Autonomous Probing Robots for the detection of abandoned landmines

Kenneth M. Dawson-Howe* **and Tomos G. Williams** **

Department of Computer Science,
Trinity College,
Dublin

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. The axial force applied to the probe is sensed as the probe is driven into the ground (at 30 degrees to the horizontal in order to avoid initiating the landmine), and the force information together with absolute position information is used to determine the presence of buried objects.
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, and details of the intended development route.

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 soliders. Landmines have also been 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 landmines [4] (and landmine production) 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 of metal detectors and manual probing. 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, although 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 can be 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.

* Kenneth.Dawson-Howe@cs.tcd.ie
** Tom.Williams@cs.tcd.ie

One such technique which is widely used is the direct 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 detected. In addition, “experience with dogs seems to show that mines do not release significant TNT vapor after 18 months of burial” [7, 8]. However this technique 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 neutralizing 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, 14, 15] is a reasonably well developed technology and has demonstrated (in a research context) a 100% detection rate for anti-personnel mines [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, 7, 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. There do, however, seem to be 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 more impressive depths (e.g. 50cm) have also been demonstrated for metal parts [8].
6. *RF/Millimetric radiometry* [7, 8, 10, 11, 19] (i.e. images of millimeter 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 neutralization 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/walking robots have been developed and proposed for landmine detection and clearance [23, 24, 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’ 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’ is being developed under the American ‘Humanitarian Demining Development Programme’ [15]. This new probe allows the deminer to remain two metres from the ground which is being probed, provides some protection in the form of a blast shield, and has a vibrator tip microphone in order to discriminate between different materials.

The proposal of this paper is that the process of probing the ground could and should be performed by tele-operated or autonomous robots as follows:

– *A tele-operated robot* which would allow the metal detection and probing tasks to be performed remotely by a trained deminer. Such a system could employ a ‘virtual reality’ type interface in order to give the operator realistic feedback during the probing operation. This possibility has been considered (although not implemented) previously [25] in which a three axis force reflective joystick was suggested as the main interface for tele-operated probing operations.
– *An autonomous robot* which would perform the metal detection and probing operations in the same manner that the current deminers use. However this robot would not suffer from deminer fatigue (as mentioned previously) which should reduce the number of mines that are set off accidentally. In addition it is possible that an inexpensive device could be developed specifically for this purpose and in such a situation the loss of a device (due to an explosion) would not be of serious concern.

6 Manual tests

In order to investigate the basic requirements, and prove the basic concept, of a probing robot a series of tests using a purpose designed manual probe (see Figure 1) were developed. This manual probe incorporated a force sensor which measured the axial forces being applied to the probe. The aim of the experiment was to determine if the axial force and probe position data would provide sufficient information to allow the detection of buried objects with a view to identification based on the shape of the buried objects as indicated by the results of probing the ground regularly.

Using the information returned by the force sensor in the manual probe together with a video recording of the tests an approximately linear relationship was found between the force value returned and the inserted

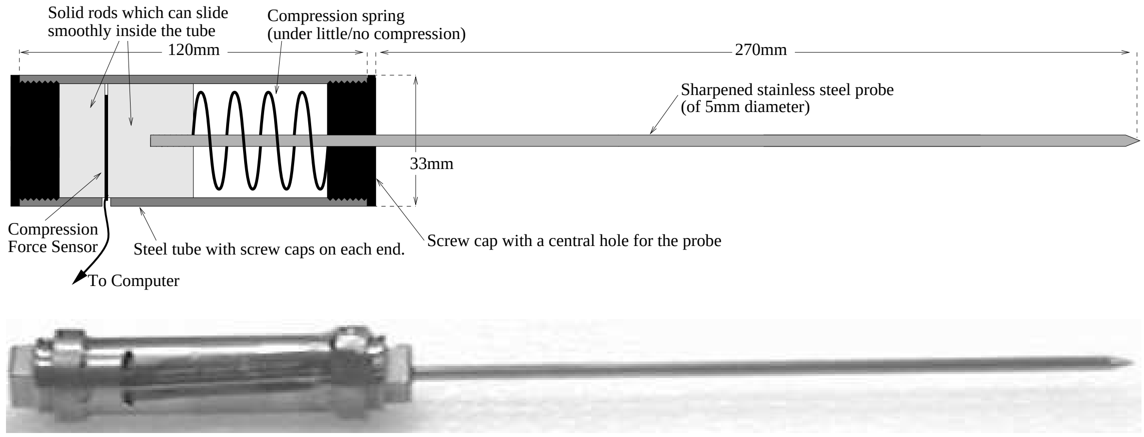


Fig. 1.: CAD drawing and photograph of the manually driven probe with built in force sensor. The sharpened stainless steel probe is connected to a larger rod of steel inside the housing of the handle. When force is applied to the probe it causes the force sensor which is between the two larger rods of steel to be compressed. This alters the resistance of the force sensor allowing the (axial) force applied to be monitored.

depth of the probe (while inserting the probe at a roughly constant speed and an angle of 30 degrees) in the case that there were no significant obstacles in the way of the probe; see Figure 2(a). In addition we performed this test in a number of different terrains and found that a linear relationship still held although the scaling factor varied considerably; see Figure 3.

When an obstacle was encountered in the path of the probe, probe insertion was halted (due to the obstacle) while at the same time force exerted by the tester was increased (in an attempt to get past the obstacle); see Figure 2(c). By combining the axial force data and the depth of insertion data it is straightforward to detect buried objects; see Figures 2(b) and (d).

From a number of other tests performed the following conclusions were drawn on probing tasks for buried object detection. These tests and results are fully described in a technical report [27].

1. Inserting the probe repeatedly into the ground showed that there are no significant differences between the reaction forces for different angles of insertion.
2. On encountering an obstacle the tester experienced both axial (reaction) forces and translational forces (orthogonal to the direction of the probe) depending on the orientation of the obstacle surface with respect to the probe. This could potentially be used to provide extra information about the shape of a buried object, although it would be most relevant when the obstacle surface is smooth.
3. No obvious differences were noticed by the tester when encountering different types of obstacles (e.g. plastic, wood, stone), but it is accepted that experienced deminers can differentiate between different types of material. This can be automatically detected using a vibrator tip microphone as reported by the American 'Humanitarian Demining Development Programme' [15].

7 Demonstrator design

The manual tests provided a reasonable level of confidence that the basic concept was sound and hence a demonstration system has been designed; see Figure 4. A linear actuator with an optical encoder for position feedback and a compression sensor for axial force feedback will be used to drive the probe into the ground. This in turn will be mounted on a linear stage in order to allow a 'scan line' to be probed while the mobile device (on which the system is mounted) remains stationery. It is intended to classify buried objects from the information returned for individual (or possibly multiple) scan lines.

To simplify the demonstration system development, it is possible that an X-Y stage will be used in place of the linear stage and the mobile platform.

The purpose of the demonstration system is to show that buried objects can be located and classified using this type of approach. The level of success of the demonstration system will also indicate whether

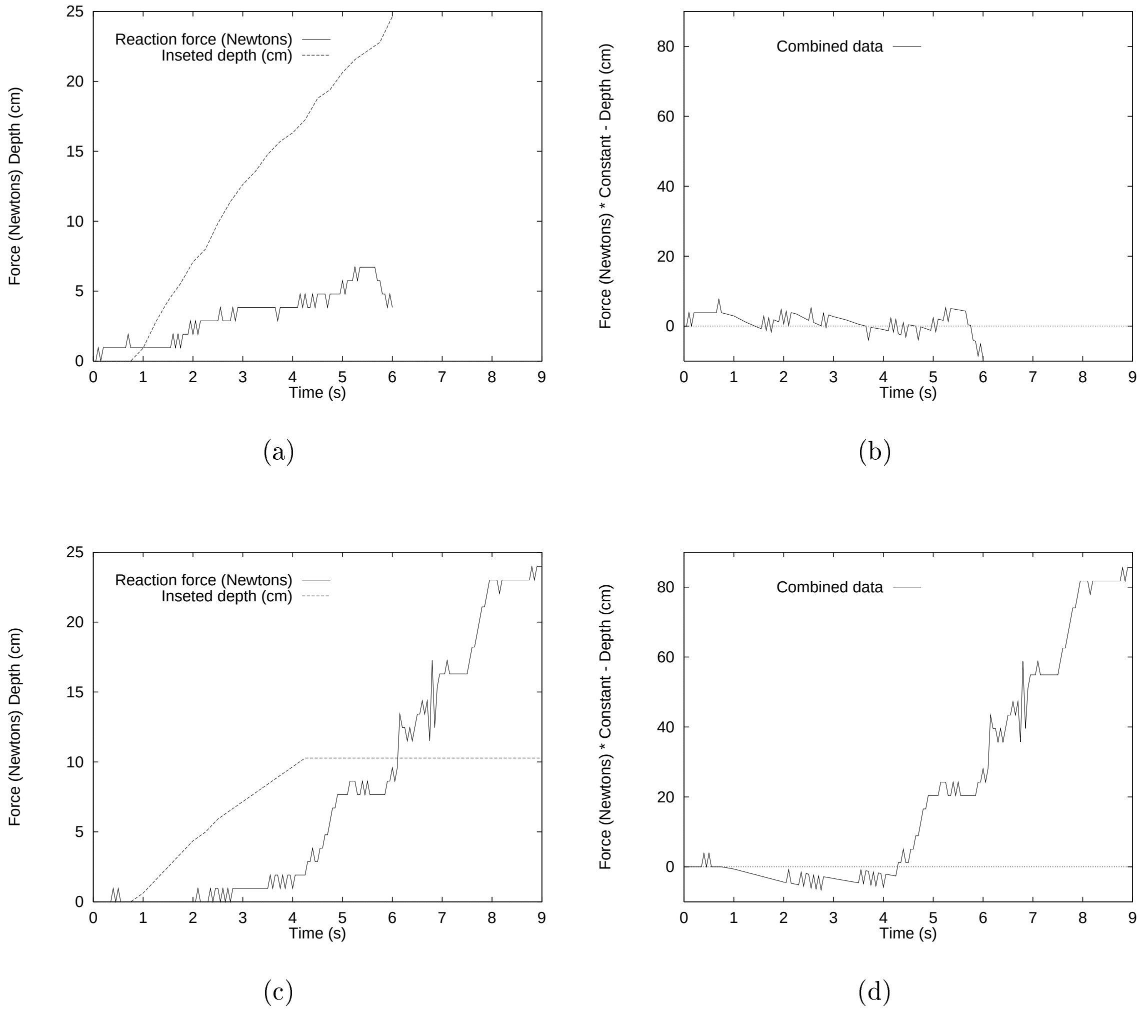


Fig. 2.: Probing tests showing the relationship between force applied and insertion depth. In (a) a test is shown with no obstacle, and the force increases in a roughly linear relationship to the insertion depth (given a constant insertion speed). In (c) the probe encountered a simulated landmine and the probe movement is halted regardless of an increase in the applied force. In (b) and (d) the force and position information are combined effectively demonstrating obstacle detection. Note that the scaling constant used (determined for these terrain conditions) was 4.

further sensors (such as a vibrator tip microphone or sensors capable of measuring translational forces) will be required to provide reliable classification.

It is recognized that the proposed demonstrator system will not address a number of issues which will be of importance to a final system:

1. 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.
2. 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).
3. Control of the mobile platform(s) (i.e. autonomous or remote co-ordinated control).
4. Appropriate 3-D representation of all possible mines for object identification.

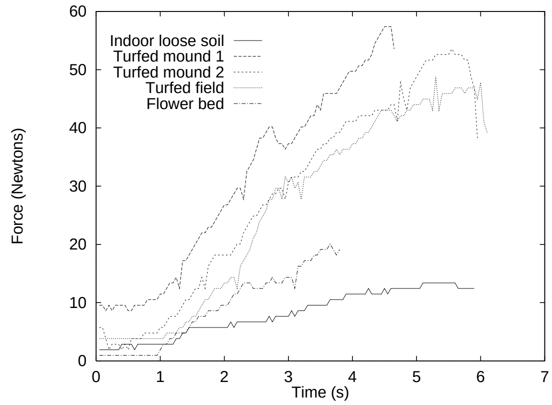
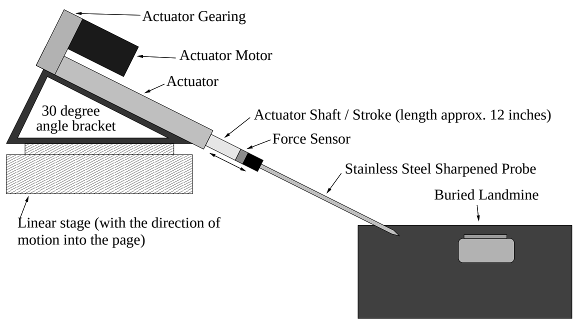


Fig. 3.: Reaction forces of the hand held probe inserted into different ground conditions at roughly the same speed. The relationship between inserted depth (not shown) and axial force recorded is roughly linear but the proportionality constant is dictated by the terrain conditions.



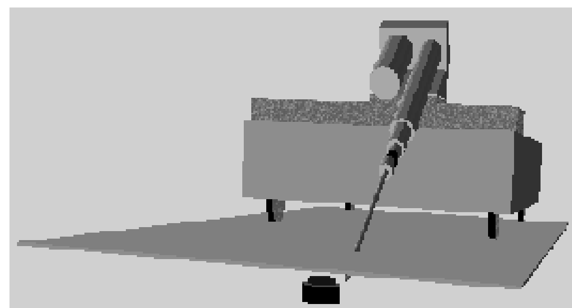


Fig. 4.: Demonstrator design. The probe will be driven into the ground using a linear actuator, which will be moved along a single axis linear stage in order to probe along a 'scan line'. This linear stage in turn will be mounted on a mobile platform, providing motion in the direction orthogonal to the linear stage.

8 Conclusions

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 proposed 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 manual, force measured probing have provided results which indicate that there is potential in the concept of force sensed automated probing. They have also paved the way for further work including the design of a demonstrator system based on a mobile platform capable of systematically probing suspected mine-fields. Future work will concentrate on realising this system and proving the concept that force sensed, automated probing is capable of buried landmine detection and identification.

The authors of this paper would like to encourage others in the robotics and the landmine detection fields to take up this idea (or address issues relating to the development of a final system) as it is believed that this concept has significant potential.

9 Acknowledgements

The authors would like to express their thanks in particular to Commandant Jim Burke and Captain Aidan Dempsey of the Irish Defence Forces for their continued assistance with this research. In addition the authors would like to thank Prof. Albert Bottoms of the Naval Postgraduate School in Monterey, California and Dr. Gerald Roston of Cybernet Systems Corporation for their assistance.

References

1. U.S. Department of State, *Hidden Killers: The Global Landmine Crisis*, Report to Congress, U.S. Dept. of State, Washington, D.C., Publication 10225, December 1994 (See also http://www.state.gov/).
2. *Anti-personnel Mines: An Overview 1996*, International Committee of the Red Cross, Geneva, 1996 (See also http://www.icrc.org/).
3. *Anti-personnel Mines - Friend or Foe? A Study of the Military Use and Effectiveness of Anti-personnel Mines*, International Committee of the Red Cross, Geneva, ref.0654, 1996.
4. *Landmines must be Stopped*, International Committee of the Red Cross, Geneva, ref.0616, 1995.
5. K. Eblagh, "Practical Problems in Demining and their Solutions", Proceedings of the Eurel International Conference on The Detection of Abandoned Landmines, Edinburgh, UK, 7-9 October 1996, IEE Conference Publication 431, pp.1-5.
6. K. Langer, "A Guide to Sensor Design for Lane Mine Detection", Proceedings of the Eurel International Conference on The Detection of Abandoned Landmines, Edinburgh, UK, 7-9 October 1996, IEE Conference Publication 431, pp.30-32.
7. A. Sieber, "Localisation and Identification of Anti-personnel Mines", Joint Research Centre, European Commission, EUR 16329 N, 1995.
8. B. Gros & C. Bruschini, "Sensor Technologies for the Detection of Antipersonnel Mines: A Survey of Current Research and System Developments", Proceedings of the 6th International Symposium on Measurement and Control in Robotics (ISMCR '96), Brussels, 9-11 May 1996, pp.564-569 (See also http://diwww.epfl.ch/w3lami/detec/).
9. A. Craib, "Standards for Humanitarian Mine Clearance Operations", Pre-conference paper at the International Conference on Mine Clearance Technology, Working Group II, Copenhagen, Denmark, 2-4 July 1996 (See also http://www.un.org/Depts/dha/mct/).
10. A. Healey & W. Webber, "Sensors for the Detection of Land-based Munitions", Naval Postgraduate School, Monterey, California, N PS-M E-95-003, September 1995.
11. J. Groot & Y. Jansen, "Remote Land Minefield Detection", TNO Defence Research, The Hague, Netherlands, FEL-94-A205, September 1994.
12. K. Macksey, *The Penguin Encyclopedia of Weapons and Military Technology*, Viking (Penguin Group), 1993.
13. C. Bruschini, B. Gros, F. Guerne, P. Piece & O. Carmona, "Ground Penetrating Radar and Induction Coil Sensor Imaging for Antipersonnel Mines Detection", Proceedings of the International Conference on Ground Penetrating Radar (GPR'96), Sendai, Japan, 30 September-3 October 1996, pp.211-216.
14. R. Chignell, "Ground Penetrating Radar - A Sensor for Mine Detection", Proceedings of the Eurel International Conference on The Detection of Abandoned Landmines, Edinburgh, UK, 7-9 October 1996, IEE Conference Publication 431, pp.103-108.
15. H. Hambric, "New Approaches to Mine Detection", Pre-conference paper at the International Conference on Mine Clearance Technology, Working Group IX, Copenhagen, Denmark, 2-4 July 1996 (See also http://www.demining.brtrc.com/).
16. S. Brink, "Bofors Schnauzer - A Biosensor for Detection of Explosives", Proceedings of the Eurel International Conference on The Detection of Abandoned Landmines, Edinburgh, UK, 7-9 October 1996, IEE Conference Publication 431, pp.103-108.
17. I. Carter, G. Bryant, M. Le Fevre & W. Wong, "Moisture and Landmine Detection", Proceedings of the Eurel International Conference on The Detection of Abandoned Landmines, Edinburgh, UK, 7-9 October 1996, IEE Conference Publication 431, pp.83-87.
18. K. Spouse, "The Detection of Buried Plastic Landmines by Electro-magnetic Induction", Proceedings of the Eurel International Conference on The Detection of Abandoned Landmines, Edinburgh, UK, 7-9 October 1996, IEE Conference Publication 431, pp.72-74.
19. R. Frost, R. Appleby, S. Price & F. Nivelle, "The Detection of Mines using RF/Millimetric Radiometry", Proceedings of the Eurel International Conference on The Detection of Abandoned Landmines, Edinburgh, UK, 7-9 October 1996, IEE Conference Publication 431, pp.92-96.
20. R. Mons, "Transformer UUV for Surf Zone MCM", Proceedings of the Autonomous Vehicles in Mine Countermeasures symposium, Naval Postgraduate School, Monterey, California, 4-7 April 1995, pp.7.22-7.36.
21. J. Nicoud & P. Machler, "Robots For Anti-personnel Mine Search", Control Engineering Practice, Vol.4, No.4, 1996, pp.493-498.
22. J. Nicoud, "A Demining Technology Project", Proceedings of the Eurel International Conference on The Detection of Abandoned Landmines, Edinburgh, UK, 7-9 October 1996, IEE Conference Publication 431, pp.37-41.

23. H. Greiner, C. Angle, T. Freed, R. Elsey, & G. Bane, "Autonomous Legged Underwater Vehicles for Near Land Warfare", Proceedings of the Autonomous Vehicles in Mine Countermeasures symposium, Naval Postgraduate School, Monterey, California, 4-7 April 1995, pp.8.14-8.22.
24. M. Tilden, "Biomorphic Robots as a Persistent Means for Removing Explosive Mines", Proceedings of the Autonomous Vehicles in Mine Countermeasures symposium, Naval Postgraduate School, Monterey, California, 4-7 April 1995, pp.7.57-7.61.
25. G. Royston & C. Jacobus, "Walking Robots for Mine-field Detection", Proceedings of the Autonomous Vehicles in Mine Countermeasures symposium, Naval Postgraduate School, Monterey, California, 4-7 April 1995, pp.8.86-8.99.
26. J. Trevelyan, "A Suspended Device for Humanitarian Demining", Proceedings of the Eurel International Conference on The Detection of Abandoned Landmines, Edinburgh, UK, 7-9 October 1996, IEE Conference Publication 431, pp.42-45.
27. T. Williams & K. Dawson-Howe, "Hand-Held Force Probing Experiment", Internal Technical Report, Dept. of Computer Science, Trinity College, Dublin 2, May 1997, (Available at http://www.cs.tcd.ie/kdawson/manrep.ps).

This article was processed using the TEX macro package with SIRS97 style