# The detection of buried landmines using Probing Robots

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**Abstract**

This paper presents a new approach to the detection of anti-personnel landmines which is based on the physical detection of landmines using a sharpened probe in a fashion similar to that employed by human deminers. Reviews of current techniques, proposed new sensor technologies, and current uses of robotic devices within landmine detection are presented. This is followed by a description of our proposed solution, a robot capable of performing the probing task, together with the results of the initial experiments.

*Key words:* Landmine Detection. Manual Probing. Force Sensing. Mobile Robot Application.

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## 1 Background: The landmine problem

It has been estimated that more than 100 million active mines are scattered throughout over 60 countries in the world, and that more than 2,000 people are maimed or killed by mines every month [1,2]. Many anti-personnel mines are designed specifically to maim rather than kill as significant resources are required to care for people who are injured by such mines, and there is a significant psychological impact on fellow soldiers. Landmines have also been

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used as a weapon against local populations although such use is contrary to international humanitarian law [3].

Landmines persist as a significant problem for civilians long after a conflict has finished and have a major impact on post-conflict reconstruction. They are invisible (as they are often buried or camouflaged) and indiscriminate, and as a result cause terror in the civilian population. Even with international efforts to ban the use and production of landmines [4], the situation continues to deteriorate with landmines being laid around 20 times faster than they are currently being cleared [1,2].

## 2 Current techniques for landmine detection and clearance

The detection of buried landmines is traditionally performed through exhaustive searching by humans using some combination basic tools. Generally, potential mines are located using a metal detector to locate metal fragments such as the firing pin of the landmine and/or by feeling for mounds or depressions which are caused by the laying of the mines or by subsequent settling of the ground. These potential mines are then investigated further through manual probing. In practive many deminers actually probe the entire ground area regardless of whether they have found a potential mine.

As a result of military action there may be up to 1,000 metal fragments to be investigated for each single mine discovered [5] resulting in potentially lethal deminer fatigue. In fact “80% of all clearance accidents occur during the investigation of metal signatures” [5], although this statistic is debated by some deminers. Such accidents can also be caused by landmines which have moved from the horizontal position such as in the Falkland Islands where 80% of the mines are laid in peat or sand [1].

The effectiveness of metal detectors is inhibited by mines with extremely low metal content or by soils with high ferrous content, and hence other detection techniques have been (and are being) investigated. One such technique which is widely used is the detection of explosive material by smell using a dog [6]. Dogs can be trained to identify the presence of explosives which are leaked by landmines, although the explosives can be detected up to 10 metres from the mine resulting in only the approximate position being identified. In addition, “experience with dogs seems to show that mines do not release significant TNT vapour after 18 months of burial” [7,8]. This technique, however, appears to have potential for the identification of the boundaries of a minefield.

Once detected, landmines are generally destroyed in situ as the risks associated with neutralising or disarming them are too great [9]. Other ‘modern’ techniques which are currently used for landmine clearance are machines such as the flail, mine ploughs, rollers and sympathetic detonation. However these devices do not achieve the standard required for humanitarian demining (which is 99.6% clearance [2]). In fact "mine clearing has not really advanced a great deal from World War II" [12] and the most effective and reliable detection technique is still manual probing [2].

## 3 New sensor technologies

As mentioned previously, new technologies are being investigated in order to improve the reliability and speed of the land mine detection operation. Recent surveys of new technologies for land mine detection include [7,8,10,11], and an overview of the main technologies being investigated is presented here.

(1) *Ground Penetrating Radar* (GPR) [7,8,10,11,13–15] is reasonably well developed and has demonstrated a 100% detection rate for anti-personnel mines in a research context [14]. However field investigations are required to determine the performance of GPR under real conditions with mines buried to varying depths. Some investigations have been performed which have found, for example, that GPR does not work well in water saturated environments due to the ground return [15].

(2) *Detection of explosive vapours by bio-sensor* [6–8,10,11,16] (in effect obtaining the same results as those achieved by a dog) has been addressed although the current systems are either too insensitive, too slow or too large to be used for landmine detection [8]. Further efforts (e.g. [16]) are ongoing.

(3) *Infrared Imaging* [7,8,10,11,15,17] relies on a natural (i.e. at certain times of day) or artificial (e.g. induced by microwave radiation [17]) temperature differential between the landmines and their surroundings. Tests have shown that there are practical limitations on the depth to which mines may be reliably detected.

(4) *Thermal Neutron Analysis* (TNA) [7,8,10,11,15] attempts to detect the explosive charge by bombarding it with radiation and detecting the gamma rays emitted by the nitrogen nuclei in the explosive material. Problems with this technology include limited depth of penetration and false positives caused by nitrogen enriched soil.

(5) *Electro-magnetic Induction* [7,8,10,11,15,18] can been used to locate shallowly buried non-conducting objects such as plastic landmines [18], although detection at more impressive depths such as 50cm has been demonstrated for metal parts [8].

(6) *RF/Millimetric Radiometry* [7,8,10,11,19] (i.e. images of millimetre wave radiation) is capable of detecting shallowly (down to 3cm [8]) buried mines at a significant distance (e.g. 35m [19]).

(7) *X-ray Backscatter* [8] is also being investigated with a view to applying it to landmine detection.

The report by the Joint Research Centre of the European Commission [7] evaluated the various sensing techniques which are being considered for landmine detection and identified three sensors as being the most promising (at least in the short term). Those sensors were a single or multi frequency 3-axis induction-gradiometer, an imaging polarimetric surface penetrating radar and an imaging polarisation-sensitive infrared sensor. None of these sensors on their own is sufficient and hence some combination of these sensors was proposed.

## 4 Mobile robots for landmine detection

Recent approaches for the use of mobile robots in landmine detection include

(1) Lightweight robots such as the Pemex-BE [21] which is “light enough not to make the mine explode” [22]. The Pemex-BE will incorporate a “combination of mine sensors”[21] including a metal detector and GPR [13]. The developers also propose that this type of technology could be employed for marking the positions of located mines and for placing charges. It has also been suggested [14] that a “swarm” of such vehicles could be employed and that even if a mine was detonated by one of vehicles “the cost of the loss would be affordable”. Inexpensive ‘crawlers’ have also been suggested [20] specifically for the neutralisation of mines.
(2) Larger and heavier robots such as those used with the Vehicle Mounted Detection (VMD) system and the Vehicle Mounted Mine Detector (VMMD) both of which are being developed under the American ‘Humanitarian Demining Development Programme’ [15]. The VMD system makes use of a metal detection array together with a thermal neutron analysis sensor for further investigation of metal targets, while the VMMD makes use of IR and UV cameras for initial detection and a GPR system for further analysis.
(3) Legged robots have been developed, and proposed for landmine detection and clearance [23–25]. A number of novel concepts have been incorporated into these robots such as material classification using the acoustic tapping sounds caused by the legs of the robot [23], continual autonomous demining by incorporating solar power cells [24], and arranging the robot in such a fashion that it is unlikely to be fatally damaged should a mine be inadvertently detonated [24].
(4) A suspended robot has been suggested [26] which would allow a sensor system to be placed just above any position in the accessible search area. Such a system could also be employed to detonate mines.

## 5 Autonomous Probing Robots

While remote sensing has the potential to develop a comprehensive solution to the general landmine detection problem, the current most reliable method remains manual probing from a prone or squatting position [2,9]. The probe used is generally just a sharpened 'stick' such as a bayonet which is inserted into the ground at an angle no greater than 40 degrees to the horizontal [9] at 2cm intervals until some resistance is encountered [1].

A more advanced 'extended probe' was being developed under the American 'Humanitarian Demining Development Programme' [15]. This probe allowed the deminer to remain two metres from the ground which is being probed, provided some protection in the form of a blast shield, and had a vibrator tip microphone in order to discriminate between different materials. According to the project manager of the American program, work on this device has been stopped as the Canadian National Defence are reportedly developing a more reliable system which bases it's classification of object type on the returned energy from an ultrasonic pulse which is sent down the probe once it is in contact with an object. (Unfortunately no formal references are available for the information detailed in this paragraph).

The proposal of this paper is that the process of probing the ground could and should be performed by tele-operated or autonomous robots. In effect these robots should emulate the work of human deminers and depending on conditions, this could involve using a combination of a metal detector and a probe or just a probe on its own. However it is worth noting that such robots are not limited to following exactly the same procedure that is followed by human deminers. For example a robot could carry a number of independent probes in order to speed up the probing task. In addition a robot will not suffer from deminer fatigue and more importantly would reduce the number of human causalities due to demining operations.

## 6 Demonstrator System

In order to demonstrate the feasibility of automatic probing a demonstrator system was constructed. This system was not intended to deal with all of the issues involved with automatic probing in a real minefield, but rather was intended to demonstrate the concept and to investigate the difficulties associated with the task.

The system consists of an XY table (i.e. two orthogonal linear stages; to allow probing to be performed over a limited test area), an electrically driven linear

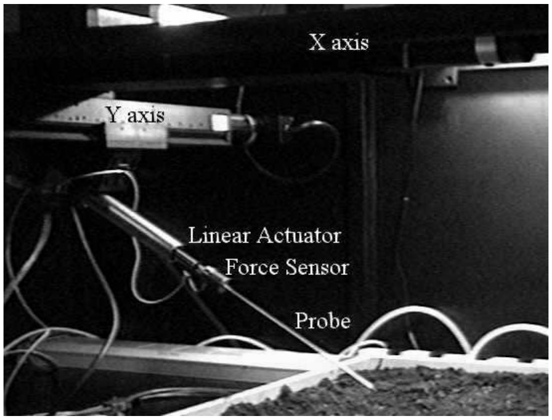


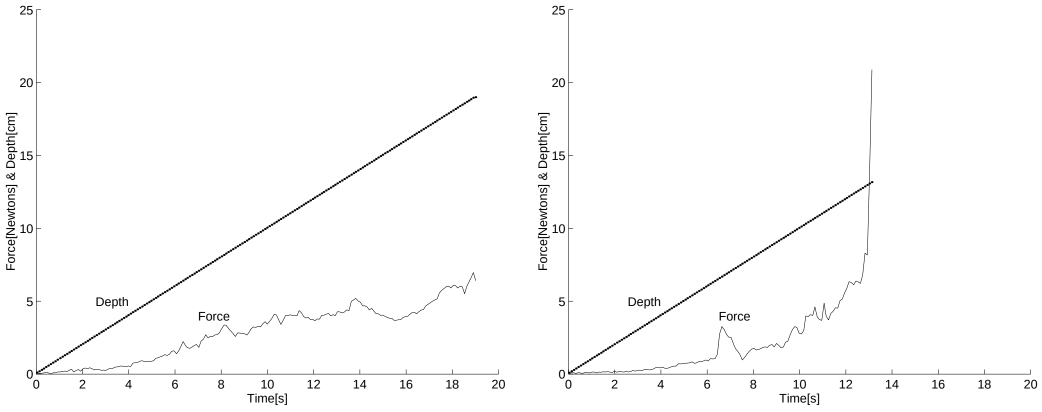
Fig. 1. The demonstrator system. The X and Y stages allow the probe to be positioned in any position over a test area. The probe is connected to a force sensor which is connected to a linear actuator which is connected to the XY table using a 30 degree angle bracket.

actuator (to drive the probe into the ground), a force sensor (to sense resistance to the probe), an angle bracket (to allow the probe to be mounted at an angle of 30 degrees to the horizontal), and a sharpened steel rod (i.e. the probe). The system is shown in Figure 1 (see [27] for full details).

The two linear stages of the XY table have ranges of motion of 900mm and 600mm respectively, and for practical reasons, the test area was limited to a 500mm square. The actuator has a 190mm stroke length (i.e. limiting the maximum insertion depth of the probe to 190mm), and this in turn limits the vertical depth of probing to 95mm (due to the probing angle of 30 degrees). Please note that this is off-the-shelf hardware and is not a limitation on the maximum depth that can be probed automatically.

Inserting the probe into the ground gives feedback on both force (from the force sensor) and position (from an optical encoder mounted on the motor of the linear actuator). The force required to insert the probe into the ground at a constant speed increases roughly proportional to the depth of insertion; see Figure 2(a). However when an obstacle is encountered the force required increases, and if it exceeds a pre-selected threshold, which was set to 15 Newtons during our tests, then insertion is stopped and the depth of insertion is recorded; see Figure 2(b).

Prior to development of the demonstrator system we performed tests using a custom made manual probe [28,29] (which provided force information) in a number of different terrains and found that a roughly linear relationship held between the depth of insertion and the force required to insert the probe at a constant speed although the ratio between the two varied considerably; see Figure 3.



(a) (b)

Fig. 2. Force and depth information returned by the probe during probe insertion where (a) no obstacle was encountered and (b) an obstacle was encountered.

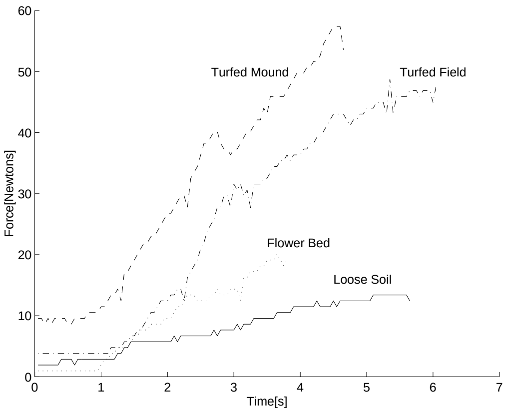
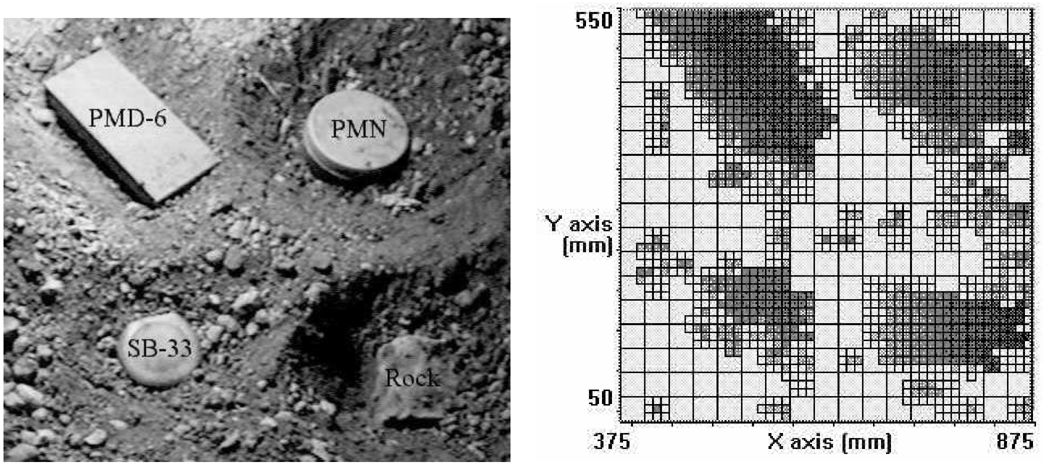


Fig. 3. Reaction forces of the manual probe inserted into different ground conditions at roughly the same speed. The relationship between inserted depth (not shown) and axial force recorded is roughly linear but the proportionality constant is dictated by the terrain conditions.

## 7 Probing tests

Three anti-personnel mines (an SB-33, a PMN, and a PMD-6) and one rock were buried in the test area in relatively loose soil (see Figure 4(a)). The test area was then probed using a simple search strategy of inserting the probe every 30mm, and if an obstacle was encountered the probing was then done every 10mm in order to obtain a better idea of the shape of the object (See Figure 4(b)). Probing was done everywhere in the test area although in reality **probing would cease if a suspect object was located** in order to minimise the risk of initiating a mine by probing on the top surface.

The data shown in Figure 4(b) are the depths to which the probe was inserted prior to encountering an obstacle (or reaching the end of the possible range



(a) (b)

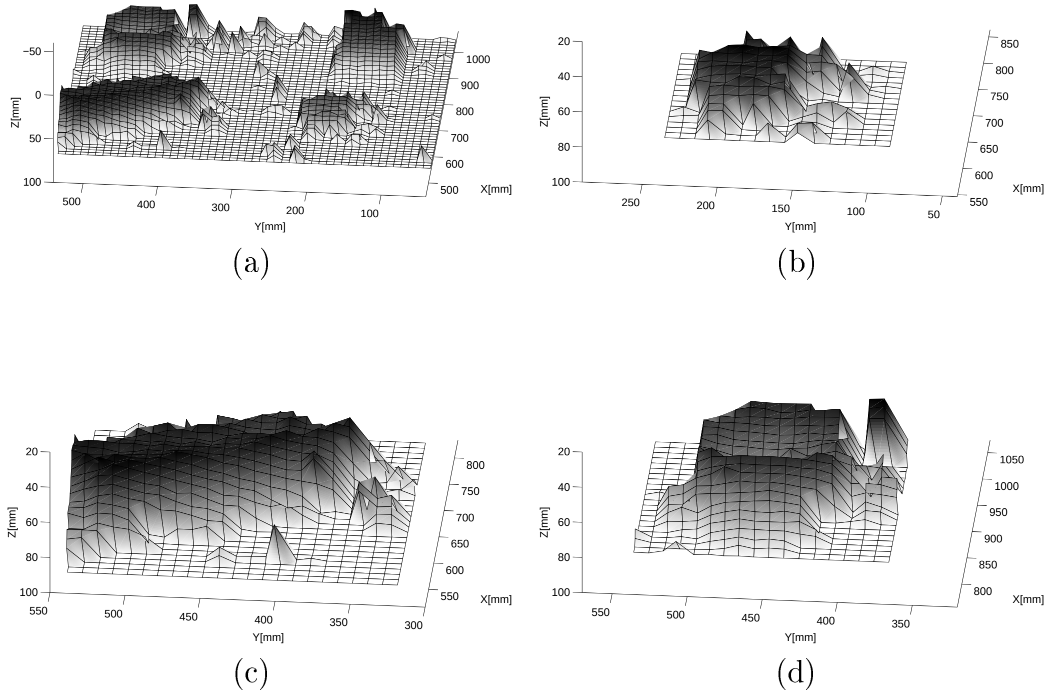
Fig. 4. Three anti-personnel mines (an SB-33, a PMN, and a PMD-6) and one rock were buried in the test area in relatively loose soil (a), and the test area was then probed the results of which are shown in (b). Note that the grey levels shown are equal to the depths (in mm) to which the probe was inserted prior to encountering an obstacle (i.e. the darker the grey level the closer the obstacle was to the surface) and also that probing was done at an angle of 30 degrees to the horizontal in a direction parallel to the X axis.

of travel). As the probe was inserted at an angle of 30 degrees it is necessary to transform this data somewhat in order to visualise the objects in 3-D; see Figure 5.

In Figure 5(a) the four objects are clearly visible. The SB-33 is in the lower corner, the rectangular PMD-6 in the upper Y, lower X corner, the circular PMD in the upper corner and the rock in the upper X, lower Y corner. A number of smaller peaks are also visible where the probe encountered smaller stones. These, however, do not distract from the four larger objects which dominate the data.

A close up of probe data on and around the SB-33 mine, Figure 5(b), provides evidence of the size and dimensions of the buried object. It appears to be of irregular shape of approximately 100mm across and 90mm in depth. It's irregularity is magnified by the presence of noise in the data caused by smaller stones being lodged between the mine body and probe tip while measurements were being taken.

The rectangular outline of the PMD-6 can be seen in the magnified data in figure 5(c) with the top edge set at an angle to the probing direction. The data points of the top surface of the mine are of lower depth than the leading edge which is caused by the probe tip sliding along the surface of the mine before the reaction force eventually reaching the threshold to terminate the probing. This is the situation where there is a discrepancy between the measure and



(a) (b)

(c) (d)

Fig. 5. The probing data from Figure 4(b) is shown in a Cartesian frame of reference (a), along with more detailed 3-D views of the SB-33 (c), the PMD-6 (b) and the PMN (d). Note that all of these 3-D views are taken roughly from the direction of probing (i.e. almost parallel to the X axis).

actual position of the probe tip due to lack of rigidity in the probe. This results in subsequent probes of the top side appearing lower than the leading edge due to the probe sliding along the surface.

Figure 5(d) illustrates the data for the PMN mine where its circular outline of diameter 110mm can be clearly recognised. It is also possible to identify one of the covering plugs of the openings at the side edge of the mine. The depression in the top surface is again caused by the probe tip sliding along the object.

## 8 Conclusions from testing

(1) The data from the tests obviously indicated the presence of the three landmines and the rock, although many other obstacles were found which were not intentionally buried. These were mainly small stones and can be seen in the test results (Figure 4(b)) as small groups of points where the probe recorded an obstacle.

(2) Some of the smaller obstacles appear beside the larger ones and on occasion were pushed up against the larger obstacles. This demonstrates that caution must be taken when using a classification mechanism based on a vibrator tip or the returned energy from an ultrasonic pulse along the probe, as a stone may be beside the real obstacle. It also introduces a degree of 'noise' into the depth data which may to attempt to classify the obstacles.

(3) The recorded inserted depth (for a specified position) suffered from an additional source of 'noise' due to a certain amount of play in the probe (i.e. the tip of the probe could be moved by up to 15 mm in any direction if a lateral force was encountered). This was particularly noticeable when the probe encountered a surface at an oblique angle (such as the curved side of the PMN mine), or when the probe just passed the side of an obstacle. The deflection could be significantly reduced in a device designed to be more rigid. Alternatively the lateral forces and deflection could be measured and used when analysing the shape of an obstacle. These lateral forces were noted in the earlier tests with the manual probe [28,29] where it was suggested that they could potentially be used to provide extra information about the shape of a buried object.

(4) Classification of the object must be based only on the leading edge of the depth data, as it is not feasible to probe the top of the mine unless an extremely low force is used or the device is capable of withstanding an explosion or is cheap enough for the loss of the device to be acceptable. It does seem that some classification should be possible especially if the depth data is accompanied by an indication of the object substance (i.e. wood, stone, or plastic), but this could result in a reasonably high false positive rate. A balance could be taken between the level of false positives and the risk to the probing device. If an object is determined not to be a landmine then the probing can continue over the top of the object. The additional data provide by continuing the probing would then allow for a more reliable classification (although if it was a landmine, probing on top would be likely to initiate the mine).

(5) It was clear from the tests that probing the ground can disturb the objects which are buried. For example in one test an SB-33 mine was disturbed from the horizontal position by the probe as the probe hit the very bottom of the side of the mine (which was buried at a very shallow deep in loose soil) so that it ended almost in a vertical orientation; see Figure 6. Although the mine itself was not visible, the disturbance of the soil around it was visible. This suggests the need for visually monitoring the area being probed or for a method of preventing such disturbances.

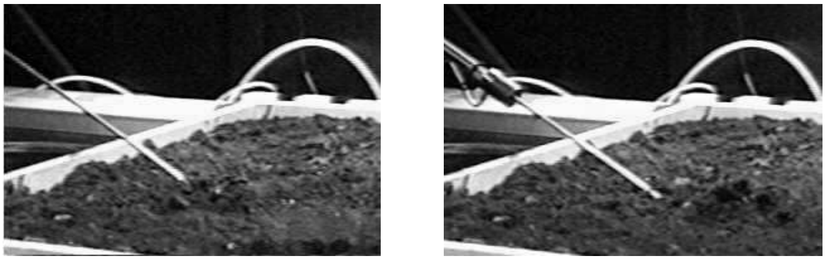

(a) (b)

Fig. 6. Probing can disturb buried objects, particularly if the object is not buried deeply. (a) shows the scene before probe insertion, and (b) shows the effect of disturbing the position of an SB-33 anti-personnel mine (look to the right of the probe) although not finding an obstacle.

## 9 Future issues

It must be recognised that the demonstrator system does not even begin to address a number of issues which are of importance to a real demining system:

- Determination of the absolute position and orientation of the mobile platform in order to allow a complete map of the probed area to be built up.
- Action to be taken when a potential anti-personnel mine is detected (e.g. marking mines with a paint marking system, or destroying mines in situ).
- Control of the mobile platform(s) (i.e. autonomous or remote co-ordinated control).
- Classification of the buried objects.

In addition many configurations can be conceived for a probing robot; such as the simple device shown in Figure 7, a robot equipped with an array of independent probes (to speed up the probing task), a robot with a flexible arm equipped with a metal detector, a probe, and perhaps even a chemical detector. Other tools could be added to these devices to mark possible mines (e.g. with a paint marking system) and to remove or destroy the mines. Other designs have been considered by the University of Alberta [30].

## 10 Discussion

Evidence of the wide spread trauma and suffering caused by landmines all over the world provides ample justification and motivation for the application of humanitarian demining. The concept of probing robots have the potential of providing increased deminer safety, a better clearance rate and improved clearance efficiency. The tests conducted thus far using a lab based demonstrator system have provided results which indicate that there is significant

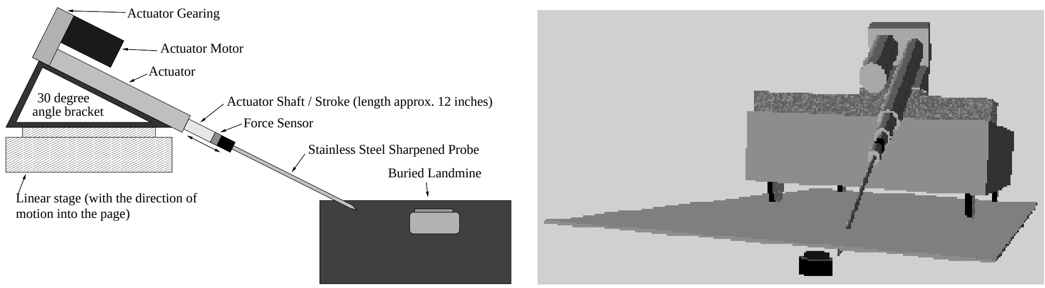


Fig. 7. Simple design for a probing robot. The probe is driven into the ground using a linear actuator, which is moved along a single axis linear stage in order to probe along a 'scan line'. This linear stage in turn is mounted on a mobile platform, providing motion in the direction orthogonal to the linear stage.

potential in the concept of force sensed automated probing. There is however significant work to be done to develop a system which is both reliable enough and robust enough to be used in the field.

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