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DIGITAL IMAGE CORRELATION FOR OFF-ROAD MOBILITY

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ABSTRACT

Digital Image Correlation (DIC) technology developed for off-road vehicle dynamics at the University of Pretoria, South Africa, was recently assessed for all-season and all-terrain viability through a Foreign Technology Assessment Support (FTAS) program at the US Army Engineer Research and Development Center-Cold Regions Research and Engineering Laboratory (ERDC-CRREL) in Hanover, New Hampshire (NH). Advancements in camera technology have brought on the proliferation of inexpensive, high resolution and high frame-rate cameras. At the same time the increase in computational power of computers has allowed algorithms to determine the depth of a scene and enable the near real-time tracking of features on an image. These advancements have enabled the application of DIC to measure surface and velocity profiles as well as deformation from a reference state (for terrain or for tires). In large off-road vehicle dynamics DIC can be used to improve maneuverability of vehicles by monitoring the road or terrain surface before and after the tire passes. From these measurements the initial road roughness and the deformation of the terrain can be determined to provide an indication of the terrain trafficability. DIC can also be used to determine the motion of the vehicle or tire, which can aid in vehicle safety systems via slip angle and traction performance.

This paper details the application of DIC on a military vehicle to measure terrain deformation and vehicle motion on varied terrain with the final aim of providing additional information to the driver or vehicle control system for performance optimization; and ultimately for providing feedback on mobility or terrain information for situational awareness at the driver or theater level. The technology was tested and validated using the CRREL Instrumented Vehicle (CIV) and two military vehicles; an unarmored High Mobility Multipurpose Wheeled Vehicle (HMMWV) (M1097) and a 20-ton Heavy Expanded Mobility Tactical Truck (HEMTT). Testing with the HEMTT on snow, ice, water, asphalt, concrete and vegetated ground will be shown to illustrate use of the technology on large military vehicles on a variety or surfaces.

INTRODUCTION

The Foreign Technology Assessment Support (FTAS) Program is funded by the US Department of Defense, Assistant Secretary of the Army (Acquisition, Logistics and Technology) to perform technology assessments, basic research studies, and test and evaluate efforts of unique foreign research and technology. The program aims to evaluate foreign technology of specific interest to the US Army and applicable to US soldiers as well as Research and Development (R&D). The FTAS Program funds science and research for preliminary assessment of technologies within TRL 1-6 for transition into laboratory research or other programs.

Digital Image Correlation (DIC) is an inexpensive method to gather information on vehicle mobility and terrain characteristics by using vehicles as mobile sensing systems. The University of Pretoria has developed image correlation technology for use in vehicle dynamics studies to measure terrain roughness, tire deformation, tire slip and slip angle and rutting. The usefulness of this technology was proven on dry and hard terrain conditions and documented by Botha and Els [1-4]. The potential of this technology for real-time application of vehicle and terrain information is quite powerful provided it works under a wide variety of terrain and environmental conditions, and thus the purpose of this FTAS project.

CRREL's mobility mission is to perform R&D related to vehicle operations in all-season and all-terrain conditions, with special emphasis on cold regions. The objective of this project is to test image correlation techniques developed at the University of Pretoria to assess those capabilities on a wide variety of terrain conditions including snow, ice and thawing soil (mud). In addition, CRREL holds well-known and validated vehicle instrumentation capabilities that were used to validate the image correlation results against existing instrumentation techniques for wheel longitudinal slip, slip angle and tire forces. Lastly, the feedback of real-time vehicle mobility measures could be used with vehicle control software for robotic systems [5, 6]; or within human-in-the-loop systems for vehicle control training [7-9]; or for assimilation of terrain data for geospatial analysis [10].

BACKGROUND AND CONTEXT

Even during war vehicle incidents cause significant harm. Soldiers are often placed in large, cumbersome and extremely heavy military vehicles in unfamiliar terrain. Driver assessment of terrain trafficability is difficult when terrain is unpredictable (e.g. soft off-road terrain such as sand, snow, mud) and mobility under off-road conditions changes rapidly with weather. While state-of-the-art measurement technology has been used to quantify off-road performance of passenger vehicles [11, 12] vehicle measurement and control technology designed for the commercial sector is not always applicable or affordable for large, off-road military vehicles.

Key to the mobility and safety of wheeled off-road vehicles is the understanding, measurement and modeling of the vehicle dynamics and tire-terrain interaction on the one hand and driver judgment and capabilities to control the vehicle safely on the other. The Vehicle Dynamics Group (VDG) at the University of Pretoria has explored the possibilities to measure vehicle-terrain related parameters using images captured with digital cameras and employing DIC techniques. This technology serves to improve the understanding and performance of new vehicle technologies, especially with respect to large, heavy military vehicles; and advance technology beneficial to soldiers operating in adverse conditions.

Mobility over unchartered terrain is of extreme importance to move soldiers and equipment during any mission. Drivers of military vehicles often have low visibility and little information about the actual terrain features in front of the vehicles tires. VDG has successfully demonstrated the use of DIC techniques for measuring rough terrain profiles [1]; tire deflection of the contact patch of the inside of the tire [13, 14]; tire slip angle on rough terrain [2]; longitudinal slip, vehicle speed and wheel speed [3, 15]. These techniques should be equally applicable to all-season, deformable, off-road terrain.

Using these techniques, each vehicle can become a sensor that collects terrain data for trafficability, sinkage, lateral and longitudinal forces and roughness. This information can be used not only for compiling databases and terrain maps for future use, but also for driver information and assist systems and ultimately to fully autonomous systems. Fast assessment of the data can provide inputs to vehicle control systems such as ABS brakes, stability control, controllable suspensions systems, and drivetrain control systems (e.g. gear selection and engine maps). The information could be displayed to the driver so that the driver can make more informed decisions on the best path and speed, as in Advanced Driver Assistance Systems (ADAS). Information on rut depth and slip can be distributed to multiple vehicles in a convoy to prepare them in advance for possible mobility challenges (by changing tire pressure, for example). Vehicle data could also be used for geospatially mapping terrain properties, and real-time updates of the terrain parameters from weather changes or other dynamic events. Apart from operational use, the techniques can be applied to research on tire design, vehicle mobility testing and modeling as well as tire testing and modeling.

With the proliferation of small, mobile, inexpensive cameras, the DIC techniques developed by VDG at the University of Pretoria can be implemented using largely commercial off-the-shelf (COTS) components combined with COTS and specialized software.

OBJECTIVES AND APPROACH

The objectives of this project included several major focuses:

1. To determine if the DIC technique as used for vehicle dynamics in South Africa could apply to deformable terrain and to a wide variety of other terrain such as snow, ice, water, frozen and thawing soil, and mud;
2. To evaluate the robustness of the technique in a variety of climates including exposure to moisture, freezing temperatures, and mud;
3. To determine if the technique could be applied to a variety of vehicles including large military vehicles and therefore fill a technology gap for inexpensive mobility measurement for large, off-road vehicles; and
4. Validate DIC against standard vehicle instrumentation and the wheel load cell calibration system.

The evaluation of the technique was performed on three vehicles: the Heavy Expanded Mobility Tactical Truck (HEMTT), an instrumented High Mobility Multi-purpose

Wheeled Vehicle (HMMWV), and the CRREL Instrumented Vehicle (CIV). These vehicles represent a range of interests in off-road and cross country vehicles ranging from 2.5 to 20 tons and from a 4x4 commercial vehicle to an 8x8 off-road military truck. The CIV and HMMWV were fully instrumented to measure the wheel forces and slip at each tire, tire angle at front wheels, true vehicle speed, vehicle accelerations and rates at or near the Center of Gravity, driver input for steering, brake and gas, and GPS tracking during the maneuvers [11, 16]. The HEMTT was not otherwise instrumented and provided a comparison for use on a large military vehicle where instrumentation costs, e.g. wheel force sensors, are generally prohibitive.

Although the full test program is described here, the results focus on the data collected using the HEMTT.

METHODOLOGY

Digital Image Correlation

The Digital Image Correlation (DIC) method is fully discussed in Botha, et al. ([1] and elsewhere) and thus described here only briefly. The DIC technique compares changes in images obtained from different viewpoints as in stereo vision [17], and changes in particle tracking between sequential images. Multiple DIC algorithms can be implemented in the same software, each measuring a different set of parameters obtained from the same set of images. The location of points, features, and regions can be tracked to obtain velocities [18], roughness, deformation and even strain. A calibrated stereo rig can be created using two cameras mounted such that they view the same scene from different viewpoints. The cameras are calibrated to align the images and remove lens distortion. A calibrated stereographic rig allows the points, features or regions to be described in 3D real world units relative to the camera (Figure 1). The method is similar to one method the human eye uses to determine depth [19]. This allows for the measurement of 3D terrain, as well as the position and velocity of multiple points to be tracked. From these tracking point data, vehicle performance parameters such as terrain roughness, rutting, slip and longitudinal slip angle can be determined [1-5]. The technique makes use of relatively inexpensive cameras and primarily COTS hardware and software.

Personnel and equipment from South Africa arrived on-site at CRREL in early February 2016 and assembly of camera equipment and mounting frames began. Once the equipment was assembled and working properly, it was tested and calibrated for obtaining images on snow. Because the technique is based on visually tracking particles, we expected that the visually homogenous signature of fresh snow and smooth ice would be problematic. Fortunately, this proved unwarranted and we observed no problems due to the visual characteristics of the snow or ice. The initial assessment of the system on snow is shown in Figure 2.

Once the initial construction and tuning for mixed terrain was completed, the stereographic rig was mounted to the CIV travelling over snow and other mixed terrain to evaluate the ability to measure the 3D profile of the snow as well as slip and slip angles with the vehicle in motion.

Vehicle Test Program

The tests took place at the US Army Engineer Research and Development Center-Cold Regions Research and Engineering Laboratory (ERDC-CRREL) in Hanover, New Hampshire (NH) during February and March of 2016. Vehicle testing consisted of several types of maneuvers to fully exercise the capabilities of the DIC technique and validate the results against measurement from existing vehicle instrumentation. After calibration of the cameras for each vehicle (to optimize field of view based on the distance to the terrain), initial vehicle testing consisted of straight-line acceleration and braking tests, then progressed to constant radius circle tests and surface transition tests. For the vehicles instrumented with wheel force transducers, the CIV and HMMWV, slalom tests and controlled lateral traction tests [20] were also performed to evaluate the ability to measure tire slip angle and infer lateral forces. The specific relationship between tire deformation and tire forces was further explored using the a Tire-Terrain Camera system (T2CAM) where cameras are mounted inside and external to the tire, described by Guthrie et al. [13, 14]. T2CAM measurements were validated by mounting the system on the CIV and comparing to the existing wheel force transducers and also to our vehicle load cell calibration system readout. The T2CAM was then exercised by driving over known geometrical shapes of a half round and trapezoidal bump, as well during as lateral traction testing [21].

Experiments were designed for three vehicles, each with a different contributions and challenges to the project objectives: 1) the CRREL Instrumented Vehicle, a 1977 Jeep Cherokee; 2) a High Mobility Multipurpose Wheeled Vehicle recently obtained and fully instrumented [16], and 3) a much larger military vehicle called a Heavy Expanded Mobility Tactical Truck (HEMTT) weighing approximately 20 tons. Figure 3 shows the vehicles and some of the surfaces involved in the test program. The vehicles have different weights, tire sizes, and treads. The CIV is a research vehicle and has been used to generate and validate vehicle performance models with results documented in many peer-reviewed publications [11, 20, 23]. While the CIV and HMMWV are of similar mass (2,540 kg), the HMMWV is designed for a large payload for off-road transport and aggressive, off-road military use, thus the tire and suspension components differ vastly between the two vehicles.

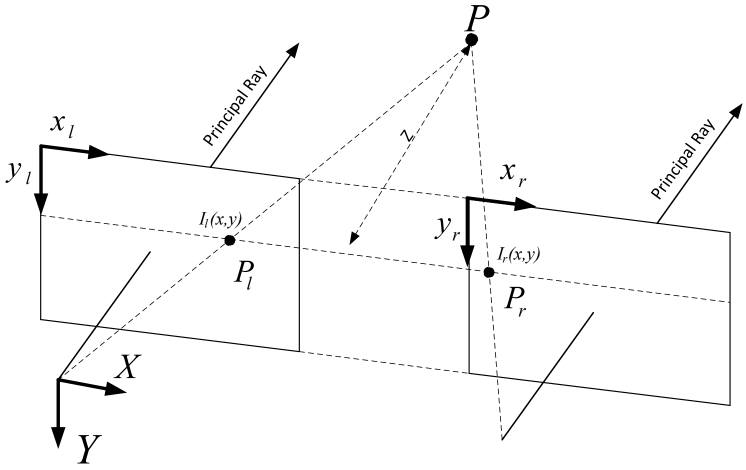

Figure 1: Stereovision methodology [22].

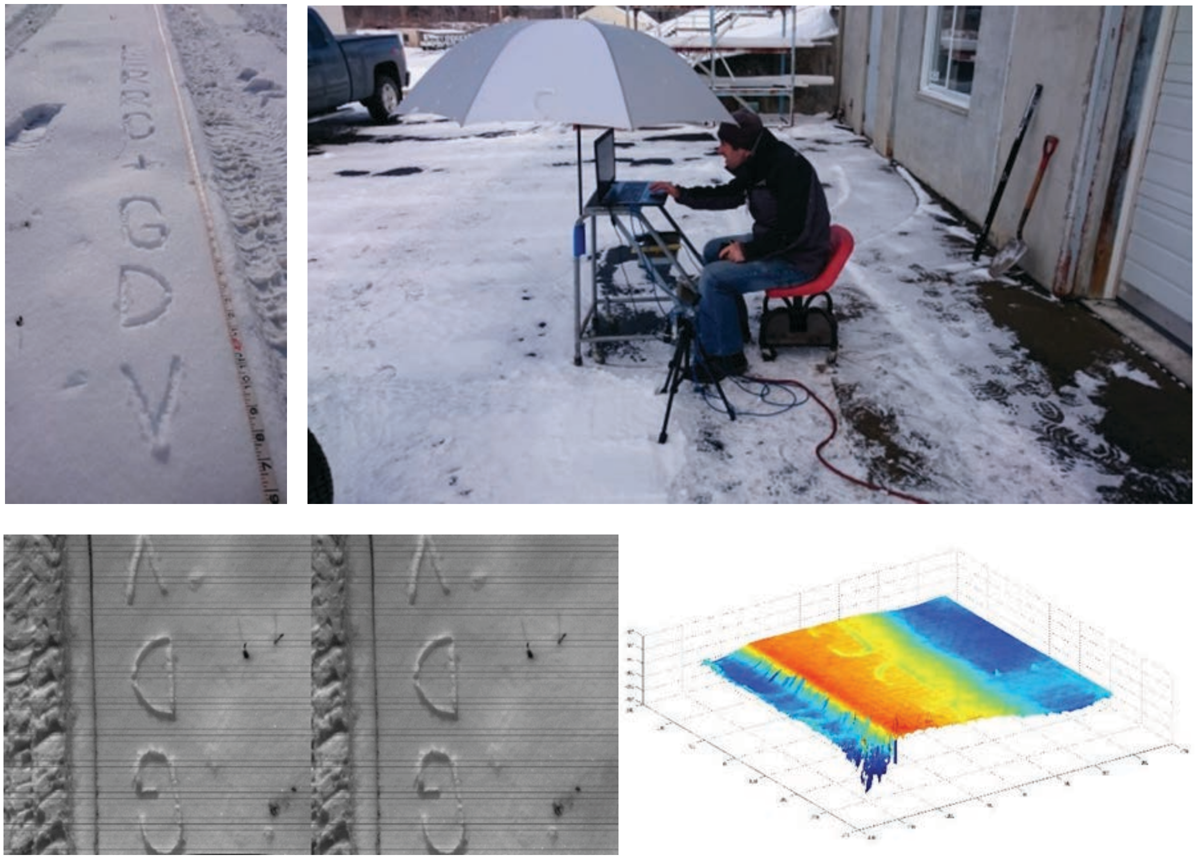

Figure 2: Checking the camera system for use on snow and low light conditions typical in winter (top) and results from stereo cameras capturing ERDC+VDG written in snow (lower left) and digitally derived depth (lower right).

Figure 3: The three test vehicles on some of the terrain surfaces tested: the Instrumented HMMWV during a slalom maneuver in snow (top left); the CIV during a high speed slalom maneuver on thawing soil (mud) at Team O'Neil Rally School (top right); and the HEMTT on snow behind the FERF at CRREL (bottom).

Experiments were scheduled for mid to late winter in New England to specifically capture a range of surface conditions such as snow, ice and thawing, wet soils (mud). Some concrete and asphalt test surfaces were also included, as were transitions between on- and off-road surfaces, some of which were grass and snow-covered grass, and ice covered water puddles. For additional soil surface conditions and higher speed tests, experiments were also performed at the Team O'Neil Rally School in Dalton, NH. The terrain surface was characterized for each of the test maneuvers and is listed in the Appendix.

The vehicle maneuvers were designed to explore the full capabilities of the DIC under a wide variety of conditions. Initial testing consisted of off-vehicle testing of the basics of using the DIC on snow. The initial vehicle testing consisted of straight-line acceleration and braking tests on snow and ice, constant velocity straight-line tests on as many types of surfaces as possible to make sure the cameras could work in all conditions, and then constant radius circle tests in snow. These tests were performed with all three vehicles. Afterwards, experiments with the instrumented vehicles concentrated on exercising both longitudinal and lateral capabilities in maneuvers such as slalom tests and lateral traction tests to evaluate the tire slip angle and force measurements, and vehicle yaw. Tests specific to using the T2CAM mounted inside the tire on the CIV concentrated on calibration of the tire deformation and tire forces, controlled tests on a rigid surface on specific geometric bump shapes, and use on frozen ground. Lastly, to fully exercise the DIC system under different soil conditions and at higher speeds, we used the CIV and the DIC system on standard motion resistance and traction testing, lateral traction testing, and finally high speed maneuvers at the Team O'Neil Rally School. At Team O'Neil, straight-line motion resistance and traction and lateral traction testing was performed at normal test speeds (8 kph); and slalom, pendulum turns and constant radius circle tests at much higher speed (60 kph).

In total, 92 individual tests were completed during the winter/spring test program (see Appendix). The location of the camera mounts varied depending on the nature of the vehicle test maneuver. The analysis is on-going with some preliminary results on rut and slip angle measurements on snow and ice and slalom and turning maneuvers with the HMMWV and CIV [16, 21, 22, 24, 25] presented later this year. The remainder of this paper will concentrate on the HEMTT experiments.

HEMTT TESTS

Fifteen tests were completed with the HEMTT and many of these included multiple maneuvers such as acceleration and braking during a single test, multiple surfaces (called "transition" tests), or replicate tests. The HEMTT experiments are listed in Table 1. The placements of the cameras on the HEMTT are shown in Figure 4. Due to the tight space between the first two axles, the camera set to measure rutting was placed after the second axle. Figure 5 shows the depth map and a visual image for the HEMTT tire during longitudinal slip.

Table 1: Summary of experiments conducted using the HEMMT.

Type of Test	Surface Conditions
Harsh acceleration and braking (3 repetitions)	1 to 3 in. snow over gravel
Right hand turn	Mud to snow
Acceleration and braking, no wheel lock (2 repetitions)	1 to 3 in. snow over gravel
Accel/braking no wheel lock	1 to 3 in. snow over gravel
Harsh accel and braking (3 repetitions)	Snow and ice, approx. 2 in snow w/ice at N end
Transition	Ice/water/asphalt
Transition	Asphalt/water/asphalt
Circle (2 repetitions)	Approx 2 in. snow
Transition	Asphalt/ice+water/grass transition
Transition	Concrete/ice+water/1.5 in. snow+grass transition

The HEMTT testing included accelerations and decelerations on snow and ice to observe longitudinal slip and vehicle speed; and circle and turning tests to check lateral movements of the vehicle. Because the second set of cameras was placed a greater distance from the leading tire, the view of the second camera set would sometimes lie outside of the rut of the first tires and thus obscure the true rut depth.

To exercise the DIC for lateral slip and yaw, the HEMTT tests include constant radius circle testing (on snow), and turning maneuvers on different surfaces. Generally, a camera would be mounted alongside the tire to measure lateral motion and tire angle. For the HEMTT, this set of cameras was mounted in-board of the tire but it was not at an angle that was particularly good for measuring tire slip angle but could measure longitudinal slip.

In addition, several tests were completed to check the adaptation of the camera field of view, depth and lighting in rapidly changing terrain and were called "transition" tests. The transition tests included:

a) a turning maneuver from frozen ground into snow,
b) moving from ice-covered water onto a concrete pad,
c) moving from concrete to ice-covered water,
d) moving from concrete to ice-covered water and onto snow covered grass, and
e) moving from asphalt to ice-covered water to snow covered grass.

Selected individual tests are discussed below.

HEMTT RESULTS

Figure 6 (top) shows the HEMTT and the test surface conditions for the straight-line acceleration and braking on ice and snow. The graphs in Figure 6 (bottom) show the distance and vehicle slip angle calculated from the DIC for a straight-line braking test of the HEMTT on ice. The vehicle slip angle captures the horizontal slide of the vehicle at the end of the test. Since the HEMTT was not otherwise instrumented, all of these results are from the DIC technology. As shown in the data, the vehicle slows and begins to slide sideways (resulting in a high vehicle slip angle) as it encounters the smooth, clear ice section at the end of the test section.

During the straight-line transition tests, we could study the capabilities on several rapidly changing terrains. One of the surfaces thought to be more challenging for the system was ice-covered water where the ice broke as the vehicle passed through. The visual and digital images from this surface, shown in Figure 7, clearly illustrate the robustness of the imaging system and show both the cracking of the ice and the depression caused by the tire lug as the vehicle moves through the ice and water surface.

Figure 8 shows the rut depth calculated from DIC for one of the transition tests going from an asphalt road, through an ice-covered water puddle, and onto snow covered grass. This test illustrates the robustness of the system in responding to rapidly changing terrain conditions.

Figure 4: HEMTT camera set mounting locations: front camera set prior to leading tire (top left); rear camera set aft of the second axle (top right); and side camera mounting location in-board of the tire to monitor tire slip (bottom).

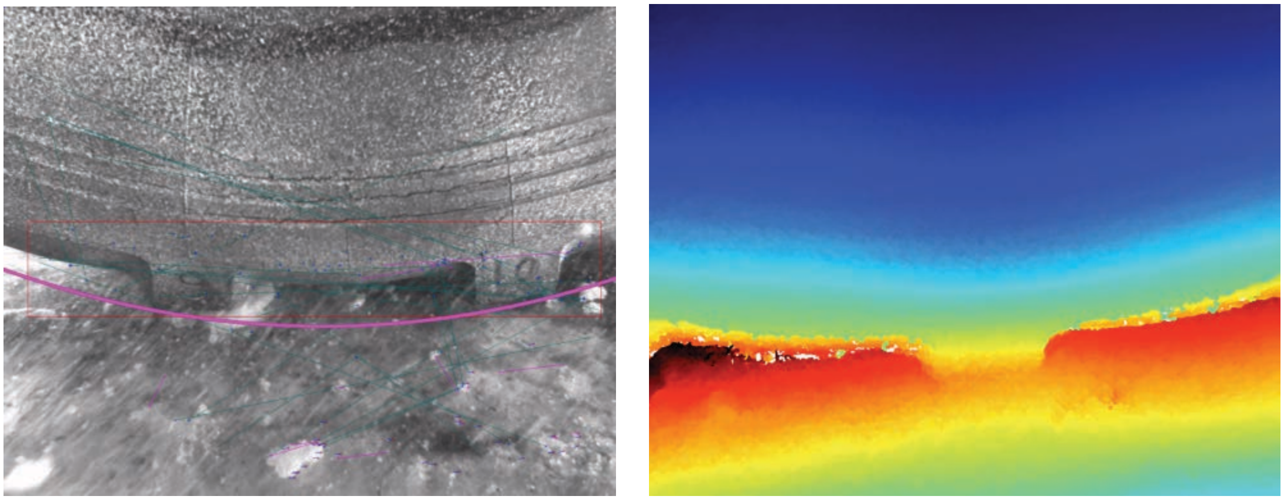

Figure 5: Side camera view indicating contact line (left) and Depth map of side view of HEMTT tire (right).

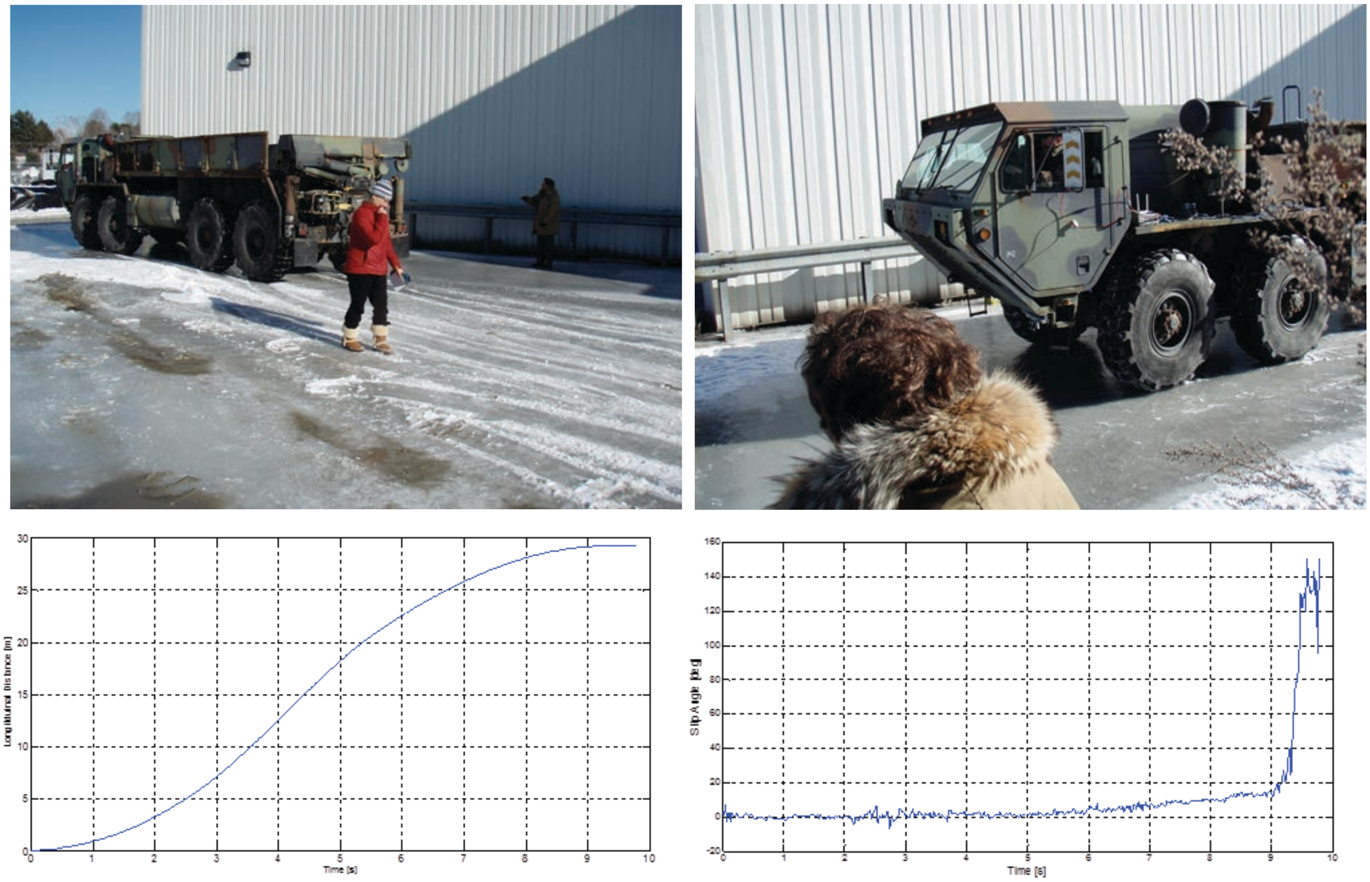

Figure 6: HEMTT during acceleration and braking testing on ice (top), DIC measured longitudinal distance (bottom left) and slip angle (bottom right). Note the vehicle sliding sideways at the very end of the braking test (high vehicle slip angle).

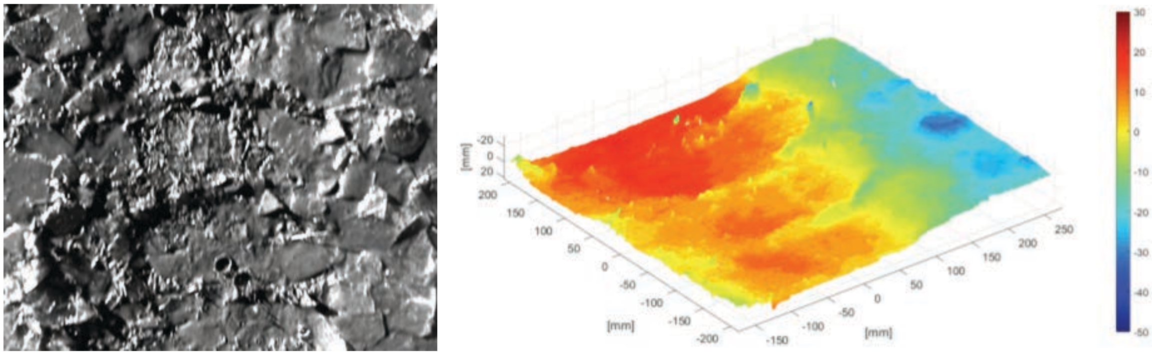

Figure 7: Cracked ice/water surface camera image (left) and digital profile of cracked ice/water surface.

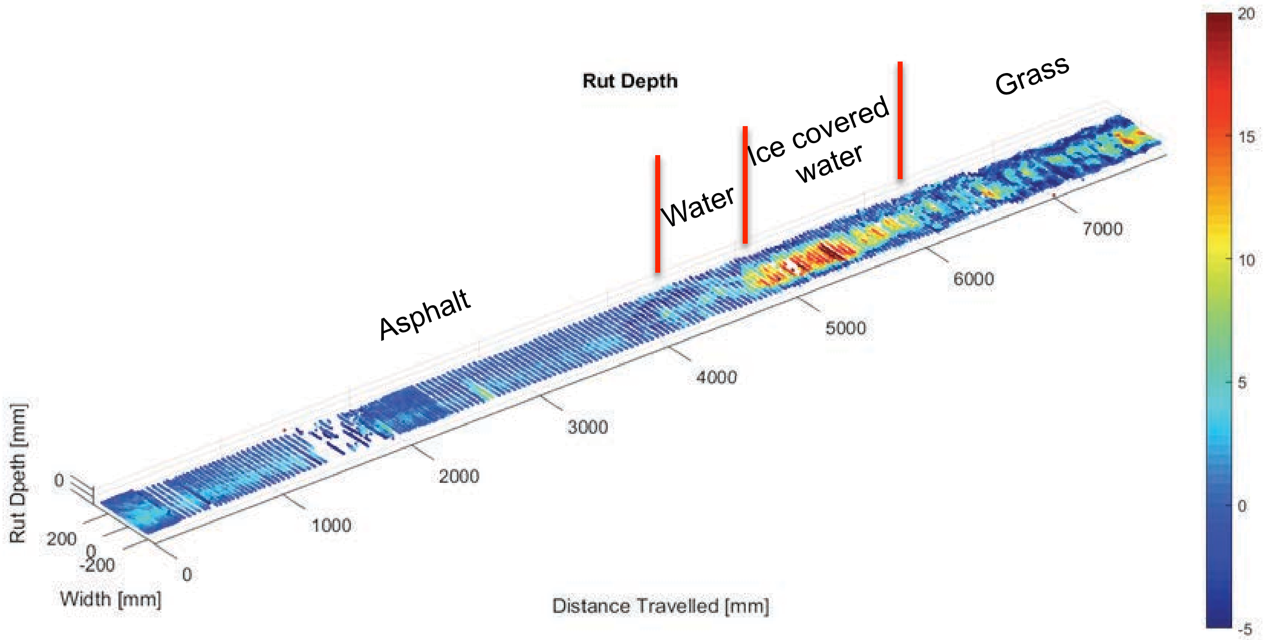

Figure 8: 3D rut profile for the transition test 13 from asphalt to ice covered water to snow covered grass

SUMMARY AND CONCLUSIONS

As part of a Foreign Technology (and Science) Assessment Support Program, sponsored by the US Department of Defense, Assistant Secretary of the Army (Acquisition, Logistics and Technology), the University of Pretoria, Vehicle Dynamics Group collaborated with ERDC-CRREL to evaluate Digital Imagery Correlation techniques for vehicle mobility use on all types of terrain surfaces. Experiments took place during February and March of 2016 in New Hampshire, US, and included using the DIC technology on three vehicles; the CRREL Instrumented Vehicle, which is a fully instrumented research vehicle; a military HMMWV with new research instrumentation; and a large off-road military vehicle called a HEMTT, which was not otherwise instrumented. In all, 92 specific tests were conducted and surfaces ranged from snow, ice, ice-covered water, asphalt, grass, frozen ground, thawing ground, and various wet soil conditions.

The technology has the potential to provide real-time vehicle performance data to a) allow development of control systems capable of interacting with real-time terrain information (for both manned and unmanned systems) b) to the driver for terrain situational awareness and response, c) for real-time terrain situational awareness and vehicle/troop progress, and. d) to R&D for performance algorithms suitable to the current vehicle fleet and operations,

The ultimate benefit of the work is agile and adaptive vehicle operations with less risk of casualties and injuries due to accidents. It will also improve vehicle and convoy mobility while reducing the risk of immobilization.

The DIC technology performed successfully on all three of the vehicles and in every combination of terrain surface and vehicle maneuver tested. The success of the program is illustrated with tests using the otherwise un-instrumented HEMTT, which illustrates the potential use of the technology on a large military vehicle tested in several types of maneuvers on a wide variety of terrain surfaces. The complete analysis of the data set will provide a resource for additional research and technology development for years to come.

ACKNOWLEDGEMENTS

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APPENDIX – SUMMARY OF ALL EXPERIMENTS CONDUCTED

Date	**Vehicle**	**Type of Test**	**Surface Conditions**	**Air Temp**
18-Feb	HEMTT	Accel/Braking	1 to 3 inch snow over gravel	30 F
		Harsh Accel/Braking	1 to 3 inch snow over gravel	
		Accel/Braking	1 to 3 inch snow over gravel	
		RHD turn	mud to snow	
		accel/braking no wheel lock (2 tests)	1 to 3 inch snow over gravel	
		Harsh accel/braking (3 tests)	snow and ice, approx 2in snow w/ ice at N end	
		Transition	ice/water/asphalt	
		Transition	asphalt/water/asphalt	
		Circle (2 tests)	approx 2 in snow	
		Transition	asphalt/ice+water/grass transition	
		Transition	concrete/ice+wate/1.5 in snow+grass transition	
24-Feb	HMMWV	Accel/braking	gravel	28-32F
		Accel/braking (2 tests)	0.5 cm wet snow over gravel	
		Accel/braking (2 tests)	0.5 cm wet snow	
		slalom (3 tests)	0.5 cm wet snow	
		circle (2 tests)	0.5 cm wet snow	
26-Feb	HMMWV	lateral traction (3 tests)	approx 1 in thawing soil	approx 30 F
		Accel/Braking	approx 1 in thawing soil	
29-Feb	HMMWV	accel/decel (3 tests)	thawing (1 to 2 cm soft mud over gravelly sand)	approx 45F
		slalom (2 tests)	thawing (1 to 2 cm soft mud over gravelly sand)	
1-Mar	CIV	Vertical Cal with T2CAM (2 tests)	indoors	60F
		Long Cal with T2CAM pulling FWD (4 tests)	indoors	60F
2-Mar	CIV	Lat Cal with T2CAM pulling OUT (3 tests)	indoors	60F
3-Mar (morning)	CIV	Accel/brake with T2CAM	dry pavement	15F
		Accel Brake at very low speed	dry pavement	15F
		low speed slalom	dry pavement	15-20F
		obstacles at low speed (2 tests)	dry pavement	15-20F
3-Mar (afternoon)	CIV with T2CAM	accel/decel (3 tests)	dry pavement	25F
		slalom	dry pavement	25F
		obstacles (3 tests)	dry pavement	25F
4-Mar	CIV with T2CAM	accel/brake	frozen gravel (braking on ice)	27F
		accel/brake	frozen gravel	27F
		lateral traction (2 tests)	frozen gravel	27F
		lateral traction in reverse	frozen gravel	27F
		accel brake with bucket loader	frozen gravel	27F
8-Mar	CIV without T2CAM	lateral traction (4 tests)	gravel/mud	56F
		rolling resistance (2 tests)	asphalt	56F
		rolling resistance (3 tests)	gravel/mud	56F
		FWD slalom (2 tests)	gravel/mud	56.5F
		slalom	gravel/mud	56.5F
		Long Traction (4 tests)	gravel/drier mud	56.5F
11-Mar	CIV at Team O'Neil (without T2CAM)			
		Motion Resistance (2 tests)	gravel/mud	38F
		Motion Resistance (2 tests)	sandy wet mud	38F
		Traction Resistance (3 tests)	gravelly/muddy area	38-39F
		Traction Resistance (3 tests)	sandy wet mud area	38-39F
		Circle breakout test	sandy mud and gravelly/muddy	38-39F
		slalom with circle at the end	gravelly/muddy	38-39F
		lateral traction (2 tests)	muddy	38-39F