The Measurement and Modeling of a World War I Mark IV Tank Using CLR and CCD Camera/Line Scanning Systems in an Outside Environment

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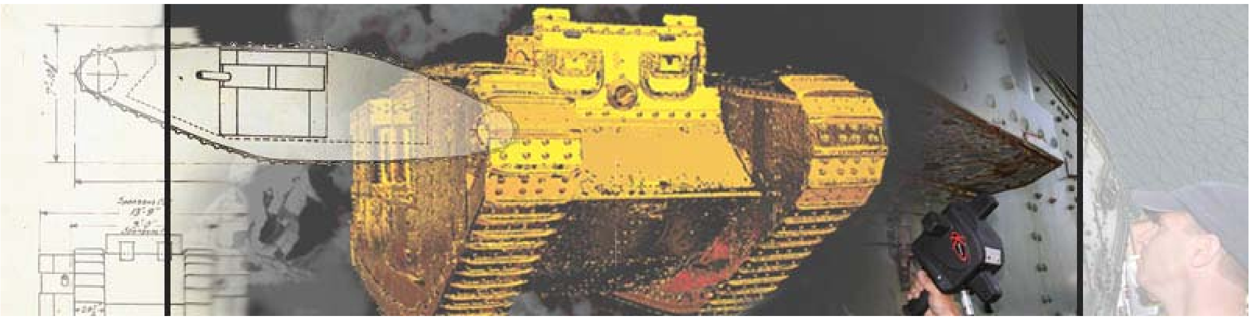

ABSTRACT

The process of measuring, documenting, and reproducing the dimensional aspects of antiquities in an outside environment requires an intricate set of protocols. This paper details some of those protocols as demonstrated in the recent scanning of a historic British Mark IV World War I tank using state-of-the-art metrology systems, including coherent laser radar (CLR) and charge-coupled device (CCD) camera/line scanner technologies. The effort was part of project to help document, preserve, and restore the weather-damaged vehicle. Originally named "Britannia," the Mark IV saw heavy combat (and success) in the Battle of Arras, France, on the Western Front. The tank and its crew were then sent to the United States to support war bond rallies (where it was renamed "Liberty" in appreciation of American participation). Finally, in 1919, the tank became a cornerstone attraction at the Army's newly established U.S. Army Ordnance Museum at Aberdeen Proving Ground, MD, where is has been on outdoor display for nearly 90 years. Today, the vehicle is scheduled to be moved from its location to a nearby refurbishment facility. However, issues regarding the tank's structural condition and its ability to withstand the move are of great concern to museum officials and other military historians. Thus, it was critical that the vehicle's dimensional attributes be fully documented to assess its level of deterioration, to mitigate further damage during the planned move, and to provide an accurate dimensional record during restoration. This writing details the planning, preparation, scanning, and data processing of the images for this national treasure.

Introduction

The U.S. Army Ordnance Museum at Aberdeen Proving Ground, MD, has been in the process of preserving and restoring its extensive collection of armored vehicles. Most of these vehicles have been on outdoor display and have suffered many years of weathering and other environmental effects. One of the most historic—and unfortunately most deteriorated—vehicles in the collection is the British Mark IV World War I (WWI) tank, named "Liberty." Museum officials and other military historians want to move Liberty to a nearby restoration facility, but they are concerned about the vehicle's structural condition and ability to withstand the move.

To help address these concerns, coherent laser radar (CLR) and charge-coupled device (CCD) camera/line scanner technologies were brought in to scan and document the vehicle's dimensions. The ultimate goal of the effort (which is still ongoing) is to assess Liberty's level of deterioration, mitigate damage during the planned move, and provide an accurate dimensional record for restoration of this national treasure.

Liberty's Major Features and History

Liberty is a highly significant and rare piece of military history. Originally named "Britannia," the vehicle is 1 of 609 produced during WWI and 1 of only 2 examples on public exhibit in the world. Of all the models of heavy tanks, the Mark IV was produced in the greatest numbers during the war. It was the workhorse of the British tank corps, comprising 60% of the roughly 1,000 heavy tanks England produced. The "male" Mark IV's were armed with two 6-pounder guns and four Lewis machine guns. The "female" Mark IV's (of which Liberty is one) had six Lewis or Hotchkiss machine guns only. A few "hermaphrodite" tanks, which had one 6-pounder and five Lewis or Hotchkiss machine guns, were also produced, but they were never considered a success.

As shown in Figure 1, Liberty has a distinctive parallelogram-type shape. It measures approximately 26.4 ft long, 10.5 ft wide, and 8.2 ft high and has a 16.5-in ground clearance. When fully combat loaded (including four crew and 13,000 rounds of ammunition), it weighed over 30 tons and exerted a ground pressure of 12.8 lbs/in^2. It had a radius of action of 15 miles and was capable of crossing a 10-ft-wide trench, scaling a 54-in obstacle, and climbing a 22° (40%) slope.

On a good day, if everything worked right, Liberty could reach a top speed of 4 mph. It was powered by a Daimler 6-cylinder, 125-HP engine with "forced water cooling." But there was really nothing cool about it. The engine sat amidships and was not separated from the crew in any way. Thus, the interior of the vehicle became extremely hot, a condition exacerbated by the crew's need to wear full leather gear (boots, trousers, jackets, and gauntlets) and steel helmets to protect it from "spalling."[i]

Figure 1. Mark IV Testing at Bovington, England

Liberty's combat experience was both historic and brief. The tank took part in the Battle of Arras, France, in 1917. In 5 hours, it raided German trenches, captured 395 prisoners, crushed 4 machine gun emplacements, and repulsed 2 German counterattacks. One particularly notable engagement during the battle occurred on Vimy Ridge (see Figure 2). In previous attacks, both the British and French had lost thousands of troops. But the job of taking Vimy Ridge was given to the Canadian Corps, which combined tanks and a creeping barrage (a continuous line of shelling moving just ahead of the troops) to win the battle. When the French heard that Vimy Ridge had been taken, one general reportedly exclaimed, *"C'est impossible!"* However, hearing that it was the Canadians that took it, he said, *"Ah! Les Canadiens! C'est possible."*

Figure 2. Battle of Vimy Ridge

Although the gains made during the Battle of Arras cost many casualties and had little effect on the overall strategic or tactical situation on the Western Front, they were spectacular by WWI standards. In addition, the battle produced numerous lessons about the relationship between tanks, artillery, and infantry—lessons that the British would be able to put into practice in 1918.

After the Battle of Arras, Liberty and its crew were sent to America for exhibition and to help sell war bonds. During a 2-hr event in Syracuse, NY, the tank raised $868.45 (the equivalent of $13,221.12 today). The purchase of a war thrift stamp allowed one to view the tank up close. For the larger purchase of a war stamp for $4.15 ($63.12 today), one was allowed into the vehicle's interior, presumably with a guided tour from the crew. It was sometime during this American tour that the crew changed the tank's name from "Britannia" to "Liberty." Appropriately, the tank and its crew were also the main attraction in the Liberty Day Parade in New York City (see Figure 3.)

Figure 3. Liberty in a Times Square 1917 Parade

Liberty found its final home in 1919 when it was taken to northeastern Maryland and added to the collection of the newly established Ordnance Museum at Aberdeen Proving Ground, MD (see Figure 4). Since that time, it has remained one of the museum's cornerstone attractions and has stood as a reminder of the significant advancements that have been made in armored warfare over the past century.

Figure 4. Liberty on Display at the Ordnance Museum

Liberty's Battle Against the Elements

Bullets have not been the only threat Liberty has had to battle in its lifetime. The metrology team's initial examination of the vehicle confirmed that many years of outside exposure have taken their toll. The armor plate is in poor condition, and the interior portions are flaking off. This indicates that while the exterior armor may retain some strength, the interior of the face-hardened steel is significantly deteriorated. There are also large cracks in the armor that generally follow the lines of rivets. In addition, water has gotten behind the rivets, and repeated freeze-thaw cycles have weakened them. Thus, a full assessment of the tank's structural integrity is needed before any attempt is made to move it.

Method of Measurement

Liberty is a large, intricate machine. To meet the requirements of documenting the mechanical details of such a machine, accuracy was considered the most important aspect in the measurement process. In conjunction with documenting the tank's dimensions, it was critical to provide extremely accurate data for analyzing the tank's structural condition. With large surface areas and detailed fabrication features (see Figure 5), issues such as point cloud densities, data processing limitations, and file sizes also had to be considered when choosing scanning technologies. Although these considerations limited the technologies available to achieve the goals of this project, two scanning systems were identified as being capable of producing acceptable results.

Figure 5. Tank Surfaces and Details

The first system was the CLR,[ii] shown in Figure 6. This system provided the accuracy and needed point density selection capabilities. In addition, its higher-frequency infrared laser was not affected by the strong sunlight conditions confronted during the scanning activities. The CLR system was also easily transportable around the vehicle, and with its ability to measure discrete tooling balls, a control network could be used to provide coordinate transformation uncertainties via the Spatial Analyzer Unified Spatial Metrology Network (USMN).[iii] Finally, the CLR's focused beam allowed for a reflective mirror to be used for exterior and interior scanning tasks.

Figure 6. The CLR System

The second scanning technology used was a CCD camera/line scanning system,[iv] shown in Figure 7. This smaller, more maneuverable system, referred to as the K-Scan, gave the metrology team referenced access into the tank's interior, including the engine compartment/crew area.[v] It also allowed the team to collect data relatively fast, thereby reducing the amount of time spent maneuvering around the sharp edges and rusty surfaces of the interior compartment.

Figure 7. The K-Scan System

Measurement Conditions

Liberty was scanned in its existing display location in the Ordnance Museum's field of armor. As shown in Figure 8, the tank rests on two concrete foundation strips, with the surrounding area consisting of grass-covered, compacted soil. During scanning, both the tank and scanning equipment were exposed to direct sunlight and ambient weather conditions. Environmental conditions and the tank's surface measurements were monitored throughout the process. These measurements were used in post-processing for scaling point cloud and surface data for material expansion compensation.

Figure 8. Field Conditions Typical During Scanning

Most of Liberty's external tank surfaces are in various stages of deterioration due to corrosion or are covered with peeling paint. The scanned point cloud data collected include these surface anomalies, which can be used in follow-on inspection and documentation efforts for further structural analysis. However, these anomalies were mitigated during the post-processing of data for reverse engineering tasks.

As noted, the tank's internals also consist of rusted and deteriorated surfaces. Most are covered in layers of iron oxide and debris from years of outside storage. In order to remove the debris and allow accurate measurements, the internals were vacuumed and preserved in accordance with typical museum conservation procedures. These procedures include collecting all residuals in plastic bags and cataloging the locations from which the materials were removed. In addition, for areas where stress corrosion has occurred, detailed measurements were taken to document the current dimensional conditions. The tank's armor plating shows many areas of classic stress corrosion, where the steel plate has pulled away from the fasteners in the direction of the hardened exterior surface. The thickness of most plates ranges from 1/4 in to 3/8 in (6 to 10 mm), and the plates show signs of buckling in high load areas. These too were measured in detail to determine potential specialized needs during restoration.

Measurement Plan

Considering all the unique conditions encountered during this project, perhaps the most important aspect of planning the task involved exposing the half-million-dollar equipment to Maryland's springtime weather. Thus, a critical element of the project's measurement plan was to continuously monitor weather conditions and be ready to quickly relocate the equipment to shelter in the metrology van or nearby museum building (where the equipment was stored overnight). As it turned out, the metrology team encountered no rain during the scanning process, but threatening clouds on the last day were cause for considerable concern (see Figure 9).

Figure 9. Threatening Weather

Another part of the project that had to be addressed before actual data collection could begin was the establishment of a control network for the previously mentioned scan technologies to share. The CLR chosen for this work performs best using 1/2-in-diameter (12.7 mm) tooling balls, noted as control network monuments (CNM). Thus, an arrangement of CNMs was placed on the tank such that each instrument location was assured of "seeing" a minimum of six CNMs when transforming into the coordinate frame (see Figure 10). For the tank's interior (which was not completely measured due to time and resource limitations), the scanners measured through the open doors below the sponsons (side turret assemblies) to value CNMs and took numerous surface scans for reference.

As noted, the accuracy/strength of the control network was analyzed using the Spatial Analyzer USMN. All point clouds were adjusted based on this analysis, with scaling factors applied for temperature compensations for each point cloud as needed.

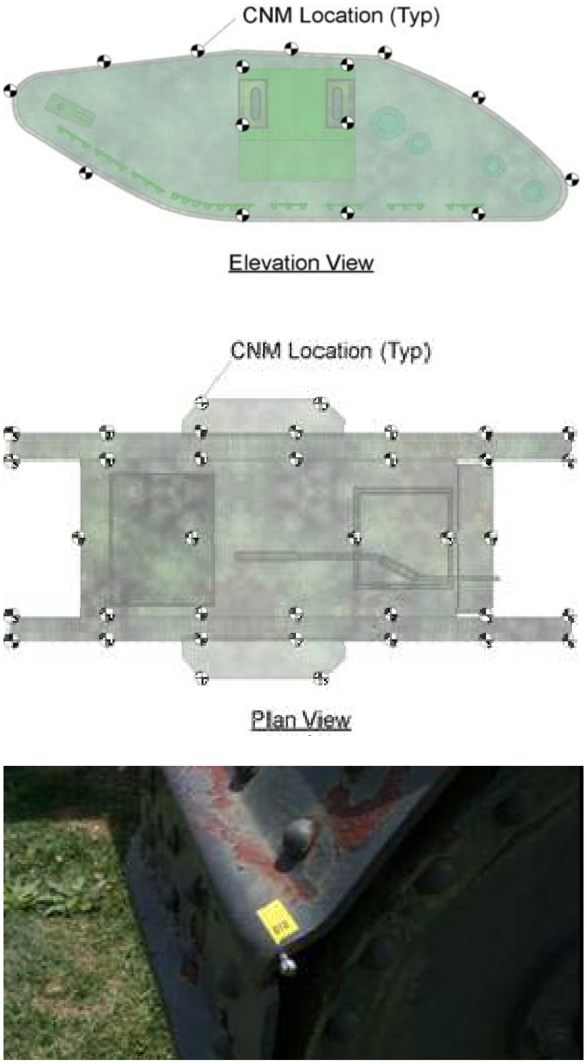

Figure 10. CNM (Tooling Ball) Locations

In addition, as illustrated in Figures 11 and 12, reflective measurement procedures were employed by using a large, optically flat mirror. This application resides within the laser radar operating modes and was critical to the measurement of the bottom surfaces of the tank, where direct measurement was not possible.

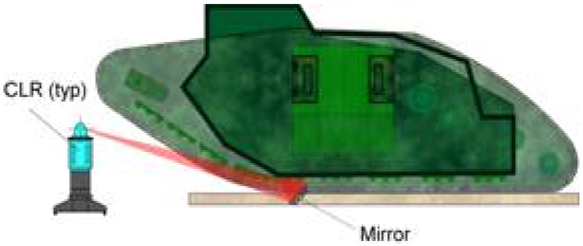

Figure 11. Reflective Mirror Measurements

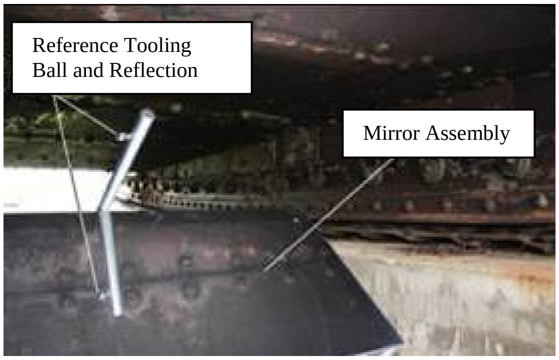

Figure 12. CNM Locations

Based on the accuracy/strength of the control network, the reflective measurements between the upper surfaces of the tank's bottom plate and the under surface of the same plate were able to yield the thickness dimensions, which can later be used for determining structural integrity of the Liberty's track assembly to its center frame and engine assembly. The scan data were also verified by spot-measuring areas with a micrometer around missing rivet holes.

In addition, line scanning was used to detail exterior features and provide supplemental data in areas where the CLR could not access low surfaces. These exterior scanning activities, using the K-Scan system, were accomplished by locating the CCD camera bar along the longitudinal axis of the tank near the front. In this position, the line scanner was used to measure the areas under the gun sponson (Figure 13).

Figure 13. K-Scan Measurement of Sponson Bottom

Finally, all data were saved in both ASCII point cloud and *.stl formats for post-processing and modeling.

Measurement Execution

To scan and accumulate adequate data to define the Mark IV tank took a total of 4 days. As is typical with most scanning projects, 80% of the data was collected during the first 20% of the project. Overall project scan information for the CLR and K-Scan systems is given in Table 1.

Table 1. Overall Scan Information

Scan Information	CLR System	K-Scan System
No. of Instrument Locations	10	3
No. of Point Clouds	73	15
Total Scan Time (hours)	50	6
Total No. of Scan Points	3,374,000	4,990,000

The bright sunlight experienced during scanning activities had no effect on the CLR; however, as anticipated, it did present some difficulty for the K-Scan CCD camera range. This difficulty required the scanning team to extend their activities in close quarters with the CLR using reflective mirror scan techniques on the bottom surfaces of the tank.

A number of surfaces were also difficult to scan because of their configuration, both mechanical and corrosion-related. But through the use of incident angles and virtually unlimited instrument location possibilities, most accessibility issues were overcome. It was also advantageous that all surfaces were non-reflective and "laser cooperative."

Environmental conditions for the 4 days of scanning are shown in Figure 14. Extremes in temperature and humidity, as well as comments regarding dew, ground conditions, and cloud cover, were also recorded. As shown in Figure 15, the tank's surface temperatures were continuously monitored to determine the variation during scanning activities and the difference between direct sunlight and shaded surfaces (which, during mid-day activities, was between 15° and 20° C (27° and 45° F). All temperature-related observations were time-stamped for reference in generating temperature compensation during the post-processing activities.

Structural details were also inspected to determine the tank's conditions in connection areas exposed during the scanning activities (see Figure 16). This supplements the structural analysis of the steel members and armor plate. Ultimately, the findings are dependent on the final processed data and will be supporting conclusions needed by the museum for the tank's movement and restoration..

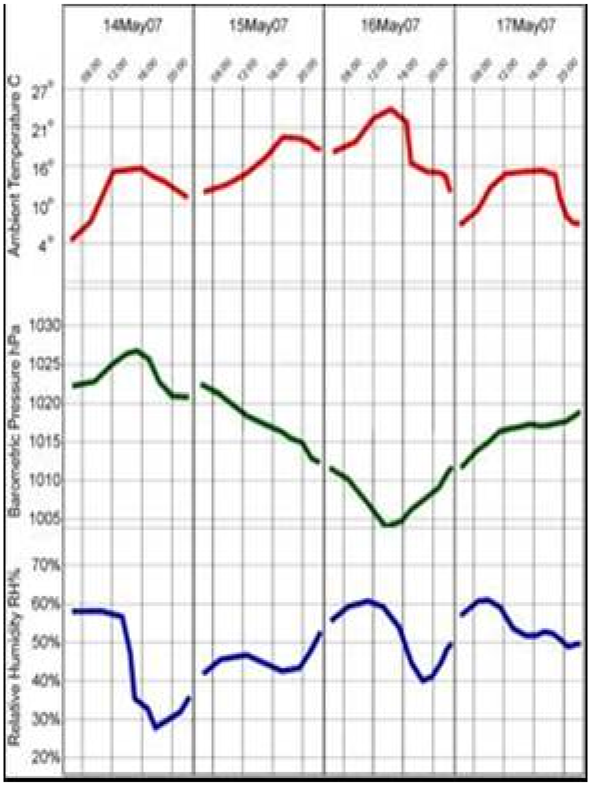

Figure 14. Environmental Conditions

Figure 15. Surface Temperature Monitoring

Figure 16. Corrosion and Flaking on Bottom Plates

Data Processing

Post-processing of point clouds was performed by meshing and aligning the measurements to produce a polygonal surface. This surface can be used for inspection and comparison. In the data assembled from the tank scans, the prime objective was to generate an accurate 3D model that specifically includes high-accuracy plate thickness measurements for structural analysis. The technique for assembling such high-accuracy data was a combination of maintaining a tight control network and assembling point clouds to that controlled network.

After scanning was complete, a final measurement of the control network was performed. The data were processed using the USMN procedures discussed previously, with the overall uncertainties as follows:

Vendor Specification	100 µm
USMN Instrument Uncertainty	15 µm
USMN Network Uncertainty	446 µm.

The uncertainties were calculated at 2 sigma and were not corrected for temperature differences. Final uncertainties were combined with best-fit convergence data from final model alignment for a comparison of control network to best-fit algorithms. This type of comparison is not mandatory, but it is a good “reality check” when processing large point clouds from different technologies.

As of this writing, some post-processing of data (as well as follow-up scans of missing surface data) still need to be completed. When finished, the final model will be assembled in sections in order to maintain file sizes suitable for most typical 2-GB (SRAM) Windows PCs. In addition, reverse-engineered models generated for 3D rapid prototyping and printing will be decimated to allow the entire tank to be assembled as a “watertight” 3D model (see Figures 16 and 17).[vi]

Additional processing on the polygonal tank model will provide dimensional documentation for future use by the Ordnance Museum and other historical organizations. For example, research work in line with generating 3D CAD and/or parasolid models from original drawings would allow the comparison of the measured model for aspects of geometric dimensioning and tolerancing (GD&T) with dimensional tolerances and manufacturing capabilities in the early 1900s.

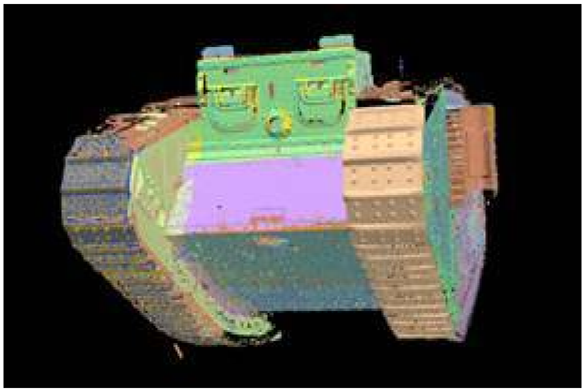

Figure 16. In-Process Model of the Liberty Tank

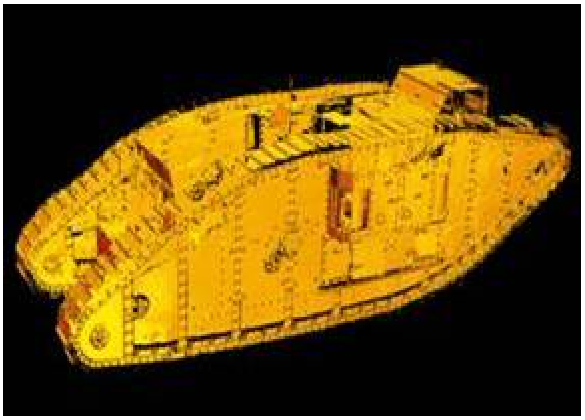

Figure 17. Meshed 3D Model of the Liberty Tank

Note that the generation of the watertight model took extra steps due to the inaccessibility of certain surfaces. For instance, the modeling of tank tread on the bottom of the vehicle required the generation of a track/rivet surface, then fitting it to the bottom side of the track. This work carried to other surfaces on the top and particularly rear details. Figure 18 highlights locations on Liberty where scan data are missing (and where follow-up scans are needed).

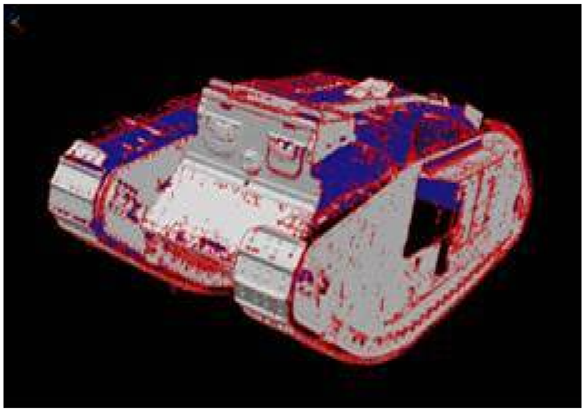

Figure 18. Locations of Missing Surface Data (in Red)

Lessons Learned

No significant deviations from the measurement plan were made for this scanning task. However, as is the case with every project, there were numerous lessons learned during the measurement and modeling of the Liberty Mark IV tank. The following list contains some of the more pertinent observations regarding task setup and data processing.

- Significant time is lost in transferring large point clouds from the CLR operating software.
- Significant loss of range in the K-Scan limits its use during times of direct sunlight.
- Adequate support for the CLR foot screws is needed in areas of grass or vegetation.
- Scanning of rough or paint flaked surfaces required additional instrument locations, mirror shots and redundant scans.

Figure 19. Battling Lawnmowers

More generally, it should be noted that when one stretches the limits of equipment and good sense, one tends to learn a great deal about both. In the case of the outdoor tank scan using indoor technology, there was a plan set in place for quick-moving thunderstorms, power outages, and periods of shutdown and equipment storage. But even the best plans cannot always anticipate a fast-attacking (and debris generating) formation of lawnmowers (see Figure 19). This event enforces the old adage that "a plan is useless; planning is critical."

Finally, when scanning in public areas, one needs to factor in time for the possible curiosity—and occasional intrusion—of the public. For instance, keeping a weary eye on a fugitive first-grader with an obvious flair for mischief is another of those line items often neglected from a measurement plan. And even the occasional question from an interested museum visitor can reduce one's planned efficiencies to critical path impossibilities.

Summary/Conclusion

Overall, the measurement and modeling of the Liberty Mark IV tank was successful with regard to the quality of the data collected and the associated transformations. Although there is still more to do, the results thus far will be beneficial in supporting the structural analysis, relocation, and ultimate preservation of the vehicle. In short, Liberty is worth saving. It is a rare and historically significant combat veteran, and it is important that we do all we can to ensure that future generations will be able to look on this vehicle and wonder what kind of person could get into something this primitive and go to war.

Nomenclature

The following is a listing of the most common abbreviations and acronyms used in this writing.

- **Accuracy** – In general, the term has been misused to the point that the word is diluted. Specifically, this writing uses the word to mean the uncertainty of any measurement technology.
- **CAD –** Computer-Aided Design.
- **CCD** – Charged-Coupled Device a silicone chip used as a light sensitive cell to replace film style cameras.
- **CLR –** Coherent Laser Radar
- **CNM** – Control Network Monument
- **GD&T** – Geometric Dimensioning and Tolerancing, referenced as the ASME 14.5M –00 Standard.
- **Line Scanner –** A profile measuring device using a laser line and offset receiver to detect surface profiles.
- **Parasolid Model –** A 3D CAD model using NURB points that develop position and curvature.
- **Point Cloud** – A group of points contained in a single file with a standard or proprietary format.
- **Tooling Ball** – Grade 25 steel ball used for reference measurements.
- **Uncertainty** – The statistical development of multiple measurements stated as standard deviation (1 sigma), 2 or 3 sigma depending on project requirements.

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End Notes

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[i] Spalling is the result of a high-velocity impact, wherein pieces of the back of the impacted armor flake off and fly around a vehicle's interior, creating a potentially lethal condition for the crew.

[ii] The CLR is produced by Metris USA and marketed as the MV-224, with the last two numbers designating the CLR's range.

[iii] [iii] Spatial Analyzer and USMN are products of New River Kinematics in Williamsburg, VA.

[iv] The CCD camera/line scanner used for this work was Metris' Krypton system, which is marketed as the K-600.

[v] As mentioned previously, the engine in the Mark IV is in the center of the tank, and the crew was positioned around it. The commander and driver were located in front of it, and the gunners were positioned intolerably close to its sides.

[vi] Data processing performed using Polyworks® by InnovMetric and Focus RE by Metris USA.

1917 U.S. Army Recruiting Poster