Aerial LiDAR Assessment of Damaged Infrastructure (ALADIN)

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ABSTRACT

The U.S. Air Force has an operational need to survey and recover bomb-damaged airfields within a very limited time frame and to do so remotely. In support of this mission, the U.S. Army Engineer Research and Development Center (ERDC) has developed a semi-automated damage and unexploded ordnance (UXO) detection and classification system called Aerial LiDAR Assessment for Damaged Infrastructure (ALADIN) deployable on small unmanned aerial systems (sUAS). This system relies upon several capabilities enabling remotely detected surface damage and UXO. First is the fast mapping capability of commercially available Light Detection and Ranging (LiDAR) sensors which can generate centimeter-accurate 3D models of airfield surfaces rapidly. Second is the automatic processing of 3D range data and GNSS information into georeferenced point clouds using YellowScan's LASONLINE software and the processing of this 3D point data in flight on a small form factor Windows-based computer using ALADIN. Lastly, damage detection and classification data products are transmitted over encrypted radio to a secure ground network. One major benefit of such a system is the small size of ERDC-generated data products (10s-100s of kilobytes) in comparison to the relatively large size of raw 3D LiDAR data (100s-1000s of megabytes). In order to achieve in-flight processing, diverse COTS and ERDC-developed hardware and software systems were fused into an all-purpose sUAS-portable package. Furthermore, the same lithium polymer batteries that power most sUAS are utilized to power the Windows-based small form factor computer and encrypted radio through a system of DC-DC converters. The LiDAR sensor system has been shown to be robust to dust obscurants, day and night lighting conditions, and shallow surface water contamination. The in-flight processing and analysis of LiDAR data using the ALADIN system allows for real-time assessment of damaged airfields in the compressed timeframe required by the Air Force's operational needs.

1.0 INTRODUCTION

Military aircraft require relatively smooth, level surfaces on which to perform landing and takeoff operations. Typically these surfaces are paved, consisting of Portland cement concrete (PCC) and asphalt (AC), and can extend upwards of 3000-m or greater in length. These large paved surfaces often become high priority targets to adversaries in theater as their damage reduces air superiority. In the current research scenario, it is assumed that the pavement surface is rendered unusable through bombing attacks that create multiple craters of varying diameters and depths. By definition [1], a crater is any depression that extends past the hardened pavement layer into the underlying base or subgrade material. A spall is a depression that extends only into the hardened layer. A camouflet is a punctured hole in which the explosive either did not detonate or detonated underground to create a sub-surface cavity (Figure 1).

Figure 1: Image of crater (left), spall (middle), and camouflet (right).

In order to bring the damaged airfield back to an operational status, a select number of craters must be repaired to create a minimum operating strip (MOS). In order to achieve this mission, the first step in the repair process is identifying the location of all damage including type and severity. The goal of the U.S. Air Force's (USAF) Rapid Airfield Damage Assessment System (RADAS) is to provide a capability to identify all airfield surface damage including type and severity across an airbase within a 30-min time window. Past research conducted in this area has focused on using aerial- and ground-based assets to provide rapid electro-optical (EO) visualization of the airfield enabling an expert to manually identify the damage from imagery alone (Filler 2011). However, this manual-visual approach, while functional and currently the state of practice, is not able to be completed within the 30-min time window.

The ERDC's approach to accomplish the identification stage in under 30 min required two fundamental changes to past research approaches. The first was to collect airfield surface data in a way that could rapidly be digitized into a three-dimensional scene, and the second was to develop and apply automated detection algorithms to identify surface damage. The combination of these two technologies could provide the capability to identify, with sufficient accuracy, the necessary pavement damage to compute an MOS.

Taking advantage of recent advances in imaging technology, this research made use of Light Detection and Ranging (LiDAR) sensors to rapidly generate a digitized airfield surface. The most recent advances in this capability involve the deployment of small form factor LiDAR sensors on a small unmanned aerial system (sUAS). The LiDAR sensor can create a high-resolution, geospatially positioned, dimensionally scaled three-dimensional point cloud from which numerical analysis is performed.

The MATLAB integrated development environment (IDE) was utilized as an interface allowing the development of algorithms necessary to identify and measure damage along with a graphical user interface (GUI) to evaluate the success of the software. Algorithms were developed using filling techniques to identify the extent of each damage type. Location of all airfield damage was determined from a global positioning system (GPS) integrated with the sensor platforms. The software generated a series of data files populated with information containing damage type, location, and scale that could be rapidly transmitted to visual planning software.

The ERDC LiDAR solution consists of both hardware and software which work in tandem. Each solution runs independent of the other with the processing software agnostic to the LiDAR collection sensor as long as a LAS formatted point cloud can be generated. This allows for greater flexibility for deployment as hardware changes occur quickly in the sUAS and LiDAR imaging space but yet the software can absorb the data product from new and improved sensors without modification. The only caveat being that lower fidelity sensors generate, appropriately, lower fidelity data products.

2.0 SENSORS AND PLATFORMS

LiDAR is a remote sensing technology that uses a pulsed laser light to measure the distance to a target surface by measuring the time of return of reflected pulses off the object's surface (Figure 2). A LiDAR system has a GPS attached to it so that each data point has a real-world location, allowing for engineering analysis to be performed on the developed point cloud. The LiDAR systems employed in this research include an inertial measurement unit (IMU) that determines the position of the laser with each pulse as the aircraft moves with the laser system to correct the GPS position for movement of the sensor. When all these systems are integrated, a dimensionally and positionally accurate three-dimensional point cloud is immediately generated.

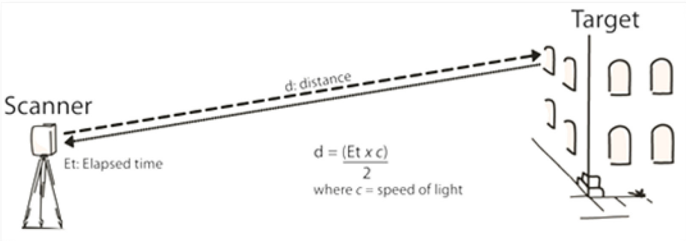


Figure 2: Illustration of LiDAR pulse and return.

The ERDC-developed automated solution made use of a Yellowscan Surveyor Ultra LiDAR sensor consisting of a Velodyne-32 LiDAR puck coupled with an Applanix APX-15 IMU for accurate point positioning during flight (Figure 3). An internal battery for the Yellowscan LiDAR sensor supplied independent power from the sUAS platform. The Yellowscan system was complimented with a custom fabricated mount to fit a Teledyne-FLIR SkyRaider R80D sUAS enabling ready deployment of the sensor. To enable real time LiDAR processing on board the SkyRaider, ERDC developed a customized system which links the Surveyor via Ethernet to an Intel NUC computer running Windows 10 that was custom mounted to the rear of the sensor via a 3D printed mounting bracket (Figure 4). A constant 50W of power was supplied to the NUC via a 15V DC connected to a 1850mah, 18.5v LiPo battery. Attached to the side of the SkyRaider via another custom fabricated bracket is a Trimble RTX GPS antenna which can provide real time GPS satellite corrections with positional accuracy to within less than 10cm. Yellowscan developed a software system in 2021 entitled LASONLINE which is able to read in the LiDAR puck file, Applanix IMU file and the RTX GPS file and resolve a geo-referenced LAS point cloud in time increments at the user's discretion. A time increment of 30 seconds was selected for this experiment. Data is then analyzed via the ALADIN software to be discussed in the next section. The results are streamed directly to a ground station laptop using 128 bit encryption via a 2.4 GHz Microhard PicoRadio radio positioned at the rear of the sUAS and connected to the NUC via Ethernet. The total hardware package deployed onto the SkyRaider platform weighs approximately 3.2 kg which falls just beneath its maximum payload of 3.4 kg using a set of heavy-left rotors.

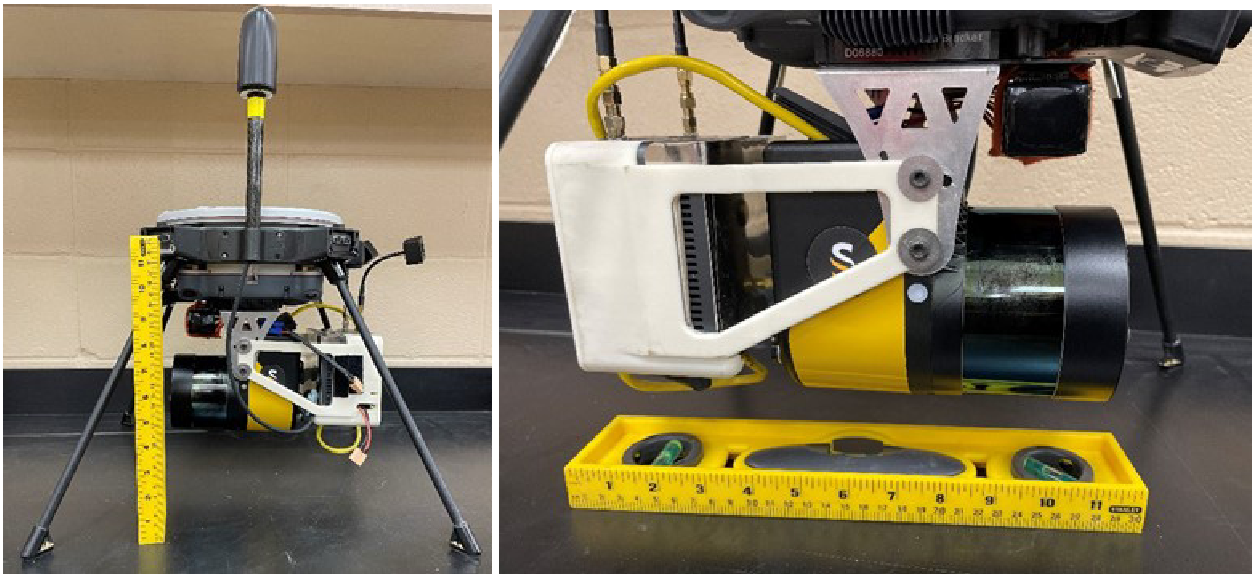


Figure 3: Yellowscan Ultra Surveyor hardware configuration on a SkyRaider R80D sUAS platform.

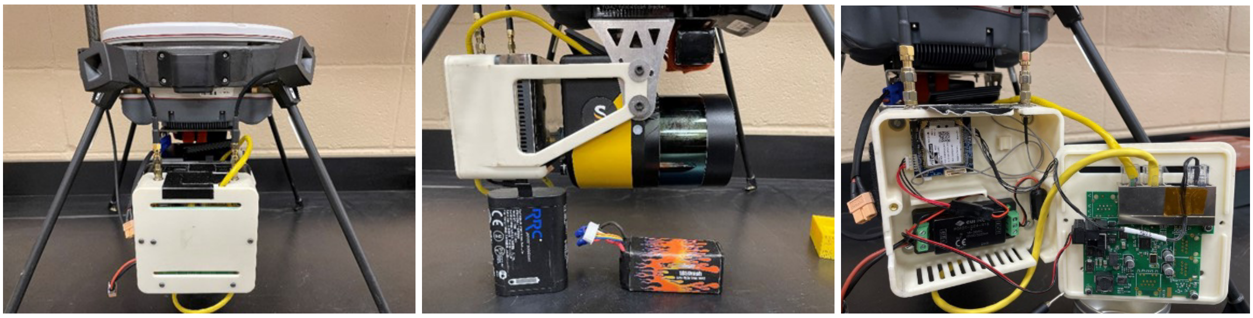


Figure 4: Custom fabricated bracket for NUC along with PicoRadio, UBEC and Ethernet switch.

3.0 DEPRESSION-FILLING METHOD

The problem of detecting bomb damage on a pavement surface can be generalized as an exercise in measuring surface depressions. As such, techniques relevant to detecting volumetric depressions are usable here. Such algorithms, commonly called depression-filling algorithms (DFAs), are used in a variety of fields including geosciences and astrophysics. In the geosciences community, DFAs are used to label watersheds [2], determine flood risk [3], and measure surface depression storage capacity [4]. In the astrophysics community, DFAs are used to monitor cratering on distant astronomical bodies [5]. For the present work, a foundational paper by Planchon and Darboux [6] provides a DFA that both converges to a unique solution for all surfaces and does so with a time complexity suitable for modern, high-resolution meshes. For the remainder of this article, the Planchon and Darboux [6] DFA will be referred to as “no-sink”.

The no-sink algorithm works, subjectively, by flooding a surface with water and draining the water in a controlled manner. For input into no-sink, the 3D LiDAR point clouds are converted into a rigid surface or mesh with all gaps filled. By applying no-sink to this continuous mesh, bomb damage can be isolated as those areas with “standing water”. In general, the no-sink algorithm iteratively decreases the “water” height until three conditions are met:

1) The final surface, S_2, is at all grid cells greater than or equal to the original surface, S_1, i.e., at all points $S_2 \geq S_1$.

2) For all grid cells in the final surface, there exists a path that leads to the boundaries in which there is a minimum descent of ε.

3) The final surface is the lowest elevation surface by which the above two properties apply.

Following these three rules, any continuous mesh can be processed into a depression-filled mesh. By then removing the depression-filled mesh (point-by-point) from the original mesh, a depression-only mesh can be generated. It is from this final mesh that measures of width and depth are made on all depressions.

4.0 DAMAGE DETECTION USING ALADIN

To implement the DFA algorithm, ERDC developed the Aerial LiDAR Assessment of Damaged INfrastructure (ALADIN) analysis tool within the MATLAB development environment to accomplish the task of rapidly assessing airfield damage from any three-dimensionally generated point cloud (Figure 5). The ALADIN software operates on point clouds in the LAS or LAZ file format, conveniently output from most LiDAR sensor units. The ALADIN software requires minimal input by the user to accomplish the task of damage detection simply requiring the user to input the file location where any LAS files will be stored or saved from the LASONLINE software package, the UTM Zone and the ground station connection information. The ALADIN software performs a connection check with the ground station providing a green light when all systems are connected. The software continuously checks the LAS file directory for new input files incoming from the LiDAR/LASONLINE system and when one is received begins analyzing that LAS file for volumetric damage and unexploded ordnance.

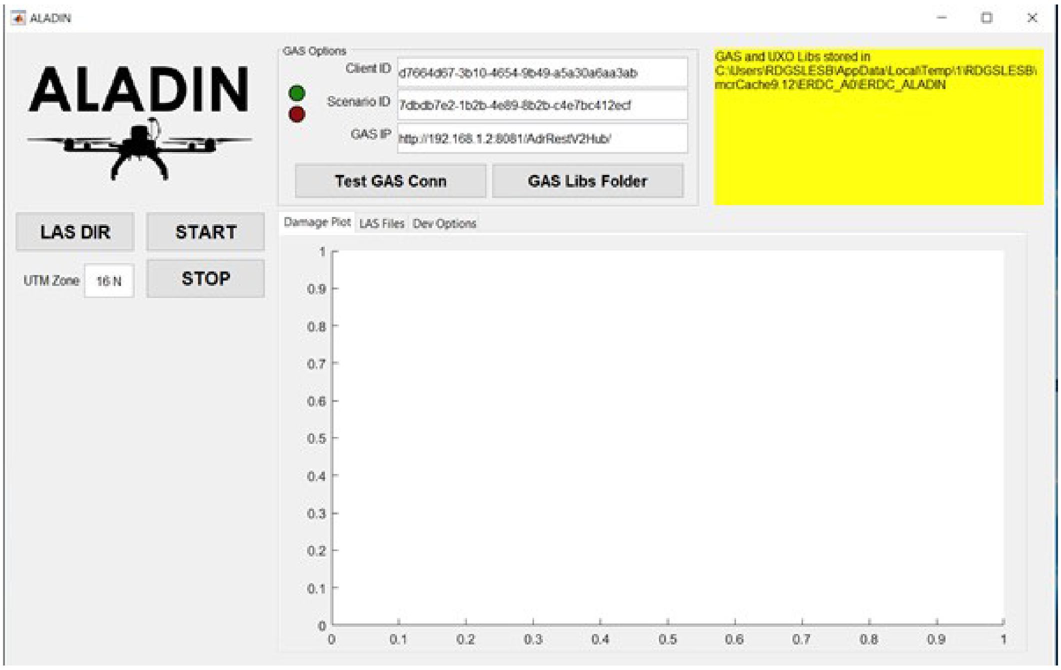
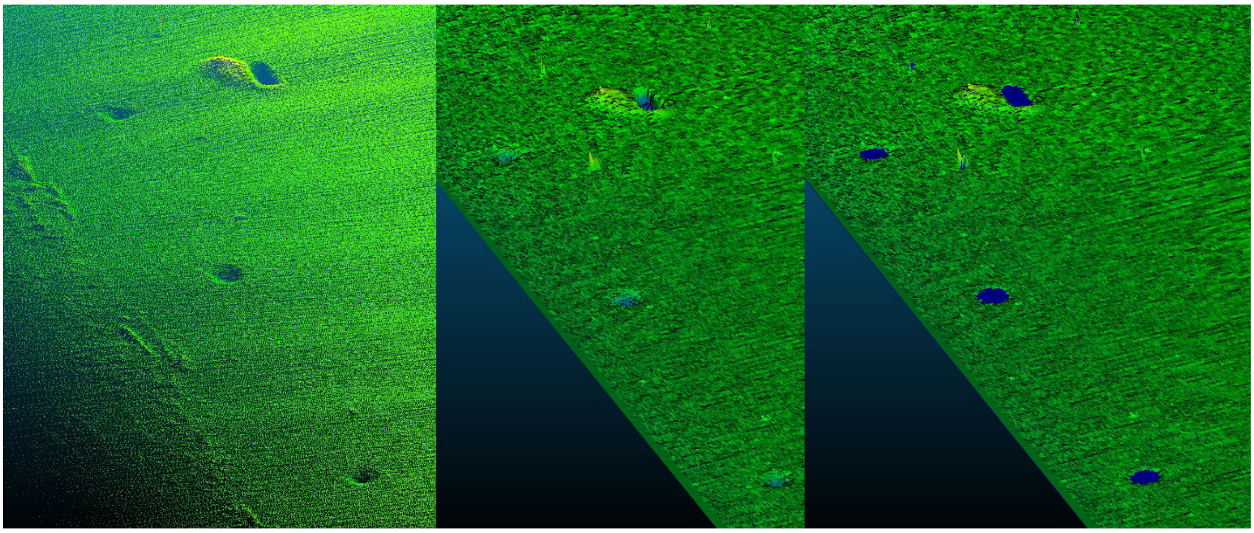


Figure 5: ALADIN software graphic user interface.

Damage detection begins by searching a user-chosen directory for LAS or LAZ point cloud files. As these files can be quite large (100s to 1000s of megabytes), the software examines the file for a period of time until it has been completely written by the originating software (LASONLINE). At this point, the 3D range data within the LAS/LAZ file is gathered into system memory and the process of damage detection begins. First, points are clipped from the input data so that only the region of interest remains (runways, taxiways, etc.). Next, the remaining points are down-sampled to a ground sample distance of 3 centimeters (cm). This value is variable and can be changed by the user; however, it is defaulted to 3 cm. Following this, the process of determining the minimum detection depth begins. For this, the input range data is removed of its global linear trend and laid flat on the x-axis. A number of processing steps take place at this point, chief among them is the measurement of the global length-width ratio and median z-differential. These values feed an ERDC-developed linear correlation that determines the minimum detection depth available for the input data. This value, in general, is smaller for more precise sensors and larger for less precise ones. For the purposes of the following step, the remaining point cloud is converted into a grid-averaged 3D mesh. The DFA algorithm is executed on the remaining points and reported depressions are segmented based on minimum Euclidean distance (defaulted to 1 meter). In order to better illustrate how this algorithm works, see the before and after meshes in Figure 6.



a) point cloud **b) mesh only** **c) depression-filled mesh**

Figure 6: Result of ERDC depression filling algorithm on input LiDAR point cloud at 30m altitude.

For a more accurate measure of depth, points from the original set of input 3D range data are sampled wherever there is a detected damage cluster. Finally, depth and width for all depressions are measured. These measurements serve to classify each cluster of points as one of four options: crater, spall, camouflet, and outlier. Resulting damage classified as a crater, spall, or camouflet are then transferred to both the remote ground station and saved on the local file system.

The user can adjust the depth and width tolerances of each damage type for classification in the software based on user requirements (Figure 7). The software then displays the position and classification of the damage on screen for each LAS file processed while simultaneously passing this data to the ground station for overlay in the Air Force's Geo Expeditionary Planning Tool (GeoExPT), and add-on to the AutoCAD software platform.

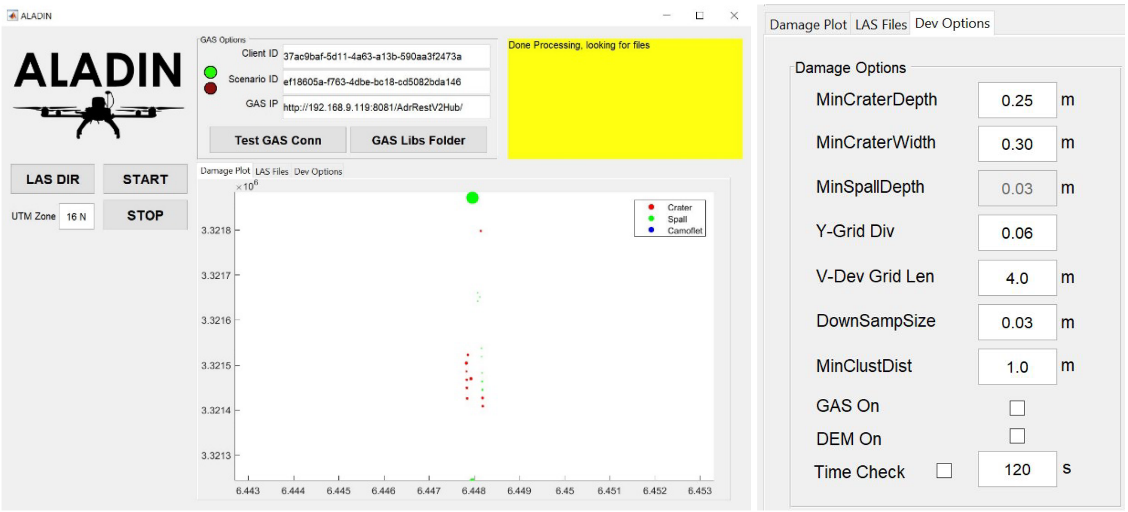


Figure 7: Processed LAS file in ALADIN with detected damage output along with parameter screen.

The ALADIN software optionally produces a digital elevation model (DEM) of the LAS file to send to GeoExPT as a visual overlay (Figure 8). The DEM is color coded based on height and therefore can provide a rapid visualization tool to the airmen to discern the location of distresses based on color changes over a small area. The DEM coupled with the GeoExPT markers for various damage classifications is displayed in real time during the LiDAR collection mission (Figure 9).

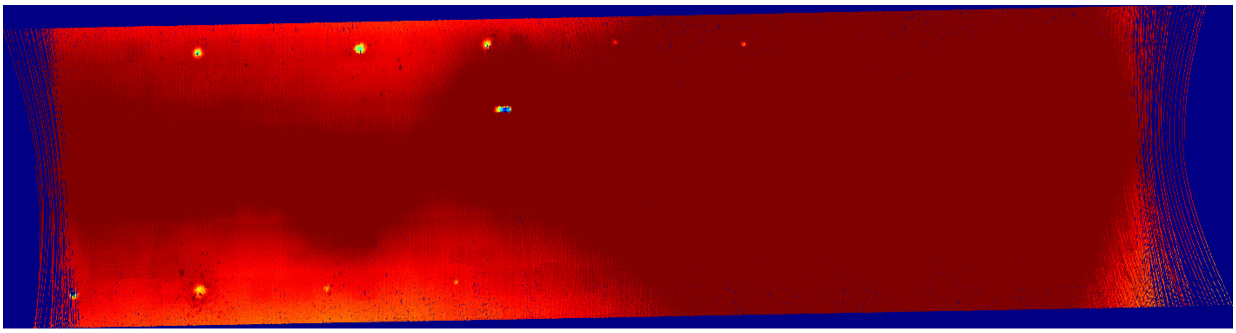


Figure 8: DEM of damaged runway (note color contour at position of craters and camouflets).

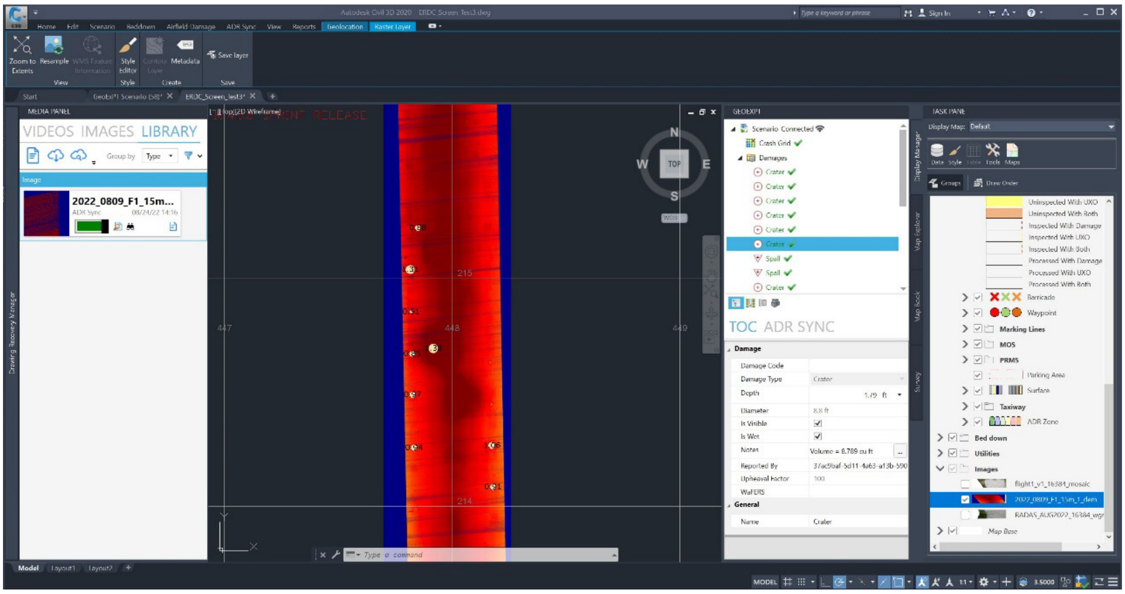


Figure 9: ALADIN output displayed in GeoExPT, crater locations on top of DEM.

5.0 SYSTEM PERFORMANCE

At the Silver Flag Assault Landing Zone (ALZ) at Tyndall Air Force Base, Florida, a section of runway surface was damaged through the explosive creation of a series of 9 craters and 6 camouflets. The performance of the Yellowscan LiDAR sensor mounted to the SkyRaider was compared to that of a Riegl miniVUX2 LiDAR mounted to a Harris Aerial Carrier HX8 sUAS to understand the importance of vertical accuracy on the detection accuracy of the ALADIN system (Figure 10). Both LiDAR systems were flown over the damaged runway section at altitudes of 15m and 30m to assess the detection accuracy of the two systems. The Riegl system was not automated like the Yellowscan system, requiring LiDAR data obtained on the miniVUX2 to be manually downloaded and post-processed using Riegl software products loaded on a ground based computer to generate the necessary LAS files that could then be analyzed by the ALADIN software.

Figure 10: Harris H8X UAS with miniVUX2 LiDAR (left), SkyRaider UAS with Surveyor Ultra (right).

Figure 11 provides a visual guide to the operation of the ERDC semi-automated data collection and analysis process deployed at Silver Flag. In stepwise progression, the operator manually powers on the sUAS, the NUC computer, and the LiDAR sensor. Once powered, the system is controlled remotely via a ground station computer and the command and control platform of the sUAS. The LASONLINE program is launched first to detect the presence of the LiDAR scanner and the ALADIN program is launched awaiting LAS point cloud data. This signals an all system go point at which the sUAS is launched on a pre-planned flight path. A simple in-air movement pattern calibrates the onboard IMU and once over the damaged pavement, the operator sends a start command to the LiDAR sensor to begin collecting data. From this point forward the LASONLINE and ALADIN programs work simultaneously to collect, process, and analyze point cloud data until the operator sends a command to stop data collection at the end of the damaged pavement segment. Depending on the number of LAS files generated and the speed of processing, LASONLINE and ALADIN may continue to work on data analysis during the return flight of the sensor and continue once landed.

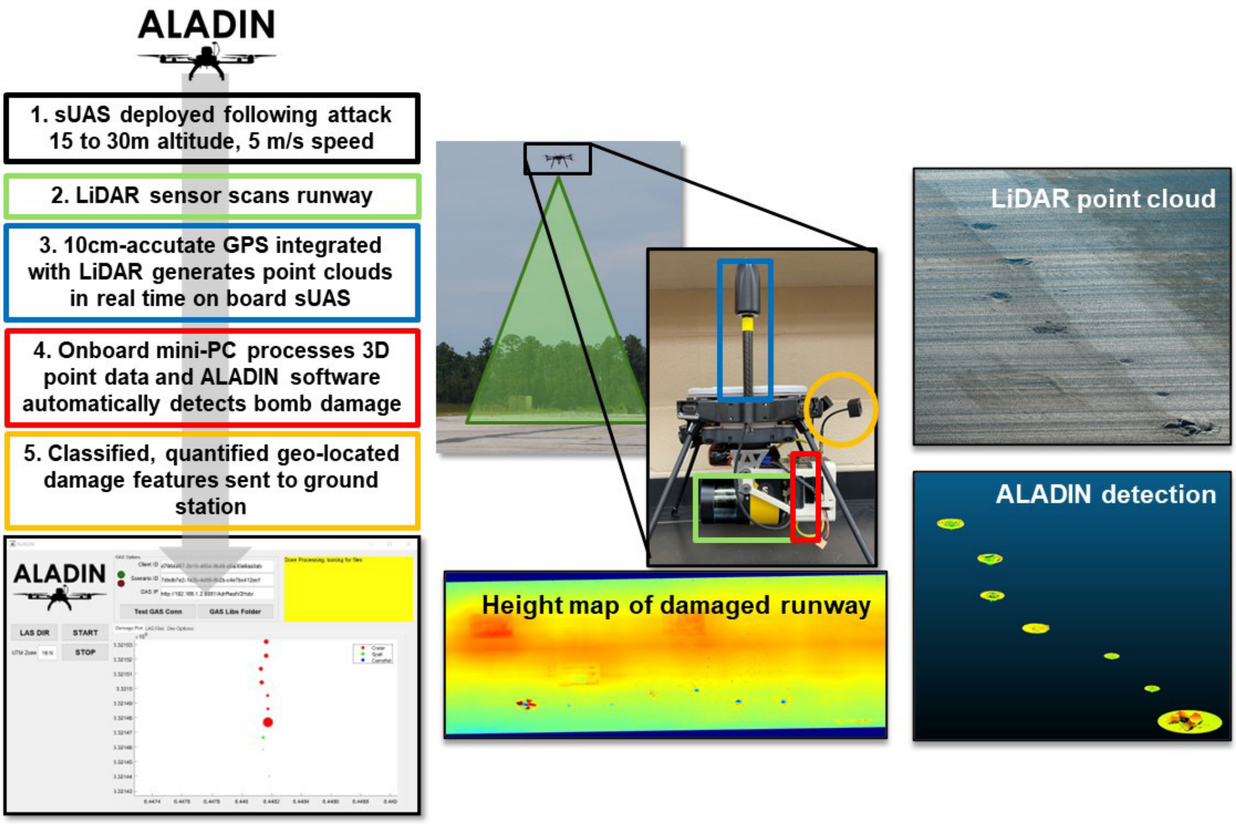


Figure 11: Schematic of automated LiDAR detection system.

An example of damage output from this algorithm during the Silver Flag exercise for both LiDAR systems can be seen in Figure 12. The center position of each damage type is noted in pink with a text label indicating whether it is a crater or camouflet. The detected items are shown as white circles. If a damage position does not have a white circle near the pink center point, then the detection was missed. It should be noted from the output that data collected by the Surveyor Ultra does not allow for ALADIN to detect all of the damage where the miniVUX2 allows ALADIN to detect all damage features, including the small camouflets. Further, the lip-to-lip diameter for each crater detection was calculated from the original 3D range data and included in both the classification and GPS position of each damage feature as was shown in Figure 7.

Figure 12: Damage point output from ALADIN for the Surveyor (left), miniVUX2 (right) at 30m altitude.

The rationale for the improved performance of the miniVUX2 system is due to an increase in the sensor's vertical accuracy versus that of the Surveyor system. The ability of a LiDAR sensor to detect flat surfaces with a tight vertical resolution reduces the surface noise resulting in higher fidelity detections. To emphasize the difference in vertical accuracy across the two platforms, sample data from a 30-m altitude and 5 m/s speed were collected using both systems. In this test, the Surveyor had a vertical error of approximately 12-cm versus the miniVUX2 which had a vertical error of 7-cm. In other words, the flat surface of the airfield pavement appears 12-cm thick to the Surveyor sensor. The ALADIN software ignores any data within the minimum noise thickness (12-cm in the case of the Surveyor) which limits its ability to detect camouflet holes or spalls that may lie within this error. The miniVUX2 system, with a narrower surface thickness retains a greater number of LiDAR points near the true surface enabling ALADIN to capture and classify damage more accurately. The importance of vertical accuracy cannot be overstated as this is a significant factor in choosing the type of sensor to deploy and the range of objects one can reasonably expect to capture. Sensors with a poor vertical accuracy will miss more subtle surface distresses and likely all UXO.

6.0 SUMMARY

To meet the rapid operational need of the U.S. Air Force to survey and recover bomb-damaged airfields within a very limited time frame, ERDC has successfully developed a semi-automated sUAS-portable capability using LiDAR sensors with onboard data analysis using the ALADIN and LASONLINE software packages. During the course of the research, two different LiDAR sensors were studied each with varying degrees of vertical accuracy: a Yellowscan Surveyor Ultra and a Riegl miniVUX2. LAS point cloud data with the Surveyor Ultra were generated automatically onboard the sUAS using the Yellowscan platform's LASONLINE software system. Riegl data, at present, required post processing until such time as a LASONLINE system is developed for this manufacturer. The LAS files were then fed to the ALADIN software which automatically processed LAS files on board the sUAS via an Intel NUC computer detecting airfield damage and transmitting location, type and size of the damage to a ground station. Vertical accuracy of the LiDAR data influenced the accuracy of the damage detection. ALADIN detected all airfield damage with no false positives using the higher accuracy miniVUX2 LiDAR whereas not all damage was detected and some false positives resulted using the Surveyor Ultra sensor. The entire data collection operation was controlled wirelessly via a ground based laptop running TeamViewer to control the NUC's desktop allowing the airmen to activate the Surveyor Ultra LiDAR, LASONLINE and ALADIN systems requiring only a physical turning on off the drone, sensor, and NUC computer prior to sUAS launch. The LiDAR-software solution provided is agnostic to the sUAS platform and can be mounted on any sUAS platform. The ability to process LiDAR sensor data in real time during flight onboard an sUAS and further, process this data while in flight is unprecedented and is a large step forward in the military's effort to enable rapid remote damage assessment.

7.0 REFERENCES

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