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# Experimenting with New Technologies for Technical Survey in Humanitarian Demining

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# Experimenting with New Technologies for Technical Survey in Humanitarian Demining

The Humanitarian Demining Laboratory of *Università La Sapienza di Roma*, Italy, currently performs research and experimental work for multisensor explosive-remnants-of-war[1] detecting platforms. In this article, the authors report preliminary testing results on a new, active thermal technique discovered through their research.

by F. Termentini [ Technical Consultant ], S. Esposito and M. Balsi [ *Università La Sapienza di Roma* ]

Technical Survey of territories that are to be cleared from explosive remnants of war is instrumental in determining efficiency, speed, cost and safety of landmine/unexploded ordnance-removal operations. After a general mine-action assessment aimed at area reduction, demarcation, and signaling, Technical Survey must localize all explosive objects within a prescribed depth[2] while minimizing the false-alarm rate (current normal levels are 100–1,000 false alarms per mine or piece of UXO detected).[3]

New technologies for detection are needed especially for low-metal content objects. Instrumentation should be reliable, sturdy, power-efficient and on-site maintainable. Additionally, it should have reasonable cost, give clear warning signals to the deminer and ideally have a zero miss rate, with reduced false alarm rate with respect to current equipment and procedures. The Humanitarian Demining Laboratory of *Università La Sapienza di Roma* is active in research for new mine- (and more generally, ERW) detection systems.

Experimental activity is being carried out on an original, active thermal technology based on localized heating and sensing, first proposed by one of the authors in 2003. At the same time, simulations, a feasibility study and experiments are starting on vibrometric/acoustic and ground-penetrating radar techniques, with the aim of developing a multi-sensor platform.

## Importance and Means of Technical Survey

The objective of making the world free from anti-personnel mines by 2009 has proven overly optimistic, after the initial emotional effect of the Ottawa Convention[4] signing. Lack of adequate funding for mine action is one of the causes, but the difficulties of dealing with vastly heterogeneous objects (anti-personnel mines, UXO, other ERW and in some areas improvised explosive devices) were probably underestimated.

The mine-action community has widely recognized that a general mine-action assessment followed by an accurate and effective Technical Survey[2] is instrumental in determining priorities about the actions to be taken (mapping, fencing and marking for area reduction, risk education, clearance, etc.) and organizing clearance operations appropriately. These actions recognize the nature of ERW existing in the area as well as their depth and distribution, the nature of soils and vegetation, and the level and type of contamination (in particular metallic ferrous and nonferrous objects), therefore enabling instrumentation and modes of operation to be used in the most effective way.

Such results can be obtained only in part by using modern metal detectors (or even dual detectors),[5] because such instrumentation is strongly affected by the metallic pollution of the soil being scanned. This "clutter," as it is known, causes a very high false-alarm rate, especially when searching for very low-metal content mines. The high incidence of false alarms strongly affects the timing of intervention and the safety of operators. For this reason, it is necessary to develop multisensor integrated instrumentation capable of yielding responses that can be interpreted reliably in real time. Ultimately, these tools reduce survey time and cost, and improve performance and safety.

What is unique about ERW is basically the presence of two components within their structure: namely, the fuze and the explosive body.[3] Such parts are essential to the functioning of the explosive device (although they are generally made of various materials of different density and quantity) and are joined together by screwing or interlocking. Also, with a majority of ERW, the presence of air gaps is very typical. This characteristic is, of course, not specific to ERW, as air gaps exist in most artificial objects, and also in natural confounders. It is important to take the gaps into account, because the presence of air is a kind of discontinuity that is often quite significant to many sensing schemes.

As sensors based on different physical principles (electromagnetic induction, dielectric properties, thermal properties, stiffness, even atomic/molecular properties) respond differently to each characteristic of the ERW (casing, fuze, explosive bulk, air gap, etc.), the combination of sensed "signatures" could be used to discriminate between possible ERW and confounders (e.g., stone, empty metal container). What is desirable is instrumentation capable of yielding a "tomography" of the underground that not only gives the position, size, and possibly form of hidden objects, but also labels them according to their nature.

Of course, just as in the case of medical equipment, the instrument should help the operator but not hide sensitive decisions from him/her, principally because they strongly affect safety. Therefore, signal processing should be based on techniques of proven reliability and yield information about uncertainty of the result. Information given to the operator should be clear and certain of significance (e.g., an optical or acoustic alarm when scanning over the detected object, or a spray of paint on the ground).[2] Topographic mapping through geographic-information-system techniques is in any case also desirable,[2] especially as long as automatic machinery is used for removal.

Nonfunctional constraints bear importance for practical operability of systems and should be taken into account when devising new instrumentation. Price of equipment is an important issue, due to scarcity of funding for humanitarian demining, as is maintainability of devices by relatively unskilled personnel in areas where supply procurement is a problem. Equipment should be sturdy enough to work in harsh conditions, as found in many operational areas, and preferably not require much power, as it should be obtained on-site, e.g., by portable generators.

The indoor sandbox of HDL, measuring 1.3 x 3.5 x $0.5m^3$, with the active thermal detector prototype.
ALL PHOTOS/GRAPHICS COURTESY OF THE AUTHORS

## Activity and Goals

The Humanitarian Demining Laboratory located in Cisterna di Latina (near Rome, Italy), was set up in 2006 by researchers of *Università La Sapienza di Roma* in order to experiment on mine-detection techniques. The first task was to realize and test a prototype of an original active thermal technique, based on localized heating and sensing, first proposed by one of the authors in 2003[6] and up to then developed only as a feasibility study through simulations.[7, 8, 9]

The goal of the laboratory is prototyping and testing a multisensory platform for low-metal content ERW detection, employing diverse techniques with special attention to the operational requirements described in the previous section, and applying state-of-the-art data fusion and decision techniques for target classification.

Facilities of the laboratory include an indoor sandbox of about 2.3 cubic meters, fitted with a motorized cart controlled by an on-board microcontroller communicating by radio link with a personal computer. The cart can scan instrumentation of the sandbox at controlled velocity. It currently holds infrared heaters and sensors for the thermal system described above.

A laser doppler vibrometer is also available for vibrometric/acoustic experiments, and acquisition of detectors with GPR is foreseen, while in the meantime simulations are underway. Small autonomous and semiautonomous collaborating robots are also being designed as a prospective solution for scanning light instrumentation on the ground. An outdoor simulated minefield has recently been realized. It will be used after weathering and grass growth, and will be extended in the future. Use of larger and certified simulated fields is also foreseen in the near future. In this way, the authors plan to move gradually from a very "friendly" environment (dry sand), to increasingly realistic settings.

Some types of instrumentation are being only, or mainly, considered for the research and validation phase because they are expensive and require careful handling and signal processing (e.g., infrared camera, laser doppler vibrometer), and simultaneously more rugged solutions are being considered for operational systems (e.g., contactless thermometers, microphone arrays).

## Active Thermal Detection of Mines

A conceptual rendering of the thermal system proposed in 2003 and currently under experimental validation at the Humanitarian Demining Laboratory is shown in Figure 1 on the next page.

Outdoor experimental field before objects (a brick, an empty plastic bottle and a surrogate mine) were buried.

An infrared heater is scanned over the surface, so as to deliver a strong heat pulse that gradually diffuses in a depth of about 10 centimeters. After the heating phase, cooling takes place through the surface, and surface temperature is recorded at one or several time lags using a contactless thermometer (pyrometer). Heating and cooling dynamics are affected by thermal properties of the bulk under the surface (assuming that the latter is reasonably uniform). When an object is buried under the soil, it modifies such dynamics. In particular, explosive materials have normally lower heat diffusivity than most soils, and air gaps act as insulation (extremely low diffusivity). Therefore, diffusion of heat downwards is prevented during heating, and cooling may be slowed by release of heat accumulated in high-heat capacity material. As heating is fast, it mostly depends on surface properties, rather than mass properties, so that we may assume that basically the same amount of energy is transferred to free soil as over a buried object. The dynamic phenomena described cause a temperature anomaly to appear on the surface that registers warmer than where no object is buried.

Dynamical thermal mechanisms have been used by several authors using natural or wide-area artificial heating and infrared camera sensing.[10,11,12,13] In our approach, heat transfer is more rapid, so that blurring by diffusion in all directions is reduced; moreover, power necessary for heating is reasonably limited, and area scanning can be faster. The instrumentation used is rugged and inexpensive, yet quite accurate.

Methods based on microwave heating were also proposed.[14] The main difference of such an approach is that heating takes place directly within the mass and is influenced by dielectric and electromagnetic properties of soil (especially water content) and target materials. A comparison of effectiveness of the two methods under similar conditions (in particular power used and speed of area scanning) has not been tried yet.

Detailed simulation of the system under study has been reported in previous papers,[10,11,12,13] proving its feasibility for shallowly buried objects, down to 3–5 cm depending on soil conditions. This conclusion is consistent with results obtained in other applications of thermography that indicate that the ratio of depth to characteristic dimensions of discontinuities rarely exceeds 0.7.[15] Therefore, the proposed system appears to be a good complement to techniques that do not work well near the surface due to clutter (e.g., GPR, acoustic). Exploration of parameter space also allows preliminary optimization for prototype design.

In the current setup, the authors employ a flat infrared heater of approximately 0.03 sq m, working at 2 kW (about 70 kW/sq m, compared with a maximum of 1 kW/sq m solar radiation), at least 80 percent of which we may assume is actually absorbed. The heater is scanned over the ground at a speed on the order of 0.01 m/s, so that about 3 MJ/sq m are transferred on a stripe of surface about 0.12 m wide, covering more than 2 sq m/hr. The limit to total scanning speed is set by heating speed because sensing can be obtained much faster. As the heater is very simple and inexpensive, scanning speed ends up being directly proportional to available power (ultimately to generator fuel supply), so that these figures are only an indication of such ratio (i.e., scanning speed to power supply) based on current settings.

Optimal delay for measurement (pyrometer scanning) depends mostly on the depth of the object, so it is appropriate to take multiple measurements during the first several minutes after heating occurs, and up to one hour after, for deep objects.

The current setup is obviously impractical for field deployment but useful for accurate characterization under controlled conditions. The system envisaged for operational purposes can be based on different actuation strategies according to possible practical scenarios. In general (this also applies to systems based on different physical principles), we should distinguish between parts of the system that are heavy, bulky and/or power-hungry, and those that are lightweight, compact and require little power. In our case, the heater is light and small, but it requires more power than can be reasonably carried by a light autonomous vehicle. Therefore, we expect to mount it on a robotic arm, stretching out from a safe area and providing power through a cable from a portable petrol generator.

The sensors are instead very small and light, and require little power. It is useful to scan the surface more densely than with the heater and to take measurements at several time lags. For this reason, we are considering use of small robots (or eventually unmanned aerial vehicles) to move relatively fast about the area under examination, with accurate positioning based on remote video and/or radio (differential global positioning system) localization. In any case, actual implementation of the system should be adapted to diverse operating scenarios.

Experimental activity is aimed at validating simulation results. The first results, published recently,[16] and new experiments currently underway are quite encouraging, basically confirming simulations. Besides optimizing operational parameters, we are currently engaged in evaluating signal-processing strategies for contrast enhancement.

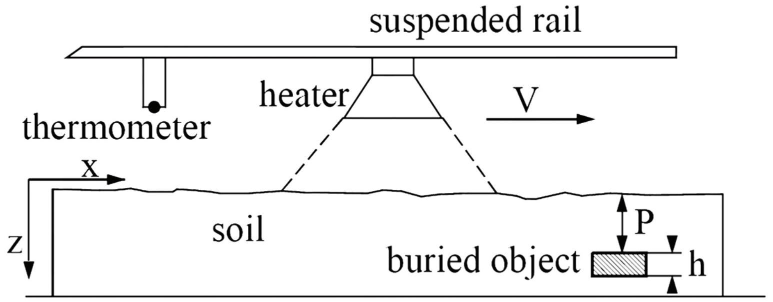

Figure 1: Conceptual rendering of the thermal detector, vertical section. The figure shows the heater and thermometer held by a suspended rail and moving at velocity V. Actual operational fixtures are discussed in the article text.

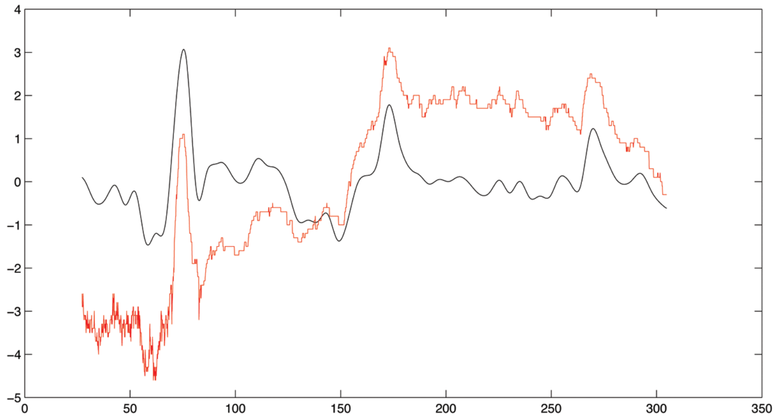

Figure 2: Temperature anomaly (˚C relative to arbitrary mean level) vs. position along the scanning line (cm). Raw data (red), and filtered data (black). The three humps correspond to empty plastic container (75 cm), surrogate mine (175 cm), block of bees wax (270 cm).

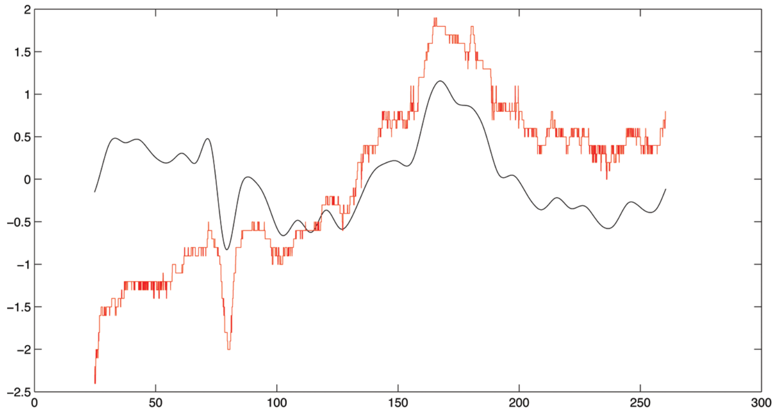

Figure 3: Temperature anomaly (˚C relative to arbitrary mean level) vs. position along the scanning line (cm). Raw data (red), and filtered data (black). The two humps correspond to a block of iron (80 cm), producing negative contrast and the surrogate mine 3 cm below surface (175 cm). In this case, contrast is lower, and the hump wider, but still clearly visible.

An example of raw data, taken from the pyrometer scanning the surface along a line passing over the centers of three buried objects 350 seconds after the beginning of the cooling phase, is shown in Figure 2 (red plot). Three "humps" are visible, corresponding to the three objects: an empty plastic container, a surrogate TS-50 mine[17] (from C. King Associates, U.K.[18]), with synthetic wax filling simulating the thermal properties of the explosive and a block of beeswax, all placed about 1 cm below surface. Along with the expected response, data also show rapid noisy variations, mostly due to non-uniformity of small-scale surface and bulk properties of the soil, and slow variations, due to gradients in large-scale properties, such as initial temperature, humidity and compactness.

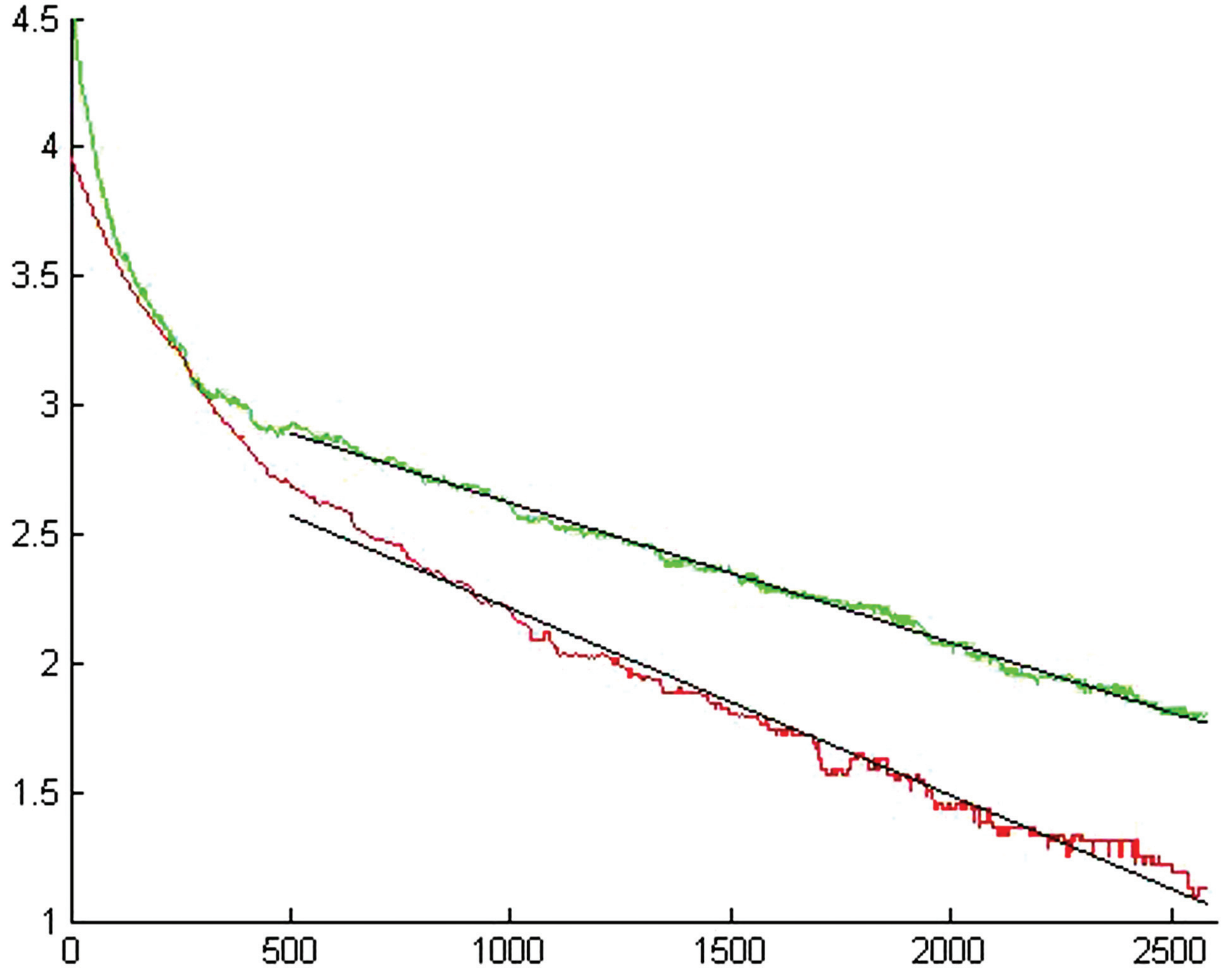

Figure 4: Logarithm of temperature anomaly vs. time in seconds, over the center of a surrogate landmine (green), and bare soil (red), along with linear fit of late decay.

For this reason, we applied to the raw data a wavelet analysis, removing components of the signal that correspond to spatial frequencies, which represent variations that are too fast (spatial frequency > (10 cm)$^{-1}$) or too slow (< (80 cm)$^{-1}$) to correspond to the reasonable size of a mine. In this way, the black plot of Figure 2 is obtained, showing positions of the three objects clearly.

The result of a scan over soil containing a surrogate mine buried 3-cm deep is shown in Figure 3 along with filtered signal. In this case, the delay was 1,600 seconds.

The physical mechanism inducing measurable contrast in these experiments is in fact a difference in (heating and) cooling speed, rather than a difference in temperature, that is the integral result of the process. For this reason, surface temperature contrast varies over time. At the beginning of the cooling process, the signal is very noisy and heat diffusion has not fully taken place down to mine depth, so the contrast-to-noise ratio (CNR) is low. As time proceeds, fast, noisy variations are smoothed by diffusion, but absolute contrast is also gradually lowered for the same reason, and humps blurred, so that an optimal delay range exists when CNR is maximum. Such optimal delay was shown by simulation to depend mostly on object depth (but also on its nature), so that a combination of "snapshots" at several delays conveys additional information.

The said processes are even more apparent when we plot temperature over a point versus time during cooling. We may assume that cooling is essentially exponential over bare soil and that a combination of exponentially decaying functions appears over a buried object:

$$T(t) = A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2} + T_\infty \, .$$

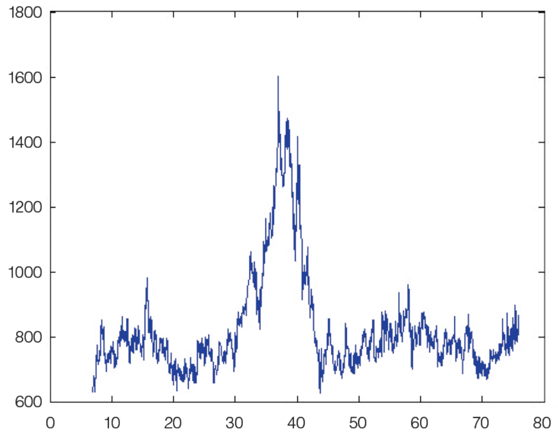

Figure 5: Time constant (slope of linear fit taken as in Figure 4) of temperature decay vs. position in cm with respect to surrogate mine center.

We also assume that, after time, temperature goes back approximately to its value before heating, so that we use for $T_\infty$ temperature measured before heating. If we also assume that $\tau_1 << \tau_2$, we can find a time $\tau_1 < t^* < \tau_2$ such that, for $t > t^*$, $\bar{T}(t) = T(t) - T_\infty \approx A_2 e^{-t/\tau_2}$ and, $\log \bar{T}(t) \approx (\log A_2) - t/\tau_2$ i.e., a straight line.

Figure 4 shows $\log \bar{T}(t)$ vs. $t$, over bare soil and over a surrogate mine. It is evident that after some time, the function becomes almost linear, as expected, showing a significant difference in time constant (slope) in the two situations. In Figure 5 the "slow" time constant is plotted versus position on a scanning line passing over the center of a surrogate mine. A very clear hump is visible, denoting presence of the buried object.

## Discussion of Results, Conclusions and Perspectives

The active thermal system discussed in the previous section of the article is being developed as a means of detecting shallowly buried low-metal content ERW. Preliminary results prove that it is a promising technique, consistent with operational requirements, as was previously stated during our discussion on the importance of a territory Technical Survey earlier in the article. However, the technique is still not mature for practical application.

In the next few months, we expect to obtain extensive characterization of performance, in particular concerning feasible depth of detection, in the sandbox. Within the same time frame, we will use robots to carry heaters and instruments, in order to perform outdoor experiments in more realistic settings. In one year, we expect to complete a feasibility study for a practical system and be ready for prototyping. Experiments with vibrometrical techniques are already under way, so that within the same year we should be able to take scans with the LDV and GPR alongside the thermal system and start evaluating the combination of information from the different sensing schemes (data fusion).

The issue of depth appears to be an intrinsic limitation for thermal systems that are basically limited by the ratio of depth to size of the object, so that 5-cm depth is probably the limit for detection of an 8-cm diameter mine (while it is in fact known that larger anti-tank mines are visible at larger depths even from aerial imaging). In our opinion, the thermal system will not be sufficient alone but is a good complement to systems that perform worse near the surface, and it works for totally metal-free objects.

Another significant issue still to be addressed is vegetation. In fact, wherever the surface is not visible, the system is easily blinded. While a light cover of low grass might only add more clutter to measurements, any significant vegetation needs to be removed before scanning. It is to be noted, however, that pyrometers are very small and light, so that they can be scanned through grass very close to the surface, while infrared cameras would suffer stronger limitations. ◆

*See Endnotes, page 114*

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## News Brief

### Angolan Demining Allows for Building of Infrastructure

The Angolan Armed Forces, the National Reconstruction Office and the National Institute for Demining deactivated and destroyed at least 120,308 anti-personnel landmines between 1996 and July 2008. The National Demining Commission also announced that two million explosive devices, more than two tons (over 1,800 kilograms) of lethal material, and 13,983 anti-tank landmines were also cleared. In the same period, more than 81,000 kilometers (50,330 miles) of roads have been repaired after being declared free from landmine danger, and more than 2,200 kilometers (1,360 miles) of railway have been similarly declared safe. Further demining will allow Angola to provide greater improvements to its infrastructure, which has deteriorated because of limited access for repairs.