PI, referred to as the “Drone Corps Team.” The team, together with the PI considered what was learned from the surveys, discussed in Task 1 above, and worked with the PI to do further investigation into comparison of alternatives and tradeoffs and selection of equipment, comprised of UAVs and instrumentation, to compose a UAV-

based system appropriate to the task of bridge inspection in and around the environment surrounding a general or worse-case bridge.

It is noted here, that the formation of the Drone Corps Team, consisting of volunteer students, UAV hobbyists, and a licensed UAV pilot, was a strategic boost in project execution, allowing the project to benefit from the practical experience and hobbyists activities of these groups while at the same time, educating other less experienced Drone Corps Team members to provide Science, Technology, Engineering, and Mathematics (STEM) outreach and to develop knowledge and capabilities for future projects.

In order to facilitate UAV and instrument selection appropriate to bridge inspection, the following activities were undertaken:

- Combined UAV and instrument package - alternatives and tradeoffs considerations: The alternatives and tradeoffs rubric included flight time, operation in windy conditions, Global Positioning System (GPS) guided flight control, fly-by-wire stabilization mechanisms, obstacle avoidance, lifting capacity, fault tolerance, software upgrade capability, durability, visibility of and with the aircraft, ease of operation by trained and untrained persons, availability of replacement parts, availability of telemetry to powerful remote controllers, and capability to fly a pre-programmed route according to way points to name a few. This was facilitated through round table discussions, drawing upon the experience of both the Drone Corps Team and the PI, and their review of literature, web-based reviews and interviews.
- Experiments, indoor with various Commercial-Off-the-Shelf (COTS) UAVs and instrumentation: Indoor flight experiments were done with the AR Parrot 2 Drone, and the Phantom 3 UAV to gain insight into aircraft and instrument performance. Data and observations were captured for analysis by the PI and the Drone Corps Team. See Appendix A6 for details regarding the indoor UAV experiments.
- Consideration of UAV enthusiasts experience with respect to UAVs they operated and with respect to current and future options in UAV system design and implementation: Input was taken from the Drone Corps Team's licensed UAV pilot, i.e. Mr. Eric Cerna, with respect to his experience in operating the Yuneec Typhoon-H UAV so as to gain insight into the pros and cons associated with UAVs manufactured by Yuneec.
- UAV procurement to facilitate demonstration: The PI, utilizing input from the Drone Corps Team, the alternatives and tradeoffs rubric, and its associated rationale, facilitated the procurement and purchase of the selected UAV aircraft so as to conduct a bridge-inspection demonstration, described further in Task 4, below.

Note: A computer spreadsheet was used to facilitate objective evaluation of which UAV to procure, based on an alternatives and tradeoffs rubric of combined aircraft and instrumentation systems established by the Drone Corps Team during the alternatives and tradeoffs activities.

4.4. Task 4: Activity and Methods – Field Test Demonstration with UAV on selected Actual Bridge

Finally, the Drone Corps Team set up and performed a field-test demonstration experiment with the purchased UAV to capture bridge images, to facilitate an experienced recommendation for a UAV system capable of practically assisting in bridge inspection in the State of Louisiana. Here, the methodology consisted of the following activity steps:

- Experiment 4.1 – Unpack aircraft and components to examine their functionality: Unpack the aircraft components, examine the components visually and functionally in the lab, and become familiar with the aircraft components on the bench, as a preliminary, prior to conducting flight tests.
- Experiment 4.2 – Examine basic aircraft and controller functions and evaluate the performance of the E90 camera: Examine basic aircraft and controller functions in the laboratory, camera panning functions, camera video and still shot functions, arming the vehicle motors (to spin without flight), as well as to perform some basic indoor flight tests, inside the lab.
- Experiment 4.3 – Walking examination of a preliminary sample bridge for important considerations a priori to planned inspection: Examine a representative bridge in the DOTD Lafayette District and to do a cursory image collection on it, a priori to an actual bridge inspection, so as to determine any structural difficulties under or on the bridge which might present a hazard for a UAV aircraft during inspection. Determine a priori of an actual bridge inspection, if the UAV would potentially lose access to its GPS signal, if flown beneath the bridge in order to get pictures of the underside of the bridge deck.
- Experiment 4.4 – Evaluate aircraft modified to apply flotation devices: Modifications to the aircraft to enable floatation were made and evaluated to determine how they might affect its flight performance. A sample bridge, imagery, video, and calculations, and a field experiment, were used in the field to capture data, for analysis.
- Plan for the bridge UAV field test demonstration: A demonstration with the UAV being used to perform the survey-inspection flight of a selected bridge was planned for. This included considerations of the issues, hazards and permits, necessary for the field test demonstration at the bridge as well as important bridge focus areas for the inspection, and the selection of an appropriate bridge, adequate for and with minimal barriers to, the performance of the field test demonstration. Finally, the weather was a factor and support team availability were a factor in scheduling and preparing for the demonstration. The UAV, imagery, satellite photos, a boat with support team, and a sample bridge site were used to facilitate planning for the demonstration, and the LADOTD District office was consulted in effort to select a bridge appropriate to the demonstration so as to minimize liability and risk, while maximizing accessibility.
- Experiment 4.5 – Perform the actual field test demonstration: Video and image data were collected from the UAV field test demonstration and for review with bridge inspection engineers at LADOTD’s Lafayette District office. The UAV, imagery,

video, and survey-interviews were all considered in the review of the demonstration experiment results. A licensed UAV pilot was on site to provide experienced evaluation of the aircraft.

- Finally, a report was prepared, covering the demonstration experiment, findings, and recommendations with respect to a long-term UAV-based system approach. The report included the identification and discussion of advantages, disadvantages, and limitations in the use of UAVs for routine bridge inspection work in Louisiana.

5. FINDINGS

Note: Findings are based upon consideration of information acquired during the surveys, with review and analysis provided by the PI, project team and Drone Corps Team members experienced with the characteristic performance of UAVs and associated instrumentation and through reviews by experimenters in projects similar to the one at hand. These findings are important to consider since they have bearing with respect to the practical usefulness and limitation of UAV-based systems to assist and augment bridge inspection in Louisiana.

5.1. Task 1: Survey Findings

5.1.1. Survey 1: General Survey on Science and Methods of Conventional Bridge Inspection

General findings for Survey 1 included:

- Defining what a bridge actually is, learning about the types of bridges, their major and minor components, and construction materials used, and learning about the types of degradation and the manifestation of, and detection of degradation in bridges and bridge components.
- Coming to an understanding of the current regulatory drivers, methods, tools, equipment, conditions, and constraints having bearing on the bridge inspection process.

In particular the survey's salient findings included the following:

- It was determined that bridge inspection was a complex topic, with no easy or simple solutions, even when applying UAV technology, since there are so many different types of bridges, each with their own inspection requirements, and even different waterways, all having bearing upon the inspection process. Figure 1 shows the Hale Boggs Memorial Bridge illustrating a type of Stayed Cable Bridge design, crossing the Mississippi, while Figure 2 depicts the Vermilion River draw bridge in Milton, LA. Moreover, within a single bridge, a number of material types are used, including: timber, concrete, steel/metal, fatigue and fracture steel, stone masonry, and fiber-reinforced polymer (FRP), to name a few, each with potentially differing wear and tear profiles, affects, and inspection requirements (*I*). Details may be found in Appendix A1.
- A thorough and complete bridge inspection is dependent upon the bridge inspector's ability to identify and understand the function of the major bridge components and their elements. This intelligence is difficult to duplicate in a UAV-based system, hence bridge inspectors will likely still be needed on site.
- The potential exists for a UAV-based system to be programmed with images of the architecture and materials types of each bridge, as well as the latest previous findings of inspectors, so that a UAV-assisted bridge inspection can be focused on the correct inspection techniques for the bridge at hand a priori of the actual inspection, allowing the inspection to be done in a more time, energy and cost-effective manner. Hence, this item for recommended future research.



Figure 1. Hale Boggs Memorial Bridge – Stayed Cable Bridge crossing the Mississippi River at Destrehan, LA.



Figure 2. Vermilion River Bridge, Milton, LA – Example of a draw or lift bridge.

- If the UAV is going to be practical as an assisting tool to bridge inspectors, it must be capable of gaining image access of a sufficient resolution to view, identify, and enable severity measurement of conditions such as potholes, ravel, cracking, spalling, and exposed rebars.

- An important section of the bridge that will be technically difficult for a UAV-based system to inspect is underside of the bridge deck. Details associated with the bridge inspection process can be found in Appendix A2.
- An important aspect of the bridge inspection process that would be of particular importance to augment using a UAV-based system is that of gaining access to dangerously high locations on the bridge superstructure, especially where equipment with booms to lift bridge inspectors currently can't reach.
- Another set of tests sometimes employed by bridge inspectors and engineers, that will be technically difficult to achieve with a UAV-based system include magnetic particle testing, X-ray, sonograms, and sounding as generally these tests require contact with the bridge structure.
- One utility provided by a UAV-based system for engineering firms taking a detailed look at changes to the bridge and riverbank, could be that of periodic and comparative 3D modeling over time, of the bridge and surrounding bank structures to note any changes. Such modeling tests are done on bridges on an as-needed basis, when a more detailed look is required.
- Another area of the bridge inspection, considered off-limits to UAV-based systems is that of inspecting portions of the bridge located under water.
- Salient problems often found by bridge inspectors include 1) delamination especially of timber bridge members, and potentially of the road surface from the bridge deck, 2) cracks which must be measured for severity, and 3) rust which must be examined for material section loss. Details can be found in Appendix A3.
- The greatest cost with respect to conventional bridge inspection are considered to be complex bridge structures, e.g. truss, or cable-stay, where booms and personnel lifts need to be rented to access high parts of the bridge structure or beneath the bridge deck. Bridge inspectors also on occasion need to use marsh buggies to get underneath bridges. Details can be found in Appendix A4.
- Although lifts can extend up 80ft, with some bridges inspectors still cannot reach the top. Sometime consultants have to be hired to climb the rest of the way, increasing labor cost and safety hazard.
- One of the toughest parts of bridge inspection is watching for and handling traffic. It is a safety hazard and it slows work down. See Appendix A4.

Summary of findings (i.e., the main “lessons learned”) from Survey 1 are:

- The project team learned what defines a bridge, including the various bridge types, bridge sections, bridge components and material types, and how all of these affect the inspection, the inspector's ability to inspect as well as time and costs for inspection. There are many bridge types each with their own inspection requirements. This survey was important since no one on the team was a civil engineer. The PI and students were all in the field of electrical engineering.
- The project team learned that the ability to do a thorough job of inspection on a bridge is not just dependent on capturing images, but the inspector's ability to capture, identify, and understand the function of the major and minor bridge components and their materials.

- The project team learned that it is important to understand the history and know what to focus on, with a given bridge, a priori to the inspection, so that an effective job is done. This may be where the UAV and its software can be programmed prior to the inspection so that the UAV optimizes its inspection time and battery life with highest priority on these important pre-identified focal areas.
- The project team learned that it is important to know how the various materials making up bridge components degrade and how that degradation is manifested, e.g. lamination in wooden timbers, so that this evidence may be captured properly and thoroughly, especially in the case of a UAV-based inspection.
- The project team learned that some degradation in bridge components is not accessible to UAV instruments, e.g. underwater, subsurface cement cracks, interiors of timber members that may be hollow, and dark tight spaces requiring a human inspector and a flashlight. Some of these require hands-on inspection techniques, not possible in UAV-based inspection currently, without significant alteration of a UAV to potentially add robotic tactile and bridge contact capabilities.
- The project team learned that imagery, not just of the bridge, but of the supporting and neighboring banks, as they and the bridge change over months and years, may be an important value added by the UAV-based inspection system.
- The project team learned that UAVs may in fact be useful in accessing high, hard to reach places to capture imagery and beneath the decks of high bridges, requiring special equipment, and extra manpower and time. Also dealing with the traffic tends to slow the work. Here, if some of these issues could be avoided, the UAV stands to benefit bridge inspections from a safety, economic and ergonomic standpoint, saving on the use of equipment such as the reach-alls and lifts, time and manpower.
- The project team learned that the inspection of complex and higher bridges is better suited to the need for UAV-based inspection, as opposed to the simpler, lower and shorter bridges. But also, there are apparently many more, shorter simpler bridges in the state than there are taller, longer and more complex bridges. Considering it is feasible to do visual and infrared inspection on most bridge components above the water line, a comprehensive economics tradeoff study is recommended for future research.
- The project team learned that many of the types of degradation described, e.g. cracks, spalling, delamination, etc. will not be recognizable by UAV based instruments without some future research being done, possibly in the area of artificial intelligence, and that currently the UAV may be best a simply capturing images, e.g. visual and infrared, as an assist so that a trained eye can review the images.
- The project team learned that the UAV-based system of bridge inspection could enhance its value as an inspection-assist tool through intelligent software which could in addition to capturing images, also take measurements, and store bridge histories prior to an inspection so as to guide the UAV in its inspection path and focus. Additionally, it is recommended that intelligent software be configured or developed that would be capable of searching through the thousands of images that may be captured during bridge inspections, to perform recognition of the most important images, so as to optimize the bridge inspector's time efficiency.

5.1.2. Survey 2: Survey of Project Similar to the Louisiana UAV Project

This survey consisted of the PI and project team taking a look and learning from projects that have been done, that are similar to the one per this project mission, so as to benefit from any of their knowledge and to potentially avoid mistakes. It includes findings based on an actual bridge inspections conducted in the State of Minnesota. While Minnesota's resources and constraints were somewhat different from those of Louisiana, and while there are some significant differences between the terrain and waterways in Minnesota versus Louisiana, some important conclusions brought out by the Minnesota UAV project are as follows (2).

Note: To distinguish between the Project at hand, i.e. 17STLSU11 "Bridge Inspecting with Unmanned Aerial Vehicles R&D," and the MnDOT similar project, whose outcome is the MnDOT Report 2015-40 mentioned herein, the Louisiana project at hand will be referred to as the "Louisiana UAV project", and Minnesota's as the "Minnesota UAV project" (2).

In particular, the survey's salient findings included the following:

- The use of UAVs to aid in bridge inspection should be considered as a tool to a qualified Team Leader when a hands-on inspection is not required. They define "Team Leader" as an individual certified by MnDoT to conduct inspections of in-service bridges in Minnesota (2).
- The use of UAVs to aid in bridge inspections should be considered for routine inspections to improve the quality of the inspection by obtaining information and detail that may not be readily obtained without expensive access methods. UAVs should be considered where they can increase safety for inspection personnel and the travelling public (2).
- Due to the schedule and funding limitations in the initial phase of the demonstration project, a second study phase was recommended to be considered by MnDoT. Topics for investigation in the future phase included:
 - Cost comparison with Aerial Work Platforms and traffic control.
 - Explore inspection-specific UAV technology including Sensfly eXom (another type of UAV).
 - Compile a best practices document.
 - Incorporate UAV technology into an actual inspection.
 - Explore the use of a UAV in the planning of an inspection.
 - Use a secondary display for the bridge inspector Team Leader.
 - Perform bridge deck surveys with a zoom camera.
 - Explore using UAV technology to perform culvert inspections, which does not require FAA approval since culverts are an enclosed space.
 - Explore using UAV technology to perform girder box inspections, which does not require FAA approval since they are an enclosed space.
 - Use a UAV with infrared (IR) to inspect a bridge with known deck delaminations at dawn.
 - Use a UAV to conduct paint assessment of an existing bridge.
 - A set of best practices and safety guidelines should be prepared and added to the MnDOT Bridge and Structure Inspection Program Manual as the

technology becomes more prevalent. This could be added as a separate chapter or added to the current chapter titled “MnDOT Inspection Vehicle Policy Manual” (2).

Summary of findings (i.e., the main “lessons learned”) from Survey 2 are:

- The Minnesota UAV project Team used a fully professional Aeyron Skyranger UAV, with an approximate purchase price of \$140,000. Moreover, it was operated by trained UAV professionals and pilots on their team. Their positive findings referenced above, for the viability of UAVs of this type, in the context of their professionally trained setting and circumstances, is not surprising. However, the Louisiana UAV project is different in that fewer resource were allocated, both human and financial. While the Minnesota UAV project Team used a \$140,000 UAV, the budget for the project at hand included for UAV purchase, i.e. approx. \$11,000, means Louisiana UAV project team is answering a somewhat different question. The question being answered in the Louisiana UAV project is with respect to the viability of UAVs for bridge inspection under a more constrained economic case.
- Based on review of the Minnesota UAV Project report, if viable and practical, Louisiana’s more economical approach may allow greater scalability, especially since UAVs and their instruments will also come with maintenance costs. Hence a more economical UAV and more economical UAV operation and maintenance may allow more bridge inspections for Louisiana, not fewer. Moreover, the Louisiana UAV project seeks to determine, not just what UAV but what UAV-centered system (i.e. including what UAVs, instrumentation, software, added components, and potentially even water craft are needed in support of a UAV-centered bridge inspection mission) is appropriate to the practical task of assisting bridge inspectors with bridge inspection in a way that has the potential to improve the economics, efficiency, and safety of the process.
- While the Minnesota UAV project mentions the limitations of UAVs for bridge inspection, i.e. where hands-on inspection is required, the Louisiana UAV project team notes that UAVs can do things not easily performed by the bridge inspectors, e.g. video of bridge spans flexing under dynamic loading, repeated visits, and especially to dangerous locations.
- The Minnesota UAV project report noted that “Current FAA rules are onerous when the application is bridge safety inspections,” citing the slow and cumbersome FAA’s Section 333 Exemption and Certificate of Authorization process. They stated that while these rules do not prevent the use of UAVs for bridge inspection, the increased time required to obtain approvals is significant and cost prohibitive as a tool for bridge inspection. They further noted that proposed FAA rules for adoption in 2016, would remove many or all of these obstacles to widespread adoption. In the Louisiana UAV project, it is observed that the FAA has provided some changes here, i.e., that provide an important relaxation of the requirements that had to be dealt with in the Minnesota case.

5.1.3. Survey 3: Survey of Available Instrumentation Suitable for Bridge

Inspection

So as to keep the Louisiana UAV project on schedule, it is expedient to seek to demonstrate with instruments that are likely to be commercially available, and lightweight for use with UAVs, or those that could be easily modified for use with them, as opposed to items that would require significant research and development time and dollars, or research to develop new capabilities in instrumentation which is considered beyond the scope of the project at hand. Further, instrumentation should have some demonstrated use, even if in another similar field so that it may be quickly and practically applied to the bridge inspection problem at hand.

Note: Other instrumentation research, i.e. not currently commercially available or at a price within the project budget, is looked at in this project, for the purpose for making recommendation for beyond the scope of this project.

Note: From the conduct of surveys 1 and 2, it appeared to the team that most of the data captured by bridge inspectors (where they are not doing hands-on inspections) is visual in nature, e.g. images, namely video and still shot photos. In the Minnesota UAV Bridge inspection demonstration case, video, infrared, and LIDAR were of interest and importance (2). They stated the following “...infrared images of bridge decks and elements are already a common and accepted way to obtain information on concrete delaminations. UAVs can provide a very efficient way to collect infrared images of bridge decks and elements as they can be equipped with an infrared camera (2).” Another potentially important capability according to the Minnesota UAV Bridge Inspection case is to be able to produce a 3D model of the bridge and its supports and surroundings, but software is also needed to process the 2D images into 3D.

The following are recommendations for project strategy based upon Survey 3:

- It was reasoned that the most valuable instruments onboard a UAV when inspecting a bridge, would be in order of importance 1) a very high resolution video and still photo shot camera, 2) infrared camera, i.e. a Forward Looking InfraRed (FLIR) camera, and 3) potentially a LIDAR instrument, where these were feasible and compatible with an available UAV for 3D imaging.
- The team found that high quality FLIR cameras and LIDAR systems, sufficient for detailed bridge inspection were relatively costly relative to the budget of the Louisiana UAV project. Moreover, the strategic philosophy driving the Louisiana UAV project is that of keeping the cost relatively low, i.e. just demonstrating what is possible with the UAV, should it be equipped with sophisticated (but expensive) instruments. Hence, the project team decided for the bridge inspection demo, to focus on flying the UAV with high quality video and still photos only, instead of also using FLIR cameras and LIDAR, for the following reasons:
 - Project Budget Limitations
 - The UAV would in inspecting a bridge, generally be flying over water, and hence the potential exists that the UAV with instruments may crash into the river, bayou, etc., with the resulting loss, not only for the UAV but even more expensive instruments, e.g. the FLIR and LIDAR.

- A demonstration of very detailed inspection images and video, could in principle also serve to show that similar FLIR and LIDAR inspection details could be achieved provided the more expensive FLIR and LIDAR instruments were used.
- The overwhelming majority of data gathered currently in Louisiana consists of still photos as opposed to other data types (4).

The Minnesota project was conducted in 2015 (2), but it appears from our survey herein, that just a short 3 years later (2018), prices for semi-pro UAVs and near Cinema grade UHD 4k video and still shot cameras is such that a bridge inspection demo can be achieved and the project can recommend a more economically scalable UAV-based system to Louisiana, currently using video and still shot photographs, only. Hence the instrument(s) selected for demo should be of high quality, and still relatively inexpensively priced, relative to the project equipment budget, and should come bundled with and compatible with the UAV, so as to ensure expedience, compatibility and to generally enable first person view (FPV) through the camera while flying sufficient for the demo purposes, leaving the study with the use of the more expensive FLIR and LIDAR instruments for future research recommendation.

As shown in Table 1, many consumer grade UAVs now standardly come bundled and equipped with compatible cameras of higher quality.

Table 1. Sample of semi-pro UAV video and still shot cameras available in 2018 (15).

UAV	Video Cam	Still Shot
Phantom 4	UHD 4K with 60fps	12.4 MP
DJI Inspire	Zenmuse X3 Camera UHD 4K, 30fps	12.4 MP
DJI Inspire	Zenmuse X5 Camera UHD 4K, 30fps	16 MP
DJI Inspire	Zenmuse X5s Camera UHD 4K, 60fps	20.8 MP
Mavic Pro	Camera UHD 4K, 30fps	12 MP
Yuneec H520	E90 Camera, UHD 4K, 60 fps	20 MP
SenseFly eXom	Camera,	38 MP ** Price Tag exceeds our budget

From Table 1, all of the UAV-camera combinations listed are considered prosumer, or even semi-pro, as in the case of the DJI Inspire, Phantom 4, and Yuneec H520. It is evident from the table that in the case of the DJI inspire with the Zenmuse X5S camera, and the Yuneec H520 with the E90 camera, respectively that both UHD 4K at 60fps video and 20.8 to 20 MP still shot images can be obtained, respectively. Price checks on both of these show that they are well within the project budget, compatible with their associated UAVs, and at the same time they are capable of producing video and images significantly better than the HD video and 15 MP still shots obtained in the Minnesota UAV bridge inspection demo project. An interview with Mr. Robert Holbrook of Holbrook Multi-Media brings out his point that 4k, UHD 60fps video gets very high quality video without having to bother with the very large files produced by the use of 6K video (16).

Note: While it is possible to achieve true Cinema-grade video with 6K CinemaDNG technology, e.g. in the case of the DJI Zenmuse X7 camera, a CinemaDNG licensing fee of \$1,000 is required, which is counter to the scalability goal for this technology in the case of Louisiana.

Survey 3 further revealed a number of technologies that should be recommended as the topics for future research projects, since their time and cost to develop and implement are considered to be beyond the scope of this Louisiana UAV project. Much of the instrumentation research pertinent and important to bridge inspection is in the area of “crack detection and characterization,” for concrete bridge structures. Hence this is an important area for future research. For example, in the paper titled “Crack detection using image processing: A critical review and analysis, (3)” the following few are cited.

- Crack Detection: The science of automatically detecting cracks from imagery, is recommended as a future research project, as it is especially pertinent to the use of UAVs in bridge inspection, to increase their utility, practically (3). See Appendix A5 for details.
- Camera Image: Processing camera images either via pre- or post-processing algorithmic and artificial intelligence techniques is important if the images that UAVs gather are going to be maximally leveraged (8). See Appendix A5 for details.
- Infrared Image: Processing infrared images offers some potential benefit when using UAVs in bridge inspection along with Forward Looking Infrared (FLIR) cameras (8). See Appendix A5 for details.
- Ultrasonic Image: Ultrasonic images may be useful provided techniques can be developed for use with UAVs to access bridge concrete structures. A number of possible future research areas have been identified (8). See Appendix A5 for details.
- Time of Flight Diffraction (TOFD) Image: These images may be used to enhance the information obtained about cracks in concrete (8). See Appendix A5 for details.
- Laser Image: Laser images may be used with conjunction with UAV inspections to obtain high spatial resolution and measurement of 3D space.

Survey 3 allowed the project team to take a sharp look at what instruments and instrument technologies are currently commercially available, ready to use, and compatible with inexpensive UAVs (i.e. 5K or less), versus those that will require more research and adaptation to use with UAVs.

The project team decided that for the demonstration project, the capturing of high quality video and still shot photos would be sufficient for demonstration purposes, since currently these make up the vast majority of the data used by bridge inspectors, and since other commercially available technologies, e.g. FLIR and LIDAR were considered to be 1) difficult to attach or adapt to an inexpensive UAV, and 2) beyond the capacity of the project budget.

5.1.4. Survey 4: Survey of Needed UAV Criteria for Bridge Inspection and Available Drones (UAVs)

Note: In order to facilitate findings under Survey 4, a brief set of important UAV criteria were described by the team as being important to bridge inspection needs, and the environment in

and around a typical bridge, and Second, a set of commercially available UAVs and their characteristics were examined in order to support the development of a rubric spreadsheet, to facilitate the alternatives and tradeoffs under Task 3 of the project.

Based on Survey 4, in addition to the price (under \$5,000) and commercial availability, the project team considered the following criteria as important to the selection of a combined UAV and instrument system for the purpose of the bridge demonstration and in any UAV selected for recommendation to Louisiana for further consideration and research:

1. Payload Attachments: The UAV should accommodate a number of payloads and have payload attach points for swapping out payloads.
2. Video Camera: The UAV should either come with a video camera, or come bundled with a video camera.
3. Gimbal: The UAV's camera should have a gimbal for panning up and down and to the extent possible, 360 degrees.
4. Camera Stabilizer: The UAV's camera should have a stabilizing mechanism to remove the UAV vibrations and keep them from affecting the video or still shot photos.
5. First Person View: The UAV should include a First Person View (FPV), through the camera at the aircraft control unit so that the pilot can see what the aircraft sees and what the camera sees while shooting video or still shots.
6. Separate Aircraft and Camera Controllers: To the extent possible, the UAV should have separate controllers for the aircraft and the camera, so as to allow the pilot to focus on flying and the videographer / photographer to focus on capturing imagery.
7. Sturdy and sufficiently large landing gear: The aircraft should have a sturdy and sufficiently large landing gear that won't be damaged or allow the craft to be damaged if the landing is a bit hard.
8. Retractable Landing Gear: The aircraft should have a retractable landing gear, especially in the case where the camera is mounted to the bottom of the aircraft, so as to allow the camera a full 360-degree horizontal pan view.
9. Flight Time in Minutes: The aircraft should have a flight time of 20 minutes or greater on a fully charged battery.
10. Self-Stabilizing, termed Fly By Wire: The aircraft should be capable of taking fast compute stabilization actions automatically with the pilot essentially just controlling the flight path, as this is necessary to have a precisely controlled flight near a bridge structure, where turbulence and wind gusts, and interference with the air flow may prevail. In such cases, human pilot cannot take action quickly enough to keep the craft stable and stability must be maintained by the aircraft's onboard computer.
11. Obstacle Avoidance: The craft should have the ability to detect obstacles and automatically prevent itself from flying into or being flown into an obstacle so as to mitigate the possibility of a crash.
12. Global Positioning System (GPS)-based Navigation: The aircraft should have the ability to have its navigation and flight path adherence and location adherence in 3D space, control assisted through signals received from GPS satellites.
13. Other Navigational Aids: Accelerometers, Gyros, or other sensors, such as mapping devices, should be available on the aircraft.

14. Waypoint Mapping and Autonomous Flight: The craft should support the mapping of a 3D flight path, prior to the flight, so that it may be capable of flying the preprogrammed path autonomously.
15. Target Tracking: The craft should support the ability to track a target on the ground or on a craft beneath the bridge, to use as a navigational aid, in cases where GPS might be lost due to the bridge's interference or blocking of the GPS signal from the satellite.
16. Wide Controller Capability: The ability of the UAV to work with a wide variety of remote controllers.
17. Fault Tolerance: The design of the UAV should have some degree of fault tolerance, e.g. maybe a hexacopter that is able to run on any 5 propellers.
18. Wind Resistance: The UAV should be reasonably heavy and powerful, with a small cross sectional area so as to promote steadiness in heavy wind.
19. Waterproof: The UAV should float, or be easily adaptable to floatation devices, and waterproof to the extent this can be achieved practically, as a crash could land the UAV in the body of water beneath the bridge.
20. Range: The UAV should have a range sufficient to be used to inspect even some of the larger bridges in Louisiana, e.g. across the Mississippi river.
21. Redundant Sensors: The UAV should have redundant sensors for some degree of fault tolerance, especially as these sensors relate to navigation.
22. Flight Experience: It would be beneficial if the UAV selected was one where some team members had previous flight experience so as to make learning and orientation to the new craft expedient.
23. Data Analysis Software: If any of the UAVs or their controllers comes with software capable of analysis of images or telemetry data, this is a plus.
24. Telemetry Feedback: The craft in communicating to its controller should be capable of providing telemetry feedback about its position, orientation, altitude, and remaining battery capacity.
25. Payload Lifting Capacity: The payload weight and lifting capacity of the aircraft should be sufficient to lift small additional payloads.
26. Professional or Semi-Professional UAV: The craft and system should be considered by hobbyists and UAV pilots to be professional level, or semi-professional level, and suited for the intended purpose, i.e. inspections of facilities like bridges.
27. Warranty: It is desirable for the aircraft system to come with a warranty in case some components fail and need repair or replacement.
28. Hobbyists Experience: It is important that hobbyist experience be considered to capture input not picked up in literature or from literature surveys.

The above criteria are considered achievable based on available UAV characteristic data, as described in Table 2.

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DJI Mavic Pro



GoPro Karma



Parrot Bebop 2



Yuneec Typhoon H



DJI Phantom 4 Pro



DJI Inspire 2

Figure 3. DJI Mavic Pro, GoPro Karma, Parrot Bebop 2, Yuneec Typhoon H, DJI Phantom Pro, and DJI Inspire 2 UAVs.



Yuneec H520

Figure 4. Yuneec H520 UAV.

Data was collected on each of the UAV aircrafts shown in Figures 3 and 4. Table 2 was developed from a review of the online literature, and/or personal experience of team members.

Note: Ratings used in Table 2 were derived from Drone Corps Team and Project Team round table discussions, and alternatives considerations based both upon findings of Surveys 1, 2, 3, 4, and input from Hobbyists, the UAV pilot, the PI, and the Drone Corps Team members as to important considerations for UAVs and instrumentation when used in routine bridge inspection work.

Survey 4 allowed the project team to examine characteristics of some relevant UAV aircraft paired with their camera, camera stabilizers and gimbaling devices, etc. Surveys 1, 2, 3, and 4 form the basis, with Surveys 3 and 4 especially forming the basis for the Alternatives and Tradeoffs Rubric utilized under Task 3 of this final report, to select the appropriate UAV and Camera package to purchase for the bridge inspection demonstration, so that a recommendation can be made as to what UAV(s) based system to recommend to assist in routine bride inspection work in Louisiana and to determine the utility of that system for routine bridge inspection work in Louisiana.

Table 2. UAV Characteristic Data.

Characteristic	DJI Mavic Pro, See Fig. 3	GoPro Karma, See Fig. 3	Parrot Bebop 2, See Fig. 3	Yuneec Typhoon H, See Fig. 3	DJI Phantom 4 Pro, See Fig. 3	DJI Inspire, See Fig. 3	Yuneec H520, See Fig. 4
1. Payload Attachments	No	No	Minor	Yes	Yes	Yes	Yes
2. Video Camera	Yes HD	Yes	Yes-fisheye	Yes	Yes	Yes	Yes UHD
3. Gimbal	Yes – not 360deg	Yes – not 360deg	Yes – not 360 deg	Yes	Yes – not 360deg	Yes	Yes
4. Camera Stabilizer	Yes	Yes	Yes – not pro	Yes	Yes	Yes	Yes
5. First Person View	Apparent	Apparent	Apparent	Yes	Apparent	Apparent	Yes
6. Sep. Aircraft and Cam. Cntl.	Apparent	Yes	Yes	Yes	Apparent	Yes	Yes
7. Sturdy Landing Gear	Yes	No	No	Yes	Yes	Yes	Yes
8. Retractable Landing Gear	Apparent	Apparent	No	Yes	No	Yes	Yes
9. Flight Time in Minutes	20	20	20	19	30	27	28
10. Self-Stabilizing Fly by Wire	Yes	Yes	Yes	Yes	Yes	Yes	Yes
11. Obstacle Avoidance	Yes	**	**	Yes	Yes	Yes	Yes
12. GPS based Navigation	Apparent	Apparent	Apparent	Yes	Apparent	Apparent	Yes
13. Other Navigational Aids	**	**	**	**	**	**	**
14. Waypoint Maps and Auton. Flight	Yes	Yes	Yes	Yes	Yes	Yes	Yes
15. Target Tracking	**	**	**	No	Yes	Yes	Apparent
16. Wide Cntl. Cap.	Yes	**	Yes	Yes	**	**	Yes
17. Fault Tolerance	No 4 prop	No 4 prop	No 4 prop	Yes	No 4 prop	No 4 prop	Yes
18. Wind Resistance	No	No	No	good	good	**	excellent
19. Waterproof	**	**	**	**	**	**	**
20. Range	7km	low	low	good	good	**	1.5km
21. Redundant Sensors	**	**	Apparent	Sonar	Apparent	Apparent	Apparent
22. Flight Experience	No	No	No	Yes	Yes	No	No
23. Data Analy. Software	**	**	**	**	**	**	Apparent
24. Telemetry	**	**	Yes	**	**	Apparent	Yes
25. Payload Lift Cap.	low	low	low	good	good	good	excellent
26. Pro, Semi-Pro	No	No	No	Semi	No	No	Yes-pro
27. Warranty	**	**	**	1 year	**	**	**
28. Hobbyist Input Ex	No	No	No	Yes	No	No	Yes
Ready to Fly:	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Estimated Price:	\$1,299	\$1,100	\$500	\$800	\$1,799	\$3,159	\$3,800

** Not apparent, unlikely

5.2. Task 2: FAA Regulations Affecting UAVs in Louisiana

For a commercial entity, like a university, e.g. like the University of Louisiana at Lafayette, or State Government, or LADOTD, to fly an Unmanned Aerial Vehicle (UAV), that is under 55lbs, the FAA permit is a blanket permit, covered by Code of Federal Regulations CFR107, where the UAV can fly immediately without needing a certificate of air worthiness, providing the following rules are adhered to:

- The aircraft must be operated at least 500 feet away from pedestrians,

- The aircraft must be properly registered with the FAA,
- The aircraft is allowed to fly only at an altitude of 400ft or less (above ground),
- The aircraft must be operated 5 or more miles away from the nearest airport, unless special permission from the airport is obtained,
- A licensed UAV pilot is required, and
- The UAV operator is required to follow visual “line of site rules, i.e. the pilot is required to maintain visual line of site with the aircraft.

If the bridge structure rises above 400 feet in altitude, the UAV operator is allowed to fly to the top of the bridge. For example, if the bridge maximum height was 500 feet, the UAV would be allowed to fly to 500 feet for the purpose of bridge inspection, i.e. not to exceed the height of the bridge.

The FAA in response to interview stated that DIY UAVs require no special registration steps. Neither will customizing the UAV for instruments or fitting for instruments require any special registration steps.

5.3. Task 3: Alternatives and Tradeoffs, Selection of UAV and Instrumentation

Based on Surveys per Task 1, and Task 3 experiments (see Appendix A6) as well as round table discussions with the PI’s Drone Corps Team, the following Rubric was developed with ratings from 1 to 10 with 1 being the worst, and 10 being the best. In addition to the ratings, R_i , the rubric included assigned weights, W_i , for metrics ($i = 1$ through 28), determined through consideration of acquired survey knowledge along with input from team members experienced in UAV technology and operation. The weights represent the considered importance to the project for metrics 1 through 28, described in Table 3.

Table 3. UAV Alternatives and Tradeoffs Rubric.

Characteristics Metric (M)	DJI Mavic Pro Fig. 3		GoPro Karma Fig. 4		Parrat Bebop 2 Fig. 5		Yunec Typhoon H Fig. 6		DJI Phan.4 Pro Fig.7		DJI Inspire Fig. 8		Yun H520 Fig. 9	
	R	W	R	W	R	W	R	W	R	W	R	W	R	W
1. Payload Att.	0	5	0	5	3	5	7	5	7	5	5	5	7	5
2. Video Cam.	8	5	7	5	5	5	9	5	9	5	9	5	10	5
3. Gimbal	7	5	7	5	7	5	10	5	9	5	10	5	10	5
4. Cam. Stab.	10	5	10	5	8	5	10	5	10	5	10	5	10	5
5. FPV	8	5	8	5	8	5	10	5	8	5	8	5	10	5
6. Sep. Cntls.	4	6	8	6	8	6	10	6	4	6	8	6	10	6
7. Sturdy LG	10	5	5	5	5	5	10	5	10	5	10	5	10	5
8. Retr. L G	0	3	0	3	0	3	10	3	0	3	10	3	10	3
9. Flight Time	10	4	10	4	10	4	8	4	10	4	10	4	10	4
10. FBW	10	5	10	5	10	5	10	5	10	5	10	5	10	5
11. Obs. Av.	10	6	3	6	3	6	10	6	10	6	10	6	10	6
12. GPS	5	5	5	5	5	5	10	5	5	5	5	5	10	5
13. NAV Aids	3	3	3	3	3	3	3	3	3	3	3	3	3	3
14. Waypoints	10	6	10	6	10	6	10	6	10	6	10	6	10	6
15. Tgt Track	3	3	3	3	3	3	2	3	10	3	10	3	6	3
16. Wide Cntl.	10	3	3	3	10	3	10	3	3	3	3	3	10	3
17. Fault Tol.	3	8	3	8	3	8	10	8	3	8	3	8	10	8
18. Wind Res.	2	10	2	10	2	10	5	10	5	10	2	10	10	10
19. Wtrproof	3	2	3	2	3	2	3	2	3	2	3	2	3	2
20. Range	10	5	2	5	2	5	10	5	10	5	3	5	5	5
21. Rdnt. Sens	2	2	2	2	5	2	8	2	5	2	5	2	5	2
22. Flight Exp	5	6	5	6	5	6	10	6	5	6	5	6	5	6
23. Data Analy	2	7	2	7	2	7	2	7	2	7	2	7	10	7
24. Telemetry	2	7	2	7	8	7	2	7	2	7	5	7	10	7
25. Pay Ld	2	10	2	10	2	10	5	10	5	10	5	10	10	10
26. Pro, Semi-	2	10	2	10	2	10	4	10	2	10	2	10	10	10
27. Warranty	2	2	2	2	2	2	10	2	2	2	2	2	2	2
28. Hobbyist I	2	6	2	6	2	6	10	6	2	6	2	6	8	6
C_{UAV} Rank	740		631		695		1127		859		861		1292	

A formula was applied to the rating column and weights column for each UAV in the table, summing the products of ratings X weights so as to calculate the overall rank for each UAV-Instrument combination in Table 3 according to a formula as follows:

$$C_{UAV} = \sum_{i=1}^{28} R_i \times W_i \quad [1]$$

where:

C_{UAV} = the calculated alternatives and tradeoffs overall ranking of a given UAV from the table,

R_i = is the metric i rating for that UAV, and

W_i = the weight, or importance assigned to metric i .

Hence, at the bottom of Table 3, the C_{UAV} values are tabulated. In decreasing order of C_{UAV} rank, the following is exhibited:

- In 1st place is the Yuneec H520, with a C_{UAV} of 1292,
- In 2nd place is the Yuneec Typhoon H,
- In 3rd and 4th places are the DJI Inspire 2 and the DJI Phantom 4 Pro, respectively, while
- In 5th and 6th places, are the DJI Mavic Pro and Parrot Bebop 2, respectively. Finally, in last place is the GoPro Karma.

Hence, the first choice for the bridge demonstration is the Yuneec H520 UAV, which uses the attachable E90 camera, producing 4K Ultra HD video and 20 MP still show photos. The camera is gimballed for a full 360-degree horizontal pan. The camera can also be panned horizontally and downward. The camera provides video and still shots as well in FPV at the aircrafts remote control screen.

Also, the team surmised it important, that if routine bridge inspection is the goal, and if routine inspection needs to be done economically, that the inspection entity needs to be in the position to build its own UAVs, similar in form and function to the first place UAV, i.e. the Yuneec H520, selected for the bridge demonstration.

The ability to produce DIY UAVs for the long term is an important capability, since over the long term with routine maintenance, mishaps will occur; hence there exists a need to have the capability of replacing every part of the UAVs put into service if inspection operations are to keep going economically, under the adverse conditions surrounding bridge inspection.

For the long-term 2nd recommendation, it is recommended that a DIY-UAV, similar to the Yuneec H520 but with augmentations, be constructed and tested with multiple instrument cameras. But, since the DIY approach will require the 3D printing of UAV components and the piecemeal-purchase of integral components, as well as comprehensively testing these components in various combination, with some software configuration, and with liability for any damage it might do, it was deemed that to develop a DIY-UAV for a bridge inspection demonstration was beyond the scope of the project at hand.

Note: the PI, utilizing input from the Team along with rubric evaluation and rationale facilitated the procurement and purchase of the selected UAV aircraft, i.e. the Yuneec H520, to be use to conduct the demonstration in Task-Activity 4, below.

5.4. Task 4: Field Test Demonstration with UAV on a Selected Actual Bridge

Finally, the team set up and performed a field-test demonstration-experiment with the purchased UAV involving the use of a UAV to capture bridge images, so as to provide an experienced recommendation for an Unmanned Aerial Vehicle (UAV) system capable of practically assisting in bridge inspection in the State of Louisiana. Please see Appendix A7 for experiment details and hence basis for findings under Task 4.

5.4.1. Experiment 4.1 Findings

All components examined appeared to fit in the Pelican case, and to function within normal parameters. See Appendix A7 for experiment details. See rationale below:

- The batteries were charged to 100 percent capacity.
- The flight and camera firmware were easily upgraded by downloading files from the manufacturer's website, installing these files on a micro SD card, inserting them into the E90 camera (where said camera was installed underneath the aircraft), and simply turning the aircraft on, to allow it to upgrade both camera and flight firmware.
- The ST16S and aircraft were turned on and the ST16S and UAV aircraft established a WIFI communications link, showing aircraft telemetry and allowing the E90 camera to be panned up and down and clockwise and counterclockwise in 360-degree rotation by control of the ST16S controller.
- Moreover, it was observed that video and still shot photos could be captured on the microSD card in the E90 camera. Further, screen snapshots from the ST controller itself *could* be captured showing shots from the FPV and telemetry at the ST16 controller without the need to retrieve the micro SD card from the aircraft.

5.4.2. Experiment 4.2 Findings

See Appendix A7 for experiment details. Main findings include:

- The E90 camera video and still photos quality and resolution are adequate to capture images of small bolts and nails from 20 or more feet distant, without noticeable pixilation.
- Flight tests indoors required manual flight mode, as opposed to GPS assisted angle or return-to-home flight modes. Indoor flight tests of the vehicle in a confined space resulted in a crash. Though no harm came to the aircraft, it is evident that manual flight mode is tricky and even an experienced pilot may lose control.
- Hence, GPS is required for safe precise operation of the aircraft because using GPS allows the aircraft to prevent drift. If the deck of a bridge blocks the aircraft's received GPS signal, it is not recommended to fly the aircraft below the bridge deck in order to capture inspection images.

Note: Whether or not a bridge deck can block GPS signals, is tested Experiment 4.3.

5.4.3. Experiment 4.3 Findings

See Appendix A7 for experiment details with the sample bridge:

- The substructure space beneath the bridge deck appears to be of significant hazard to a UAV during flight, as the UAV would potentially have to fly in very tight spaces, with the potential of running into columns and crashing either into the bridge deck from below and/or falling into the water below the bridge.
- There is also a potential that the UAV could become somehow entangled into the bridge superstructure up near the road surface lifts. In the case of a drawbridge, this entanglement could present a hazard to the bridge operation the UAV or its debris is not removed subsequent to such a mishap.
- In accordance with Experiment 4.3, Part 2, the aircraft intermittently lost its GPS receive signal. The implication of this result is that flying an unaltered COTS-UAV beneath the deck of a bridge using GPS for position location, in angle or return to home flight modes, needed for craft stability, could potentially result in a crash of the UAV into the underside of the bridge deck. The only other alternative with a COTS unaltered

UAV is for it to be flown in manual flight mode, which may be even more hazardous, especially in the tight spaces beneath the bridge deck.

- Based on the outcome of this experiment, it is recommended that the demonstration of the selected COTS Yuneec H520 UAV only be flown alongside or near the selected demonstration bridge to avoid a crash, as to fly the UAV beneath the bridge deck for demonstration purposes, would require significant design modifications to the aircraft.
- Recommended Design modifications to the aircraft to accomplish UAV-based inspection beneath the bridge deck are discussed in final report Recommendations.

5.4.4. Experiment 4.4 Findings

Experiment 4.4 involved modifying the aircraft (Yuneec H520) to apply flotation devices (i.e., balloons). The aircraft will be sufficiently capable of assisting with outdoor flight and potentially with flight in and around a bridge where moderate wind and gusts are present, even with worse-case flotation devices as designed and tested. See Appendix A7 for experiment details.

5.4.5. Experiment 4.5 Findings

Experiment 4.5 involved the actual bridge inspection demonstration experiment at the selected LSU Bridge. See Appendix A7 for experiment planning, experiment details and data review-analysis. Summary findings are below:

- Aircraft, images, and video captured were sufficient as an assisting aid to bridge inspectors, per 1) LADOTD Lafayette District, survey / comments, and 2) Aircraft pilot – professional opinion statement.
- Aircraft performed very well. No mishaps occurred. The aircraft was steady and easy to pilot. Three fully charged batteries were brought out into the field for the bridge inspection experiment (See Appendix A7). These batteries combined, provided more than enough ample flight time allowing us to perform the bridge inspection adequately. See Appendix A8 for figures 29 and 30, showing still shots of the aircraft as it is used to obtain video and snapshots of the bridge using the E90 4K camera. Following are rationale:
 - From field experimentation, the aircraft could be accurately controlled such that an average pilot can position it within a 2'×2'×2' box in 3D space, while capturing clear, high resolution, video and still images. The aircraft was operated in angle flight mode, using the GPS assist for angular and position reference.
 - From field experimentation, a high level of performance was maintained even in somewhat windy conditions (i.e. 7 to 8 MPH), and even with balloon flotation devices. While each of the four orange balloon flotation devices represented a cross sectional area of about 9 square inches, the craft remained steady even in moderately windy conditions.

Mr. Eric Cerna (a licensed remote UAV pilot) conducted the demonstration. The following are his comments regarding the Yuneec H520 aircraft and E90 camera:

“I have flown a good handful of capable entry-level commercial UAV aircraft in my time as a licensed pilot. I must say that the Yuneec H520 with all of its features and the integrated platform it comes in is a very capable, stable, aircraft. This is a real machine; it is designed towards capturing detailed photos and video. With its smart features, it also has obstacle avoidance (front facing) so as to maximize safety and enhance the process of data acquisition. This is a must have for any application that requires a pilot to get as close as possible and maintain stability at high altitudes and in any unstable air conditions. I would say confidently that this this model of unmanned aircraft could be utilized extensively in bridge inspection.”

A survey was conducted during the meeting at the LADOTD Lafayette District office, in Lafayette, Louisiana, with Mr. Jerry Begnaud, District Bridge Engineer, allowing Jerry and his bridge inspectors to view the data (i.e. video and photos) collected from the UAV bridge inspection demonstration experiment, i.e. Experiment 4.5 (see Appendix A7). After viewing of the images and video aforementioned, the survey presented the following questions:

1. Did you view Images and/or Videos provided by UL Lafayette, collected in the LSU Bridge inspection, performed May 26, 2018 (Yes/No)?: **Response: Yes**
2. In your opinion, could the images acquired in the LSU Bridge by UL Lafayette’s UAV inspection, be useful to bridge inspectors if same or like quality images or videos were done for bridges in general (Yes/No)? **Response: Yes**
3. Are images and/or videos of sufficient quality to be potentially useful to bridge inspectors (Yes/No)? **Response: Yes**
4. Could UAV inspection of difficult to reach bridge structures or components, or other bridge structures or components be potentially useful to bridge inspectors (Yes/No)? **Response: Yes**
5. If you could improve the UAV bridge inspection survey done by UL Lafayette with its UAV and E90 camera, what suggestions or recommendations for improvement would you have? **Response: See general comments below:**
 - a. UAV-based inspection would be a good tool to reach difficult parts of the bridge structure.
 - b. The best approach is with a bridge that as undergone previous conventional inspections; where you review focus areas with the bridge inspector, prior to the UAV inspection, especially those in difficult to reach parts of the bridge, and in addition to a general UAV-base bridge inspection, the UAV also captures imagery and data pertaining to the a priori identified focus areas, i.e. identified by the bridge inspector as being important.
 - c. Another approach would be to do a general UAV-based inspection so as to capture bridge imagery and data, and then to sit down with the bridge inspector to review this data. Based on the bridge inspector’s review, certain focus areas would be identified, including those focus areas in difficult to reach parts of the bridge. Then a subsequent UAV-based inspection would be done to get imagery and data from these focus areas.
 - d. For examining the metal structures of the bridge, e.g. steel runners, longitudinal, transverse, hinges, gusset plates, flooring, stringers, images are adequate and

useful as an assist to the bridge inspector. Here what is most important is to look for any section loss or flacking in rivets or bolts, or other component fasteners, and structures. Here, what is important too, is that imagery from the inner side of the metal truss structures also be captured, so that inspectors can examine fasteners, plates, and other components for section loss due to corrosion.

- e. While the video and still picture imagery is good for examining metal parts of the bridge as metal corrosion and section loss are generally evident by examine the metal surface imagery, the same is not true for wooden timbers or concrete. With concrete, being able to tell the size of cracks is important, and it may be difficult to determine crack size strictly from images, without going out in the field and performing a measurement. With wooden timbers, the wood condition at the surface does not necessarily indicate the timber's inner condition. A timber may appear to be fine at the surface and still contain an interior hollow void that would weaken its structural support. For timbers like this, it is not enough, merely to capture imagery, but to also use a hammer, or other tool to do "sounding" of the timber to determine if there are any hollow voids.

Overall, the UAV-Based bridge inspection appears useful as a tool to assist bridge inspectors, especially in difficult to reach sections of the bridge, and especially where it is used to access focus areas or areas of interest to the bridge inspector as a follow up. While imagery obtained from a UAV-based bridge inspection is useful in regards to inspecting the bridge's metal components, it is not as useful in examining concrete and timber portions of the bridge. Moreover, a really useful capability of a UAV-based bridge inspection where feasible would be for imagery to be captured below the bridge deck.

6. CONCLUSIONS

The objectives of the project have been achieved, since 1) a recommendation for a UAV system to practically assist in routine bridge inspection work in the State of Louisiana has been provided and is described below, and 2) advantages, disadvantages, and limitations of UAVs for routine bridge inspection work in Louisiana has been provided as described below:

1. Recommendation for a UAV-based system to practically assist in routine bridge inspection work in the State of Louisiana:
 - a. It is recommended that the Yuneec H520 Aircraft with E90 4K UHD Camera be the basis UAV and camera instrument for routine bridge inspection work in the State of Louisiana.
 - b. The system should be augmented by use of a boat, where bridges span waterways.
 - c. The boat may be a custom designed vessel that serves both as a landing pad, a place to keep charged batteries, and as a craft to position the UAV closer to the inspection work, crucially saving battery life, and serving as a rescue vehicle for cases where a mishap causes the aircraft to impact the water.
 - d. Since bridge inspection using UAVs does carry some real risks of loss of the aircraft and expensive instrumentation, the system should be augmented by developing the capability to 3D print and duplicate any structural component, to install and program the aircraft's computer, motors, sensors, and mapping software, and to otherwise be capable of performing any required general maintenance and economic DIY duplication so as to achieve economies of scale, as aircraft will invariably be lost through mishap at some point, due to the many real hazards that exist.
2. Advantages, disadvantages, and limitations of UAVs being employed for routine bridge inspection work in Louisiana:
 - a. Advantage: According to review by the LADOTD Lafayette District bridge inspectors, the craft and its video and still shot camera, would be useful in the capture of imagery generally to assist bridge inspectors, especially in hard-to-reach places, such as at high altitudes on bridges where boom lifts can't reach. Most of the data captured by bridge inspectors during conventional bridge inspections consist of still photos, and this is what the current demo aircraft configuration does well.
 - b. Advantage: UAV-based bridge inspection offers an advantage especially where more frequent repeat visits are needed for focused image capture, to places along the sides of the bridge substructure, sides and tops of the bridge superstructure, and top of bridge decking.
 - c. Advantage: The state of the art in UAV systems currently permits image capture software for 3D modeling of the bridge, potentially permitting new and more in-depth analysis of the bridge structure as well as inspection planning, and to determine changes to the bridge structure over time.
 - d. Limitation: The craft requires GPS for navigation, and so must not be flown beneath the bridge deck as this may result in loss of control of the aircraft. Hence the aircraft currently cannot capture data very well beneath the bridge

deck, (or under the water) but instead must focus on the sides of the substructure, sides of the superstructure and tops of the superstructure and the deck.

- e. Limitation: According to LADOTD Lafayette District bridge inspectors, the craft and its still shot camera would be able to capture the outside appearance of bridge timber members, only, but to get an adequate idea as to whether timber members need replacement, sounding with a hammer or some other tool is normally done, with the bridge inspector listening for the echo. Currently the UAV instrumentation is not equipped to do sounding, and so as of the state of current technology, this function would still need to be performed manually by the bridge inspector.
- f. Limitation: The aircraft is not currently equipped for infrared imagery or LIDAR, which may prove useful some cases to examine changes in a bridge such as delamination of the bridge deck. Currently, funding limitations for this project prevent effective demonstration of bridge inspection with infrared and LIDAR instruments.
- i. Limitation: Weather conditions that may be acceptable for manual bridge inspection may still prove to be unsuitable for UAV-based bridge inspection, for example light rain may allow manual bridge inspection but may not be suitable for UAV-based bridge inspection.
- g. Disadvantage: The perceived advantages, i.e. the potential cost reduction, time reduction, and safety improvement of UAV-based bridge inspection as compared to traditional manual methods, may be rendered insignificant due to the overburden of regulation that comes with UAV-based inspection that will tend to slow the work and complicate the inspection process. The overburden of regulation described is comprised of the following:
 - i. FAA regulations under CFR 107 requiring a licensed UAV pilot on site to fly the aircraft. Since the UAV-based method is only capable of augmenting manual bridge inspection work by human bridge inspectors, this means that a UAV pilot, a human observer, and bridge inspectors may all be needed to be on site.
 - ii. FAA regulations under CFR 107 restricting the airspace, and requiring special permission if the bridge to be flight inspected is located within 5 miles of an airport.
 - iii. The time and paperwork involved in getting permission from the highway department to inspect a given bridge using a UAV.
 - iv. Any time a UAV is operated in the presence of motorists a liability may be incurred through merely distracting motorists, even if the UAV does not contact any motor vehicles.

7. RECOMMENDATIONS

The following are the main recommendations of this study:

- **Inspection Process Using UAVs:** Recommend inspections be done by coordinating with bridge inspectors firstly to gain insight into the bridge and its history and what bridge parts to focus on, thereby ensuring the efficient gathering of important data, especially in hard-to-reach places high up on the bridge superstructure.
- **UAV Use in Field:** Recommend UAV be used in the field alongside bridge inspectors to review data produced on site and to make recommendations for improving ergonomics, data capturing and analysis capabilities. Findings from these studies should be integrated into the highway system for improving procedures, methods, and techniques.
- **Economics Alternatives-Tradeoff Study:** Recommend a comprehensive cost-benefits study, with analysis of alternatives and tradeoffs be done as a project with UAVs in general, assisting bridge inspectors in the field for condition like those found in the State of Louisiana.
- **Automatic Parachute and Floatation devices:** It is recommended here that research needs to be pursued into augmented UAV aircraft design for fault tolerance, such that automatically activated parachute systems and automatically inflated floatation devices be developed for practical use in case of mishaps which cause the craft to fall on land or in water.
- **Top-Mounted Camera:** It is recommended here that capabilities need to be developed for low-cost UAVs, along with illumination to allow capture of imagery under bridge decks in low lighting.
- **Under-bridge navigation:** It is important to inspect beneath the bridge's deck. However due to potential loss of GPS position reference beneath the deck, the UAV is limited. Hence, it is recommended that alternatives to GPS navigation for the UAV be considered to allow the aircraft to fly beneath the bridge deck for inspection.
- **Recommended Second Aircraft Approach:** In seeking to make recommendations for UAV-based systems to assist in bridge inspection, it is important that every component making up the aircraft be capable of being either purchased for a very economical price or manufactured since mishaps will invariably occur. The capability to 3D print UAVs exists currently. Hence it is recommended that further research be done to develop a printable UAV system so that UAV parts and structures can be replaced economically so that the UAV-based system is economical in the long-term routine case.
- **Onboard Bridge Standards and History:** It is recommended that software and data files with bridge histories or important bridge data and its location on the bridge be kept and research be done to determine how to load such data onto the aircraft so that it can be a priori programmed with important waypoints to focus on, making the actual UAV-based bridge inspection more effective.
- **Intelligent Image Analysis Software:** Bridge inspection with UAVs may produce large numbers of image and video files, i.e. too many for the average bridge inspector to review in an effective manner. Research into intelligent image analysis software is

needed to allow software to scan thousands of images and videos for bridge deterioration spots or areas in need of further attention by the bridge inspector.

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16. Interview with Mr. Robert Holbrook, Holbrook Multi-Media, Lafayette, LA.

APPENDIX A0. TASK 1: SURVEY 4 METHODOLOGY DETAILS

Survey 4 included portions of an on-site interview conducted with pilot, Mr. Dacoda Bartels of Aerobotics, Inc. of Lafayette, LA (5). Survey 4 was further based upon round table discussions by the project team including the PI's established "Drone Corps Team," of undergraduate students, hobbyists, and a Licensed UAV pilot after considering the Aerobotics Interview (5), the DOTD Interview (4), and Surveys 1 and 2, which especially including the BIRM (1) and the Minnesota UAV demonstration project (2).

APPENDIX A1. BRIDGE MATERIALS DETAILS, RELEVANT TO THE BRIDGE INSPECTION PROCESS

A1.1. Timber (*I*)

- Timber Shapes: Timber members are found in a variety of shapes. The size of timber members are generally given in nominal dimensions, however sawn timber members are generally seasoned and surfaced from the rough sawn condition making their actual dimension about $\frac{1}{2}$ to $\frac{3}{4}$ inches less than the nominal dimension. The physical properties of timber enable it to resist both tensile and compression stresses, hence it can function as an axially loaded or bending member.
- Timber bridge members: are made into three basic shapes: i.e. 1) round as in piles, columns, or posts, 2) rectangular as in planks, beams, columns, or piles, and 3) built-up shapes and beams.
- Planks are most often used for bridge decks on bridges carrying light or infrequent truck traffic.
- Beams are generally installed with the larger dimension vertical, e.g. under the deck for support of the deck planks. Beams are larger and heavier than planks and can support heavier loads, and can span greater distances. As such, timber beams are used in bridge superstructures and substructures to carry bending and axial loads.
- Timbers can be solid, sawn, or built-up glued and laminated. Glued laminated timbers are advantageous in that they can be fabricated from smaller more readily available pieces. This method allows larger rectangular member to be formed without the presence of natural deficiencies such as knots.
- Glue-laminate timbers are normally manufactured from well-seasoned wood and display very little shrinkage after they are fabricated. Observation: As a matter of inspection, one may want to look for shrinkage over time, esp. in the case of a new bridge.
- Piles & Columns are normally round and slender, and support the structure footing or partially form the substructure. Piles may be partially above ground or completely buried.

A1.2. Concrete (*I*)

- Concrete is a unique material for bridge members because it can be formed into an infinite variety of shapes. Concrete member are used to carry axial and bending loads.
- Since bending results in a combination of compressive and tensile stresses, concrete bending members are typically reinforced either with reinforced steel (to produce conventionally reinforced concrete) or with pre-stressed steel (to produce pre-stressed concrete) in order to allow it to carry tensile strength in the member. Reinforced steel is also added to increase the shear and torsion capacity of concrete members.
- Concrete shapes can be 1) precast or 2) cast in place, and the most common shapes are slabs, decks, rectangular beams, tee beams, and channel beams. Bridges utilizing these shapes and mid steel reinforcement were typically cast-in-place (CIP). Concrete members of this type are used for short and medium span bridges.

- Rectangular beams are used for both superstructure and substructure bridge elements. Concrete pier caps are commonly used with rectangular beams to support the superstructure. In slab bridges, the slab spans the distance between piers of abutments, forming an integral deck and superstructure.
- Tee beams are generally limited to superstructure elements. Distinguished by a T-shape, tee beams combine the functions of a rectangular stem and flange to form an integral deck superstructure.
- Channel beams are generally limited to superstructure elements. They are formed in the shape of a “C” and placed legs down when erected. They function as both a superstructure and deck and are typically used for bridges with shorter spans.
- Precast shapes include I-beams, bulb-teas, voided or solid slabs, box beams, and box girders, generally used as superstructure members.
- Axially Loaded Compression Members: These members are conventionally reinforced to carry bending forces and to augment their compression load capacity.
- Substructure Columns: are straight members that can carry axial load and bending, are used for substructure elements. They are commonly square, rectangular or round.
- Arch Superstructure: an arch is a curved column and is commonly used as a superstructure element. They are generally square or rectangular.
- Piles: are slender columns that support the substructure footing or partially form the substructure. They may be partially above ground but are usually completely buried, and may be conventionally reinforced or pre-stressed.

A1.3. Iron (*I*)

- There are two basic types of iron members, i.e. cast iron and wrought iron. Cast iron is formed by casting, whereas wrought iron is formed by rolling the iron into the desired form.
- Cast Iron: preceded wrought iron. It can be formed into almost any shape, but it is brittle and has a low tensile strength. Hence, cast iron bridge members are mostly used to carry axial loads, and are boxed shaped to efficiently resist loads.
- Wrought Iron: is better suited to carry tensile loads and advances in rolling made it possible to form a variety of shapes, including rods, wire, bars, plates, angles, channels, and I-beams.
- Steel: Steel surpasses iron in both strength and elasticity. Steel can carry heavier loads and better withstand the shock and vibration of ever-increasing live loads. Due to their strength, steel bridge members are used to carry axial as well as bending forces. Steel shapes are generally either rolled or built-up. Shapes include bars and plates, angle channels, s-beams, American standard I-beams, W-beams, and wide flange I-beams.
- In 1896, I beam weights and dimensions were standardized when the association of American steel manufactures adopted the American Standard Beam. Measurements determine the type and strength of the beam. Types include S, W, WF, M and H.
- Built-up shapes: offer flexibility in designing member shapes. Hence they allow the bridge engineer to customize the members for a particular need. They are fabricated by either riveting, bolts, or welding techniques to attach components into the built-up shape. Typical riveted shapes include truss members, girders, and boxes.

- Riveted girders: are large I-beam members fabricated from plates and angles.
- Welded boxes: are commonly used for superstructure girders, truss members, and cross girders.
- Steel cables: are tension members and as such are used in suspension, tied arch, and cable stayed bridges. They are used as main cables and hangars of these bridge types. Example of use include the Golden Gate Bridge with its suspension cables and hangars.
- Connections: rolled and built-up steel shapes are used to make stringers, floor beams, girders, trusses, frames, arches, and other bridge members. There are several different types of bridge member connections, including pin riveted, bolted, welded, pin and hangar, and spliced connections.
- Pins: are cylindrical bars produced by forging, casting, or cold rolling. The pin sizes and configurations include 1) a small pin, 1 ¼ to 4 inches in diameter, is usually made with a cotter pin hole on one or both ends, 2) a medium pin, which is up to 10 inches in diameter, usually has threaded end projections for recessed retainer nuts, and 3) a large pin, over 10 inches in diameter, is held in place by a recessed cap at each end and is secured by a bolt passing completely through the caps and pin. Note A: Pins are often surrounded by a protective sleeve that may act as a spacer to separate member elements. Pin connectors are commonly used in eye bar trusses, hanged arches, pin and hangar assemblies, and bearing supports.

Note: The main disadvantage of pin connection details are the resulting vibration, pin wear, unequal eyebar tension, unseen corrosion, poor ability to inspect. Vibrations increase with pin connections because they allow more movement than more rigid types of connections. As a result of increased vibrations, moving parts are subject to wear.

Note: Where measuring a channel, it is not possible for the inspector to know how much as channel weighs. In order to identify a channel, measurements of average thickness, flange width, the web depth, and thickness are needed. From this information, the inspector can then determine the channel designation through the use of reference books such as those from the American Institute of Steel Construction (AISC) manual of steel construction

APPENDIX A2. BRIDGE INSPECTION PROCESS DETAILS

The following are notes of a general bridge inspection process developed from a survey of LADOTD bridge inspectors (4):

- Three major components of a bridge include the deck, the superstructure and the substructure. In addition to the ability to recognize these major components, it is important to be able to recognize and identify basic member shapes, which requires an understanding of timber, concrete and steel shapes used in bridge construction.
- Every bridge member is designed to carry a unique combination of tension, compression, and shear.
- Bridge inspections must follow the code of federal regulations (CFR) guidelines.
- DOTD Bridge Inspectors have Louisiana manuals for guidance that are derived from federal manuals. The district bridge inventory includes pipe, box culvert bridges, truss bridges, fixed bridges, swing bridges, lift bridges, timber bridges, railroad flatcars, metal pipes, and any kind of typical bridge structure. “We collect and keep all the data that Federal Highways requires for each bridge, and we keep it in a database for use by state, parish and federal governments (4).” All AASTO records are public records. The bridge inspection program is outlined in the federal register, CFR.
- “We use training manuals for a two-week bridge course (4).”
- It is important to know what to look for before a bridge inspection is done, so as to catch important data in the field.
- It is also important to be aware as to the kind of degradation that might be present in a bridge, so that you know how to assess the degree of that degradation.
- The bridge is examined according to its elemental sections, i.e. the substructure, superstructure, and the deck. The inspection is broken into three parts, which is the superstructure, the substructure, and the bridge deck. Within each of these classifications, inspectors look at elements and sub-elements.
- A few of the degraded conditions looked for include potholes, ravels, cracking, spalling, exposed rebar, etc. i.e. the visual things, and then they look for the degree of severity of each.
- Once these items are found, for example in the substructure, we need to examine and often measure the degree of degradation, e.g. is it a hairline crack in the cement, or spalling, and the severity of same. Essentially you have both the specific defect and the size or severity of each.
- Next these are combined to get an overall rating for the substructure.
- Likewise the superstructure is examined. The bridge inspectors look for bent members, cracked members, hollow members, corrosion, section loss, flaking, paint, abutments, fender systems & guard rails and bridge rails, and in essence, every piece of every bridge, as well as attachments to the bridge.
- In the current approach we’ve got to get equipment out with booms to put people under the bridge deck to do inspections. This requires planning, and of course there is cost and time involved. There are also parts of the superstructure that are in difficult to access and dangerous to access places, up high.

- Important techniques and comments from DOTD bridge engineers and inspectors: The kind of testing bridge inspectors use depends on the type of bridge being inspected. Some sophisticated types of non-destructive testing we employ include magnetic particle testing, X-ray, sonograms, infrared, sounding i.e. with a hammer and listening for the type of echo. We don't currently use HD cameras and we don't have software to analyze such images.
- We've had some bridges that were laser scanned for two or three days, two or three hours each, from different angles, to create a 3D model of a couple of movable bridges because they had some members that they thought were bent, and they wanted to quantify how they were performing and what they looked like. Currently in the district we don't study bridges over time to see if they move. This is beyond what is done in the district. But observed changes in bridges are noted through the bridge reports.
- Inspectors: also examine the bank and riprap to note changes there, including scouring of abutments, channel, and piles.
- Bridge inspectors in the Lafayette District – cover 8 parishes.
- Inspectors: also look at underwater portions of the bridge for issues, e.g. for a simple pile in more than 4 feet of water, every five years a diver needs to inspect.
- Most common types of bridges in our area are: Most common bridges in our area are getting to be concrete bridges, flat span 20 to 40ft spans. The district still has a lot of timber bridges, e.g. 100ft total length, with multiple spans, 20ft spans each. But timber bridges are the most troublesome because they require the most maintenance. You have to keep up with them. Most of the other bridges are truss bridges that have a lot of paint failure and corrosion. We have to watch them for a long time before we repair them, because they are so expensive to repair. This year, we have two of them coming up for repair including painting projects.

APPENDIX A3. SALIENT PROBLEMS FOUND BY BRIDGE INSPECTORS

The following are notes of potential bridge inspection problems developed from a survey of LADOTD bridge inspectors (4):

- Delamination (e.g. timber, wood grain and growth rings): as timber deteriorates, it splits and tends to follow those growth rings. When timbers are new they are all nice and touching and no cracks, but as they deteriorate, they split and end up existing more as slices instead of a single unit. Same with concrete, you might have rebar top and bottom, when you lose the concrete cover on the bottom or top or even internally. Critical delamination may be defined as something that show surface failure or something that could be otherwise identified as having loss of capacity.
- Cracks Severity: typically the crack itself is not the issue, instead it's how the crack affects the structural capacity of the bridge. As the bridge deteriorates over time, we get our bridge engineers and consultant community to look at the condition of the existing bridge, compare it to the original plan. It's not just the cracks that are looked at, but the crack severity in relation to the type of structure being examined. For example – if we have a bridge where 4-foot slabs by 20ft and then they are bolted together, a precast flat slab bridge with rebar on the top and bottom, say we have 12 of these bolted together with a key so that they transfer the load to each other, with the bottom slab and top slab being typically pre-stressed. Cracks on the top section can be just due to flexure, i.e. we know the ones on top are not as troublesome as the ones on the bottom slab. But it is the rebar of the pre-stressed strand we are concerned with, not the concrete cracks. Until the concrete cracks grow from hairline to eighth, to quarter, longitudinal spalls, and then when you have 12 of these lined up does the load get shared enough with adjacent spans to reduce your capacity? That's the question. So we are not concerned with every crack, we are concerned with significant cracks and at certain places. If it is a mid-span crack, on the bottom and open, and that's where our maximum moment is, then we want to make sure the load can be transferred to adjacent panels. So that this point, bridge ratings people will have a look, and they may say, we don't recommend it be rated at 40 tons anymore, we recommend it being posted at 10 to 15 tons. So we go from a full capacity bridge and through its life span we change its bearing capacity.
- Rust: we take a picture of it to capture it, and estimate the section loss, and the location and length, and record that to give to bridge ratings. Who may decide to do a structural repair or repost at a lower load, or take no action depending on the severity. Complex bridges have multiple load paths, i.e. many ways the load can be shared. Hence failure of one or more members, may not be critical. That's another reason why some bridges painting can be delayed, especially since we know it is expensive.
- Measurements: each defect is visually identified, e.g. a spall 18 inches long, two inches deep, and four inches wide. Concrete tends to break in triangles. We have the picture to quantify it, but we don't go so far as to calculate the volume, instead we show where it is in relation to the bridge member, and record its dimensions. The visual picture is a lot of our documentation in those cases.

APPENDIX A4. GREATEST COST AND THE TOUGHEST PART OF THE BRIDGE INSPECTOR'S JOB

The following are additional notes developed from a survey of LADOTD bridge inspectors (4):

- Biggest cost – with respect to bridge inspection is – truss, or cable-stay, etc. Complex bridges take longer. We have to rent reach-all (called a snooper) equipment to look underneath, using a boom. We own some of these statewide that go to each district on a rotation. We also use man-lifts on occasion that we have to rent. We can use marsh buggies to get underneath some of our bridges. We have retainer contracts. Baton Rouge will send us the equipment when are schedule to use it. After that, it's how many things do you have to look at? If it is just one 20ft span, I'm not going to spend all day looking at it. I'll spend a lot of time traveling to it, sometime inspecting it, and then on to my next inspection job. I can usually do three to four simpler bridges per day, but then when we get on a complex bridge we might be there for three days.
- On a lot of our major truss bridges, we do what we can with the reach-all, but in some cases we cannot reach the top. We get the 80ft man-lifts and we don't always get all the way to the top, so every so often we hire a consultant to climb it and or get some other specialized equipment. Morgan City Bridge is pretty tough. Labor involved is our personnel, e.g. we operate the reach-all ourselves.
- Toughest part of our job – depending on where you are, e.g. if you are on the interstate, you are watching the traffic. That's a problem and it slows work down. Sometimes we are going to a bridge that has some issues, such as section loss. We also go to classes to tell us where the most likely places for cracks and defects are. So, we generally know where to look, since we are familiar with the bridges over the years. Then it's a matter of looking at these things and then getting back into the office to do the paperwork. We have six inspectors and tend to inspect about 100 bridges per month. We do about 100 per month, with some bridges on a 6-month cycle, some on a 1-year cycle, and some on a 2-year cycle. Six persons, 40 hours per week, and about 100 to 115 bridges per month average. Cost calculates to about \$101 to \$116 per bridge for our inspector labor, with most bridges being small ones.

APPENDIX A5. RECOMMENDATIONS FOR FUTURE PROJECT RESEARCH

A list of future research includes:

- Crack Detection: Once aspect of bridge inspection is the detection and understanding of cracks in cement structures that are part of bridges. Cracks on the concrete surface are one of the earliest indications of degradation of the structure. Manual inspection is the acclaimed method of inspection. In manual inspection, the sketch of the crack is prepared manually, and the conditions of irregularity are noted. But since manual inspection depends on specialist's knowledge and experience, it lacks objectivity in the case of quantitative analysis. So, essentially, the authors propose automatic image processing technologies and techniques for identifying cracks and their depth in the structure. Note: It may or may not be feasible from a form, fit, function, price, effectiveness, or other criterion to obtain commercial-off-the-shelf (COTS) instruments suitable for bridge inspection using UAVs. Moreover, it may be necessary to augment any selected COTS instruments or otherwise, so as to make these more effective as assists in the bridge inspection process. Hence, a brief summary of these techniques and technologies was considered here as a basis to understand the potential solution set for instruments which may be applicable to bridge inspection on UAVs (3).
- Processing of Camera Images: Some techniques here include 1) Preprocessing, image segmentation, and feature extraction, 2) Numerical representation of defects, and crack quantification & detection via neural network and a 3D visualization model that assists in predicting crack depth, 3) techniques that combine digital image correlation and acoustic emission, allowing a determination of crack opening and spacing, and 4) proposed methods for detecting crack-like patterns in noisy environments, to name a few (8).
- Processing of Infrared Images: Infrared techniques include 1) an infrared (IR) thermography method based on IR image rectification with the extraction of isotherms allowing the detection of cracks as well as geometric characterization and orientation of the crack to assist in the prediction of the direction of propagation through the material, 2) the detection of the crack by using notches found in irregularities, 3) a method for crack detection based on the reflection of an IR source from the surface of a crack, where the proposed system uses specular reflection to identify the presence of cracks, 4) a method for crack detection called laser excited thermography using a laser spot source, where instead of imaging a crack by scanning a single laser spot, superimposing the local discontinuity images with the present laser excited thermography are used, and 5) a proposed method for use of ultrasonic IR thermography, to name a few (8).
- Processing of Ultrasonic Images: These techniques include 1) a proposed system using laser-ultrasonic scanning excitation and piezoelectric air-coupled sensing and the UFT and WUPI algorithms to extract damage features, 2) a method where ultrasonic sound (non-image) is used to detect a surface crack with conceptual crack feature extraction, 3) a method whereby ultrasonics is used to assist in crack detection depth, shown to be

- useful in providing information related to the severity of damage, and 4) a method using an ultrasonic tandem array, detecting the reflected wave at the incomplete penetration and the bottom of the irregularity structure (crack origin) to name a few (8).
- Time of Flight Diffraction Image: With Time of Flight Diffraction, i.e. TOFD, scattered images are exploited with the cross-sectional imaging technique. Some cases here include 1) a method of sparse matrix replacing image formation, where a set of hyperbolas are used to correspond to crack tip positions, and 2) a method for the automation of the ultrasonic image interpretation using the Time of Diffraction technique to aid in decision making.

APPENDIX A6. TASK 3: BASIS METHOD AND SOURCE FOR FINDINGS

Indoor flight experiments were conducted with the AR Parrot 2 Drone, and the Phantom 3 UAV, and an outdoor flight test with the Yuneec Typhoon H, to gain insight into aircraft and instrument performance, so as to facilitate recommendations, subsequent to the actual bridge demonstration experiment.

UAVs were flown inside a lab with a 30-foot ceiling in the Mechanical Engineering building at UL Lafayette. The purpose of the experiment was to do some characterization testing to facilitate knowledge about the performance of various UAV types on hand.

The objective: was to notice flight, handling and stabilization characteristics and to determine if pipes, cable tray, and other structures could be video recorded with acceptable viewing clarity from the drone's onboard camera. Note: The lighting in the LAB was adequate and the ventilation system provided a consistent horizontal airflow, estimated at 5 mph, noticeable starting at approximately 2 meters from the ceiling, and continuing all the way up to the ceiling. The airflow was believed to be laminar, instead of turbulent and might be the case with airflow surrounding a bridge, but the airflow at hand nevertheless is a good baseline indicator of UAV stability in wind.

Two UAVs were selected for indoor comparison, i.e. the Parrot AR2.0 Drone and the DJI Phantom 3:

1. Test of the Parrot AR2.0: the aircraft was flown with the indoor hull on, which has a larger cross-sectional area than the Parrot in its outdoor configuration, i.e. without the hull. This is considered closer to real conditions, i.e. similar to the case without the hull but in a stronger wind than 5 mph.
 - Finding: The drone proved somewhat difficult to control and hold its position especially as it approached the ceiling area of the lab, where the air currents were present. Within approximately four (4) feet from the ceiling, the drone had a tendency to be sucked toward the ceiling. This made it rather difficult to get a good first person view with the camera. Hence it was not steady enough to get adequate video for analysis.
2. Test of the DJI Phantom 3:
 - Finding: the aircraft was never able to launch due to a communications issue between the aircraft and its controller. The test failed.
3. Test of the Yuneec Typhoon H UAV outdoors: Pilot, Mr. Eric Cerna:
 - Finding: In Eric's experience handling the Yuneec Typhoon H, the results vary depending upon the weather conditions. Flight stability is moderate to moderate-high efficiency. It stays within 2-5 inches of exact location in the air when affected by variable winds of 5-10 mph. Performance could do with some modifications due to battery life. It performs effectively without concern. Flight times are noted around 18-20 minutes around 100-200ft of altitude on a low-wind day. Payload carrying capacity can be measured successfully at 3000 grams according to other owners but will severely reduce

flight time, functionality and maneuverability. Appendix A7. Task 4:
Experiments pursuant to basis for Findings

APPENDIX A7. TASK 4: EXPERIMENTS PURSUANT TO BASIS FOR FINDINGS

A7.1. Experiment 4.1

The purpose of this experiment is to unpack the aircraft components, examine the components visually and functionally in the lab, and become familiar with the aircraft components on the bench, as a preliminary, prior to conducting flight tests.



Figure 5. The Yuneec H520 UAV, shown next to its integral components in the Lab alongside its black protective Pelican case



Figure 6. The Yuneec 520 UAV showing six (6) flight arms in the down position, for installation in the Pelican Case.

From Figure 6, the Yuneec H520 UAV aircraft main section came out of its protective Pelican Case with arms folded down. Each of the six arms are easily extended in place for flight, manually. Once fully extended, one hears a distinct click as arms come in to place for flight.



Figure 7. Six propellers were included for six motors.

From Figure 7, six propellers come with the Yuneec H520 UAV aircraft for quick click-on installation onto the shafts of each motor. The craft has two sets of motors, i.e. Set A and B, with Set A motors rotating directionally opposite from Set B motors. Both propellers and motors are labeled as to which set they belong, and it is a simple matter to click-install each Set A propeller onto a Set A motor shaft and each Set B Propeller onto a Set B Motor shaft.



Figure 8. Showing two illumination cubes and potential mounting brackets – for illumination beneath bridge deck.

From Figure 8 above, two (2) illumination cubes (i.e. spot lights) and a potential mounting bracket were purchased with the UAV aircraft, so as to allow illumination for beneath bridge-deck flight inspection, if same was considered feasible.



Figure 9. Showing main power unit for charging both the UAV flight power battery and/or the aircraft's ST16S remote controller.

From Figure 9, the main power unit can, with its adapter slot and micro USB cable, be use to charge the UAV's flight battery, and /or its ST16S remote flight controller.



Figure 10. Showing the battery charge slot plugged into the main power unit for charging both the UAV flight power battery and/or the aircraft's ST16S remote controller.

From Figure 10, the battery charge slot is plugged into by a power cable coming from the main power unit, shown which in turn is plugged into a standard wall outlet. The UAV's orange flight battery is then inserted into the charge slot shown for charging which may require up to 3 hours for charging each battery fully.



Figure 11. Showing the UAV's ST16S remote flight controller.

Figure 11 shows the UAV's ST16S remote flight controller. It includes an integral Android tablet, which displays the UAV's flight telemetry, including flight battery remaining charge level, altitude, compass heading for the aircraft, angle orientation of the E90 camera with respect to the aircraft, as well as FPV from the perspective of the aircraft's E90 camera. The ST16S unit can capture screenshots of its own screen showing both the FPV image at the time along with telemetry from the aircraft.

The ST16S controller-Yuneec H520 aircraft combination, supports manual, angle, and return-to-home flight modes, with the latter two flight modes requiring receipt of GPS signal to function, while the manual flight mode does not.

The joystick on the left of the ST16S controller, controls aircraft altitude, with upward motion for gaining altitude, and downward motion for losing altitude. A slight leftward motion of the left joystick causes the aircraft to rotate counterclockwise, when looking at the aircraft from above, e.g. if originally facing north, rotating toward the west, while a slight rightward motion of the left joystick causes the aircraft to rotate clockwise, when looking at it from above, e.g. if originally facing north, rotating toward the east. The degree to which the joystick is moved linearly controls the degree to which the aircraft responds.

The joystick on the right of the ST16S controller, controls the aircraft translation, i.e. forward motion with respect to the nose of the aircraft, or backward motion, or movement to the right or left. Hence, moving the joystick up causes the aircraft to move forward, while moving the joystick down causes backward movement in the aircraft. Moving the joystick to the right causes the aircraft to move right and moving it to the left, causes the aircraft to move left. The degree to which the joystick is moved linearly controls the degree to which the aircraft responds.



Figure 12. Showing the UAV's plug-in flight battery.

Note: While the UAV's literature claims that the UAV flight time with these batteries is approx. 28-30 minutes. Actual measured flight time, in the field was approx. 20 minutes if battery is operated according to recommendations, i.e. allowing a battery discharge to no lower than 30 percent remaining capacity.



Figure 13. Close up photo of the ST16S controller's long-range WiFi antenna, used for communicating control to and receiving telemetry from the Yuneec H520 UAV aircraft.

The antenna has a flexible stem allowing it to be tilted in the direction of the aircraft for better connectivity between the aircraft and the ST16S remote controller, from Figure 11.



Figure 14. Close up photo of the E90, 4K UHD video, 20MP still shot photo camera and attached gimbal and gyro stabilizing mechanism.

The UAV's E90 camera is much more than just a camera, as it is integral with both the video/image stability mechanism and the UAV's stability mechanism. Underneath the camera is a slot for a micro SD card, where images from photo shots and videos taken during flight are stored, and where the firmware that controls the aircraft flight is put for firmware updates. The aircraft appears to depend upon the stabilization and gyro sensing in the camera stability mechanism for stable flight operation, as it also depends upon the GPS signal. It is not possible to communicate between the ST16S controller and the aircraft without the camera installed on the aircraft.

A7.2. Experiment 4.2

The purpose of this experiment is to examine basic aircraft and controller functions in the laboratory, camera panning functions, camera video and still shot functions, arming the vehicle motors (to spin without flight), as well as to perform some basic indoor flight tests, inside the lab.

A7.2.1. Camera Functions



Figure 15. PI preparing to perform basic tests, per Experiment 4.2, in the lab, holding the ST16S flight controller.

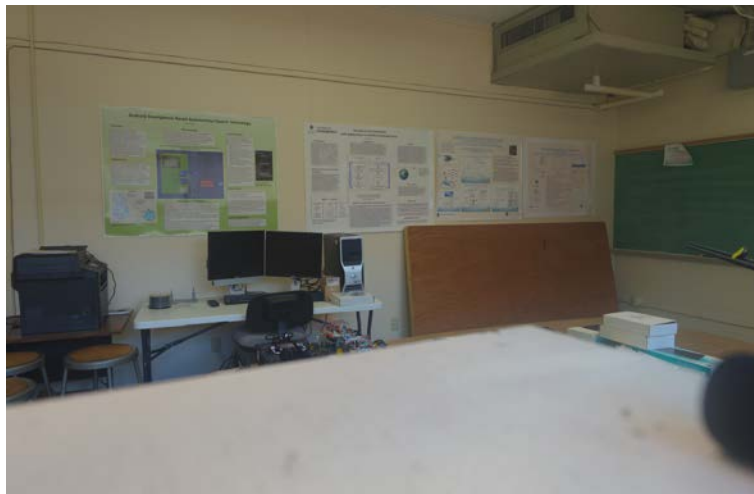


Figure 16. PI, from the perspective of the Yuneec H520 and its E90 camera. It is sitting on a file cabinet in the lab, about 20 feet from some of the PI's student academic posters, next we do a digital zoom to get a close up of the mostly green poster on the left.

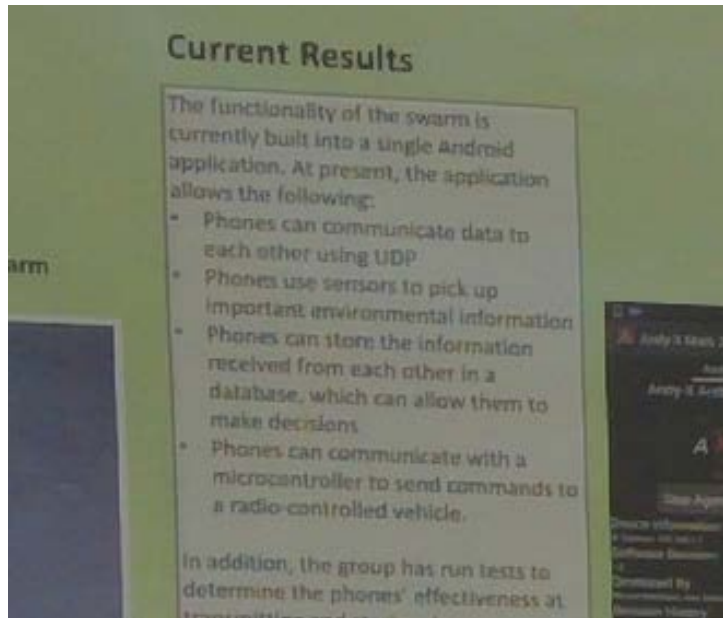


Figure 17. Digital zoom or enlargement of the photo image shown in Figure 16.

From Figure 16, the photo has not been digitally enlarged or zoomed. Very little poster detail is obvious in this image. However, this and other images taken by the aircraft's E90 camera, contain many pixels of information as is evident from the image shown in Figure 17, which contains a digital zoom of Figure 16, where it is possible to read text from the left-most (mostly green) poster, where letters are not much more than $\frac{1}{4}$ inch in height. This would allow a UAV and camera to capture images of sufficient resolution to show bridge rivets, small cracks, and section loss in bridge members, or even nails or bolts in bridge deck boarding, from a camera as far as 20 feet away, under lab lighting conditions. Better camera performance is expected in full sunshine illumination levels.

In Figures 19 and 20, we see Figure 18 digitally zoomed to yield close ups. Note that the camera has zoomed in on the $8\frac{1}{2}$ by 11 inch paper sheet taped to the top center of the blackboard. Note by examining the image contained in Figures 19, and 20, that lettering in the print, and on the blackboard, little more than $\frac{1}{4}$ inch in size can be viewed and recognized from more than 20 feet away, using the E90 camera, again allowing enough resolution to capture bridge rivets, and deck board nails, as well as small cracks and evident section loss, provided sufficient illumination is present, as evidence by the thumbtack at the top center of the $8\frac{1}{2}$ by 11 inch sheet.

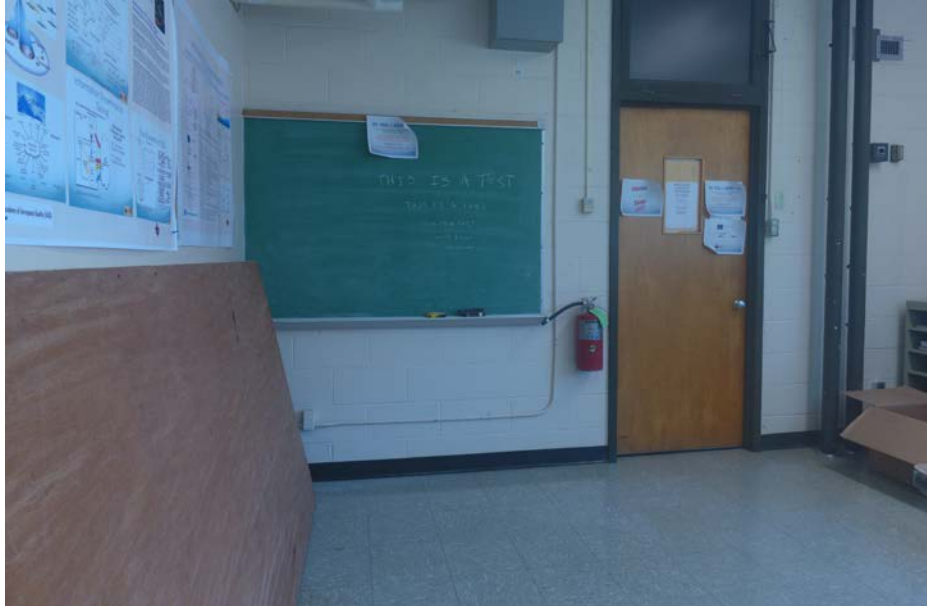


Figure 18. Test of snapshot with E90 camera looking toward a blackboard in the lab from a distance of about 20 feet. The blackboard contains letters as small as $\frac{1}{2}$ in size, and a sign on an $8\frac{1}{2}$ by 11 inch paper sheet, for comparison, at the board top-center.



Figure 19. Digital zoom or enlargement of the photo image from Figure 18.

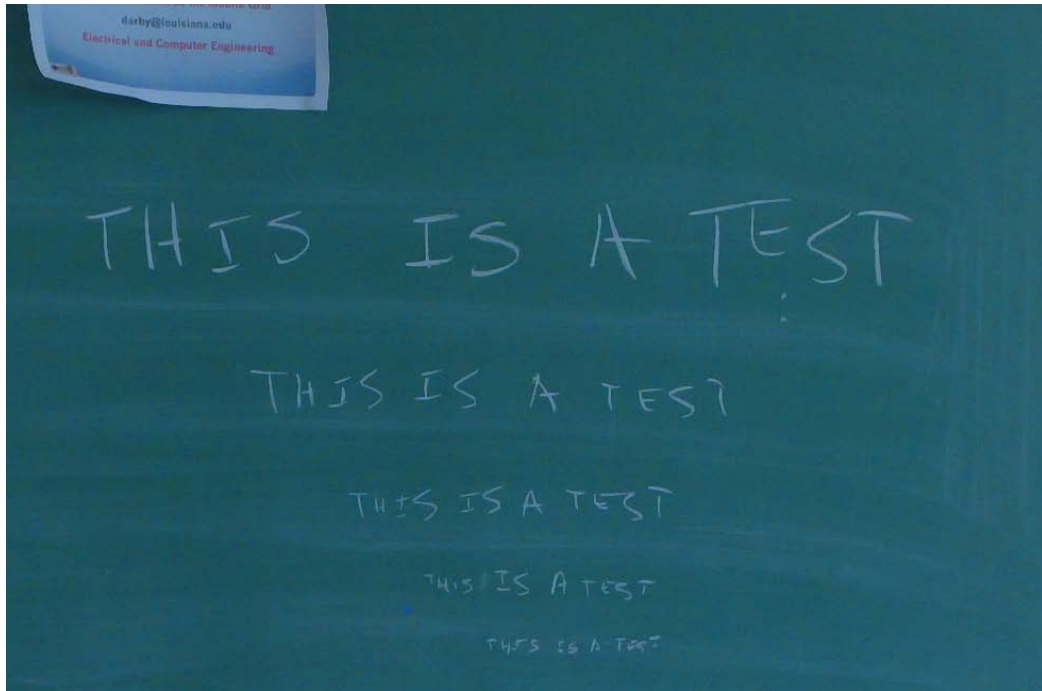


Figure 20. Lower shot of blackboard - digital zoom or enlargement of the photo image from Figure 18.

Examining video captured during the experiment, shows the capability of the E90 video camera to capture video motion, high resolution, and color. It was noted, in the final frame, the poster text, showed clearly visible in the background. Examined videos also show the capability of the E90 video camera to capture video motion while panning. While panning clear video of motion was noted.

The video's captured, show the capability of the E90 video camera to capture video motion while gimbaling downward. Video also captured the flight battery being charged.

A7.2.2 Arming and Spinning Motors of Aircraft

The ST16S remote controller verified to connected wirelessly via WIFI to the aircraft and turned on. Then the controller was used to send a signal to the aircraft arming it, allowing the propellers to be started, spinning in slower speed non-takeoff or standby mode, such that the propellers just spin but the aircraft does not take off.

A7.2.3. Aircraft Indoor Flight Test

Because the aircraft cannot access the Global Positioning System (GPS) indoors, as was expected, the flight test had to be conducted with the aircraft being flown by the pilot in manual mode. In manual mode the aircraft is very difficult to control, and requires the pilot to be highly skilled with quick reactions. But sometimes, especially when testing indoors, wind currents interacting with the floor, ceiling and walls, especially in cramped indoor environments, can cause the aircraft to pitch quickly so that even the most skilled pilots cannot compensate quickly enough. The aircraft ended up crashing in this test, which could have been anticipated, and was not out of line with the aircraft being forced to operate in manual mode, as opposed to "angle flight" or "return-to-home" modes, both of which utilize GPS to prevent drift.

Test result failed, but in keeping with the forced manual control. However this does not render the aircraft unacceptable for out-of-doors inspection use. The main conclusion for this indoor flight test, should be that flying the vehicle in manual flight mode is very hazardous and is likely to result in the crash of the vehicle, especially when near structures that affect wind patterns, such as a bridge.

A7.3. Experiment 4.3

The purpose of this experiment is twofold:

1. To examine a representative bridge in the DOTD Lafayette District and to do a cursory image collection on it, a priori to an actual bridge inspection, so as to determine any structural difficulties under or on the bridge which might present a hazard for a UAV aircraft during inspection.
2. To determine a priori of an actual bridge inspection, if the UAV would potentially lose access to its GPS signal, if flown beneath the bridge in order to get pictures of the underside of the bridge deck.

The bridge chosen was the Vermilion River Bridge in Milton, LA. This bridge is a drawbridge, built in 1947, that is typical of a few other bridges across the Vermilion River in and around Lafayette, LA. Photos taken with Iphone7.

Part 1 of Experiment 4.3 involved examination of bridge for structures which might be challenging or difficult for the aircraft; this examination was merely a photo examination of the bridge looking at both the super structure and the structure beneath the bridge deck.



Figure 21. Shows an overview of the Vermilion River Bridge in Milton, LA, i.e. the sample bridge.



Figure 22. Shows a close up of the bridge superstructure top section showing tight spaces between structural members.

Observations from Figures 21 and 22:

- The drawbridge mechanisms, superstructure, and winches appear to be of significant hazard to a UAV during flight, as to capture video or photos of the top sections may present the UAV with having to travel in tight spots, especially in the case of windy conditions.
- Should the UAV crash while flying over the bridge superstructure, there is a potential for it to get tangled or wrapped up in the bridge winch mechanism, potentially causing damage to the bridge.



Figure 23. Shows tight space confinement beneath the deck of the sample bridge.



Figure 24. Again shows tight space confinement beneath the deck of the sample bridge.

Part 2 of Experiment 4.3 determined a priori of an actual bridge inspection, if the UAV would potentially lose access to the GPS if flown beneath the bridge in order to get pictures of the underside of the bridge deck.

The Yuneec H520 selected for the actual bridge inspection demonstration as per Task 4 of the project, can detect whether or not it is receiving the GPS signal. If it is not getting the GPS signal, the UAV aircraft will only support manual flight mode. However, if it receives a GPS signal it will additionally support both angle and return to home flight modes, respectively.

The aircraft was walked beneath the bridge deck in various spots so as to determine if any gaps on GPS coverage would be realized.

While GPS coverage remained in some areas beneath the bridge deck, i.e. particularly closer to the edges of the bridge deck, where some view of the sky could still be had, it was found that beneath the bridge deck and closer to the center of the deck, GPS coverage would terminate intermittently. As the craft was walked about beneath the deck GPS coverage would come in and then go out again. With most COTS-UAV aircraft, like the Yuneec H520, losing GPS causes the craft to gain altitude and then return to its home base, i.e. where it launched from.

A7.4. Experiment 4.4

During the bridge inspection demonstration, should a mishap occur, e.g. a crash of the aircraft into the river, bayou, etc., it would be desirable 1) to rescue what is left of the aircraft so that repairs could be effected where possible, and 2) to prevent contamination of the water environment by the aircraft's Lithium Polymer (LiPo) battery.

Hence, a plan was developed to 1) equip the craft with small, lightweight floatation devices, so that it would not sink when impacting the water, and 2) to have someone on hand during the actual bridge inspection demonstration experiment, with a boat and a net to retrieve the craft and its battery from the water. The plan was to provide four (4) orange floatation balloons, i.e. orange in color for visibility, attached, or tied to the aircraft's landing gear, that would displace sufficient volume of water to float the aircraft. But the question this brings up is whether or not the aircraft's flight, and flight and image stability or flight time will be impacted severely enough to render these balloon floatation devices not advisable.

The vehicle mass must be supported with some small safety factor, e.g. 20%, by displacing this weight in the mass of water. The aircraft with attached E90 camera, and battery is 1645g, or 1.645 Kg. Increasing this value by 20% for safety yields 1.974 Kg, or approx. 2 Kg, or about 4.4lbs. The weight of water is 62.427lbs per cubic foot, therefore, 4.4/62.427 Cu ft or 0.07048 Cuft of water displacement would be needed. With 1,728 Cu inches in 1 Cu ft, we need 1,728 X 0.07048, or 121 Cu inches, total. Now, since we will be using four balloons, the volume each balloon must displace is: 30.44 cu in.

Assuming the balloon can be represented as a sphere, with the area of the sphere, computed as

$$\frac{4}{3}\pi r^3. \text{ Hence, } r = \sqrt[3]{\frac{3}{4\pi} \times 30.44} = 1.94 \text{ inches in radius, or approx. 3.9 inches in diameter.}$$

For the purposes of the experiment, four balloons were attached symmetrically to the aircraft's landing gear as shown in Figure 25, in a worse-case size of approx. 5 inches in diameter.



Figure 25. Aircraft shown, modified to include four (4) balloon floatation devices, 5 inches in diameter.

Subsequently, the aircraft was flight tested without and with the floatation devices. The aircraft without floatation devices has a very steady flight result even in a 12 mph wind with gusts. The aircraft with floatation devices, performed very nearly as good as without floatation devices, without causing instability or jitter or sever vibration that would impact the video or still shot.

The aircraft will be sufficiently capable of assisting with outdoor flight and potentially with flight in and around a bridge where moderate wind and gusts are present, even with worse-case floatation devices.

A7.5. Experiment 4.5

A7.5.1. Plan for Field Test Demonstration

The plan for the bridge UAV field test demonstration includes considerations of the issues and hazards and permits, surrounding the field test demonstration at the bridge as well as consideration of focus areas and factors pertaining to the field test with the bridge, and selection of the appropriate bridge to perform the field test demonstration on. Finally, the weather must be considered, the UAV and instruments prepared, and the demonstration support team and persons must be chosen and scheduled to coincide with the demonstration event. The UAV, and imagery, satellite photos, and a boat, as well as a field sample bridge site were used in analysis. The LADOTD Lafayette District office was consulted in effort to select a bridge for demonstration based on risk and accessibility criteria.

Prior to the actual bridge flight demonstration the following plan was developed:

1. Bridge Selection/Choice: The Lafayette district office was consulted about the project to do a UAV flight for bridge inspection. It was discovered that the required paperwork time to line up all the permits for inspection of a bridge is long, with a number of potential issues, and obstacles as follows:
 - a. Permission: bridges under LADOTD's charge, state bridges require permission for these purposes, which is not easy or timely to obtain.
 - b. Many bridges are close to major airports, which can present a permission problem with the FAA.
 - c. Hence it is best to select a private or semi-private bridge that is rather remotely located, to avoid the lengthy permit process. See Item 3 below.
2. Hazards Plan: There are a number of hazards to consider in doing a bridge inspection demonstration with a UAV, as follows:
 - a. Weather: Out in the open and especially near a metallic bridge structure, or even in a boat on the bayou, lightning can present a hazard, especially in afternoon as Louisiana thunderstorms develop quickly.
 - b. Flotation and Boat: Both flotation and a boat should be used when inspecting over water, as the UAV could sustain an impact with the water, resulting in the corresponding loss of the valuable aircraft and its LiPo battery, i.e. a potential hazard to the environment.
 - c. A Licensed UAV pilot: A licensed UAV pilot must fly the aircraft and there must be an observer on hand to help keep the aircraft out of harms way.
 - d. Liability: Most bridges carry quite a lot of automobile traffic. Even if the aircraft does not hit any motor vehicles when doing a bridge inspection demonstration, it could distract or scare drivers, causing them to loose control of their motor vehicles and hence, to sustain an accident. So, if the UAV is going to fly over a bridge that has traffic on it, some type of liability insurance should be obtained or the UAV needs to fly-inspect a bridge guaranteed to have no traffic or where the traffic has been stopped, which again requires a lengthy permission process again.
3. Plan the date, time and place of the demonstration: After considering Items 1, and 2 above, it was decided to focus on the LSU bridge spanning the Bayou Teche and located between Jeanerette and New Iberia, connecting LA HWY 182 and Old Jeanerette Road, i.e. HWY 87, to service the LSU Agricultural Research Station. See Figure 26 below.

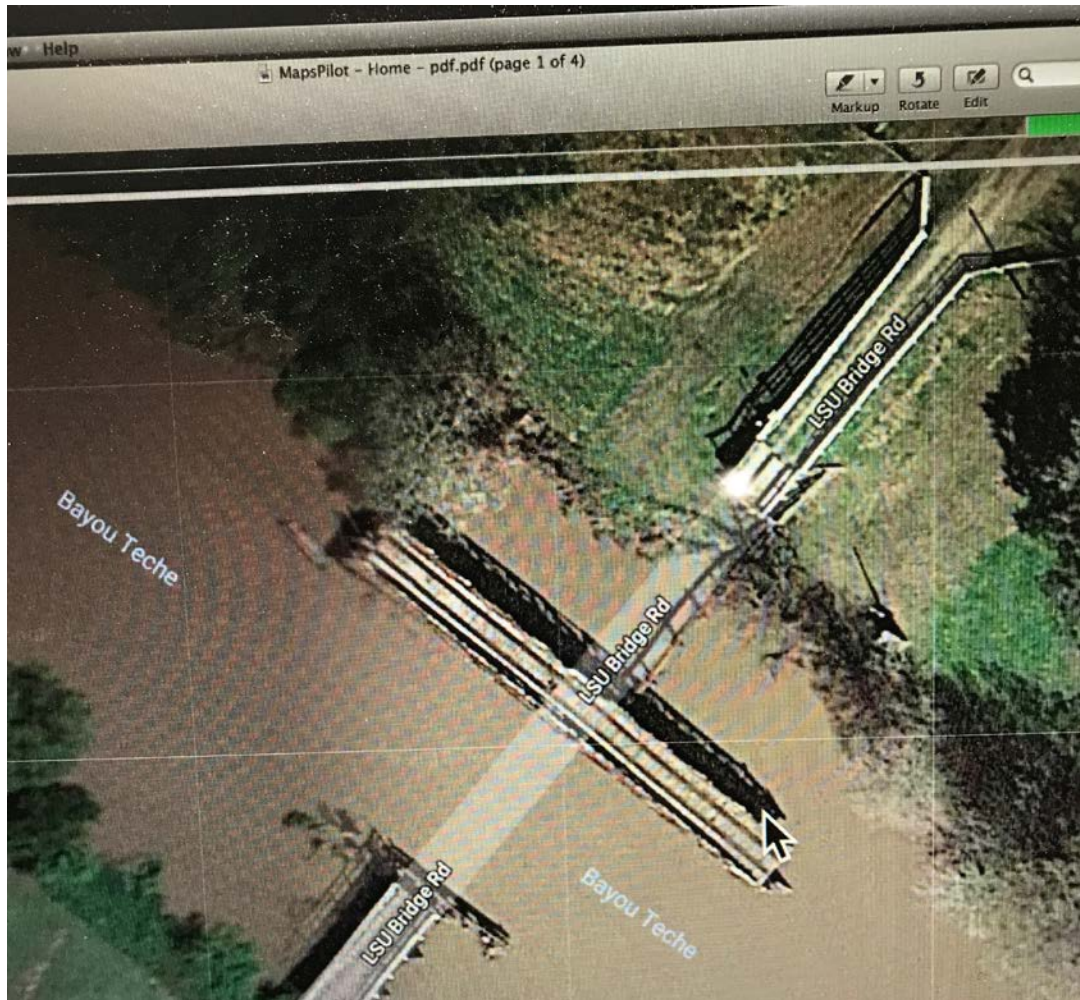


Figure 26. Satellite photo of the LSU Bridge, in open position in the Bayou Teche.

The advantages of using this bridge in the demo are many:

- The bridge is always in the open position and hence there is no traffic of concern, and the liability will be minimal.
- The bridge is easily accessible on foot, by car, and by boat, since there is also a boat ramp in the Jeanerette City Park, approximately 3 miles southeast of the bridge site.
- The bridge is a good and diverse sample bridge, composed of timbers and metal, making up a significant component of the older bridges in the Lafayette LADOTD District, and providing a broad spectrum of diverse materials to examine.
- The bridge is not too high; nor does it span a wide waterway which might present a high-risk mission.
- The bridge will not need permission for the inspection flight.
- The bridge is remote from major airports.
- The fixed bank-access decks of this swing-bridge make a good landing pad for the aircraft and operation base for the pilot, as they extend into the bayou about 30 feet, allowing a good view, both of the swing-bridge and the bayou, so that flying over

boaters can be avoided while at the same time allowing a view of the aircraft unobstructed by trees on the bank.

A7.5.2. Field Test Demonstration

The demonstration was slated to take place in the morning on a Saturday, so as to allow the designated UAV pilot, i.e. Mr. Eric Cerna, and the boater, Mr. Pat DuBois to participate. The time of day was set for early morning, so as to avoid where possible, afternoon thunderstorms, and to allow good sun intensity to provide sufficient light for photography. The aircraft was equipped with four (4) balloon floatation devices (See Figure 28). One main and two spare fully charged flight batteries were prepared for the demonstration experiment. Pat, and his assistant Terry were to power the boat, equipped with a grabber net, from the landing in Jeanerette to the bridge site to serve as lookouts in case the craft impacted the water. Prior to the actual trip to Jeanerette for the bridge inspection, the PI, Eric, Pat, and Terry all discussed the demo mission plan and then commended with it.

The bridge inspection demonstration experiment was conducted Saturday, May 26th, 2018 with Mr. Eric Cerna as the UAV pilot.

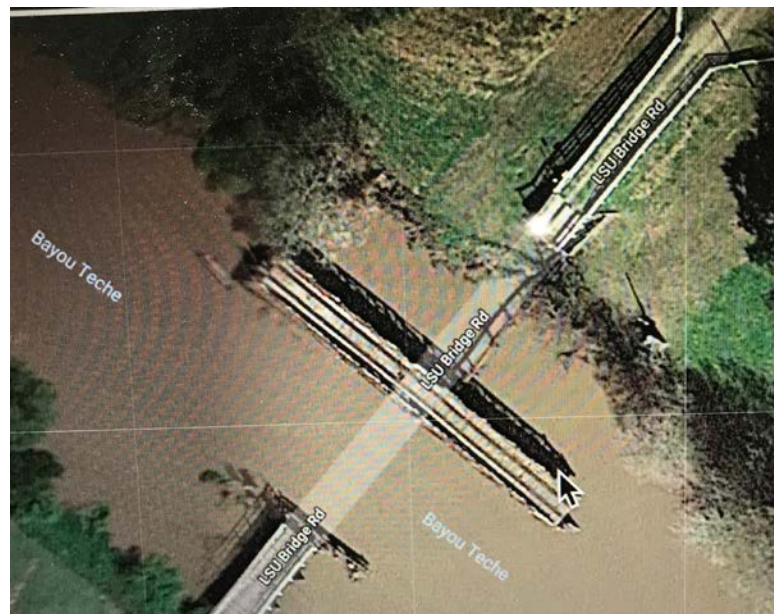


Figure 27. Selected LSU Bridge site, satellite photo.



Figure 28. Yuneec H520 aircraft with attached balloon floatation devices, and E90 camera, taken at the LSU Bridge.

The experiment was conducted using the Yuneec H520 hexacopter UAV, with mounted orange balloons, intended to serve as floatation devices, should the UAV craft impact the water beneath the bridge. See Photo, i.e. Figure 28. The aircraft was operated in angle flight mode with GPS assist active and equipped with the E90 4K Ultra HD video, and 20 MP still shot photo camera.

Below the bridge, in the Bayou Teche, two assistants were positioned in a boat in case the aircraft (UAV) were to experience a mishap and impacted the water. This is important, not only to be able recover what would be left of the aircraft and the data, but also to prevent the Lithium Polymer battery from contaminating the water.



Figure 29. Aircraft gets photos.

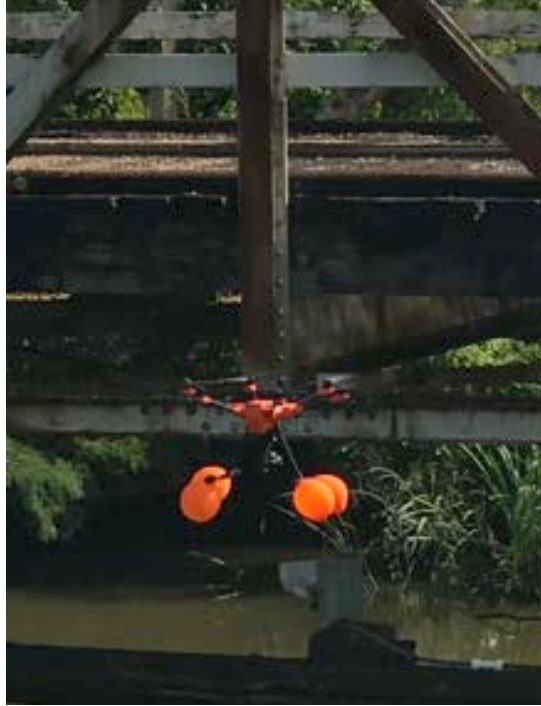


Figure 30. Aircraft gets lower shots.

In earlier experiment, i.e. Experiment 4.4, it was determined at the sample bridge, that GPS coverage beneath the sample bridge deck was spotty, meaning that certain areas beneath the bridge deck had GPS coverage while others did not. Should the aircraft be flying beneath the bridge deck and lose GPS coverage, its programmed response is to gain altitude and try to return home. Such a response underneath the bridge deck would likely result in the aircraft crashing into the bridge deck as it attempted to gain altitude beneath the bridge. Hence, it was decided by the experiment team, that flight beneath the deck of the LSU Bridge (bridge under inspection) would not be attempted.

Note: Future design research and considerations are needed. These may allow capturing of images beneath a bridge deck using a UAV-based system.

The Drone Corps Team previously debated whether or not to perform the bridge demonstration experiments using an infrared camera, in order to capture bridge deck delamination as was depicted in the case of the Minnesota study (2). The team decided against using an infrared camera due to its price, which can range anywhere from several thousands to more than 10 thousand dollars. Moreover, should the aircraft impact the water beneath the bridge, a considerable financial loss would be incurred. Hence, it was the recommendation of the Drone Corps Team that in principle, showing that good conventional images and videos of the bridge can be captured with sufficient resolution, would infer that similar infrared images could also be captured, and potentially prove useful.

The following Images and videos were captured by the Yuneec H520 UAV aircraft equipped with the E90 4K camera. An excerpt of photos are included below:



Figure 31. Upper view, bridge inspection, SW-side.



Figure 32. Lower view, bridge inspection, SW-side.

A7.5.2. Analysis of Imagery and Video Taken during Field Test Demonstration

A meeting was held, at the offices of Mr. Jerry Begnaud, the District Bridge Engineer, and Bridge Inspector for Louisiana Department of Transportation and Development, Lafayette Section, on Tuesday, May 29, 2018, approximately 9:00 am.

Persons present were allowed to view excerpts both of the photo images without and with digital zoom, as well as all videos captured during the LSU Bridge inspection, conducted on Saturday, May 26, whose photo and image excerpts are listed herein this experiment report.

Additionally, persons present viewed the PowerPoint presentation containing selected photos captured during Experiment 4.5. These photos are shown in Figures 33 through 34, below.

Note: All of the bridge inspection photos captured during this experiment, as referenced herein, can be zoom-enlarged to a significant degree, digitally.

Digital Close-ups (enlargements), selected from bridge inspection photos referenced herein, were included in the PowerPoint presentation viewed at the DOTD meeting. Excerpts showing enlarged photos are included here, in the next few pages, with commentary.



Figure 33. Photo enlargement showing the condition of bridge superstructure joint and outside rivets.

Note: That while some exterior rust is apparent in parts of the bridge superstructure members, the exposed side of the rivets in view appear to be in relatively good condition with no section loss.



Figure 34. Photo enlargement showing the condition of the near and far rivets in the lower members of the superstructure truss.

Note: Rivets appear to be in good condition.



Figure 35. Photo showing the original image from which the photo enlargements shown in Figures 33 and 34 were developed.

Note: Image is taken from distance exceeding 30 feet, yet digital enlargements still contain sufficient information to allow individual rivet conditions to be viewed for section loss.



Figure 36. Photo enlargement showing the condition of joint and rivets in the northeast side of the bridge superstructure truss.

Note: Rivets appear to be in good condition, some rust on members, but no section loss on rivets or members or any part of the joint is apparent.



Figure 37. Photo – greater enlargement of same joint shown in Figure 36, again showing closer snapshot the condition of joint and rivets in the northeast side of the bridge superstructure truss.



Figure 38. Photo showing the original image from which the photo enlargements shown in Figures 36 and 37 were developed.

Note: Image is taken from distance exceeding 30 feet, yet digital enlargements still contain sufficient information to allow individual rivet conditions to be viewed.



Figure 39. Photo enlargement showing the condition bridge deck boards shown from top, where cracks in the exterior of deck beam are visible as are nail heads slightly protruding from the deck board.

Note: Board exterior cracks and protruding nails clearly visible.



Figure 40. Photo enlargement of another section of the bridge deck, showing the condition bridge deck boards shown from top, where apparent board misalignment is seen as are the heads of protruding nails.



Figure 41. Photo enlargement even closer of another section of the bridge deck, showing board cracks and protruding nail heads.



Figure 42. Photo showing the original image from which the Photo Enlargements shown in Figs. 39, 40, and 41 were developed.

Note: Image is taken from distance exceeding 20 feet above the deck, yet digital enlargements still contain sufficient information to allow individual nails and cracks to be viewed.



Figure 43. Photo enlargement of another section of the bridge superstructure shown from the inside deck, view, showing the condition rail with apparent crack near rivet.



Figure 44. Photo enlargement of timbers supporting the entire bridge swing mechanism, showing apparent exterior wood decay.



Figure 45. Further enlarged image from Figure 44, showing close view of the affected support timbers.

Note: All enlarged photos, so described in this report were also derived through digital zoom enlargement of the image.