Terrain Analysis in Eastern Ukraine and the Design of a Robotic Platform Carrying GPR Sensors for Landmine Detection

T. Bechtel[1], G. Pochanin[2], S. Truskavetsky[3], M. Dimitri[4], V. Ruban[2], O. Orlenko[2], T. Byndych[3], A. Sherstyuk[3], K. Viatkin[3], F. Crawford[5], P. Falorni[4], A. Bulletti[4], L. Capineri[4],

[1]Dept. of Earth & Environment
Franklin & Marshall College
Harrisburg Ave., Lancaster, PA 17603 USA
tbechtel@fandm.edu

[2]O.Ya. Usikov Inst. for Radiophysics and Electronics
National Academy of Sciences of Ukraine
Akademika Proskury St. 12, 61000 Kharkiv, UA
gpp_15@ukr.net

[3]National Scientific Center
«Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky»
Chaikovska 4, 61000 Kharkiv, UA
romanych2001@ukr.net

[4]Dipartimento di Ingegneria dell'Informazione
Università degli Studi di Firenze
Via di S. Marta, 3 - 50139 Firenze, IT
lorenzo.capineri@unifi.it

[5]Dept. of Physics & Astronomy
Franklin & Marshall College
Harrisburg Ave., Lancaster, PA 17603 USA
fcrawfor@fandm.edu

Abstract — **We are designing and building a multi-sensor semi-autonomous vehicle to assist in humanitarian demining in the Donbass conflict zone, Ukraine. The vehicle will carry impulse GPR for fast target detection, and holographic GPR for discrimination of mines from clutter. The design includes the possibility to add additional sensor. To ensure that the vehicle is compatible with actual Donbass conditions, the COTS dimensions of the selected vehicle (Clearpath Robotics "Jackal"), and relief profiles from two transects collected on the edge of the conflict zone, were compared using morphological filtering terrain analysis. The analysis shows that the vehicle can traverse the recorded transects with no threat of nose-in failure, and minimal threat of hang-up failure. Preliminary testing of the holographic radar mounted on the vehicle show that it can effectively image the footprint of mine-like targets, with resolution of a little more than one centimeter.**

Index Terms—**robot, terrain, mobility, holographic radar, landmine detection, electromagnetic properties**

I. INTRODUCTION

Large portions of the Ukrainian Oblasts of Donetsk and Luhansk ("Donbass") have been occupied by separatists since April of 2014, in an area designated by the government as the Anti-Terrorist Operations (ATO) Zone. Inside and near the ATO Zone, landmines have killed over 3000 persons [1].

In preparation for post-conflict humanitarian demining, we are developing a low-cost, multi-sensor robotic scanning device based on a commercial off-the-shelf (COTS) vehicle; the Clearpath Robotics (Kitchener, Ontario, Canada) Jackal (Fig. 1) with a wheelbase of 262 mm, wheel diameter of 200 mm, and ground clearance of 65 mm [2]. Additional specifications include weight of 17 kg, payload up to 20 kg, maximum speed 2.0 m/s, and drive power of 500 W.
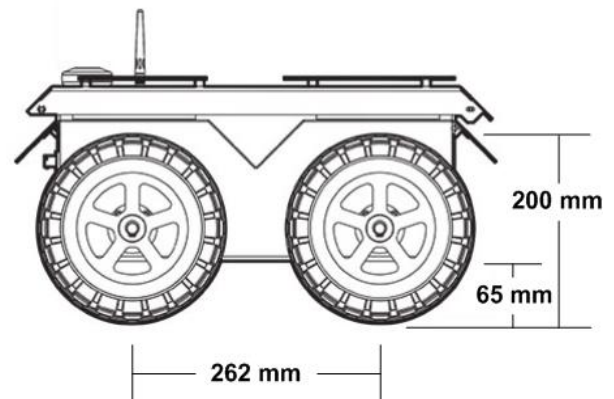

Fig. 1. Jackal Robot, side view. Modified from manufacturer's drawing: https://www.clearpathrobotics.com/jackal-small-unmanned-ground-vehicle/

This vehicle is being modified to autonomously operate an impulse ground penetrating radar (GPR) for fast detection of shallow mine-like targets, and a holographic GPR for high-resolution imaging of targets to allow discrimination of dangerous mines from harmless, but ubiquitous, clutter. Eventually, based on the electronic and software architecture, it will also be simple to add a metal detector (MD) coil and other sensors.

In developing this system, we are particularly mindful of the critical factors espoused by Jane's Mines and Mine Clearance editor C. King who says that "To develop realistic techniques and procedures that will truly enhance the process of mine clearance, two primary factors must be considered: {1} **mines** {the variety and the ways they are used}, and {2} the **environment** {limitations imposed by real minefield conditions}… with equipment and techniques closely tailored to the specific threat {and conditions} in each minefield" [3].
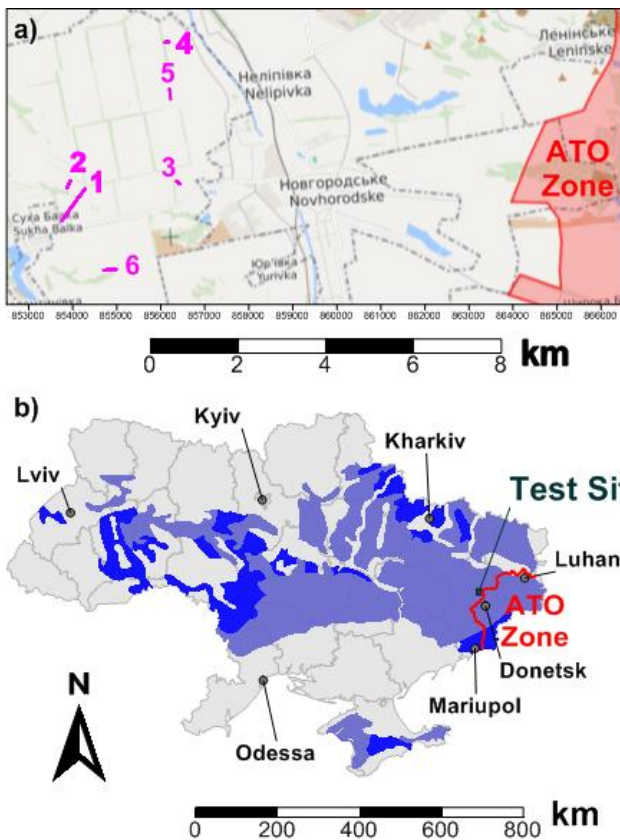

Fig. 2. a) Study area and profiles, b) location of test site. Blue areas are covered by highly fertile chernozem soils.

To accommodate issue {1}, we have previously reviewed the types of anti-tank (AT) and anti-personnel (AP) landmines reportedly in use in the ATO zone [4]. An important component of this issue is the threat from tripwires. Personal communications from the Ukraine State Emergency Services indicate that this threat is greatly diminished since 2014, however, the design of the multi-

sensor system includes optoelectronic devices (Pico Flexx camera by PMDTECH, Seigen, Germany) for real-time 3-D forward-looking image analysis.
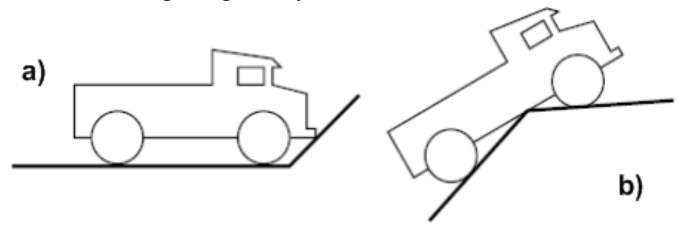

Fig. 3. a) Nose-in failure, b) Hang-up failure.

To address GPR and MD performance relative to C. King issue {2}, we reviewed existing information on the chemical and physical characteristics of Donbass soils [4], and made field measurements of magnetic permeability (μ), electrical conductivity (σ), and dielectric permittivity (ε) [5] along six transects at an experimental station of the «Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky» in Sukha Balka, approximately 7 km to 10 km west of the ATO (Fig. 2). On Fig. 2, the blue shading shows the extent of chernozem soils. These are famously fertile and productive, so many of the blue areas are dominated by agriculture.

This work addresses another important aspect of C. King issue {2}; the physical configuration of the environment and accessibility to the Jackal Robot. Specifically, our goal was to analyze the potential for two of the basic types of failure [6] that a wheeled vehicle might suffer; nose-in failure (NIF), and hang-up failure (HUF). These are depicted in Fig. 3. modified after [7].

II. METHODS

Along portions of transects 1 and 6 (Fig. 2), high-precision topographic profiles were recorded using a Technidea Corporation (Escondido, California, USA) ZIPLEVEL® high-precision (0.2 mm) pressurized hydrostatic altimeter (Fig. 4). The profile segments were selected to span transitions from cultivated fields into adjacent roadways and meadows. Unfortunately, woodlands could not be sampled because they are still considered unsafe due to possible remaining mines.

Fig. 4. Field measurement of topographic relief

The ZIPLEVEL® was zeroed at the beginning of each profile, and then recorded relative elevation. Measurements were recorded at 10 cm intervals marked on a fiberglass tape. The measurement unit was fixed to a monopod with a bubble level to ensure verticality. To record each station, this system was allowed to rest under its own 0.45 kg weight while the reading stabilized, and was recorded Fig. 4). The resulting ground surface relief profiles are shown as the brown lines in Fig. 5.

To perform a 2-dimensional modelling of the movement of the Jackal robot along these profiles, morphological filtering [8] was applied. First, the potential for NIF was analyzed by dilating or upward-continuing the topographic profile using a 100-mm circle as the structuring element. This produces the track of the Jackal wheel axles as they traverse the profile as shown by the purple lines in Fig. 5. Where the axle track for any sampling point is below the next topographic point, this represents NIF, and these points would be highlighted with purple vertical lines. Note that no such points are shown for either profile. That is, for these profiles, there are no NIF locations for the Jackal.

To evaluate HUF, at each sampling point, the relative topographic elevation (brown line) was compared to the elevation of imaginary lines connecting every calculated wheel axle elevation pair with a separation of 300 mm which spans that sampling point. The minimum elevation at that sampling point for all considered wheel axle pairs was lowered an additional 65 mm to represent the elevation of the Jackal chassis (see Fig. 1). A wheel separation of 300 mm was chosen to conservatively represent the true wheelbase of 262 mm (which is not an integer multiple of the sampling point separation).

The minimum chassis elevation is shown on Fig. 5 as a gold line. Where the chassis elevation falls at or below the topographic elevation (brown), this represents HUF, and these locations are highlighted by a vertical red line on Fig. 5. Potential HUF is present at two locations on transect 6 (Fig. 5 bottom), and extrapolates to a rate of about 17 locations per line km based on this admittedly small sample (0.125 km) of Donbass terrain.
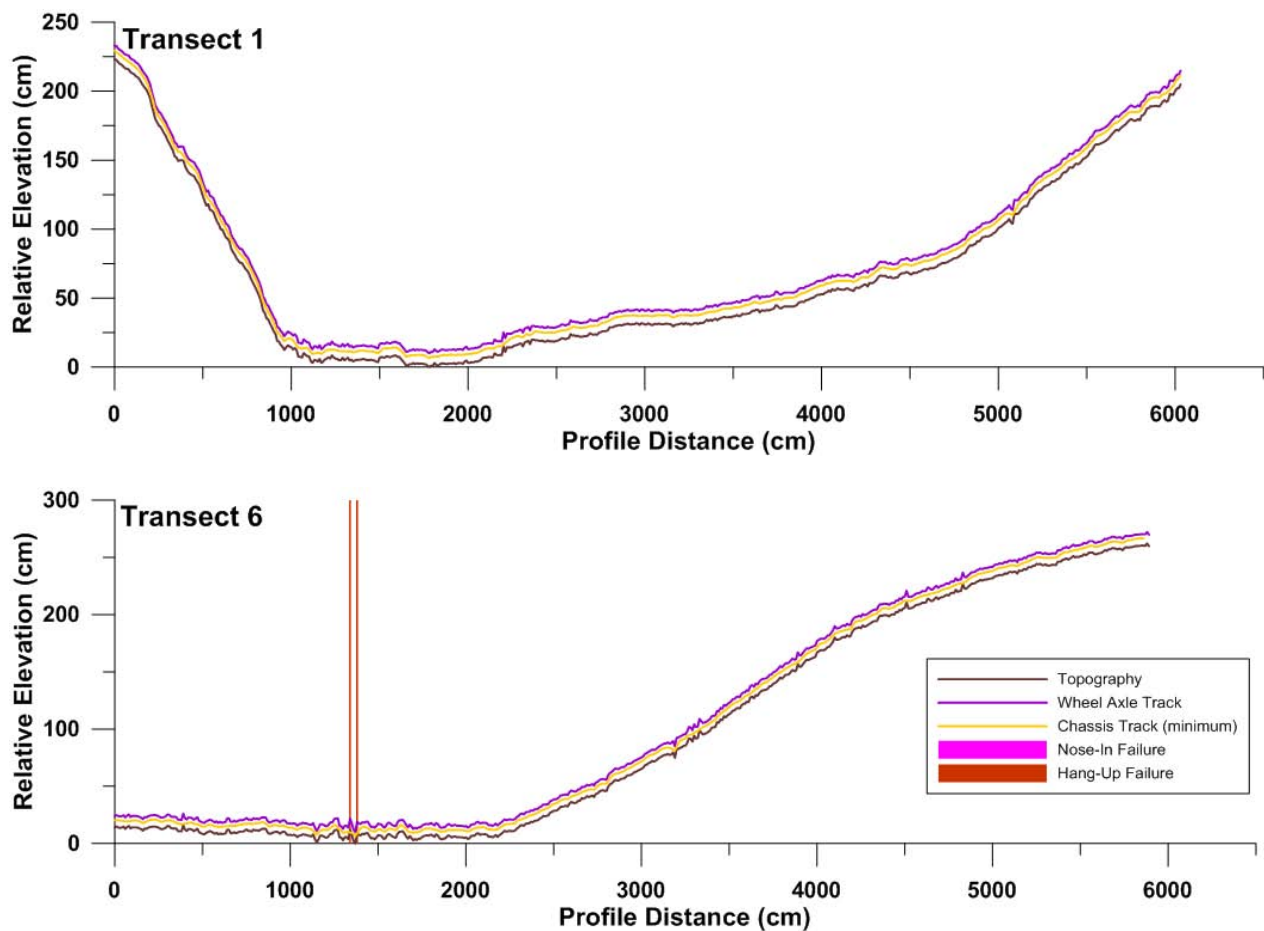

Fig. 5. Measured relative topographic relief (brown), wheel axle track (purple), and minimum chassis track (gold). Locations of potential HUF marked by vertical red lines. No potential NIF locations (vertical purple lines) are present.

III. Preliminary Tests of Holographic Radar Mechanical Scanner

The previous analysis of the electromagnetic properties of Donbass soils [4,5], indicated that an operating frequency of 2 GHz should provide adequate signal penetration to at least 10 cm depth. The corresponding theoretical holographic radar spatial resolution [9] is SR=λ/4=1.25 cm for an average soil with velocity 1×10^8 m/s and GPR antenna in contact with the soil. The holographic radar developed for the robotic platform has amplitude (A) and phase (φ) output channels to allow numerical hologram reconstruction [10], and selectable operating frequency from 1.97 to 2.0 GHz. The electro-mechanical scanner mounted in front of the Jackal robot is shown in Fig. 6, with the holographic GPR antenna placed vertically (grey cylinder) and the impulse antenna array [11] placed horizontally (green box).
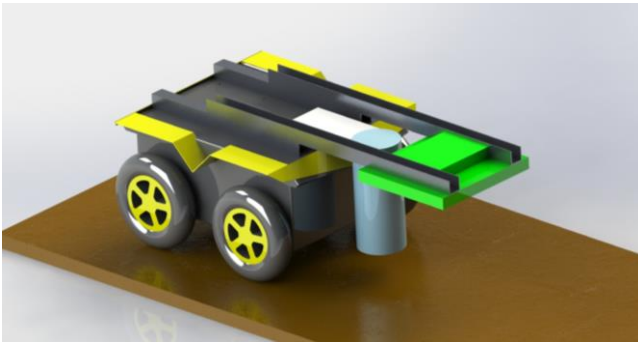

Fig. 6. Robotic platform model.

In a preliminary laboratory test of the holographic radar scanner, an AP mine surrogate (metallic disk with 65 mm diameter) was scanned using the prototype system at 1.97 GHz signal frequency. The disc was positioned with an air gap of 85 mm to the cylindrical antenna aperture. The antenna was swept with a spatial step of 5 mm in both x and y. Recording a 30 x 30 cm^2 image required three minutes.

The intensity of the holographic interference pattern image (V^2) is calculated as the squared module obtained by the amplitude and phase of the voltage output. The resulting grayscale image of the holographic interference pattern is shown in Fig. 7. The image reproduces accurately the circular footprint of the metal disk/mine surrogate. The presence of the interference fringe is in accordance with the theory of microwave holography, and would be reduced when the data are subjected to numerical holographic reconstruction/focussing. The SR is worse than that predicted above because the antenna is not in contact with soil. This is unavoidable because an air gap will be required for operation in the uneven terrain described in the previous section. Subtle asymmetry of the circular shape is due to a small tilt of the disk relative to the scanning plane of the holographic radar. In addition, the mass of the scanner system tends to oscillate slightly when the scanning speed is

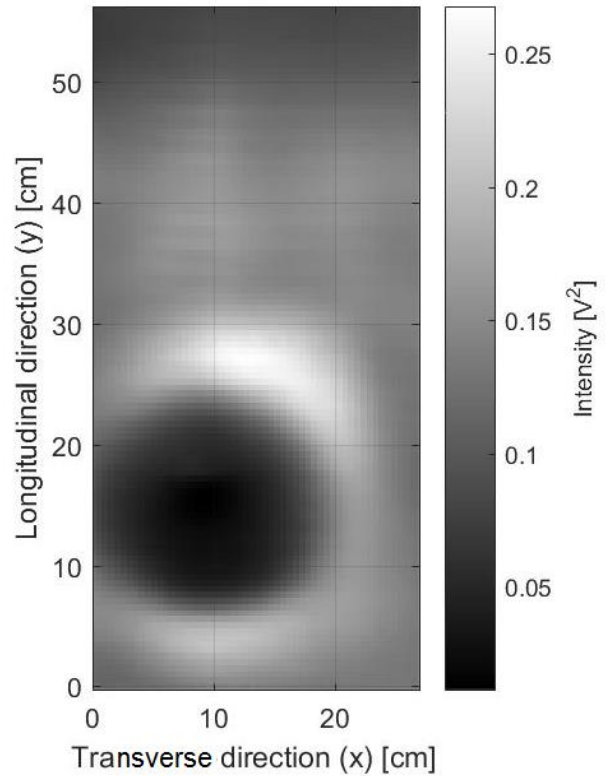high enough to complete a scan of 30 x 30 cm^2 in less than three minutes.

Fig. 7. Intensity of the holographic interference pattern of a metallic disk of 65 mm diameter at 1.97 GHz, spatial step 5 mm, air gap 85 mm.

IV. Conclusions

This preliminary analysis of actual Donbass terrain near the ATO suggests that the Jackal COTS robot could be suitable for carrying an impulse and holographic GPR system for landmine detection – at least across cultivated and fallow fields, meadows and roadsides. Further terrain analysis is necessary (and planned) to evaluate wooded areas and obtain a larger and more representative sample of Donbass terrain. Inclusion of urban areas and residential lots is also planned. In the areas sample, HUF is not ubiquitous, but will present an occasional obstacle. This can be easily managed by mounting a forward-looking time-of-flight camera that can record upcoming terrain (in 3 dimensions). As the remote data collection and processing system receives these data wirelessly, it can perform real-time morphological analysis, and will notify the operator to divert the robot around HUF (and NIF) locations, and these locations can be recorded for later manual mine clearance. Initial laboratory testing of the vehicle-mounted holographic radar indicates that mine-like targets can be effectively imaged.

REFERENCES

[1] G. Marchenko, "Humanitarian Demining Measures in the De-Occupied Areas of Donetsk And Luhansk Oblasts Of Ukraine And Assistance To Victims Of Explosive Ordnance And Military Operation Of Russian Terrorist Groups", GICHD, Geneva, 2015.

[2] S. A. Bonadies, A. Lefcourt, and S. A. Gadsden. "A survey of unmanned ground vehicles with applications to agricultural and environmental sensing." SPIE Commercial and Scientific Sensing and Imaging. International Society for Optics and Photonics, 2016.

[3] C. King "Demining: Enhancing the Process", in Landmines and human security: international politics and war's hidden legacy. R. A. Matthew, B. McDonald, and K.R. Rutherford, (eds.), SUNY Press, 2004.

[4] T. Bechtel, S. Truskavetsky, L. Capineri, G. Pochanin, N. Simic, K. Viatkin, A. Sherstyuk, N. Byndych, P. Falorni, A. Bulletti, and P. Giannelli "A survey of electromagnetic characteristics of soils in the Donbass region (Ukraine) for evaluation of the applicability of GPR and MD for landmine detection", 2016, IWAGPR 16, pp. 1-6.

[5] G. Pochanin, V. Ruban, L. Varianytsia-Roshchupkina, O. Orlenko, I. Pochanina, S. Truskavetsky, K. Viatkin, A. Sherstyuk, T. Byndych, L. Capineri, P. Falorni, T. Bechtel, L. Houser, "Field Measurement of Permittivity, Electrical Conductivity, Magnetic Susceptibility, and Topographic Relief of Soils in Donbass, Ukraine for Robotic, Multi-Sensor, Humanitarian Demining System Design", 2017, URSI GASS 32. P. 86.

[6] M. G. Bekker "Introduction to Terrain-Vehicle Systems. Part I: The Terrain. Part II: The Vehicle", 1969, Michigan University Press, Ann Arbor.

[7] L. Pettersson "Terrain analysis as a design tool for autonomous vehicles in difficult terrain", 1998, Proceedings of the Second NordDesign, Sweden, Stockholm, pp. 1-10.

[8] S. Lou, X. Jiang, and P.J. Scott "Algorithms for morphological profile filters and their comparison", 2012, Precision Engineering, 36(3), pp. 414-423.

[9] S. I Ivashov, V. V. Razevig, I. A. Vasiliev, A. V. Zhuravlev, T. D. Bechtel, L. Capineri "Holographic subsurface radar of RASCAN type: Development and applications", 2011, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, Vol.4 , N. 4, pp. 763-778

[10] A. Zhuravlev, S. Ivashov, V. Razevig, I. Vasiliev, and T. Bechtel, "Shallow depth subsurface imaging with microwave holography", 2014, Proc. of SPIE Symposium on Defense and Security, Radar Sensor Technology XVIII Conference Vol. 9072, p. 1.

[11] G. Pochanin, L Varianytsia-Roshchupkina, V. Ruban, I. Pochanina, P. Falorni, G. Borgioli, L. Capineri, T. Bechtel "Design and simulation of a "single transmitter – four receiver" impulse GPR for detection of buried landmines", 2017, IWAGPR2017, Edinburgh, Scotland, 28-30 June 2017, DOI: 10.1109/IWAGPR.2017.7996112