



# **NAVAL POSTGRADUATE SCHOOL**

**MONTEREY, CALIFORNIA**

## **THESIS**

### **AIRFIELD DAMAGE ASSESSMENT USING LIGHT DETECTING AND RANGING (LIDAR)**

by

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December 2018

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**AIRFIELD DAMAGE ASSESSMENT USING LIGHT DETECTING AND  
RANGING (LIDAR)**

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Submitted in partial fulfillment of the  
requirements for the degree of

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from the

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## **ABSTRACT**

Airfields are essential to the U.S. military and coalition forces' logistical lines of communications as well as force projection in any theater around the world. Given their utility and importance, airfields should be available for use anytime, and in case of damage, airfield damage repair (ADR) should start as quickly as possible. Before ADR can commence, however, an Airfield Damage Assessment (ADA) must be conducted. ADA assesses the damage to the airfield in detail so that the right type and amount of materials and teams to repair the airfield can be organized. This research focused on developing a low-cost, low-power system equipped with a Light Detecting and Ranging (LiDAR) system and a Global Positioning System (GPS) to accurately conduct an ADA operation. The system was designed and tested in a near operational environment and successfully demonstrated that an ADA can be conducted via a UAV. During tests on realistic damage at McMillan Airfield at Camp Roberts, the system produced rapid and accurate measurements of the diameter and depth of a crater. Also, the system was able to identify a camouflaged target that is hidden within a spall field.

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## TABLE OF CONTENTS

|             |                                                                    |           |
|-------------|--------------------------------------------------------------------|-----------|
| <b>I.</b>   | <b>MOTIVATION AND PROBLEM DEFINITION .....</b>                     | <b>1</b>  |
| <b>A.</b>   | <b>INTRODUCTION.....</b>                                           | <b>1</b>  |
| <b>B.</b>   | <b>RESEARCH FOCUS.....</b>                                         | <b>2</b>  |
| <b>C.</b>   | <b>SCOPE AND BOUNDARY .....</b>                                    | <b>2</b>  |
| <b>D.</b>   | <b>BENEFITS TO THE DEPARTMENT OF DEFENSE .....</b>                 | <b>2</b>  |
| <b>E.</b>   | <b>THESIS ORGANIZATION.....</b>                                    | <b>3</b>  |
| <b>II.</b>  | <b>BACKGROUND INFORMATION .....</b>                                | <b>5</b>  |
| <b>A.</b>   | <b>AIRFIELD DAMAGE ASSESSMENT/AIRFIELD DAMAGE<br/>REPAIR .....</b> | <b>5</b>  |
| <b>B.</b>   | <b>THE STRATEGIC IMPLICATIONS .....</b>                            | <b>5</b>  |
| <b>C.</b>   | <b>CURRENT TACTICS, TECHNIQUES, AND PROCEDURES<br/>(TTPS).....</b> | <b>6</b>  |
| <b>1.</b>   | <b>Emergency Operation Center .....</b>                            | <b>7</b>  |
| <b>2.</b>   | <b>Airfield Damage Assessment Process.....</b>                     | <b>7</b>  |
| <b>D.</b>   | <b>DANGERS IN THE CURRENT ADA TTPS.....</b>                        | <b>10</b> |
| <b>E.</b>   | <b>HISTORY OF ADA.....</b>                                         | <b>11</b> |
| <b>F.</b>   | <b>CURRENT USE OF SIMILAR TECHNOLOGIES .....</b>                   | <b>12</b> |
| <b>G.</b>   | <b>LIGHT DETECTION AND RANGING (LIDAR).....</b>                    | <b>14</b> |
| <b>H.</b>   | <b>CURRENT USES OF LIDAR .....</b>                                 | <b>15</b> |
| <b>I.</b>   | <b>LOW-COST, LOW-POWER, SMALL COMPUTER DEVICES .....</b>           | <b>16</b> |
| <b>1.</b>   | <b>Raspberry Pi.....</b>                                           | <b>16</b> |
| <b>2.</b>   | <b>Arduino Uno .....</b>                                           | <b>17</b> |
| <b>J.</b>   | <b>SUMMARY .....</b>                                               | <b>18</b> |
| <b>III.</b> | <b>SYSTEM DESIGN.....</b>                                          | <b>21</b> |
| <b>A.</b>   | <b>ADA SURVEY SYSTEM OVERVIEW .....</b>                            | <b>21</b> |
| <b>1.</b>   | <b>Housing .....</b>                                               | <b>22</b> |
| <b>2.</b>   | <b>Depth and Diameter.....</b>                                     | <b>22</b> |
| <b>3.</b>   | <b>Virtual Network Computing.....</b>                              | <b>23</b> |
| <b>4.</b>   | <b>How Data Is Analyzed .....</b>                                  | <b>25</b> |
| <b>5.</b>   | <b>Aerial Unit .....</b>                                           | <b>25</b> |
| <b>B.</b>   | <b>LIDAR-GARMIN LITE V3.....</b>                                   | <b>25</b> |
| <b>C.</b>   | <b>GPS-ADAFRUIT ULTIMATE GPS.....</b>                              | <b>27</b> |
| <b>D.</b>   | <b>VNC-REAL VNC.....</b>                                           | <b>29</b> |
| <b>E.</b>   | <b>UAV-DJI MATRICE 600 PRO .....</b>                               | <b>29</b> |
| <b>F.</b>   | <b>EXTERNAL BATTERY .....</b>                                      | <b>30</b> |

|     |                                                          |    |
|-----|----------------------------------------------------------|----|
| G.  | HAVERSINE FORMULA .....                                  | 30 |
| H.  | SUMMARY .....                                            | 32 |
| IV. | IMPLEMENTATION AND TESTING .....                         | 35 |
| A.  | PURPOSE OF EXPERIMENTATION .....                         | 35 |
| 1.  | ADA Survey System.....                                   | 35 |
| 2.  | Error Calculation.....                                   | 36 |
| B.  | EXPERIMENTS .....                                        | 37 |
| 1.  | Procedure for Airborne and Non-airborne Operations ..... | 38 |
| 2.  | Naval Postgraduate School Experiments.....               | 39 |
| 3.  | Lesson Learned .....                                     | 43 |
| 4.  | Camp Roberts Experiments.....                            | 43 |
| 5.  | Lessons Learned.....                                     | 47 |
| 6.  | Performance of Non-airborne ADA Survey System.....       | 47 |
| 7.  | Airborne ADA Survey System.....                          | 49 |
| 8.  | Airborne Camp Roberts Experiment.....                    | 49 |
| 9.  | Lessons Learned.....                                     | 53 |
| C.  | PERFORMANCE OF ADA SURVEY SYSTEM.....                    | 54 |
| 1.  | Quantitative Trends.....                                 | 54 |
| 2.  | Qualitative Trends .....                                 | 55 |
| D.  | SUMMARY .....                                            | 55 |
| V.  | CONCLUSIONS .....                                        | 57 |
| A.  | SUMMARY .....                                            | 57 |
| B.  | PERFORMANCE .....                                        | 57 |
| C.  | CONCLUSIONS .....                                        | 57 |
| D.  | RECOMMENDATIONS FOR FUTURE WORK.....                     | 58 |
|     | LIST OF REFERENCES .....                                 | 61 |
|     | INITIAL DISTRIBUTION LIST .....                          | 65 |

## LIST OF FIGURES

|            |                                                                                                               |    |
|------------|---------------------------------------------------------------------------------------------------------------|----|
| Figure 1.  | The Airfield Damage Repair model. Source: DAF (2018).....                                                     | 6  |
| Figure 2.  | The difference between spalls and craters. Source: DAF (2018). ....                                           | 8  |
| Figure 3.  | Rendering of ADAT conducting mounted assessments. Source: DAF (2018).....                                     | 10 |
| Figure 4.  | The Digital Surface Model of the area that was surveyed. Source: Xu and Lum (2018).....                       | 13 |
| Figure 5.  | DEM crated by the inexpensive software. Source: Dorninger and Pfeifer (2008).....                             | 14 |
| Figure 6.  | The Point cloud data before and after separation. Source: Sun and Salvaggio (2013).....                       | 16 |
| Figure 7.  | The Raspberry Pi 3 Model B .....                                                                              | 17 |
| Figure 8.  | The Arduino UNO microcontroller .....                                                                         | 18 |
| Figure 9.  | Left, is the front view of the ADA Survey System; Right, is the rear view .....                               | 21 |
| Figure 10. | A view of the Serial Monitor that illustrates the 2-D graph of a depression in the ground .....               | 23 |
| Figure 11. | An illustration of what VNC provides to the user. Source: RealVNC (n.d.).....                                 | 24 |
| Figure 12. | The LiDAR used in the project. Source: Garmin (n.d.).....                                                     | 26 |
| Figure 13. | Adafruit Ultimate GPS. Source: Industries (n.d.). ....                                                        | 28 |
| Figure 14. | DJI Matrice 600 Pro. Source: Matrice 600 Pro (n.d.).....                                                      | 30 |
| Figure 15. | A rendering of how the distance between points A and B are determined. Source: Mwemezi and Huang (2011). .... | 31 |
| Figure 16. | The Haversine Formula. Source: Mahmoud and Akkari (2016). ....                                                | 32 |
| Figure 17. | Precision and Accuracy. Source: Carlson (2002). ....                                                          | 37 |
| Figure 18. | Camouflet. Source: United States Marine Corps [USMC], 2017.....                                               | 39 |

|            |                                                                                  |    |
|------------|----------------------------------------------------------------------------------|----|
| Figure 19. | Aerial view of Glasgow East Building located at NPS.....                         | 40 |
| Figure 20. | View of the notional crater at King Hall.....                                    | 42 |
| Figure 21. | The crater that was used in the first two experiments at Camp<br>Roberts .....   | 44 |
| Figure 22. | Comparison of LiDAR generated graph to actual spall and camouflet<br>field ..... | 47 |
| Figure 23. | Crater used in airborne experiments .....                                        | 50 |
| Figure 24. | Airborne operations .....                                                        | 51 |
| Figure 25. | Comparison of LiDAR generated graph to actual spall and camouflet<br>field ..... | 53 |

## LIST OF TABLES

|          |                                                                                  |    |
|----------|----------------------------------------------------------------------------------|----|
| Table 1. | Results for the first experiment at Glasgow East Building at height zero.....    | 41 |
| Table 2. | Results for the second experiment at King Hall at height zero.....               | 43 |
| Table 3. | Experiment 1: Crater at McMillan Airfield at height 4.16 ft above damage .....   | 45 |
| Table 4. | Experiment 2: Crater at McMillan Airfield at height 7.16 ft above damage .....   | 46 |
| Table 5. | Experiment 1: Crater at McMillan Field at airborne height 2 m, or 6.56 ft .....  | 52 |
| Table 6. | Experiment 2: Crater at McMillan Field at airborne height 4 m, or 13.12 ft ..... | 52 |
| Table 7. | Experiment 3: Crater at McMillan Field at airborne height 6 m, or 19.68 ft ..... | 53 |

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## EXECUTIVE SUMMARY

Current and future operations around the world both combative and humanitarian are only possible with open lines of communication. The airfield provides U.S. and coalition forces a rapid hub for staging supplies and military personnel. Thus, in an event that the closest airfield is damaged from kinetic operations or a natural disaster, the need for rapid airfield damage repair (ADR) is necessary in opening that strategic hub. Before an ADR can commence, however, an airfield damage assessment (ADA) must be conducted. ADA assesses the types and dimensions of damage such as craters and camouflages that can be hidden in spall fields. The objective of an ADA is to aid in the estimation for the right type and amount of materials and teams to repair the airfield. The current Tactics, Techniques and Procedures are conducted by personnel on the ground, which is often tedious, time-consuming and dangerous. As a result of advances in unmanned aerial vehicles (UAV) and remote and local sensors, an ADA can be accomplished autonomously, thus keeping the service members safe while expediting the process allowing for the ADR to be conducted rapidly and efficiently restoring the lines of communications.

This research is aimed at fabricating a low cost, low power system, equipped with a Light Detecting and Ranging (LiDAR) system and a Global Positioning System (GPS) to accurately conduct an ADA. To accurately depict the damage to the airfield, the system needs to be able to scan the depth and diameter of the damage. Based on this two-dimensional requirement, the LiDAR was chosen to scan the depth and the GPS unit was chosen to scan the diameter. LiDAR emits a near infrared light towards an object and then calculates the time that it takes to reflect the light from the object and back to the sensor converting that data into a distance. The GPS unit will measure the diameter by recording the latitude and longitude coordinates from the start and end of the damage. Using the Haversine formula these coordinates will be converted into a distance ultimately into the diameter of the damage. Using the constraints of low cost and power the ADA Survey System was fabricated. Arduino microprocessor boards are connected to each sensor allowing the user to update and modify the code that controls the data rate and action. These

Arduino boards are connected to a Raspberry Pi that is connected to the user's computer via a Virtual Computing Network providing the user with a live stream of the data acquisition. The system is held together by a 3D printed housing made from Polylactic Acid filament. The system in total weighs 0.86 kg, or 1.9 lb, and was constructed for \$244. The ADA Survey System is mounted onto a commercial-off-the-shelf UAV and tested in near operational conditions and on realistic damage in order to investigate the validity of the system.

The system was tested in a near operational environment on a realistic crater and a spall field with a camouflet. In order to properly test the ADA Survey System three trials were conducted at a specific height above the damage to produce an average error for both the LiDAR and GPS units. Each individual trial error was then averaged for both sensors and converted into a unit of measurement that was compared to the control measurements. The best results occurred at a height of 2 m, or 6.56 ft, above the realistic crater. The diameter error was 5.09%, or 5.60 in., when converting that to a unit of measurement and the depth error was 2.94%, or 0.47 in. The system was also able to determine the existence of a camouflet within a spall field.

From the experiments that were conducted in a realistic environment on realistic damage the system does produce rapid and accurate measurements of the diameter and depth of a crater to calculate the necessary materials and personnel needed to repair the damage. Subsequent result of this system is that the system is able to identify a camouflet that is hidden in a spall field. These results will decrease the search time for the Airfield Damage Assessment Teams and provide pertinent information to allow planners to calculate the necessary materials, equipment and personnel to conduct an ADR.

Although the system's accuracy was validated during experimentation it also raised some recommendations for future work. The network that the data is being streamed on needs to become large enough to allow for the system to be pushed forward by a great distance. As of right now, that system's offset distance is dictated by the range of the network. Also, to effectively use a system such as this one, researchers should look into autonomous data gathering. The first fly-over of the runway should mark potential damage areas with GPS coordinates allowing for the ADA Survey System to just focus on the

damage itself and not scan the entire runway. Finally, since this research has validated the outstanding accuracy of the LiDAR, future work should look at mechanicalizing the LiDAR to determine the diameter instead of using a GPS unit.

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## **LIST OF ACRONYMS AND ABBREVIATIONS**

|       |                                 |
|-------|---------------------------------|
| ADA   | airfield damage assessment      |
| ADAT  | airfield damage assessment team |
| ADR   | airfield damage repair          |
| AFPAM | air force damage repair         |
| COTS  | commercial-off-the-shelf        |
| DEM   | digital surface model           |
| EOC   | Emergency Operations Center     |
| EOD   | explosive ordnance disposal     |
| LiDAR | light detection and ranging     |
| MOS   | minimum operating strip         |
| OS    | operating system                |
| RPI   | raspberry pi                    |
| TTP   | techniques, and procedures      |
| UAV   | unmanned aerial vehicles        |
| UXO   | unexploded ordnance             |
| VNC   | Virtual Network Computing       |

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# **I. MOTIVATION AND PROBLEM DEFINITION**

## **A. INTRODUCTION**

Airfields are essential to the U.S. military and coalition forces' logistical lines of communications and force projection in any theater around the world. No matter if they are used for combat operations or humanitarian assistance or disaster relief, these airfields hold immeasurable value. Upon seizure of an airfield by U.S. or coalitions forces, an airfield damage assessment (ADA) must be conducted in order to determine the requirements to repair the airfield to a threshold that is acceptable for operational use by a vast assortment of aircraft. This assessment surveys the different kinds of runway damage, often classified as craters, spalls, and camoufllets. This survey is essential in providing accurate information to the Emergency Operations Center (EOC) to estimate the types of personnel, materials, and equipment needed to rapidly repair the airfield.

The ADA is conducted in two phases, with Phase I being a visual very rudimentary estimate, and Phase II being personnel on the ground providing an accurate hands-on estimate. A major concern while having military personnel on the ground surveying a damaged runway is the high possibility of their encountering unexploded ordnance (UXO), which can cause injury or even death if not properly identified. Because of this, current tactics, techniques, and procedures (TTPs) dictate that military personnel conduct a vehicle mounted survey of the damage during Phase II. This mounted assessment is often very time consuming, tedious, dangerous, and logistically burdensome.

During the last 15 years, the airfields that were seized by U.S. and coalition forces during combat operations in Iraq and Afghanistan provided key staging and logistical hubs for operations. These key strategic footholds came at the cost of service member's time by conducting the ADA inspections personally. Recent advances in unmanned aerial vehicles (UAV) and remote sensor technologies have made it possible to reevaluate different TTPs of operations that are conducted by hand in dangerous locations.

## **B. RESEARCH FOCUS**

This research investigates the use of low-cost, low-power UAS with different sensors in order to accurately and rapidly conduct an ADA. A feasible and suitable solution would be a sensor or a combination of sensors that can accurately measure the diameter and depth of craters and spall fields, and can detect the presence of camouflages within specific areas.

The fully developed system would have to transmit the data that are collected to the civil engineers, explosive ordnance disposals technicians, and other planners at the EOC. This system would be the conduit between the damage and the EOC in order to calculate the necessary material, equipment, personnel, and types of aircraft that can initially land at the airfield to conduct the airfield damage repair (ADR). An accurate system that can identify the dimensions of the damage, the location of camouflages, and UXO would thus greatly increase the accuracy of Phase I of the assessment and would lessen the amount of personnel on the airfield in Phase II, thus rapidly completing the ADA while keeping service members safe.

## **C. SCOPE AND BOUNDARY**

This research uses commercial-off-the-shelf (COTS) UAVs and sensors that are low-cost, and low power to conduct an ADA. The system itself should be low-complexity. The use of COTS equipment is important because of its easy availability, reparability in case of damage or malfunction, and support from the commercial industry. Low power is a must, as many of these airfields are located in remote locations and therefore the logistical support for power is very scarce. Low-cost and low-complexity are also requirements, because this system should be kept at the lowest tactical level meaning that this system should be able to be operated by anyone with very little technical knowledge.

## **D. BENEFITS TO THE DEPARTMENT OF DEFENSE**

A system like the one that is explained above would have a twofold benefit to the DoD. Our system can turn a rudimentary first phase into an accurate depiction of the airfield damage, which in turn would provide the necessary information to planners to

rapidly repair the runway. The accuracy and speed would equal the rapid ADR in order to restore the lines of communications to the U.S. and coalition forces to continue their projection of power. The second benefit is the increased safety of service members. An accurate initial survey would decrease the number of service members on the ground to verify the dimensions of the craters, thus allowing them to observe any UXO or other camouflages that were not identified in the initial survey allowing for a precise depiction of the damage. Additionally, it would reduce the risk associated with a manual damage assessment,

This research would not only benefit the ADA/ADR operations, but also the other elements of the military on the tactical level. This system could be used as an overwatch for a convoy or for a foot patrol in a hostile environment. The system can survey the area ahead of the convoy or patrol, allowing service members to identify possible obstacles in the road or any improvised explosive devices, keeping them out of harm's way.

## **E. THESIS ORGANIZATION**

This thesis details the steps between the current problem statement all the way to the design, experimentation and results of the proposed system. Chapter II provides background information of what ADA is and an in-depth look into the current TTPs and how this system can lessen the burden. It also presents historical cases in which ADA/ADR was extremely relied upon for the success of the mission. Chapter II concludes with the introduction of the sensors and microprocessors that collect the data and transmit it back to the EOC.

Chapter III examines the design of the system, to include how the different sensors work together to produce an accurate depiction of the damage and to identify the camouflages. Also, it discusses the connection between the EOC and the ADA Survey System in great detail. Chapter III concludes with how the data is sifted and plotted in order to produce useful damage information.

Chapter IV provides a detailed analysis on the experimentation process of the system. This chapter includes the incremental process of establishing the different sensor error in a controlled environment to a more realistic operating environment. This chapter

concludes with the results of the ultimate objective of mounting this system onto a UAV and assessing different types of damage in the realistic operational environment. A discussion between initial data to the data captured from the UAV is presented.

Chapter V concludes this research, and identifies the overall performance of the system in both quantitative and qualitative results. Recommendations for future work are presented as in any system, the more testing that is executed in realistic operational environments the more questions are raised to perfect a system.

## **II. BACKGROUND INFORMATION**

This chapter provides an overview of ADA and how this operation is the fundamental foundation of the ADR process. Additionally, it provides detailed information of the process of ADA and a detailed examination of what occurs in each phase. Also, past and current technologies, and uses of LiDAR are introduced throughout the chapter.

### **A. AIRFIELD DAMAGE ASSESSMENT/AIRFIELD DAMAGE REPAIR**

According to the air force pamphlet (AFPAM) titled “Airfield Damage Repair Operations,” “Airfield Damage Repair (ADR) encompasses all actions required to rapidly prepare airfield operations surfaces and infrastructure to establish or sustain operations at a new forward operating location (FOL) or to recover operations at a main operating base (MOB) or FOL that has sustained damage from attack” (Department of the Air Force [DAF], 2018, pp. 10–11). Prior to commencing any ADR operation, an ADA for the site must be completed to determine the damage and hence the amount and type of materials and type of personnel needed to complete the ADR. ADA is a survey that assesses the damage of the airfield and is completed in two phases. Phase I is a rudimentary survey conducted from overwatch positions and imagery captured by UAVs, in order to provide a rough location of visible damage. Phase II, is a more precise survey that is conducted at the airfield by servicemembers on the ground verifying the damage (DAF, 2018). The information gathered from both phases is transmitted back to the civil engineers in the EOC for material and personnel calculations. The AFPAM states that an ADA involves the damage assessment of the following: “Take-off and landing surface, assess pavement to launch and recovery surfaces, aircraft shelters and parking areas, navigation aids, aircraft arresting systems, aircraft maintenance, rearming, refueling areas and any other areas of interests specified by the EOC” (DAF, 2018, p. 57). An accurate ADA is necessary to rapidly initiate and complete the ADR in a timely and successful manner.

### **B. THE STRATEGIC IMPLICATIONS**

ADA/ADR is often overlooked but has key strategic implications; if conducted poorly or delayed, it can severely impact a unit’s ability to carry out the mission. Per the

AFPAM “Airfield Damage Repair Operations,” ADA “Provide[s] the installation commanders and the combatant commander with improved capability to restore operations at an existing airbase or establish flying operations after opening an expeditionary airbase to ensure the rapid, timely, and effective deployment, employment, sustainment, and redeployment of U.S. airpower in support of America’s global interest” (DAF, 2018, p. 11). Since September 11, 2001, there has been a steady increase for ADA/ADR operations, since most of the airfields seized in Iraq and Afghanistan are in remote locations and have been destroyed from U.S. and coalition air raids conducting denial operations (DAF, 2018). These airfields have been an essential staging area for forward deployed forces and the needed supplies to conduct operations.

### C. CURRENT TACTICS, TECHNIQUES, AND PROCEDURES (TTPS)

The overall process of the ADR concept that is presented in the AFPAM “Airfield Damage Repair Operations” consists of seven phases, from the initial “Pre-action Assessment and Planning” to the final “Airbase Recovery” phase (DAF, 2018). ADA is the focus of Phase I “Pre-action Assessment and Planning” to Phase II “Open the Airbase” (DAF, 2018). Figure 1 illustrates the seven phases of the ADR concept in a timeline fashion and shows the actions that occur at each phase.

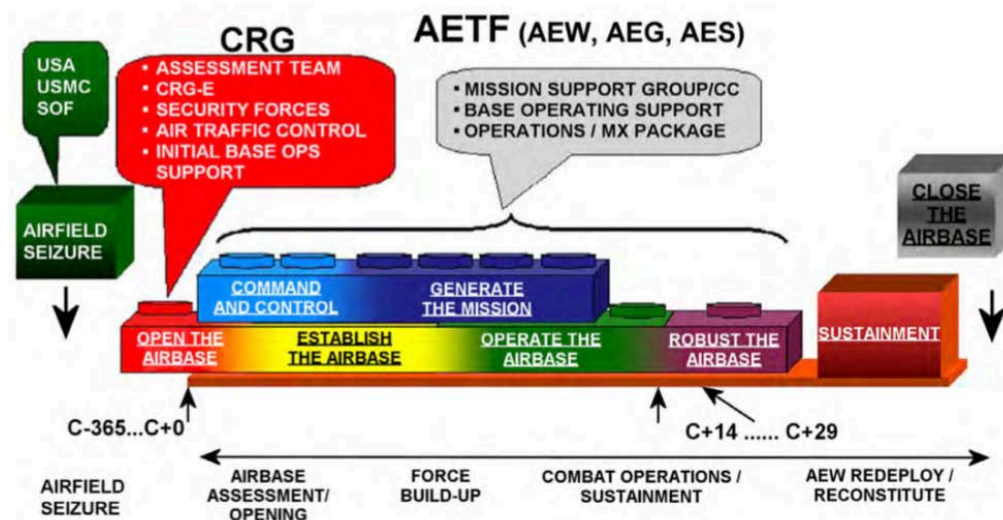


Figure 1. The Airfield Damage Repair model. Source: DAF (2018).

During Phase I, an expeditionary site survey process (ESSP) is conducted to establish the overall condition of the airbase. The other areas that are surveyed and assessed are: “overall assessment of facilities, explosive storage siting; petroleum, oil, and lubricants (POL); terminal control; environmental issues (including, but not limited to) potable water and potential public health hazards” (DAF, 2018, p. 13). An ADA is just a part of the ESSP. The overall goal of the ESSP is to present an accurate depiction of the airbase during Phase I.

### **1. Emergency Operation Center**

The EOC is the command and control (C2) center for the ADA operation and is the conduit for providing the required information to the ESSP (DAF, 2018). As any C2, the EOC has many responsibilities during the ADA in order to insure an accurate and rapid process to survey the damage. An ADA consists of two phases, the first phase is very basic in that the damage is assessed from afar often from overwatch positions or UAVs. The Airfield Damage Repair Manual explains that during Phase I the EOC will develop a repair plan in order to direct the airfield damage assessment teams (ADATs) during the comprehensive Phase II. An ADAT is typically composed of five members each with their own expertise. An ADAT will have one of each expertise: An explosive ordnance disposal technician, an engineering specialist, a vehicle operator, a recorder, and a communication specialist. (DAF, 2018). Once the ADATs are established and deployed forward to the airfield the EOC will direct the damage assessment, record and evaluate damage reports, plot the airfield damage locations and work with EOD to mark and dispose of any UXO (DAF, 2018). The goal of the EOC is to determine the minimum operation strip (MOS), which is a length of undamaged runway that is used to determine what aircraft can land in order to assist with the requirements set by the ESSP in order to complete the ADR (DAF, 2018).

### **2. Airfield Damage Assessment Process**

As stated in the ADA/ADR section, ADA is conducted in these two phases, with the second phase producing the accurate data needed to establish the MOS as well as the material and personnel needed in order to repair the runway. The objective of the ADA is to locate any UXO and classify the type of damage caused to the runway (DAF, 2018). The

three types of damage classifications are craters, spalls, and camoufllets. Figure 2 illustrates the classification for a spall, and crater and provides the minimum and maximum dimensions for each. A spall can often be thought of as a “pot hole” in that the pavement surface is damaged but the ground underneath is not penetrated. A crater is created when ordnance penetrates the pavement surface and the ground underneath, causing a wide gap in the runway.

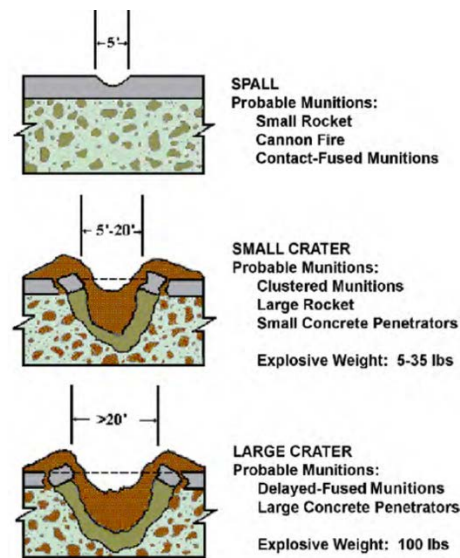


Figure 2. The difference between spalls and craters. Source: DAF (2018).

A camoufllet is often referred to as a “bomb crater” and is created when ordnance penetrates the surface and ground causing a void underneath the penetrated surface. This can be thought of as a combination of a crater and a spall, in that the penetration diameter of the runway is small like a spall, while the void created underneath is as large as the ground disruption of a crater. These camoufllets are often hard to locate and can cause extensive damage to aircraft if they are not located because if an aircraft maneuvers overhead the camoufllet will collapse due to the void and the pressure applied by the aircraft (DAF, 2018).

**a. Phase I**

Phase I is referred to as the “Initial Reconnaissance” Phase (DAF, 2018). The objective of this phase is to provide the EOC with a gross estimate of the locations of visible damage on the airfield in order to conduct planning for Phase II. The AFPAM “Airfield Damage Repair Operations,” states that acceptable estimates can be determined from “observation posts, camera feeds, pictures, other remote devices such as flight line camera system, airbase point defense positions, aircraft shelter, overflight, and mini-UAVs” (DAF, 2018. pp. 51–52). These gross estimations, though intended to give just a rough estimate of damage locations, create a huge reliance on Phase II to produce rapid and accurate results. Such a reliance on Phase II dictates a heavy presence of boots on the ground (BOG) in order to produce the accurate estimates. This huge BOG presence increases the probability of injury as well as the logistical burden to supply them with needed instruments and infrastructure to conduct the second phase.

**b. Phase II**

The second phase of the ADA process is known as the “Detailed Reconnaissance” Phase (DAF, 2018). This phase commences with the deployment of the ADATs to the airfield. The objective is to locate and report any damage and/or UXO back to the EOC in order for them to establish the MOS. The AFPAM “Airfield Damage Repair Operations,” directs that this survey is done by either walking or driving the airfield (DAF, 2018). Both methods used to conduct the ADA present pros and cons in themselves. Conducting an ADA on foot would be very time consuming because of the length that the teams would need to cover, and it would be dangerous because they do not have any protection from any UXO besides their own personal protection equipment, which is an armored plate jacket, a helmet, and eye/ear protection. Although this would be very time consuming and dangerous, the result that it would yield would be more accurate because their vantage point would not be obstructed as it would be from a vehicle (DAF, 2018). Using standard military armored vehicles would decrease the danger and the time but due to their small windows and often terrible vantage points the accuracy in what is being reported would decrease. Currently, according to the AFPAM “Airfield Damage Repair Operations,”

“Field test results have proven that, with practice, the damage assessment teams can estimate short distances (less than 100 feet), crater diameters, and spall counts with acceptable accuracy without tape measurement” (DAF, 2018, p. 48). An ADAT relays the location and dimensions back to the EOC using a handheld radio verbally issuing the GPS coordinates and dimensions. The path that the ADATs take in order to conduct their individual surveys is determined by the EOC in Phase I and is constantly updated throughout their maneuver by the use of check points. The EOD technician relays the location and description about any UXO back to their counterpart in the EOC using a handheld radio but on a different frequency than that one being used for the location of the damage (DAF, 2018). This can cause confusion within the EOC because depending on the number of ADATs that are communicating back both damage assessments, UXO locations, and team locations using two radio frequencies the chance for error rises thus increasing the time to complete the ADA while lowering its accuracy. Figure 3 is a representation of what the ADATs would normally see while conducting a mounted ADA.

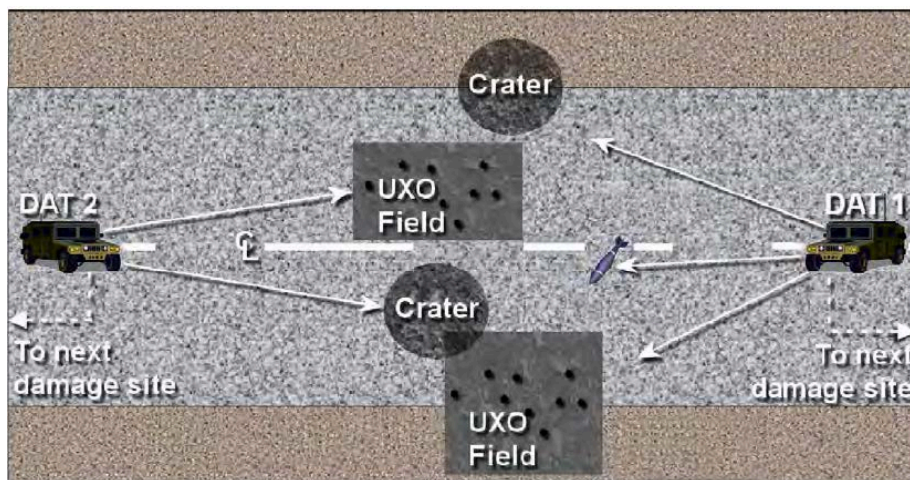


Figure 3. Rendering of ADAT conducting mounted assessments.  
Source: DAF (2018).

#### **D. DANGERS IN THE CURRENT ADA TTPS**

As in any operation, the more BOG in a volatile environment presents a greater risk of harm to any U.S. or coalition service member. Even after the airfield is secured and force

protection is provided, the unknowns during the ADA, such as UXO or camouflages, present a danger to the ADATs. The inaccuracy of Phase I creates a huge dependence on the accuracy of Phase II in order to provide accurate results in a timely manner.

This thesis's intent is to improve the accuracy of Phase I, which would lessen the BOG during Phase II. Less ADATs on the ground for Phase II would free up transport space to the damaged airfield that would allow for other specialties such as EOD or Air Traffic Controllers to conduct their assessments in order to rapidly and accurately complete the ADA, progressing the airfield into the second phase of ADR process which "Open the Airbase" (DAF, 2018). Our concept to increase the accuracy of ADA Phase I is to use an electro-optical called Light Detection and Ranging (LiDAR). Like Radio Detection and Ranging (RADAR), LiDAR uses light to calculate the distance instead of sound. The use of LiDAR to measure the dimensions of the damage would decrease the error that exists in today methods of "eyeballing" anything less than 100 ft and verbally reporting the data back to the EOC over a handheld radio that is currently employed.

## **E. HISTORY OF ADA**

ADA/ADR has been an essential part in combat operations and humanitarian assistance/disaster relief (HA/DR) operations. During the vital hours after the earthquake and tsunami struck Japan in March of 2011, ADA was needed in order to survey the surrounding airfields to allow for the rapid ADR to begin so that international aid could arrive as quickly as possible (Feickert & Chanlett-Avery, 2011). The United States military deployed a long-range UAV called the RQ-4 in order to conduct such initial surveys of the disaster areas focusing on vital infrastructures (Feickert & Chanlett-Avery, 2011). Long-range UAVs were equipped with different optical sensors for optical surveillance of the damaged infrastructure (Feickert & Chanlett-Avery, 2011). The U.S. Army Corps of Engineers assisted in the ADA as well by using the data gathered in the overhead surveillance to assess the damage caused to the airfields around Japan (Feickert & Chanlett-Avery, 2011). They were able to clear the debris allowing for the necessary logistics to begin to flow in order to help with the wounded and those effected by the horrific events.

The combat operations conducted in Iraq and Afghanistan also produced a need for ADA/ADR. Because of this need, rapidly deployable teams were established to repair airfields to be later utilized by the U.S. and coalition forces. The U.S. Air Force created two specialized and deployable teams in order to support such ADA/ADR Operations; these teams were called the Rapid Engineers Deployable Heavy Operations Repair Squadron, Engineers (RED HORSE), and Prime Base Engineer Emergency Force (Prime BEEF) (Brown, 2008). In support of counter insurgency operations (COIN), these teams were able to work with U.S. and Coalition forces during the planning of airfield seizure operations in order to best estimate the future requirements to repair these airfields because most of the damage caused in capturing these airfields from the Taliban was caused by U.S. and Coalition forces (Brown, 2008). Once the airfield is secure these teams can assess which aircraft can use the runway since most of the airfields are in very remote locations and have not been properly maintained (Brown, 2008). These two events, although completely different, demonstrate the need for a rapid and accurate ADA of an airfield in order to support combat operations or HA/DR operations. From delivering much needed supplies to people wounded or displaced from a natural disaster or to the COIN operations where the U.S. and coalition partners need a staging foothold, ADA/ADR is an essential task that must be well-executed and constantly updated to enable success for any operation.

#### **F. CURRENT USE OF SIMILAR TECHNOLOGIES**

There have been several different publications and research projects completed using Airborne LiDAR and other electro-optical sensors in order to create different computer models to investigate everything from land surveys to changes in the environment. Different publications have discussed the work flow of data gathered from these electro-optical sensors and how to produce three-dimensional computer models on a variety of different objects that were surveyed. The researchers were able to convert all collected data points, referred to as the “point cloud,” into commercial software such as “Pix4D” in order to create the digital surface model (DSM) of the surveyed area. These commercial programs are often very expensive, limiting their availability and use. Figure 4 illustrates the detail that can be achieved from the data collected from these electro-optical sensors. From these rendering the researchers are able to survey an open field next

to a road in order to determine the volume of points of interest within the area. Their error in volume ranged from 3.56% to 8.75%, and the error in area ranged from 1.31% to 5.95% (Xu & Lum, 2018).

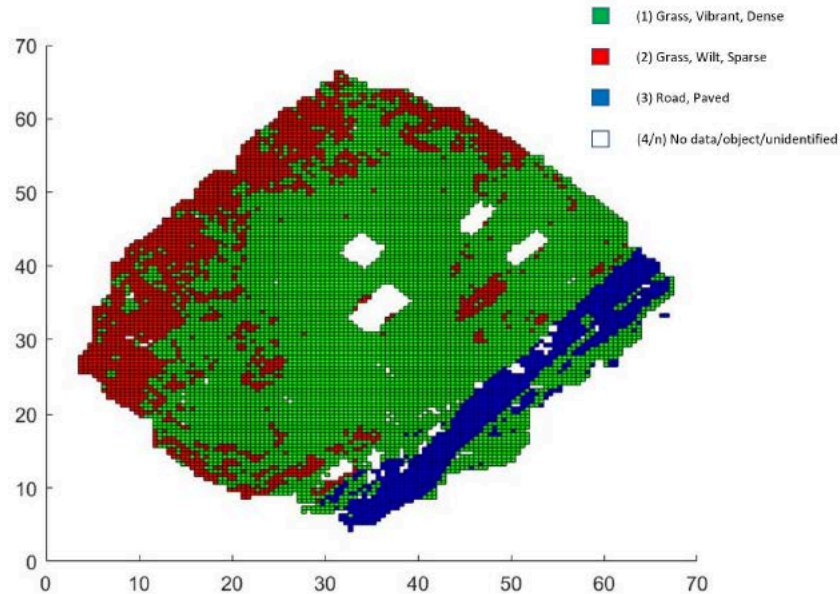


Figure 4. The Digital Surface Model of the area that was surveyed.  
Source: Xu and Lum (2018).

Other research has demonstrated the ability to use inexpensive software such as MATLAB and CAD in order to create a DEM of a city using an electro-optical sensor. Figure 5 displays the final DEM after the point cloud data was processed by MATLAB then by a CAD software in order to produce their rendering. Since they sought to map a section of a city, they concluded that the DEM that was created was around 75% accurate (Dorninger & Pfeifer, 2008). Much of the error occurred in the different angles of the roofs compared to the angle of the Airborne electro-optical sensor. They concluded, that by comparison of their DEM to the actual city, their acquisition of data using very inexpensive software was not only achievable but accurate as well (Dorninger & Pfeifer, 2008).

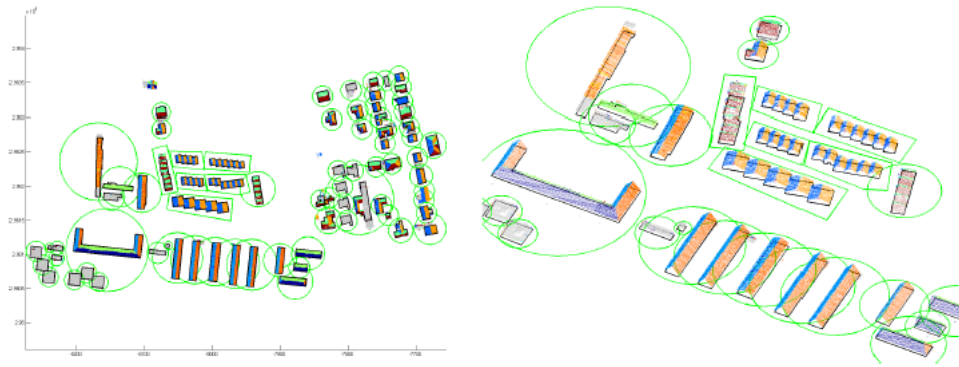


Figure 5. DEM crated by the inexpensive software.  
Source: Dorninger and Pfeifer (2008).

## G. LIGHT DETECTION AND RANGING (LIDAR)

LiDAR has similar properties to the more known RADAR, in that they both project energy and distance to the object of interest is determined by calculating the time it takes for the energy to travel from the system to the object and then back to the system. LiDAR utilizes the same concept and emits light towards an object instead of sound waves, as is done in a RADAR. Basically, LiDAR is an electro-optical remote sensor that uses light to measure distance by calculating the time delay between each pulse (National Oceanic and Atmospheric Administration, n.d.). LiDAR works by first initializing a reference signal that is sent from the transmitter to the receiver in order to establish a zero or a reference point. The transmitter and receiver are located on the same unit side by side, essentially one side of the LiDAR will project (transmitter) the near-infrared laser and the other end (receiver) will absorb the laser coming back to the unit in order to calculate the distance (Garmin, n.d.). Once a zero has been established, the LiDAR begins its measurements by performing a series of data acquisitions, which is basically just a series of laser emittance from the transmitter to the receiver where the difference in time is used to calculate the distance beneath the LiDAR (Garmin, n.d.). The LiDAR uses the known speed of light constant (300,000 km/s) and the time it takes to travel from the transmitter to object and back to the receiver in order to determine the distance of an object from the system (Garmin, n.d.).

## **H. CURRENT USES OF LIDAR**

Currently, LiDAR can be applied to almost every project that requires a survey or a visual DEM. In particular, Forestry Services around the world have been using LiDAR in order to collect and analyze changes in their specific areas of interest. LiDAR is used because it can survey a vast area such as a forest in a small amount of time while producing accurate results.

In order for national and local lawmakers to decide what areas of the forest they need to preserve, construct parks, or maintain biodiversity and National Forest Inventories (NFI) is needed to provide pertinent information about the conditions of certain areas (Nilsson, 1996). They conducted three studies in one year during the months of June, October, and December to compare the results to verify the condition of the sample forest (Nilsson, 1996). Using a 4-hectare plot of forest that was outlined in white with a white dot in the center for situational awareness, the researchers developed two desired goals: “To investigate how different laser beam footprint sizes and sampling densities affected height estimates,” and “to determine if stand volume could be estimated using a scanning laser system” (Nilsson, 1996, p. 2). Employing the LiDAR system and a GPS on a helicopter they surveyed the designated area to correct any position error that could occur (Nilsson, 1996). Running the survey at a rate of 62 to 160 infrared pulses per second and four different beam sizes at a height of 300 m the system produced usable data points (Nilsson, 1996). The results yielded a threshold of 10%, from which the Swedish government concluded, “An airborne laser could provide objective data correlated to tree height or stand biomass for the area of interest” (Nilsson, 1996, p. 6). The Swedish government accepted the data and agreed its accuracy is valid for future research for forestry projects (Nilsson, 1996).

Shaohui Sun, and Carl Salvaggio were able to use LiDAR for a different concept in their research. They were able to sort the noise gathered from the LiDAR point cloud to map the city of Rochester New York (Sun & Salvaggio, 2013). Developing an algorithm, they were able to separate the point cloud data into vegetation, building footprints, and terrain, once separated they were able to create a 3D rendering of the city (Sun & Salvaggio, 2013).

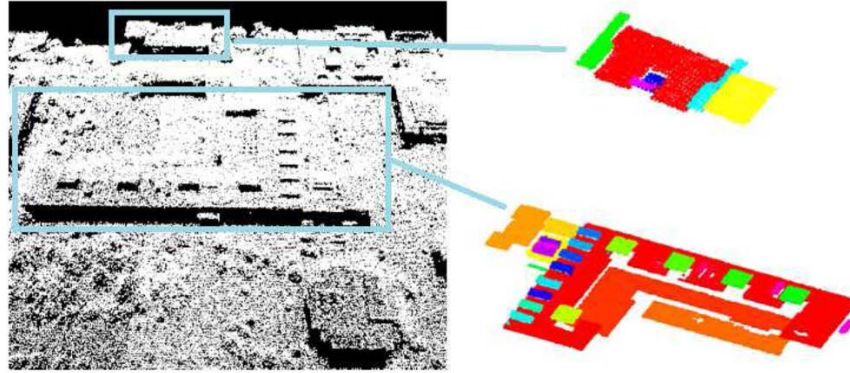


Figure 6. The Point cloud data before and after separation.  
Source: Sun and Salvaggio (2013).

Figure 6 illustrates the point cloud data that were gathered from the LiDAR system then converted to their three classifications based on noise using their algorithm (Sun & Salvaggio, 2013). The two articles discussed above demonstrate the capabilities that LiDAR can produce. The data points are simple and clean, and can be produced into any product depending of the software.

## I. LOW-COST, LOW-POWER, SMALL COMPUTER DEVICES

A requirement for this research is to utilize low-cost, low-power devices to build a system that can acquire data rapidly and accurately. Low-power and low-cost allows system utilization by those with little technological knowledge and training. Low-power enables these systems to be used in very remote locations where power is limited and batteries are in short supply, and often a logistical burden due to their weight and storage requirements. So, in order to meet the above requirements, this research utilizes a very small computer (the size of a deck of cards) called a Raspberry Pi, and a microcontroller (also, the same size as deck of cards) called an Arduino Uno board.

### 1. Raspberry Pi

Raspberry Pi (RPI) is a small computer, which supports all the essential capabilities of a standard computer such as a processor, memory, storage, and network connectivity. Figure 7, depicts the overall simplicity of the RPI; it has a 1.4 GHz 64-bit quad-core ARM Cortex-A53 processor, Dual-band 802.11 AC wireless LAN, Bluetooth 4.2 and an ethernet

port and four USB ports (Raspberrypi, n.d). RPI's power consumption is about 240 mA or roughly 1.2 watts, well within the requirement for this project. A reasonably configured RPI can convert data gathered from the LiDAR and produce an accurate depiction of the size of each crater that is being surveyed.

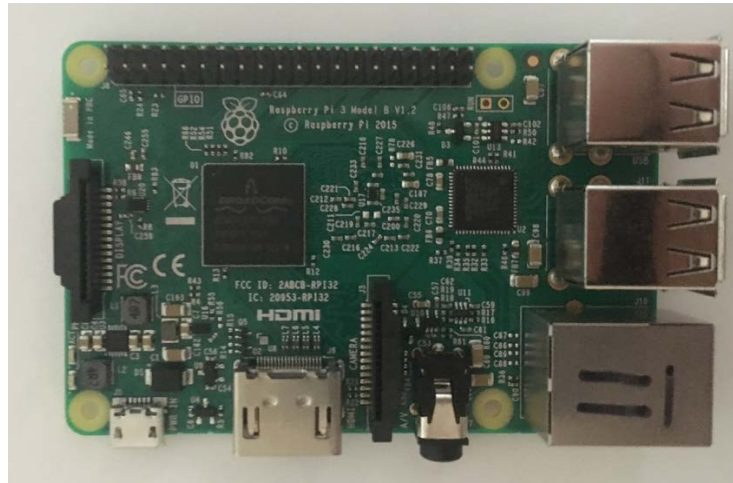


Figure 7. The Raspberry Pi 3 Model B

The RPI would allow the user to visually see the live stream of data, which they can correct if any error presents itself. This capability is a must in order to produce rapid and accurate results. As in any device, there are some pros and cons; the RPI is within the low-cost (\$35), low-power (240 mA), and it provides a seamless transition between data acquisition to data conversion. The RPI is however slow compared to the standard personal computer due to its size and power consumption. Also, security is a concern because its connections to other devices are through its vulnerable Wi-Fi and Bluetooth. However, the RPI meets our requirement and provides real time data collection in order to accomplish the survey both rapidly and accurately.

## 2. Arduino Uno

The RPI can be thought of as the brains of the operation, the Arduino is the nervous system converting raw information into readable data. The Arduino is a microcontroller board that can execute code using C++ language to collect data from a wide aspect of

sensors such as LiDAR, humidity, rain, tilt, etc. Figure 8 depicts the Arduino Uno Rev 3 which has 14 digital input/output pins, six analog inputs, 16 MHz quartz crystal, USB connection, and ICSP header (Arduino, n.d.). The Arduino board executes the code per desired sensor, converting the sensor information into readable data using its own application. Within the board it uses a Universal asynchronous receiver-transmitter (UART) to simultaneously transmit data while receiving data. The Uno falls within the requirements of low-cost (\$22) and low-power (45mA) (Arduino, n.d.). All Arduino boards come with pre-installed C++ libraries, saving the user time from coding and allowing the ability to customize any project to the needs of the operation. However, the Uno can only process a single thread at a time, so every sensor will need its own microcontroller, and code can only be uploaded from a computer through a USB cable so adjustment have to be made physically. Just like the RPI, the Arduino Uno fits well within the requirement and produces rapid and accurate results.



Figure 8. The Arduino UNO microcontroller

## J. SUMMARY

This chapter provided an overview of what ADA is and its relationship to ADR while introducing some of the rudimentary TTPs. While the current phases of ADA have proven to work and produce strategic results over the past 15 years of combat operations and HA/DR operations, there are several areas of improvement and innovation. As U.S.

and coalition forces continue to conduct operations around the world, the time to repair airfields has become more valuable in order to continue the fight forward. LiDAR technology has shown that it can accurately survey different areas from a forest to a city while using low-cost, low-power technology. The time that is spent during the first phase of the ADA can be improved by accurately surveying the damage which would then lessen the amount of ADATs needed to verify the results. This increase in accuracy of the first phase would not only expedite the ADA/ADR process but it would also reduce the number of personnel needed on the ground during the second phase. Chapter III presents and describes the system that uses a LiDAR system to increase the accuracy of the survey conducted in phase I of an ADA process.

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### III. SYSTEM DESIGN

This chapter presents an overview of the ADA Survey System, and a detailed description of each component of the entire system. In addition to the physical system, the computer code and how the data is organized, presented, and examined.

#### A. ADA SURVEY SYSTEM OVERVIEW

The main requirement of this research is to develop a system that is low-cost and low-power that can yield accurate results during the Phase I of an ADA in order to decrease the number of ADATs needed to verify the damage in Phase II of the ADA. In order to accomplish these requirements a system was designed. As in Figure 9, one RPI (located in the top shelf), two Arduino boards (located in the middle two shelves), one Garmin lite v3 LiDAR (attached to the bottom left of the system), one Adafruit Ultimate Global Position Device (GPS) with antenna (attached to the bottom right of the system), and a rechargeable solar battery (located on the rear) all produce the ADA Survey System.



Figure 9. Left, is the front view of the ADA Survey System;  
Right, is the rear view

## **1. Housing**

The system's housing was created using a 3D printer and a filament called Polylactic Acid (PLA). Made from 100% renewable items such as corn, PLA is a multifaceted material used to construct a variety of different products (Drumright, Gruber, & Henton, 2000). PLA was selected as the material to be used for the housing of the system because it has a high-temperature melting point of 207°C (roughly 404°F), which makes it capable of withstanding the high temperature that it would experience in the vicinity of an airfield (Drumright et al., 2000) and the heat generated by the various electronic components in the system. This particular housing print had an infill of 40%, took around 36 hours to print, and was designed using an AutoCAD program called "Autodesk Fusion 360." The 40% infill describes the thickness of each layer, which can be thought of as the cross-section of a corrugated cardboard box; the higher the infill the less space one would see in the cross-section. The system's total cost, including all the COTS electronics components, is \$244, and with the mounting bracket the total weight is 0.86 kg, or 1.9 lb.

## **2. Depth and Diameter**

As stated in the previous chapter, the main component of this system, the LiDAR, is located on the bottom left of the left-hand picture in Figure 9. The LiDAR is used in the system to determine the depth of the spalls, craters, and/or camouflages by subtracting the total distance the LiDAR is broadcasting from the known altitude and the 14 in. offset in which the LiDAR is located below the altimeter on the UAV. For example, if the LiDAR is reporting a depth of 900 cm, or 29.52 ft, at an altitude of 5 m, or 16.4 ft, and the LiDAR offset is 14 in., or 1.167 ft, the total depth of the damage would be  $29.52 \text{ ft} - (16.4 \text{ ft} + 1.167 \text{ ft})$ , which would yield a damage depth of 11.953 ft. Using the Arduino boards as the connection between sensor and data, the data is live-streamed on the RPI to verify the maximum depth. A new organic feature on the Arduino 1.8.5 software, as shown in Figure 10, provides a "serial plotter" that constructs a two-dimensional graph of the distances over time. This is useful because the user can verify the closest shape that the damage represents, such as a hemisphere or cone, in order to use the dimensions in the best manner to calculate the correct material needed to fill in the damage. This feature works automatically with the

LiDAR to plot the distance of each pulse at that exact moment of time. The two-dimensional graph moves with time in order to produce the shape of the damage.

Located on the bottom right of the left-hand picture in Figure 9, the GPS unit will work simultaneously with the LiDAR to provide the diameter of the spalls, craters, and/or camouflages. The latitudinal and longitudinal coordinates at the start and end of the damage will be recorded and converted into distance to yield the overall diameter.

The user can control the speed in which the Arduino board is acquiring the data for their respective sensor by increasing or decreasing the baud rate. The rates that are organic to the Arduino boards, between 300 to 115200 bits per second, per operation can be changed to prevent an over/under flow of data (Arduino, n.d.). The LiDAR uses a baud rate of 9600 and the GPS unit has a baud rate of 115200. In addition to the Serial Plotter, the Arduino also has a serial monitor that is used to live-stream the data. This is utilized with the GPS, since latitude and longitude coordinates cannot be graphed. Together, the depth from the LiDAR, the diameter from the conversion of latitudinal and longitudinal coordinates into a distance, and the serial plotter provide the user an accurate depiction of the damage.

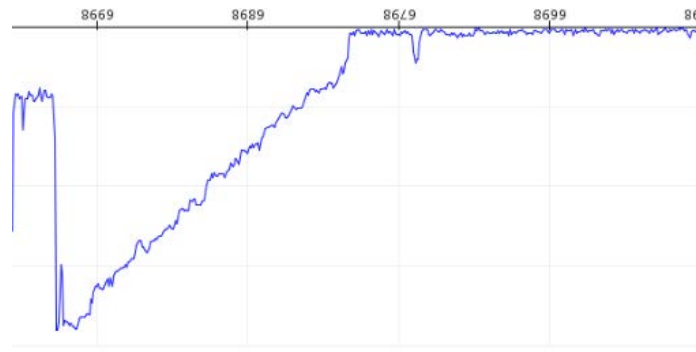


Figure 10. A view of the Serial Monitor that illustrates the 2-D graph of a depression in the ground

### 3. Virtual Network Computing

If the RPI is the brains and the Arduino boards are the nervous system, then the cloud-based system that connects all the systems to broadcast to the EOC is the backbone.

This cloud-based system is called Virtual Network Computing (VNC), and in this system it allows the user to view and control everything that is occurring on the RPI on their computer as if the RPI is plugged into their monitor. The purpose of a VNC is to give the user centralized access to other devices they are connected to around the world. The idea is that “in the virtual network computing (VNC) system, server machines supply not only applications and data but also an entire desktop environment that can be accessed from any Internet-connected machine using a simple software” (Richardson, Stafford-Fraser, Wood & Hopper, 1998 p. 33). “Whenever and wherever a VNC desktop is accessed, its state and configuration (right down to the position of the cursor) are exactly the same as when it was last accessed” (Richardson et al., 1998, p. 33). As in Figure 11, this application allows the user to have full control of the RPI during the ADA in order to correct and verify the information it is receiving without him being physically attached to the RPI. This flexibility provides the user the convenience of using their standard PC OS and the OS on the RPI to interact with the data from the LiDAR, GPS, and serial plotter on the Arduino. The use of a VNC can occur on different OS, such as PC, MAC, and, LINUX as well as a combination of OS. For example, the RPI with a LINUX OS can be viewed and controlled on a MAC or PC OS. The VNC does need Internet connectivity to work, so the use will be limited by the weakness of the network. For most outdoor Wi-Fi routers, the range is up to 300 ft, and most smartphone hotspots broadcast up to 66 ft (Quora, n.d.).

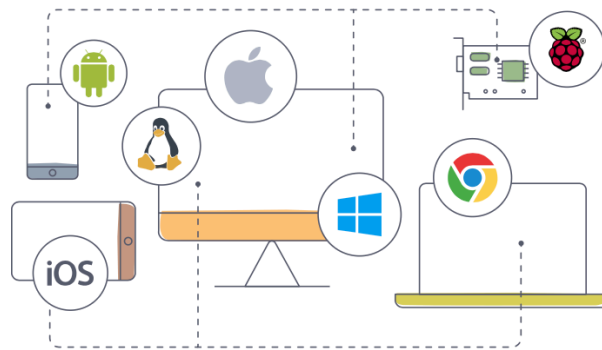


Figure 11. An illustration of what VNC provides to the user. Source: RealVNC (n.d.).

#### **4. How Data Is Analyzed**

One of the problems with some of the sophisticated software is the vast knowledge the user needs in order to properly utilize the capabilities. In order to allow this system to be utilized at the lowest level, the software used to organize the data is very simple and has pretty much been used by everyone in great detail. As described in Chapter II, the RPI has a similar program to Microsoft Excel called “LibreOffice Calc,” which just like Excel, this program will organize and record the data. Within this program the user can convert the latitude and longitude coordinates from the start and end of the damage to the diameter and record the depth for the damage. Furthermore, it will document the exact location of the damage, since GPS coordinates are being used for the diameter. From the GPS data that is recorded by the Serial Monitor, the user enters into the converter the coordinates in the standard degrees-minutes-seconds (DD:M:S) fashion for both latitudes and longitudes. The code embedded within the Excel book automatically converts the difference between both sets of coordinates into the diameter of the damage. The system’s simplicity between its sensors (LiDAR, GPS) and the software (LibreOffice Calc) and its low-cost and low-power use increases its operational utility.

#### **5. Aerial Unit**

As Chapter II described, the use of Airborne LiDAR systems yielded quick and accurate results in many different applications. Just like those previously discussed, this system should be airborne to best survey the damage to an airfield. The UAV that we used still has the same systems requirements such as a low-cost, and low-power use and its controls utilizes the same Wi-Fi or hot spot as the VNC in order to control the UAV.

#### **B. LIDAR-GARMIN LITE V3**

Creating an airborne unit automatically assigned a weight restriction. In order to purchase a low-cost, low-power UAV the amount of external payload capacity dramatically shrunk with the price. As in any project, certain items must be looked at in a different light when weight is an issue. For this system, the LiDAR that was selected was the Garmin Lite v3 due to its low-cost (\$130), low-power (4.75 to 5 VDC), and the newest requirement weight (22g).



Figure 12. The LiDAR used in the project. Source: Garmin (n.d.).

As presented in Figure 12, the LiDAR used from Garmin has both a transmit, and receive lens next to each other; its range is from 5 cm to 40 m with an accuracy of  $\pm 2.5$  cm. This range and weight are excellent for an airborne unit because at 40 m the UAV can maintain a safe altitude above the damage while conducting accurate readings with the LiDAR unit.

As previously stated, the LiDAR unit measures the time delay between transmission to an object and back to the receiver to determine the distance. On this system there were two different settings in order to connect the LiDAR, which were an I2C interface or a Pulse Width Modulation (PWM). The I2C was used because the refresh rate of data transfer was faster by 400 kHz, and the physical wiring was less complicated and stable, especially since the unit was to be airborne (Garmin n.d.). The fewer the pieces the better. Below are the exact steps from the technical manual of how the Garmin Lite v3 initiates the process of the recording of a distance.

- 1 The master initiates data transfer by establishing a start condition, which is when a high-to-low transition on the SDA line occurs while SCL is high. The following byte is the address byte, which consists of the 7-bit slave address followed by a read/write bit with a zero state indicating a write request. A write operation is used as the initial stage of both read and write transfers. If the slave address corresponds to the module's address the unit responds by pulling SDA low during the ninth clock pulse (this is termed the acknowledge bit). At this stage, all other devices on the bus remain idle while the selected device waits for data to be written to or read from its shift register.

- 2 Data is transmitted over the serial bus in sequences of nine clock pulses (eight data bits followed by an acknowledge bit). The transitions on the

SDA line must occur during the low period of SCL and remain stable during the high period of SCL.

3 An 8 bit data byte following the address loads the I2C control register with the address of the first control register to be read along with flags indicating if auto increment of the addressed control register is desired with successive reads or writes; and if access to the internal micro or external correlation processor register space is requested. Bit locations 5:0 contain the control register address while bit 7 enables the automatic incrementing of control register with successive data blocks. Bit position 6 selects correlation memory external to the microcontroller if set. (Presently an advanced feature)

4 If a read operation is requested, a stop bit is issued by the master at the completion of the first data frame followed by the initiation of a new start condition, slave address with the read bit set (one state). The new address byte is followed by the reading of one or more data bytes succession. After the slave has acknowledged receipt of a valid address, data read operations proceed by the master releasing the I2C data line SDA with continuing clocking of SCL. At the completion of the receipt of a data byte, the master must strobe the acknowledge bit before continuing the read cycle.

5 For a write operation to proceed, Step 3 is followed by one or more 8 bit data blocks with acknowledges provided by the slave at the completion of each successful transfer. At the completion of the transfer cycle a stop condition is issued by the master terminating operation.

(Garmin, n.d, p. 7)

The accuracy of +/- 2.5 cm is an average that can vary with diffuse reflective surfaces and specular surfaces. Diffuse reflective surfaces are porous surfaces such as asphalt, and concrete that can cause abnormal results in the LiDAR readings because of their inconsistent surfaces. Specular surfaces are materials that are smooth and reflect the infrared light from the LiDAR instead of dispersing the energy. Water and polished metals exhibit this trait and just like diffuse reflective surfaces, these should be noted when using this LiDAR as an area of concern that would need multiple measurement to confirm a distance (Garmin n.d.).

### **C. GPS-ADAFRUIT ULTIMATE GPS**

The primary use for the GPS on the survey system is to determine the diameter of the damage by converting the start and end latitude and longitude coordinates into a

distance. The GPS unit that is installed on the system is the Adafruit Ultimate GPS with an extended antenna to increase the accuracy. This unit exceeds all requirement in that it is low-cost (\$40), low-power (3 to 5.5 VDC), and low-weight (8.5 g) (Industries, n.d.). Specified by the developers of the chip and as displayed in Figure 13 with the extended antenna, this GPS unit can track up to 22 satellites on 66 channels, and has a sensitivity of -165 decibels (Industries, n.d.). The unit is roughly the size of a matchbook, and with a coin battery it can hold its current GPS position and decrease the time it takes to “fix” on a satellite. The unit also only uses about 20 mA of power during navigation and updates its location 10 times every second, although this can be controlled within the code (Industries, n.d.).



Figure 13. Adafruit Ultimate GPS. Source: Industries (n.d.).

This specific GPS unit transmits through the TX port on the Arduino board from the GPS module to the microcontroller using 3.3 V logic level, and likewise it receives through the RX port using a 5V logic level shifter (Industries, n.d.). The GPS unit will “fix” on three different satellites at an altitude of 20,000 km and triangulate with all three to determine its position (Bulusu, Heidemann, & Estrin, 2000). The accuracy of the Adafruit Ultimate GPS that is stated in the user manual is about 1.8 m, or 5.9 ft; however, that is without the external antenna that will increase its accuracy. Also, with a GPS unit such as this one, the time to fix a position can be lengthy in that any overhead obstructions prevent a clear transfer of data to and from the satellite.

#### **D. VNC-REAL VNC**

The VNC that is used to create the connection from the user's computer to the RPI is called "Real VNC." This open source program is free for users and allows up to 10 connections per account (RealVNC, n.d.). This program allows the user to have real time control of the device, and in this research the devices that the user will connect through is the RPI. By establishing this connection, the user is free to verify the validity of the data that is collected and make any necessary changes on the spot. The connection that is made using this open source program is encrypted with Advanced Encryption Standard (AES) 128.

The program sets up a secure cloud server in order to access the other devices that are set up by installing VNC Connect on each device. Once the VNC Connect has been installed on the device, the connection between the user and that specific device is established through the Internet Protocol address on the device that is being accessed. Once that link is established the user can take control of that device as discussed at the beginning of the chapter. Of course, the strength and distance away from the Wi-Fi router or smartphone hotspot will dictate the speed and limitations of the acquisition of data.

#### **E. UAV-DJI MATRICE 600 PRO**

Beside low-cost and low-power consumption, the UAV that is used also has to be a COTS system. A COTS UAV means it is readily available and, most importantly, its supply chain such as spare parts and support is established to reduce the maintenance wait time. As in Figure 14, the DJI Matrice 600 Pro consists of six motors with two propellers each and can carry an external load up to 5.5 kg, or 12.15 lb (Matrice 600 Pro, n.d.). According to the specification from the manufacture, its maximum speed is 40 mph and the maximum range is 5 km, or 3.1 mi. With the ADA Survey System weighing 0.86 kg, or 1.9 lb, the estimated flight time per full charge of the six batteries would be around 36 minutes (Matrice 600 Pro, n.d.).



Figure 14. DJI Matrice 600 Pro. Source: Matrice 600 Pro (n.d.).

The DJI Matrice 600 Pro is controlled from a standard remote control with throttle and pitch controls. An iPad is connected to the UAV to provide the user with a way to view a camera, if attached and the usual pilot instruments such as altitude, speed, and battery life. These COTS UAV are beneficial because the manufactures can push updates to the firmware to increase security and keep the UAV up to date and improve performance to extend the battery life.

#### **F. EXTERNAL BATTERY**

The battery that is displayed on the right side of Figure 9 has a storage capacity of 10,000 mAh and can recharge while in use, from the solar panels, or from a 120-V wall socket. According to the manufacturer's the RPI and Arduino boards use 240 mAh, and 45 mAh, respectively. Battery life is calculated by dividing the total capacity of the battery by the total consumption, then multiplying it by an external factor of 0.70 (DigiKey Electronics, n.d.). So, with a battery capacity of 10,000 mAh and a total consumption of 330 mAh (one RPI plus two Arduino boards), the system can operate for 21.2 hours on a single charge (DigiKey Electronics, n.d.). This system can continue to operate throughout the duration of multiple flights in order to accurately and rapidly estimate the damage of an airfield.

#### **G. HAVERSINE FORMULA**

Data organization is key in this research in order to rapidly and accurately conduct an ADA and produce an estimate of the damage for the ESSP. As previously mentioned,

Excel is the primary source to record the depths and diameters of the damage. Determining the depth is a simple equation as discussed at the beginning of the chapter but the conversion of latitude and longitude coordinates can be a challenge. In order to convert degree, minutes, and seconds to a distance, the Haversine Formula is used. Known as the “great distance formula” the Haversine Formula is often utilized in navigation to compute the distance between two points given the latitude and longitude of each point (Mahmoud & Akkari, 2016). This formula is used in everyday GPS systems to calculate the distance between two points and is based on the spherical Earth with the known radius as presented in Figure 15. Mahmoud and Akkari determined that, using the Earth’s radius of 6378.1 km, the error in determining distances with the Haversine Formula ranges between 0 and 0.334 percent (Mahmoud & Akkari, 2016).

- a) The great circle arc joining the two positions  
(arc c in figure 1)
- b) The meridian (longitude) through position 1  
(meridian joining C and A in figure 1)
- c) The Meridian (longitude) through position 2  
(meridian joining C and B in figure 1)

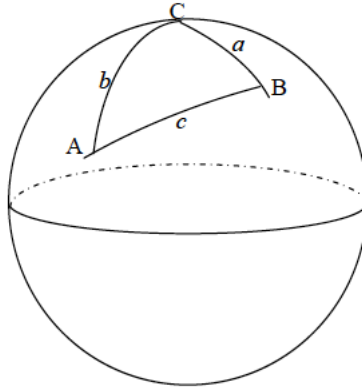


Figure 15. A rendering of how the distance between points A and B are determined. Source: Mwemezi and Huang (2011).

As stated above, the Haversine Formula determines the distance between two points by using the latitude and longitude of each point. To explain this process, the example latitude of 36 degrees 34 minutes and 96 seconds north will be represented as 36° 34' 96" N, and then will be converted through the process. First, both points need to be converted

from degrees, minutes, seconds to decimal, so in order for this to be completed the example latitude's degrees would remain 36. However, to convert minutes and seconds to decimal 34 is divided by 60 and 96 is divided by 3600. So, in step one, the latitude of 36° 34' 96" N would be 36.5933. Once both latitudes and longitudes are converted into decimal, a negative sign is placed on those coordinates that were west and south. The example latitude's direction is north so no additional negative sign will be added. Following that addition of a negative sign to west and south coordinates the decimal is converted from decimal into radians by dividing it by 180 then multiplying the solution by Pi (Mwemezi & Huang, 2011). In step two, the decimal latitude of 36.5933 would be 0.6387 in radians. After each coordinate is converted into radians it can be applied to the Haversine Formula as presented in Figure 16. The " $\theta$ 's" represent the latitudes and the " $\lambda$ 's" represent the longitudes from points 1 and 2, respectively, and "r" is the radius of the Earth (6378.1 km) as seen in Figure 16 (Mahmoud & Akkari, 2016)

$$d = 2r \arcsin \sqrt{\sin^2 \left( \frac{\theta_2 - \theta_1}{2} \right) + \cos(\theta_1) \cos(\theta_2) \sin^2 \left( \frac{\lambda_2 - \lambda_1}{2} \right)}$$

Figure 16. The Haversine Formula. Source: Mahmoud and Akkari (2016).

Knowing the latitude and longitude coordinates on the damage also assists in plotting the damage on a map. Not only does this information helps the user determine the diameter, but it also help assist in the location so a primary MOS can be determined in Phase I and verified in Phase II in order to aid in the planning process, even before service members are on the airfield.

## H. SUMMARY

This chapter provided an overview of the ADA Survey System that is used in this research to increase the accuracy during the first phase of ADA. A new requirement of weight was added in this chapter but the system, and the UAV, meet all the requirements in order to allow this system to be utilized by the lowest level. Excluding the UAV, this system was built at a cost of \$244, and between the PRI and two Arduino boards it

consumes 330 mAh of power which using the external battery it can operate for 21 hours. Chapter IV discusses the results from the field experiments that took place at the Naval Postgraduate School in Monterey, California, and Camp Roberts in San Miguel, California. The chapter takes an in-depth look into the setup and results of specific terrain that are tested during the experiments. Control data is established by hand measuring the area of damage then compared to the results gathered by the ADA Survey System.

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## **IV. IMPLEMENTATION AND TESTING**

This chapter presents the purpose of implementation and experimentation as well as the procedure for the ADA Survey System. As in systems engineering, systems must be introduced into an operating environment steadily to control the areas that can produce error. The ADA Survey System is tested in two environments; there are two different ways to examine the potential errors and issues, and observations that are made at each step. This chapter concludes with an overall assessment of the system and a comparison of trends.

### **A. PURPOSE OF EXPERIMENTATION**

The purpose of experimentation is to test the speed and accuracy of the ADA Survey System that encompasses the Garmin v3 Lite LiDAR and Adafruit Ultimate GPS. An exact procedure is followed in order to record the results from each experiment. This is not only to compare the results to the control data, but also to note physical observations, and to help identify trends that occur under different conditions. The overall objective is to identify expected errors in both depth and diameter and the impacts certain environmental conditions have on the system.

#### **1. ADA Survey System**

The system is tested in an incremental process in order to detect and correct the process and procedure, and note any errors and trends before introducing the system into an operational environment. In addition to the examination of the data that the system produces, the overall stability is noted in order to determine if it is durable enough to withstand the extreme elements expected in an operational environment. The initial set of experiments are conducted at the Naval Postgraduate School (NPS) using notional craters to test the system at heights greater than 10 ft to establish the expected error in the LiDAR and GPS. The second and third sets of experiments are conducted at the McMillan Airfield at Camp Roberts on craters, spall and camouflet fields to provide the expected realistic operational results. Each experiment introduces the location, description of the area being used in the experiment, and environmental conditions. The data gathered is compared to the control data that is measured at the start of experimentation, and the overall lessons

learned for each experiment are presented. Craters are examined for diameter and depth, and the spall fields for the detection of camoufllets. The examination of the spall field assists the EOC to determine the initial MOS, and the depth of the camoufllet assists the ADATs in determining the overall area that might be affected by the presence of the camoufllet. There are multiple experiments performed in a more controlled setting (NPS) and a more realistic setting (Camp Roberts) in order to refine the processes. The main objective is to attach the system onto a UAV and verify if the system yields acceptable results for its intended use.

## **2. Error Calculation**

The experimental error is calculated using the standard experimental error formula, which is the magnitude of experimental results minus the control results divided by the control results. This formula yields a percentage that is converted into a unit of measurement of either inches or feet by dividing the percentage by 100, then multiplying that by the control depth or diameter measurement. Initially, upon site selection for experimentation, the diameter and depth are measured to produce the control results. Three trials are conducted at specific heights above the damage to produce a reasonable representation of the errors in the diameter and depth results. These three trial errors are added together and divided by three to produce the average error for that specified height above the damage. This average error per height is then converted into a unit of measurement to best describe the error as indicated above.

The quantitative results, only produce half of the true error of the system. Additionally, qualitative error must also be examined in order to produce an accurate representation of the true accuracy of the ADA Survey System. Qualitative data investigates precision, accuracy and observed trends which are compared with the quantitative results to produce the overall error of the system. Figure 17 presents the concept of precision and accuracy and how it relates to experimental data vice the control data.

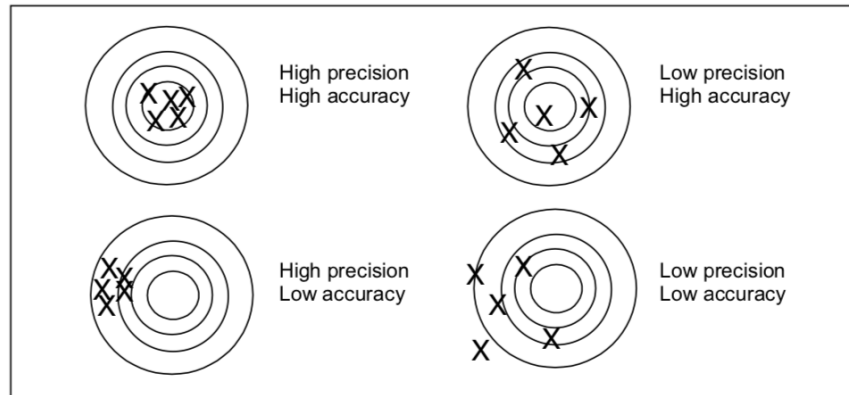


Figure 17. Precision and Accuracy. Source: Carlson (2002).

A marksman's bullseye best represents how precision and accuracy can be correlated with one another with regard to the control data. The center of the bullseye can be thought of as the control results of the depth and diameter for a specific experiment. The closer the results are to one another the higher precision is for that specific data set. However, if the results are all over the bullseye, that experiment would yield a low precision. Concurrently, the closer the results are to the center of the bullseye the higher the accuracy that is presented. Additionally, the farther away the results are from the center, the lower the accuracy of the experiment. Therefore, by observing the raw data from each trial per height, the data produces beneficial information to complement the overall experimental error in percentage and measurement.

Investigating the errors in both diameter and depth, as well as the specific precision and accuracy results, produces different trends to be noted. These trends produce the overall picture of how the ADA Survey System performs in the different environments and at different heights. The trends assist in further experimentation and improvements to the system if needed.

## B. EXPERIMENTS

The following experiments were conducted at two different sites (NPS, Camp Roberts) in two different ways. The first two sets of experiments were conducted without a UAV to refine the process and procedures in order to effectively utilize the UAV's flight time. Upon refinement, the system was secured to the UAV and the results compared to

the first two sets of experiments. The procedure and results are presented for both sets of experiments.

### **1. Procedure for Airborne and Non-airborne Operations**

Upon selection of a designated crater, spall, or camouflet, these areas were measured by hand to establish the control data for both the diameter and depth of that area. A team of two individuals using a standard measuring tape recorded the diameter and depth, measuring each three times for consistency. As stated in the error section, three trials were performed at different heights to establish an average error and overall observed precision and accuracy of the system. Each trial consisted of two scans of the selected damage by the system, both conducted over the center of the damage area. The first scan utilized the GPS unit to determine the diameter of the crater by recording the coordinates of the start and end of the damage. They also outlined the shape of the damage by using the LiDAR's Serial Plotter to produce a 2-D image. The second scan utilized the LiDAR to determine the depth by recording the max value and employing the equation from Chapter III to determine the maximum depth of the damaged area. For spall fields, the same first step of the procedure was followed in order to outline the spall field. If the LiDAR scan indicated a potential camouflet when conducting the initial scan of the spall field, the system was diverted to focus on the potential camouflet. If there was a large void underneath the surface with a small entry, it was treated as a good indicator of a camouflet. The system scanned for the depth of the possible camouflet using the LiDAR. Figure 18 is a cross-section image of a standard camouflet.

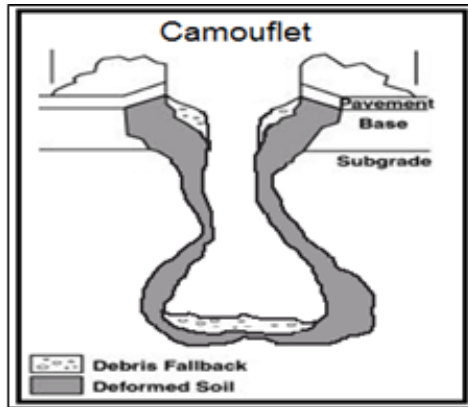


Figure 18. Camouflet. Source: United States Marine Corps [USMC], 2017.

After the data for all three trials was recorded, the system height was increased above the damage in order to commence another three trials. The ultimate goal of these initial non-airborne experiments was to calculate the error and accuracy at different heights above the damage area with control in order to refine the process and producers, and to be able to anticipate any shortfalls that can appear when attaching the system onto a UAV. The data from the non-airborne experiments is compared to the airborne experiments in order to localize any sources of error if the results greatly vary.

## 2. Naval Postgraduate School Experiments

The initial set of experiments were conducted at NPS at two different locations on campus during the month of July, 2018.

### a. Objective

The initial experiment set was conducted at NPS in order to partially introduce the system to environmental elements and to establish the best way to control future experiments. The buildings at NPS are partially outdoors and allow for unobstructed views from different floor levels to the ground level. This unobstructed position allows the LiDAR to be tested at a greater height for the first time in the fabrication of the system. Also, guardrails provide stability to the system to reduce error when testing the accuracy of the LiDAR. The location of the lab adjacent to the test locations allows for rapid repairs to be made since it is the system's first introduction to a non-lab environment.

***b. Glasgow East Building***

The first experiment was conducted on the second floor of the Glasgow East building. Figure 19 provides a view of the second-floor catwalk that was used because it provides an unobstructed position onto the concrete pad located on the ground floor. The experiment was conducted at 10 a.m., with clear conditions, sunny, humidity of 73%, and a temperature of 71°F. The guardrail on the second floor, designated as height of zero feet, creates a notional crater from the top of the guardrail to the ground floor. The distance between the two walls is considered the notional diameter of the crater.



Figure 19. Aerial view of Glasgow East Building located at NPS

**(1) Data Collection**

Following the experimental procedure, the diameter and depth of the notional crater from the second-floor catwalk was measured. Table 1 reflects the control data of the diameter and depth as 37.5 ft and 17.5 ft, respectively. Also, the table presents the coordinates from each scan and the experimental diameter and depth. The table concludes by both reflecting the error in a percentage, and a distance to reflect the error with regard to the control data. Only two trials were conducted in this experiment because the hotspot that was used to connect the user's computer to the RPI through the VNC overheated due to the direct sunlight. This is noted and should be controlled in future experiments to prevent delays in experiments. However, the first experiment presents some usable results;

the diameter's error is roughly 1.71%, but with a difference between both trials of 1.3 ft this represents that the GPS unit is not precise or accurate. The depth's error is just over 1%; these trials demonstrate that, with a difference between both results of 2.23 in., that the LiDAR is precise and accurate. This initial experiment provides both quantitative and qualitative results that refine the process for future experiments.

Table 1. Results for the first experiment at Glasgow East Building at height zero

| Control                   |                         |              |           |            |               |            |
|---------------------------|-------------------------|--------------|-----------|------------|---------------|------------|
| Diameter (ft)             | 37.5                    |              |           |            |               |            |
| Depth (ft)                | 17.5                    |              |           |            |               |            |
| Trial                     | Initial LAT             | Initial LONG | Final LAT | Final LONG | Diameter (ft) | Depth (ft) |
| 1                         | 36.359023               | 121.526093   | 36.358933 | 121.526035 | 37.03         | 17.814     |
| 2                         | 36.358929               | 121.526035   | 36.359023 | 121.526093 | 38.33         | 17.65      |
| 3                         | N/A Hot Spot overheated |              |           |            |               | 17.6       |
| Error (%)                 |                         |              |           |            | 1.714         | 1.06       |
| Avg Error to control data |                         |              |           |            | 7.71 in       | 2.23 in    |

### c. *King Hall*

The second experiment was conducted on the ground level of King Hall that overlooks an open sub floor. The sub floor is utilized because there is also guardrail to provide stability to the system and the terrain provides a more realistic look to an actual operational environment. Figure 20 provides a view of the experiment area. The experiment was conducted at 11 a.m., with clear and sunny conditions, humidity of 68%, and a temperature of 67°F. The guardrail on the ground floor was set at a height of zero feet, creating a notional crater from the top of the guardrail to the sub floor. The distance between the intersection of where the vegetation meets the ground floor and the intersection of where the vegetation meets the sub floor is designated the notional diameter.



Figure 20. View of the notional crater at King Hall

#### (1) Data Collection

The control data for the diameter and depth are 18.58 ft and 12.33 ft, respectively. Using the lesson learned from the past experiment, the hotspot was positioned so that it did not overheat, allowing for all three trials to be completed. Being able to complete all three trials provided more validity to the GPS and LiDAR. The diameter's error is 0.135% lower than the previous experiment, and the dispersion between all three experimental trials of 0.8 ft provides results that are more precise than before. Still, the accuracy is not absolute. The depth's error is 0.031% higher in this experiment compared to the first experiment. The dispersion between the experimental trials of 0.2 ft still provides precision, but it was consistently above the control value of 12.33 ft, thus lowering the accuracy of the LiDAR for this experiment.

Table 2. Results for the second experiment at King Hall at height zero

|                           |             |              |           |            |               |            |  |
|---------------------------|-------------|--------------|-----------|------------|---------------|------------|--|
| Control                   |             |              |           |            |               |            |  |
| Diameter (ft)             | 18.58       |              |           |            |               |            |  |
| Depth (ft)                | 12.33       |              |           |            |               |            |  |
| Trials                    | Initial LAT | Initial LONG | Final LAT | Final LONG | Diameter (ft) | Depth (ft) |  |
| 1                         | 36.357006   | 121.524785   | 36.357033 | 121.524840 | 18.94         | 12.5       |  |
| 2                         | 36.357009   | 121.524790   | 36.357045 | 121.524835 | 18.65         | 12.56      |  |
| 3                         | 36.357015   | 121.524782   | 36.357034 | 121.524839 | 18.14         | 12.72      |  |
| Error (%)                 |             |              |           |            | 1.579         | 1.091      |  |
| Avg Error to control data |             |              |           |            | 3.52 in       | 1.61 in    |  |

A reason why the diameter precision was high in this experiment is that all three trials are conducted to provide a valid result of the diameter. Also, the introduction of the system to a more realistic operational environment can explain the decrease of the accuracy in the LiDAR. When measuring the diameter and depth, only three points were chosen to best represent the control data. When conducting the scan for depth, the max value reported was recorded to calculate the depth, so in thick vegetation there is a point that is deeper than the largest measured value.

### 3. Lesson Learned

This initial set of experiments help refine the process and procedure and help anticipate the expected errors when introducing the system to a more realistic environment. The biggest take away from the first two experiments is the environmental effect on the support systems, such as the user's computer for plotting the data and the hotspot for the VNC, which needs to stay in a cool and shaded place for better performance.

### 4. Camp Roberts Experiments

Camp Roberts is a California National Guard Post located 101 miles south of NPS. The environment is arid and desert like, with summer temperatures ranging from 50°F in the morning to 100°F from mid-day to the late evening. The second set of experiments took part in the Joint Interagency Field Experiment (JIFX), which allows military and civilian entities to test technology valuable to the DoD. More information can be found at: <https://my.nps.edu/web/fx/home>. The following set of experiments were conducted

between 8 a.m. to 11 a.m., with clear and sunny conditions, humidity of 10% , and a temperature ranging from the mid-70s to the mid-80s throughout the set of experiments. A total of three experiments were conducted at a mock crater and spall field located on the West end of the McMillan Airfield, as in Figure 21. This location allows for the introduction of the system to not only realistic damage but also a realistic operating environment.



Figure 21. The crater that was used in the first two experiments at Camp Roberts

**a. Objective**

The purpose of conducting experiments at Camp Roberts is to advance the system in the systems engineering process. Since a base-line has already been established in the initial set of experiments at NPS, the system was introduced to a different environment. Camp Roberts offers a near operational environment in which a system like this would be operating, so it offers insight to its performance both mechanically and physically. Introducing the system to an environment like Camp Roberts yielded different results and different explanations and questions to be answered in order to ultimately test the system airborne. Since the Camp Roberts terrain is realistic and there are mock craters and spall fields with camouflages, an objective of this experiment is to not only observe the accuracy of the system but also to see if the system can detect and accurately depict a camouflage.

**b. Data Collection**

The objective of the first two experiments conducted at Camp Roberts was to verify the error, precision, and accuracy of the two sensors on realistic damage with the system at different heights. Just like the previous set of experiments at NPS, the control measurements are gathered before experimentation. Figure 21 is the crater that was used in the first two experiments at Camp Roberts; it has a diameter and depth of 7.67 ft and 16 in., respectively. The depth is measured in inches in order to easily visualize the distance. The system's first height above the damage is 4.16 ft. Two scans of the damage were performed using the system for three different trials as seen in Table 3. The individual trial results for the diameter shown in Table 3 indicates that the GPS unit has high precision but the accuracy is still low since the results are almost nine inches more than the actual diameter. The accuracy of the depth error is high, but the precision is low due to the dispersion of 0.79 in. between the three trials.

Table 3. Experiment 1: Crater at McMillan Airfield at height 4.16 ft above damage

| Control Data              |           |            |            |             |               |            |
|---------------------------|-----------|------------|------------|-------------|---------------|------------|
| Diameter                  | 7.67      | ft         |            |             |               |            |
| Depth                     | 16.0      | in         |            |             |               |            |
| Trial                     | Start Lat | Start Long | Finish Lat | Finish Long | Diameter (ft) | Depth (in) |
| 1                         | 35.432241 | 120.464716 | 35.432224  | 120.464698  | 8.19          | 16.363     |
| 2                         | 35.432287 | 120.464628 | 35.432302  | 120.464650  | 8.539         | 15.969     |
| 3                         | 35.432270 | 120.464658 | 35.432275  | 120.464630  | 8.527         | 16.756     |
| Error %                   |           |            |            |             | 9.761         | 2.395      |
| Avg Error to control data |           |            |            |             | 8.98 in       | 0.38 in    |

The system's height above the same crater in Figure 21 is increased in experiment 2 ft by 3 ft, to 7.16 ft above the damage, and the same procedure is followed as in the first experiment. As seen in Table 4, the error did increase for the diameter. The precision and accuracy for experiment 2 are the same as in the previous experiment: the diameter has a high precision and low accuracy, and the depth has a low precision but high accuracy.

Table 4. Experiment 2: Crater at McMillan Airfield at height 7.16 ft above damage

| Control Data              |           |            |            |             |               |            |
|---------------------------|-----------|------------|------------|-------------|---------------|------------|
| Diameter                  | 7.67      | ft         |            |             |               |            |
| Depth                     | 16        | in         |            |             |               |            |
| Trials                    | Start Lat | Start Long | Finish Lat | Finish Long | Diameter (ft) | Depth (in) |
| 1                         | 35.432290 | 120.464619 | 35.432297  | 120.464592  | 8.424         | 16.189     |
| 2                         | 35.432294 | 120.464609 | 35.432290  | 120.464580  | 8.752         | 16.583     |
| 3                         | 35.432290 | 120.464619 | 35.432312  | 120.464610  | 8.464         | 15.402     |
| Error %                   |           |            |            |             | 13.955        | 2.8534     |
| Avg Error to control data |           |            |            |             | 10.52 in      | 0.46 in    |

The third experiment utilizes the spall field located at the rear of the crater field at McMillan Airfield. At a height of 5.16 ft above the spall field, the depth of the camouflet is 19 in. Not only is the LiDAR very accurate in this experiment, but it also successfully identified the camouflet that is located within the spall field as in Figure 22. The LiDAR is able to successfully graph the two spalls (middle and right of the picture and graph) and graph the camouflet (left side of the picture and graph). This graph is useful because to the naked eye the camouflet cannot be detected and blends into the spall field. The error in the depth is around 1.94%, yielding a difference of 0.37 in. Just like the previous experiments, the LiDAR has low precision but high accuracy.

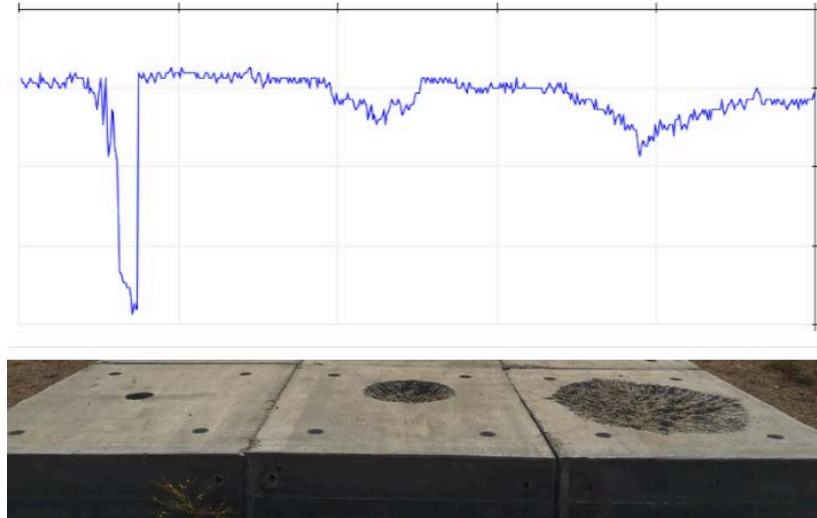


Figure 22. Comparison of LiDAR generated graph to actual spill and camouflet field

## 5. Lessons Learned

These experiments were conducted in a more realistic operational environment that introduced new observations to consider in the future. A key precaution is that since the infrastructure is not suitable for high heat environments, all experiments were performed in the morning hours. After noon, the heat did affect the processing speed, thus delaying the collection of data. If this system were to be used in an operational environment, the computer system needs to be in an environment-controlled space. Besides the slow processing speed due to the high heat, everything else held up to the conditions. The housing of the LiDAR did not melt, the microprocessors did not need to be replaced, and the sensors were not affected. As in any new system, the introduction to new environments is essential in order to learn what conditions affect the system that are not really thought about in a lab setting. The three experiments at Camp Roberts are very beneficial and carry over to future experiments.

## 6. Performance of Non-airborne ADA Survey System

The first observation was the increase in the error of the diameter in those experiments conducted at Camp Roberts. Experiments 1 and 2 have an increase in diameter error of 9.76% and 13.95%, respectively. This is compared to the two NPS experiments

that have an error percentage of 1.71 and 1.57, respectively. The measured diameter of the Camp Roberts experiment is 7.67 ft compared to the diameters of the NPS experiments, which range from 18.58 ft to 37.5 ft. This increase in error corresponds to the characteristics of the GPS used in the experiment. Research for short distance measurements for GPS is not readily available, as most research deals with a dispersion of hundreds or thousands of meters. However, research in sports medicine has produced data that reveals the accuracy of GPS units in tests under 30 m (Castellano, Casamichana, Calleja-Gonzalez, Roman, & Ostojic, 2011). Using handheld GPS units, the “Accuracy improved with increased distance, and the mean SEM [Standard Error of the Mean] of 10.9% when running 15 m was reduced by half over 30 m” (Castellano et al., 2011, p. 2). Therefore, with regard to the ADA Survey System, and as the NPS experiments presented, in order for the GPS unit to accurately triangulate a position, there needs to be some dispersion between the two points. So, the error of the diameters in the NPS experiments is less because the distance between the two points is greater than that of the crater at Camp Roberts. Therefore, by comparing these different experiments, the trend is that a large distance decreases error but an increase in altitude increases the error as well.

The second observation is the increase in error of the depth in the experiments performed at Camp Roberts. The error in depth of the three experiments at Camp Roberts is 2.39%, 2.85%, and 1.94%, respectively, compared to the error of the depth of the experiments at NPS, which are 1.06%, and 1.09%, respectively. The increase in error can be contributed to the rocky and desert-like terrain at Camp Roberts, as seen in Figure 21, compared to the smooth concrete surfaces at NPS. Also, unlike the experiments at NPS, there is not a guardrail to provide stability to the system so human error may have contributed to this increase.

Taking this system from a controlled setting to a more realistic operating environment provided very useful feedback that applies to the system as it is mounted onto the UAV. The error is within expectations and its statistical information is compared to the data that is gathered from the system mounted on the UAV.

## **7. Airborne ADA Survey System**

The ultimate objective of the research was to develop a system that can rapidly and accurately survey the damage to an airfield. The only way that this is possible is to mount the system onto a UAV to fly it over the damage and observe the results from an EOC which is not located on the damaged airfield. The two sets of experiments have perfected the process and procedures and have established known errors to expect with the system. However, mounting the system to a UAV creates a need to update the experimental procedure and present new errors and lessons, just like our two sets of experiments. Once the airborne ADA Survey System experimentation is concluded, those errors can be compared to those of non-airborne operations in order to determine if the system is suitable for use in the operational environment.

## **8. Airborne Camp Roberts Experiment**

The Airborne experiment was conducted at Camp Roberts. The experiments were conducted between 9:00 a.m. and 1:00 p.m., with conditions ranging from 54°F with scattered clouds at the start to 82°F with sunny conditions at the conclusion. The humidity also dropped during experiments from 84% to 35%. Four experiments are conducted at the mock spall and crater fields at the west end of McMillan Airfield. Again, as in Figure 23, this location was chosen due to realistic environmental and physical conditions a system like this one would certainly operate within.

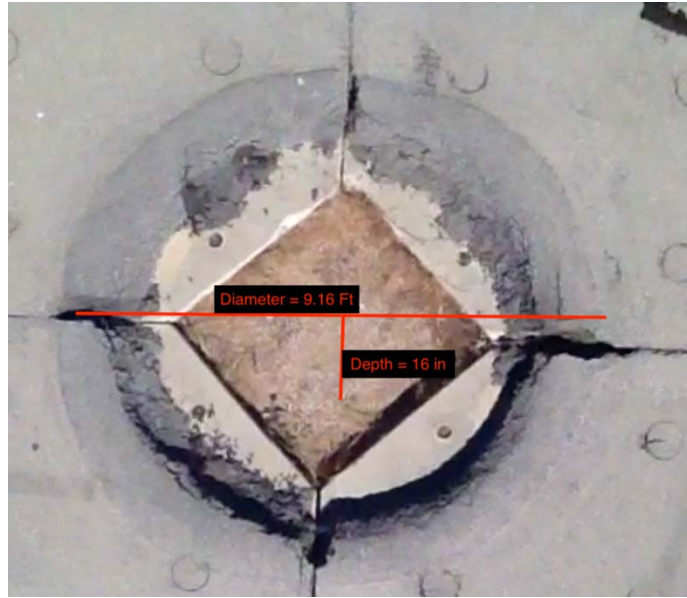


Figure 23. Crater used in airborne experiments

**a. Objective**

As stated, the ultimate objective of this research is to determine the feasibility of using an inexpensive system to rapidly and accurately conduct an ADA. The following experiments were conducted using the COTS UAV, the DJI Matrice 600 Pro, which has an estimated flight time of about 36 minutes per full battery charge for the 1.9 lb system. Following the same procedure as the non-airborne experiments, the data was collected and compared to the non-airborne data to verify its feasibility.



Figure 24. Airborne operations

***b. Data Collection***

Just like the nonairborne experiments, the objective of the four airborne experiments is to identify the error, precision and accuracy of the system at different heights above the realistic damage. The first three experiments are conducted over a man-made crater at three different heights above the damage, each height having three trials. As in Figure 24, our system was attached to the DJI Matrice 600 Pro UAV which was used in three trials at three different heights. The first height selected was 2 m, or 6.56 ft, above the damage. As in Table 5, the system performed well with regard to both the LiDAR and GPS units. The GPS unit is not precise in that the diameters it produced spanned 1.19 ft, but it is accurate in that the error was just above five percent, yielding an average of 5.60 in. in error to the control diameter of 9.16 ft. The LiDAR unit is precise and accurate in that the data spanned 0.39 in. and had an overall error of 2.94%, yielding an average of 0.47 in. of error.

Table 5. Experiment 1: Crater at McMillan Field at airborne height 2 m, or 6.56 ft

| Control Data              |            |             |            |             |               |            |
|---------------------------|------------|-------------|------------|-------------|---------------|------------|
| Diameter                  | 9.16       | ft          |            |             |               |            |
| Depth                     | 16.0       | in          |            |             |               |            |
| Trials                    | Start Lat  | Start Long  | Finish Lat | Finish Long | Diameter (ft) | Depth (in) |
| 1                         | 35.4323090 | 120.4646190 | 35.4323070 | 120.4645900 | 8.67          | 16.73      |
| 2                         | 35.4323090 | 120.4646190 | 35.4322850 | 120.4646190 | 9.86          | 16.34      |
| 3                         | 35.4322850 | 120.4646190 | 35.4322870 | 120.4646490 | 8.95          | 16.34      |
| Error %                   |            |             |            |             | 5.09          | 2.94       |
| Avg Error to control data |            |             |            |             | 5.60 in       | 0.47 in    |

As hypothesized, the increase in height increases the error in the diameter as well. That is exactly what happened at the heights of six and eight meters, as reflected in Table 6 and Table 7, respectively. An interesting observation is how the accuracy of the diameter decreased by about three feet with the addition of two meters. At 4 m, or 13.12 ft, the reported diameter is about six feet, and at a height of 8 m, or 19.68 ft, the reported diameter is around three feet. The GPS unit's accuracy and precision are low at these heights, as seen in Table 6 and Table 7, reflecting that this system is only accurate at two meters. The LiDAR unit however, is both accurate and precise at four and six meters. The LiDAR's error is about two percent in both heights, yielding around 0.30 in. of total error.

Table 6. Experiment 2: Crater at McMillan Field at airborne height 4 m, or 13.12 ft

| Control Data              |            |             |            |             |               |            |
|---------------------------|------------|-------------|------------|-------------|---------------|------------|
| Diameter                  | 9.16       | ft          |            |             |               |            |
| Depth                     | 16.0       | in          |            |             |               |            |
| Trials                    | Start Lat  | Start Long  | Finish Lat | Finish Long | Diameter (ft) | Depth (in) |
| 1                         | 35.4322750 | 120.4646190 | 35.4322900 | 120.4646280 | 6.09          | 16.32      |
| 2                         | 35.4322880 | 120.4646190 | 35.4322970 | 120.4646390 | 6.78          | 16.32      |
| 3                         | 35.4322800 | 120.4646190 | 35.4322990 | 120.4646280 | 7.44          | 16.32      |
| Error %                   |            |             |            |             | 26.09         | 2.00       |
| Avg Error to control data |            |             |            |             | 28.68 in      | 0.32 in    |

Table 7. Experiment 3: Crater at McMillan Field at airborne height 6 m, or 19.68 ft

| Control Data              |            |             |            |             |               |            |
|---------------------------|------------|-------------|------------|-------------|---------------|------------|
| Diameter                  | 9.16       | ft          |            |             |               |            |
| Depth                     | 16.0       | in          |            |             |               |            |
| Trial                     | Start Lat  | Start Long  | Finish Lat | Finish Long | Diameter (ft) | Depth (in) |
| 1                         | 35.4322850 | 120.4645990 | 35.4322940 | 120.4645940 | 3.6           | 15.91      |
| 2                         | 35.4322940 | 120.4645990 | 35.4323020 | 120.4645940 | 3.28          | 16.69      |
| 3                         | 35.4322940 | 120.4646090 | 35.4323210 | 120.4646010 | 3.01          | 16.3       |
| Error %                   |            |             |            |             | 64.01         | 1.88       |
| Avg Error to control data |            |             |            |             | 70.36 in      | 0.30 in    |

The fourth experiment surveys the spall field in order to verify if the system can identify a camouflet within a spall field. As in Figure 25, the system is flown over the spall field at a height at two meters and identifies the existence of a camouflet as well as the depth, indicating that in fact the area of concern was a camouflet. The LiDAR is again both accurate and precise in that the total error is 1.79%, which is 0.34 in. in actual measurement.

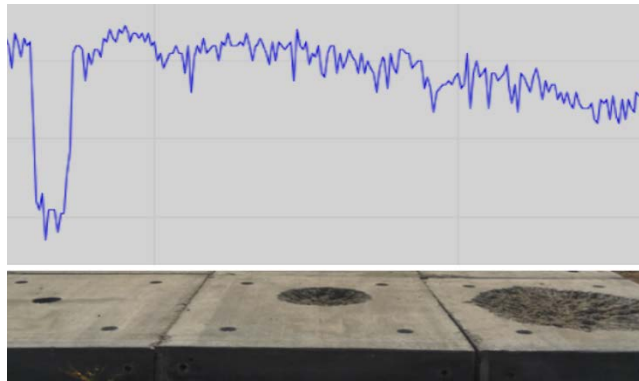


Figure 25. Comparison of LiDAR generated graph to actual spall and camouflet field

## 9. Lessons Learned

Mounting this system onto a UAV led to several different lessons; the biggest lesson is that experience is needed in order to fly a UAV of this magnitude. It is estimated that with a payload of 1.9 lb the flight time would be around 36 minutes. The four experiments used three flights that all averaged around 30 minutes per flight before the

batteries needed to be recharged. That was six minutes less than predicted, but the UAV auto-landed with 10% of battery remaining, a result not included in the initial calculations. Also, just like environmental conditions affect the processing speed in the first set of experiments at Camp Roberts, the UAV itself is also affected by these conditions. Wind was a factor in trying to position the system over the damage in order to gather accurate results. So, it only makes sense that the higher above the damage the UAV is, the harder it is to position thus more battery power is used to stabilize the UAV. The location of the controller of the UAV also caused interference with the VNC when it was near the user's computer. This slows the processing speed of the RPI, and thus causes the UAV to hover over certain locations for longer time to correct this error. However, even with these lessons the airborne experiments conclude the feasibility of an airborne ADA Survey System can produce accurate results at two meters above the damage.

### **C. PERFORMANCE OF ADA SURVEY SYSTEM**

This incremental process of introducing the system to different environments, locations, and applications produces different trends to be noted. As previously mentioned, the non-airborne and airborne results are compared to produce quantitative and qualitative trends.

#### **1. Quantitative Trends**

This system performed within expectations at each experiment, yielding results with expected error as noted from the inherited error of each device (LiDAR, GPS units) individually. One of the more apparent trends is that the system performs better when airborne vice non-airborne. As can be seen in the above data, when airborne, the diameter and depth errors are less than non-airborne experiments. This decrease in error is contributed to the UAV being more stable than experiments by hand. Also, the acquisition of data is faster onboard the UAV vice handheld, which is due to a clear line of sight from the UAV. Also, the depth data is consistently more than the actual control measurement which is to be noted for operational usage.

## **2. Qualitative Trends**

As both locations, NPS and Camp Roberts, have shown in their respective results, the error in the depth by using the LiDAR is much lower than the error in the diameter by using a GPS unit. The LiDAR unit for the most part has a consistent error of less than two percent, which is independent of the different environment, locations, and applications. The diameter error using the GPS is much more dependent on the environment, locations, and applications. It can be noted that the GPS unit on this system is less accurate at smaller diameters and greater heights and more accurate at greater diameters and smaller heights.

## **D. SUMMARY**

This chapter presented the experimental data from two different locations, and two different methods of application. The system was tested nine different times with 26 trials in order to produce the results. The airborne results from Camps Roberts at a two-meter height above the damage demonstrated that this system provides accurate and rapid results with regards to an ADA. The error in diameter and depth was only 5.60 in and 0.47 in, respectively. Compared to current TTPs it provides more expeditionary and safer means to conduct an ADA. The backbone of this current system is just an Internet connection, a computer, and a UAV. This makes this system inexpensive, logistically light and expeditionary, as well as simple to operate. Chapter V provides the overall conclusion of this research with recommendations and future focused research to improve upon the current design and implementation.

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## **V. CONCLUSIONS**

### **A. SUMMARY**

Military airfields are used by U.S. and coalition forces for staging supplies and military personnel; thus, it is important to keep them operational. Given this need, ADA becomes a pivotal step in order to rapidly repair an airfield in case of a damage. We designed and developed an ADA Survey System to support this need. The system performed well and provides an increase in accuracy of damage detection and classification in Phase I of an ADA. This contributes to a rapid establishment of a MOS and the overall decrease in the time to conduct the ADR. This inexpensive system constructed from COTS sensors and an aerial platform increases the operability and sustainability of the system. The system can be used with limited experience level, in any operational environment, and provides the service member the ability to conduct the ADA rapidly while increasing their safety.

### **B. PERFORMANCE**

This system demonstrates that it is possible to survey the runway damage by the use of a LiDAR and a GPS unit at a height of two meters above the damage. The LiDAR is both accurate and precise, with the error staying below two percent. These experimental results suggest that the LiDAR is the correct electro-optical sensor to determine the depth of damage. The GPS unit has a low precision but a relatively medium to high accuracy. Due to the low precision, the use of a GPS unit in a real-world ADA will require the system to perform at least three trials at two meters to produce the accuracy as seen in our experimental results. The two Arduino boards and the RPI performed well, given the environmental conditions and the use of the VNC to connect the user to the system.

### **C. CONCLUSIONS**

From the data gathered in our field experiments, this system produces rapid and accurate measurements of the diameter and depth of a crater to calculate the necessary materials and personnel to repair the damage. Additionally, the system is able to identify a

camouflaged that is hidden in a spall field. This result decreases the search time for the ADATs and provides pertinent information to the EOC so an MOS can be established during Phase I.

#### **D. RECOMMENDATIONS FOR FUTURE WORK**

This system can be improved upon for better performance. This research looked at whether a system by itself can rapidly and accurately report the dimensions of damage to an airfield. Our key constraints were that the system must be inexpensive, consume low power and be mounted onto a COTS UAV. With these constraints in mind, the ADA Survey System produces useful and accurate results in a near operational environment with realistic runway damage. However, additional research as described below, should be considered in future work.

To understand the full functionality of the ADA Survey System it should be tested in all possible operational environments and conditions. Once this is accomplished, the true physical and mechanical behaviors of the system will be understood.

Network and network security should be studied in order to make the system secure. The system in this research relies heavily upon a hotspot generated from a smart phone that only produces 66 ft of coverage to connect the user to the system via a VNC. This very limited coverage is the weakest link in the chain for this research and would hinder the use of this system in an actual ADA for obvious reasons.

Individually scanning for the location of the damage and then surveying each crater and spall field would either take substantial time or the use of many systems on UAVs that cause other issues. To effectively use a system such as this one, researchers should look into autonomous data gathering, either by performing a first flyover of the runway to mark potential damage areas with GPS coordinates or by using pre-installed ground acoustic and/or vibration sensors. This would allow the ADA Survey System to just focus on the damage itself and not spend time to scan the entire runway.

As presented in the results, the use of the GPS to determine the diameter with the Haversine formula worked at a height of two meters above the damage but is not accurate

above that height. However, the results did demonstrate the Garmin v3 Lite LiDAR is not only accurate but its error is very low in every experiment. Research should be done to mechanically move the LiDAR a total of  $180^\circ$  over the damage in order to survey the diameter of the crater and the depth. The LiDAR would be able to mechanically scan the entire crater while hovering in the middle of the damage. From the height above the damage and the angles from both ends it would be possible to calculate the overall diameters, which, given the proven accuracy of the LiDAR, is more precise than the GPS unit.

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