Utilizing advances in industrial dual beam x-ray scanners to create new capabilities in humanitarian demining and explosive detection

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Humanitarian de-mining requires 100% detection and removal of landmines to enable safe use of a region. Progress in removing approximately 50 million landmines spread throughout over 70 counties is not fast enough. The hope is that non-invasive radiation-based detection technologies will yield radical better approaches to this problem. Improved sensitivity of the x-rays technologies in analyzing compositions of materials is occurring in industry. More directly dual energy x-ray absorption (DEXA) systems link the effective atomic number to composition change while maintaining high throughputs in often demanding operational environments. This report discusses the field trials of a DEXA scanner and the potential to transfer the trial findings to improved mine detection. The scanner reported on is the Smiths Eagle FA 720 "Bulk" a new version of which is just being released in the USA [1]. It is in terms of the new industrial capability that a radical new capability may be possible in mine detection. This report examines in what way such new capability may be implemented.

I. INTRODUCTION

One outcome sought from this Technical Meeting is to set a pathway to a radically new capability in mine detection. The current demining technologies are slow, expensive and dangerous to apply and may only cover a few hundred square metres per day. The current rate of humanitarian mine clearing is about 100 thousand per year. It is estimated there is $45-50$ million landmines left as a legacy from wars that restricts access to large areas of usable land and kill or maim $15\,000 - 20\,000$ civilians a year [2]. It is urgent to develop detection and removal techniques to increase the efficiency of operations by several orders of magnitude in order to significantly reduce the numbers of anti-personnel mines within a reasonable time frame and cost.

This Technical Meeting highlights the use of neutron based techniques supported by the capabilities of x-rays and gamma rays. The non-nuclear methods are included, as combinations of technologies that may provide the best approach [3]. Neutrons have an inherent capability to penetrate sufficiently into the ground to reach mines and produce a signal that distinguishes mines from metal and other debris in the ground. However, the signal produced by neutrons and other radiation-based interrogation of the ground is at best statistically poor and detection is uncertain. Near 100% detection even for close by mines cannot usually be assured. Attempts to improve the detection process often requires much higher costs and use of large difficult-to-manipulate equipment that increases danger in implementing the method.

It is a contention of this report that the x-ray technologies especially using the dual energy x-ray absorption technique (DEXA) have an inherent advantage over the other radiation-based techniques. X-ray technologies have continued to advance rapidly whereas neutron technologies in part through limited implementations have developed less. It is no accident that x-rays are the preferred scanning technology in medicine, security and industry. A major advantage of x-ray systems is the ability to produce much higher radiation fluxes than the other methods, using compact devices such as tube sources (e.g., at least 10^{13} photons/sec/mA). Radioisotope and accelerator neutron sources seldom exceed 10^7 or 10^9 neutrons per second, respectively. Another important capability that makes x-ray systems workable in public places and in the field despite the inherent high fluxes is the ease with which x-rays can be shielded using low bulk shielding. Only a few mm thickness of lead is required to meet the regulatory requirements of acceptable doses to personnel. For other types of high energy radiations like neutrons there is no equivalent low mass/volume shielding. In industry, an x-ray tube source operating at a few mA enables high speed scanning and imaging at conveyor speeds of 1 metres per second or higher. The adequacy of compact shielding also allows compact and flexible equipment designs. The space occupied by equipment is often critical to success of implementations in industrial and field situations.

This work is based on a partnership between GNS Science [4], and its industrial partner ANZCO Foods working in partnership with Smiths Detection [5], the world's largest manufacturer of industrial x-ray equipment — in the new industrial applications where DEXA scanners are being developed for the meat industry. In this report we describe and illustrate field trials for bulk scanning applications [6, 7, 8]. It is proposed that the field trials of the new industrial scanners can be interpreted generically and applied to other applications such as the detection of explosives and landmines. Proposals for a major advance in the capability of mine detection systems are presented.

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II. FEATURES OF X-RAY TECHNOLOGIES

A. Background

In our previous paper [10] the features and cost effectiveness of compact x-ray sources operating in the $100 - 150$ kV range with currents in the range $1 - 5$ mA were discussed. Such sources are routinely used in security and industrial applications and produce high fluxes (typically 10^{13} photons per mA per second) at an economic price that reflects mass production of the units. Such x-ray systems are now accepted in public areas such as at airports, hospitals and now industry fundamentally because x-ray systems can easily be made safe using low mass shielding material despite the high fluxes used. We previously discussed conceptual aspects of x-ray systems in the demining context but had not undertaken relatable field trial data. Some prior work by others with x-rays systems used high operating voltages (see Ref. [10]) such as 450 kV that increased beam penetration but increased (probably unacceptably) the bulk and the cost. An aim of the current work is to avoid using such high voltage systems but rather make use of the improved sensitivity of the industrial scanners using the lower voltage systems.

B. Major new capability in x-ray technology - the Eagle FA Scanner

The Eagle FA was recently announced by Smiths Detection [1]. The development of this system was initiated by the GNS science team. GNS Science is linked to ANZCO Foods NZ (through a JV) and now work in partnership with Smiths Detection. The major advances in the capability of industrial x-ray scanners are in the realm of material discrimination (DEXA) at high speed in demanding environments. The press release (Smiths Detection October 2007) states:

> "The Eagle FA System is the most advanced image analysis system in the marketplace. The system has been designed with key features that allow for overall low-cost of ownership, including a simple low-cost maintenance and replacement structure."

The Eagle FA Bulk scanner system features are illustrated in Fig. 1. The scanner assesses compositions and structures in products on a pixel-by-pixel basis. The product may be inputted on another conveyor, through a hopper (hopper shown in the figure in a "parked" position) or by other conveyance systems such as an auger. In Fig. 1, the conveyor is shown is in its loosened state as required for removal prior to cleaning. The unit is weather-proof (and hose-able at high pressure), can be operated in environments between 0 to 50 degrees C, has an ability to be assembled and dissembled without tools, and scan product up to 160 tonnes per hour.

FIG. 1: Some functional capabilities of the Eagle FA Bulk scanner (October 2007).

In effect, the combination of x-ray source/detector and software now enables composition change for effective atomic number differences of ± 0.015 units (SD) to be measured for thicknesses up to an equivalent of 0.25 m water. Very small anomalies (contaminants) approximately 1 mm in diameter can also be detected. The long-term operational stability of x-ray scanners has improved dramatically over recent years. In essence the high performance depends on "normalizing" and maintaining the same operational state in continuous applications without interruption. Normalization is implemented whenever the x-ray system is switched on or pauses in production are detected. Advanced scanners implement auto-normalizations and calibrations in real time where gaps occur between products on the conveyor. These advancing engineering and measurement capabilities for x-rays systems are transferable to the proposed landmine scanning machines with improved discrimination.

C. Ideas for deployment of x-rays systems for the detection of explosives and landmines

Table I shows a list of typical explosives, their compositions and their effective atomic numbers. Differences in the effective atomic numbers of these explosives from that of RDX and from that of sugar (an organic material with a similar signature to explosives) are also given.

It is noteworthy that the current industrial scanners with an ability to detect changes of ± 0.015 electronic units, can distinguish explosives not only from sugar but also from one another. Such capability improves the detection of landmines hidden in soils, clays and sands.

TABLE I: List of explosives compositions and associated effective atomic numbers.

Explosives based on Nitrogen	Formula	wt % C	wt % H	wt % N	wt % O	EAN	Delta RDX	Delta Sugar
Ammonium nitrate (AN)	$H_4N_2O_3$	0	5.04	35.01	59.97	7.28	0.16	0.55
Ammonium picrate (Expl D)	$C_6H_6N_4O_7$	29.28	2.46	22.76	45.5	7.05	-0.08	0.32
Cyclonite (RDX)	$C_3H_6N_6O_6$	16.22	2.72	37.84	43.22	7.12	0.00	0.39
Ethylenediamine dinitrate	$C_2H_{10}N_4O_6$	12.91	5.42	30.15	1.58	7.06	-0.06	0.33
Guanidine nitrate	$CH_6N_4O_3$	9.84	4.95	45.89	39.32	6.99	-0.13	0.26
Hexamethylenetriperoxide diamine (HMTD)	$C_6H_{12}N_2O_6$	34.62	5.81	13.46	46.11	6.78	-0.34	0.05
Hexanitrohexaazaisowurtzitane (HNIW or CL20)	$C_6H_6N_{12}O_{12}$	16.45	1.38	38.36	43.82	7.22	0.09	0.49
Hydrazine nitrate	$H_5N_3O_3$	0	5.3	44.2	50.09	7.16	0.04	0.43
Mannitol hexanitrate	$C_6H_8N_6O_{18}$	15.94	1.78	18.59	63.69	7.39	0.27	0.66
Monomethylamine nitrate	$CH_4N_2O_3$	13.05	4.38	30.43	52.14	7.13	0.01	0.40
Nitrocellulose	$C_6H_7N_3O_{11}$	24.24	2.37	14.14	59.23	7.24	0.12	0.51
Nitroglycerin (NG)	$C_3H_5N_3O_9$	15.87	2.22	18.5 6	3.41	7.36	0.24	0.63
Nitrotriazolone (NTO)	$C_2H_2N_4O_3$	18.47	1.55	43.08	36.9	7.11	-0.01	0.38
Octogen (HMX)	$C_4H_8N_8O_8$	16.22	2.72	37.84	43.22	7.12	0.00	0.39
Pentaerythritol tetranitrate (PETN)	$C_5H_8N_4O_{12}$	19	2.55	17.72	60.73	7.29	0.16	0.56
Picric acid	$C_6H_3N_3O_7$	31.46	1.32	18.34	48.88	7.14	0.02	0.41
Tetrazene	$C_2H_8N_{10}O$	12.77	4.29	74.44	8.5	6.68	-0.44	-0.05
Tetryl	$C_7H_5N_5O_8$	29.28	1.76	24.39	44.58	7.08	-0.04	0.35
Sugar	$C_{12}H_{22}O_{11}$	42.1	6.44	0	51.46	6.73	-0.39	0.00

In Fig. 2 the calibration curve [7] is for scanning 60 lb packages of organic material (meat of various fat content) having similar effective atomic numbers to explosives.

In Fig. 3, two Eagle FA installations in industry during 2007 are illustrated.

In these field applications, combos of 2000 lbs of meat were assessed for composition (fat content), and physical contaminants using hopper and 19" auger feeds, respectively.

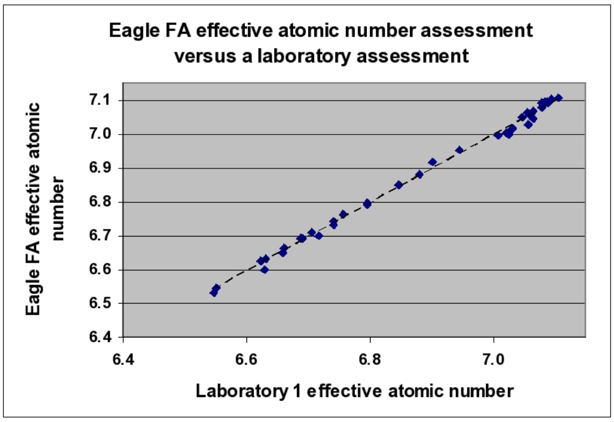

FIG. 2: Measurement of the effective atomic number of meat with the Eagle FA in an industrial context is illustrated.

Detection of small changes in effective atomic number in real time is illustrated in Fig. 4. The product was assessed from a series of images (typically each sized 450×350 pixels) recorded sequentially during the product flow. Very small changes in the product compositions are thus revealed throughout the volume of the combo and this is of interest to processors. Figure 5 shows the detection of small lead contaminants (1 mm diameter lead shot) in an organic matrix (meat). In the context of demining, land mines constitute much larger anomalies (e.g., being 50 mm or more in diameter) but, on the other hand, have lower effective atomic number to metals (e.g., made of plastic) having reduced contrast depending on surrounding materials (e.g., soil composition). Rock or sand (inorganic content) would provide the best contrasts. Demining applications provide lower detectable radiation fluxes suggesting use of large more efficient detectors at the cost of poorer resolution compared to the industry case [10].

III. REDESIGNING THE EAGLE FA SCANNER FOR LANDMINE DETECTION

Detections using x-ray imaging systems are easier to apply in transmission geometry as illustrated in the in-

FIG. 3: Photographs of the Eagle FA at two recent installations in industry.

dustrial applications on a conveyor. The traditional approach to the landmine detector however requires a scattering geometry (see earlier presentation [10]) and modelling as illustrated below in Fig. 6.

The equation representing the detected signal (S_1) is

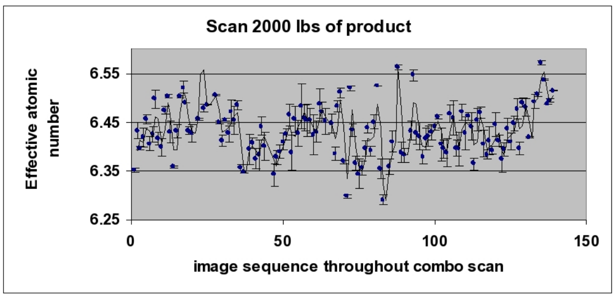

FIG. 4: Detecting small changes in effective atomic number in a field trial.

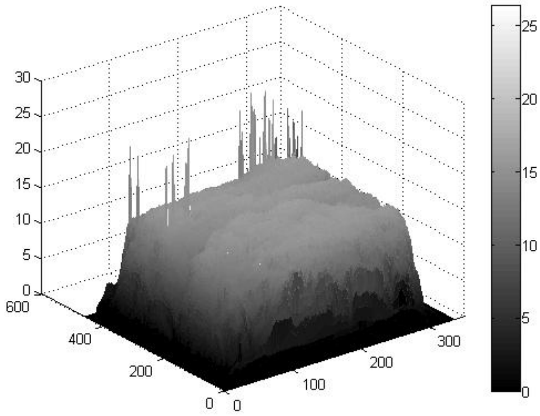

FIG. 5: Detection of very small anomalies (shown as spikes) within an organic material matrix. The image is approximately 600 mm long by 450 mm wide and the material 160 mm thick.

given by:

$$S_1 = N_A \cdot g_{10} \cdot g_{11} \cdot e_1(1 - A_1)(1 - A_4)\sigma \cdot V \cdot \delta \cdot t_1 \quad (1)$$

where N_A is the source intensity, g_{10} is the geometric acceptance between the source and the intersection volume between the beams, g_{11} is the geometric acceptance between that volume and the detector, e_1 is the detector efficiency, A_1 and A_4 are the beam absorptions along the paths 1 and 4, respectively, σ is the electron scattering cross-section at that angle and energy, V is the effective

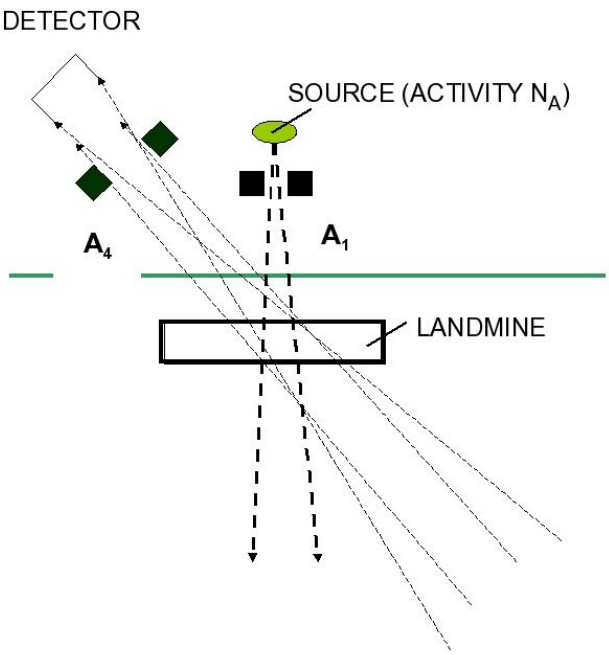

FIG. 6: The basic scheme for a x-ray detection system with one-sided access.

FIG. 7: The component lay out in the Eagle FA scanner used in transmission geometry. Top part contains x-ray source, bottom part contains the detector box.

volume defined by the beams, δ is the weighted average electron density in this volume, and t_1 is the time.

In practice in this one-sided geometry, selection of forward scattering is preferred by suitably angling both the source and detector collimation. Forward scattering leads to higher scattering fluxes aiding mine detection.

The component layout of the Eagle FA systems for transmission geometry used in industry is illustrated in Fig. 7. As shown, the detector array is built into a box.

The proposed redesign in a landmine detection system using scattered x-rays would require conceptual rearrangement as illustrated in Fig. 8.

The linear array of small detecting elements used in the transmission measurements in industry would be replaced by a landmine detection array with probably larger elements to increase efficiency. Calibration and normalization procedures would be maintained using a method appropriate to the scattering geometry. The absence of a transmitted beam may be overcome by periodically introducing a scattering material (rod) directly

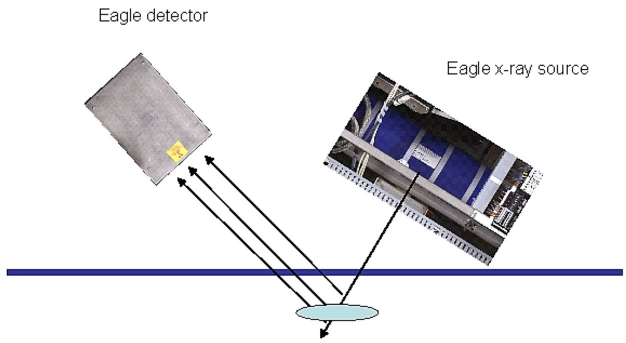

FIG. 8: The conceptual rearrangement of the Eagle FA component layout for use in a scattering geometry is shown. A fan beam is still used and the scattered x-rays are detected with a new type of detector the design of which is yet to be determined.

into the fan beam near the ground surface, such that a scattered beam can then be detected. This rod could be rotate continuously and through having a slot in the rod, the beam reaching the detectors is modulated due to in one case scattering from the rod and in the other case scattering from the ground. The detector array is thus continuously renormalized based on the rod-scattered beam and applied to landmine detection when scattering from the ground.

IV. EXAMINING TECHNICAL DIFFICULTIES IN UNDERTAKING HUMANITARIAN DEMINING

In developing a range of strategies in detecting landmines the inherent difficulties in mine detection can be examined to provide a focus for how advanced x-ray systems may overcome them.

A. Attributes of the humanitarian demining problem

Particular difficulties in undertaking humanitarian demining include:

- Taking the detection equipment to the landmine location often within difficult-to-access terrain.
- Dealing with the location of an object where only one-sided access is available.
- Finding that even for equipment located near a landmine the detection probability is much less than 100% and detection of an anomaly due to inert materials such as metal casings (false positives from clutter) constituents greater than 98% of the detections.
- Increasing the detection probability is often very expensive, difficult to implement and may increase the danger to personnel due to the bulkiness of the equipment.

– All equipment deployments involve significant danger.

Ideally difficulties would be resolved with procedures such as:

– Moving the landmine to the detector.
– Making the landmine detection problem a two-sided access problem rather than a one-sided detection problem.
– Optimizing the implementation of any two-sided detection capability to make the probability of detecting a landmine high.
– Ensuring the cost of the system is moderate/low.
– Ensuring the placement of the equipment does not pose a risk.
– Ensuring that the landmines once detected are "easy" to remove at minimal risks.

FIG. 9: Industrial scanner bulk material scanning pathway.

B. New approaches combining invasive and non-invasive technologies

Despite decades of effort, more can be done for humanitarian demining. One outcome of a successful detection technology is that mines are detected with the option of removing them for disposal elsewhere. Unfortunately current methodologies are too slow and uncertain. Combinations of techniques using non-invasive radiation based sensors combined with invasive methods offer some new opportunities for sensor development. Kawasaki technologies describe a BULLDOG system [11] that has been used in Cambodia. The BULLDOG system consists of three parts:

1. the MINE DOG, a mine detecting vehicle equipped with mine detection sensors and a variety of cameras,
2. the MINE BULL, a mine clearing vehicle equipped with a drum that drills the earth to excavate and detonate mines and a mechanism to collect waste products, and
3. a system of devices for remote control and operation.

To start with then, any advances in the non-invasive sensors enhances the MINE DOG capability in anticipating mine detonations. However the aim in the concept being developed here is to avoid such detonations when detecting and disposing of mines. Progressing with this idea, the industrial x-ray scanner described in Sec. II C optimizes the product flow path as illustrated into Fig. 9. The industrial detection problem thus utilizes the favorable factors outlined in Sec. IV A, by uplifting the product, using a conveyor to provide two sided access.

The MINE BULL detonates anti-personnel mines by means of a high-speed digging drum that turns the soil in front of the vehicle, and a system using magnets and a conveyor is used to extract waste materials. Creative use of conveyor belts in mine clearing is described in many patents, for example in the U.S. patent No. 4,727,940. It describes a means of "uplifting mines" from a surface layer through use a specialized plough. To quote from the a patent description [9]:

> U.S. Pat. No. 4,727,940 describes a mine clearing apparatus for attachment to a vehicle and comprising a frame mountable on a vehicle for selectable positioning in a raised or lowered orientation and apparatus mounted on the frame for raising and shunting aside mines, including a plow section that defines a plurality of plow teeth which extend below the ground surface when in operation, and a conveyer apparatus extending along the length of the plow section and adapted to convey the contents of the earth raised by the plow section to one side of the vehicle.

The patent attributes feasibility to the concept of uplifting the surface layer that may include mines, using the patented plough and then removing them in such a way that detonation can be avoided. While the plough must be designed to withstand detonations, it is not the aim of this equipment to detonate the mines as is the case for the MINE BULL. Thus extending this idea to non-invasive detection, once the layer is uplifted non-invasive technologies could be applied to detect the possible presence of landmines. Once the layer is cleared for the presence of landmines, or detected landmines are removed, the layer can be returned to the ground layer. The machine always has its footprint placed on cleared ground and only the plough section extending into new territory. The conceptual machine is shown in Fig. 10. A refined plough concept using a tubular plough providing a minimum degree of uplifting (disturbance) is illustrated in Figs. 11 and 12.

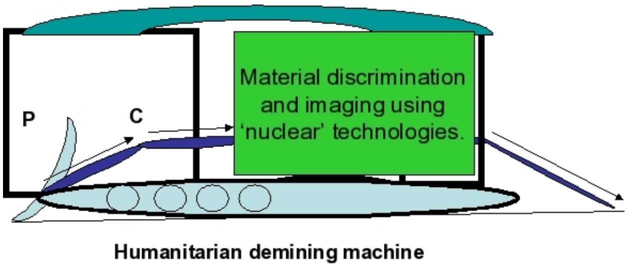

FIG. 10: A demining machine combining invasive and non-invasive technologies. The outlined rectangle front zone including the plough is armored (note: the plough and the scanning system could be separate vehicles connected by a conveyor link).

V. CONCLUSIONS

Modern landmines are constructed mainly from plastics favoring the development of "nuclear-based" technologies which offer a degree of material discrimination to distinguish mines from other "clutter". This is important as clutter may constitute 98% of detections. Use of "non-nuclear" based technologies has limited ability to distinguish mines from other inert materials that dominate minefields. Neutron-based systems offer features of good ground penetrability and potential to identify mines through the detection of characteristic radiations from the mine elemental constituents. A fundamental difficulty in the use of neutrons remains the relatively low neutron fluxes from radioisotope or accelerator sources compared to compact low cost x-rays systems. Building compact and well-shielded neutron sources for the field is difficult. Compact low cost x-ray tube sources can produce 10^4 times greater fluxes than expensive and massive accelerator based neutron sources and 10^6 times greater than the larger radioisotope sources. Thus the reduced penetrability of x-rays compared to neutrons in some land mine soils can usually be countered through improved statistics arising from higher fluxes. This paper focuses on utilizing recent advances in the dual energy x-ray absorption (DEXA) technologies which are preferred in detections and diagnoses in medicine, security and now industry. New approaches using DEXA in demining have been discussed with a view to creating radically new capability that is urgently needed to speed up detections.

This report is a sequel to that presented at the first Technical Meeting held at Padua in November 2006 [10] and proposes new capabilities in mine detection utilizing advances in industrial scanning. The report presents results from industrial field trials of the Eagle FA bulk scanner where small anomalies in composition and density in highly attenuating media or at low contrast are detected e.g., effective atomic number changes of a few one hundreds of an electron unit are detectable. Detection of small chemical changes in 2000 lbs of an industrial product originating from a "combo" was illustrated. Performance levels are maintained for long periods without re-calibrations in situations translatable to field applications.

In one conceptual mine detection design, the scanner is presented in a scattering mode configuration based on one-sided access only. In a second scenario, an innovative method using ground uplifting concepts already part of existing patents enables two-sided access to be achieved prior to scanning with the non-invasive detection. An adaptation of a system used by Kawasaki in Cambodia is proposed where the aim is no longer to intentionally detonate mines in the field, but to optimize the detection probability prior to removal to a safe area.

Sources of funding remain a major obstacle to the development of new demining ideas such as the leading edge DEXA capabilities discussed in this report. Many potential users of the demining equipment have limited resources and manufacturers need to be convinced of meeting development costs and the commercial value in diverting from security and industrial markets.

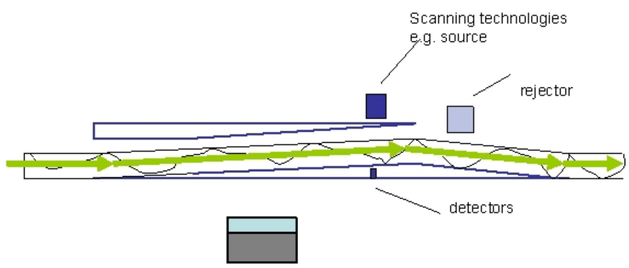

FIG. 11: The concept of using a tubular plough for uplifting the surface layer.

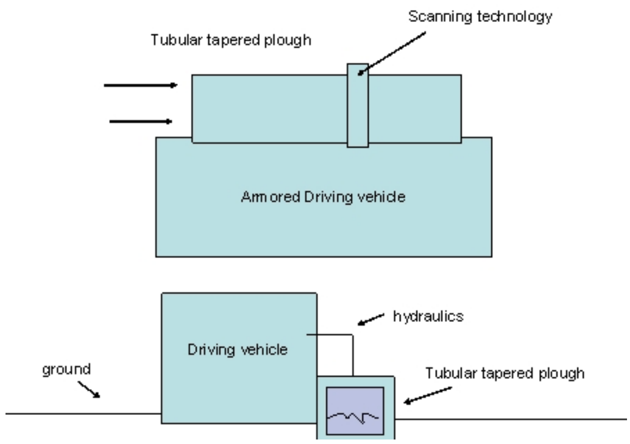

FIG. 12: Minimal uplifting the surface layer using a tubular plough.

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[4] IGN 4000 Globe 19
[5] See www.gns.cri.nz and www.smithsdetection.com
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[8] C.M. Bartle, C. Kröger and J.G. West, “Comparing neutron and X-ray-based dual beam gauges for characterising industrial organic-based materials”, Appl. Radiat. Isotopes **63** (2005) 553-558.
[9] Patents Storm
[10] C.M. Bartle, C. Kröger, W. Stephenson and J.G. West, “Advances in industrial dual energy x-ray scanners and improved methods for detection of explosives and humanitarian demining” in “Proceedings of the technical meeting on combined methods for humanitarian demining and explosive detection”, Padova, Italy, November 13-17, 2006, **STI/Pub/1300** (2007) ISBN 978-92-0-157007-9.
[11] The MINE DOG system is discussed on the web. For example search on Google “Kawasaki BULLDOG to sweep Cambodian landmines” (2007).