An Alternative to the 99.6% Demining Standard

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Summary

This paper is a draft for discussion and is not to be released to third parties without the consent of the author. Comments are welcome.

This paper shows how the probability of detecting mines could be directly and reliably measured by inserting known targets into suspect land before (or during) mine clearance. The number of targets discovered by the deminers can indicate the quality of their clearance efforts. Practical implementations of this could provide a basis for a new standard for manual mine clearance to replace the current 99.6% UN standard which cannot be verified or complied with.

The new method seems to be less expensive than current quality assurance methods and more reliable.

1 The Need for a New Standard

Paddy Blagden (1999) attributes the 99.6% clearance standard to himself. He once estimated that it would be sufficient to remove 249 out of every 250 mines likely to be found along every 3 km along an 80 km stretch of a road in southern Africa. This would be an acceptable reduction of risk for road users. A long time later when the 80 km of road had been cleared, a total of only 50 mines had been found. However, by then the 99.6% was well on the way to being enshrined in the first UN standards for mine clearance.

The UN standard for humanitarian demining calls for mine clearance to be 99.6% of the specified level appropriate for the land use. Usually the specified level is complete clearance of all mines.

This figure now governs many mine clearance operations around the world and is specified (or referred to) in countless contracts and work programmes. Yet it cannot be verified or enforced because:

i) The number of mines originally placed in the minefield is almost always unknown, so it is impossible to know if any mines have been missed.

ii) The job of inspecting a completed mine clearance task to verify compliance with the UN standard to, say, a statistical level of 95% certainty would require much more work than the original clearance task. Typically 10 - 20% of the completed area is checked independently after clearance , and this cannot provide a statistically reliable assessment of the clearance level achieved. If, say, two mines were missed, the chance of finding either of them after inspecting 10% of the cleared area is quite small.

There is, therefore, a need to establish an alternative standard for clearance which:

- can be specified in a work contract and can be reliably monitored during and after completion of the work,
- provides acceptable standards for humanitarian mine clearance, and,
- is soundly based on known engineering principles.

Compliance with quality standards has become an issue in several demining programmes. In Afghanistan, there have been concerns that pressure to clear more land has led to a decline in clearance quality. Demining teams are being judged on average area clearance rates without taking the work input needed into account. Teams which have to take time to deal with high metal fragment contamination levels feel they are being unfairly treated. In Bosnia and Croatia, some demining organisations are thought to be working too fast and some minefield accident investigation reports have suggested that non-compliance with standing operating procedures may be the result of commercial pressure to cut costs.

Some organizations interpret the 99.6% clearance rate as 'complete clearance' over 99.6% of the area specified for clearance. If a missed mine is found, then it follows that it must have been in the 0.4% of area missed.

There is also some concern that the current practice of ensuring (as far as possible) complete clearance of all explosive devices may not be appropriate for all demining tasks. For example, the use of demining machines has been controversial because it is well known that no machine, by itself, has yet been able to achieve 99.6% clearance level in neutralising or destroying mines and other hazardous objects. Yet these machines may offer a vital resource in 'risk reduction' where complete mine clearance is not economically feasible. However, this approach is not feasible while the current UN standard remains.

2 Achieving quality in demining

The principles of achieving quality in production or construction work have been well understood for many years and have been successfully applied in many industries. A series of international standards (ISO 9000 series) have been agreed and many companies now use compliance with these standards to promote their reputations. Many demining organisations are making concerted efforts to maintain high quality standards. However the absence of appropriate standards for demining allows other organisations to compromise the safety of their own deminers and endanger the people who will use the land they clear.

The best current practice in demining relies on achieving clearance quality by:

a) Ensuring that deminers follow correct procedures, and

b) Ensuring that equipment operates correctly.

We have learned that compliance with operating procedures requires good initial training, refresher training, daily reviews on-site, appropriate motivation and understanding, appropriate work values or ethics, independent on-site inspections, and constant supervision.

Equipment performance is easier to establish and can often be readily tested in the field. For example, metal detectors can be checked with 'test targets' or 'calibration targets', or less formal techniques such as detecting the metal eyelets in the deminer's boot. High quality maintenance support is also essential in achieving good equipment performance.

Working with mine detection dogs introduces new requirements. Many deminers have come to accept that dogs always work reliably and seldom question their performance. However poor results in Bosnia have raised questions on dog performance across many demining programmes. Dogs can be tested in the field, however, and several demining organisations do this as part of their normal procedures.

Thus the principle means of ensuring quality in mine clearance is to ensure that the 'process inputs' (procedures and equipment) are correct.

The main difference between demining and other engineering processes is that it is not easy to measure the quality level which is actually achieved by following these procedures. A mine or tripwire which has been missed is usually invisible. It is most likely to be discovered when a deminer steps on it, and may kill or injure nearby personnel as well.

The current methods used to detect missed mines include:

a) Repeat the clearance using original technique (e.g. metal detector and prodder).

b) Where all metal has been removed during mine clearance, checking with a metal detector alone should be sufficient.

c) Use a dog to check the area cleared by deminers (some time later).

d) Use a machine (e.g. flail) to check the area (used in Jordan).

In Afghanistan, deminers often run over the area they have cleared or play football to re-assure villagers that the land is clear. However this is not appropriate if missed mines are a real possibility.

2.1 Measuring Outcomes

In almost all other industries for whom quality has been a serious issue, the key to maintaining quality has been to collect measurements to check the outcomes of the process. Only by measuring outcomes can quality levels be guaranteed. Further, measurement of outcomes allows a process to be improved or made more efficient, and the resulting quality improvement (or decline!) can be measured.

We have already seen how measuring outcomes in demining is currently difficult and sometimes fatal.

> What new measurements could be introduced into demining processes to monitor quality without compromising safety?
>
> What are the process variables which affect the outcomes?
>
> What needs to be measured to ensure appropriate outcomes?
>
> What are appropriate outcomes?

These questions lead to some interesting conclusions and possibilities.

2.2 Right first time

Experience in many industries has shown that the key to high quality standards lies in performing the process correctly rather than in detecting and rectifying mistakes later. No amount of quality control checking can improve the outcome if the work was not done properly the first time. Production workers maintain higher quality standards when they receive immediate and direct feedback on the results of their work.

For instance, in a process making aluminium alloy wheels for cars, it is better to provide the casting workshop with expensive equipment for detecting flaws and holes in the cast metal. The original practice was to provide this equipment only to a quality inspection department which examines the finished wheels before they leave the factory. Because the casting workers see the results of their work, they take more responsibility for ensuring that every wheel leaves the casting workshop free of defects. This saves the work needed to machine and polish the wheels which later turn out to have flaws in them.

This means that the most effective way to improve or maintain quality standards is to provide immediate feedback on quality to the deminers. In this paper we describe a method for measuring quality which is easy to use and can provide almost immediate feedback to the deminers.

3 The Process

We need to review the demining process to answer the questions posed in the previous section. This may seem tedious and pedantic but it is necessary to define the process variables and deduce ways to measure them.

We need to define concepts and variables with care. The demining community tends to use words such as 'clearance' and 'productivity' in many different contexts, and here it is essential to use terms carefully to avoid mistaken arguments.

I will use the following terms and definitions:

> Process: all work activity which is part of mine clearance task.
>
> Production: area cleared (square metres per hour: sq. m/hr).

Productivity: area cleared in relation to resources used for specified process.

Missed mine: mine which is not detected and removed by clearance processes.

Detection probability: probability that mine or other device (possibly specified) will be detected by a specified process.

Quality: Probability that all dangerous devices have been destroyed and/or removed from the minefield.

Outcome: measurable result of process which contributes to mine clearance.

Appendix 2 sets out many of the process variables which affect the two main outcomes: detection probability, and production. The table is entirely qualitative, but indicates the large range of variables which affect what seems at first to be a simple process, and their likely effect on outcomes. The headers in the table are defined as follows:

'Variable'	Aspect of process which may change.
'Units or Definition'	Units of measurement, or, description of the variable aspect which may not be measurable in terms of simple physical units.
'Measurable? If so how?'	Describes how variable aspect can be measured.
'Controllable?'	Indicates whether the aspect is controllable to compensate for effects on the outcomes, and if so how that control is effected.
'Effect on outcome (missed mines)':	describes likely effect of this aspect of the process on the probability of missing a mine, if known.
'Effect on outcome (production per day)'	describes the likely effect of this aspect of the process on the rate at which work is completed.

3.1 Need for direct measurement of detection probability

It is clear from the table that many aspects of the demining process could be measured, both to understand what is happening, and to improve the consistency of the work. However, all the measurements are indirect in the sense that there is no direct connection between most of the variables being measured and the principal desired outcome: no missing mines.

We can use cooking as an analogy. We can carefully weigh all the ingredients for a cake, and carry out measurements on the equipment needed: a mixer and an oven. We could ensure that all the ingredients are purchased from reputable suppliers and are brands with consistent quality. We could even carry out measurements on the ingredients to check for any variation from one batch to the next. We can precisely control the mixing times and speeds, the oven temperature, and even the placement of the cake in the oven. Yet none of these would guarantee that the cake turns out perfectly. For that visual inspection is needed through the oven window, and a skewer needs to be inserted to see if it is cooked through the middle before removing it. Finally we will only be satisfied if the taste and consistency of the cake comes up to our expectations.

In the same way, we can only be sure of maintaining a satisfactorily low probability of missing a mine if we can measure the outcome directly, or as directly as possible. Direct measurement (finding missed mines as described above) is hazardous, slow, and requires too much work to obtain a large enough sample to have confidence in the measurement.

3.2 Using known targets to measure detection probability

We could overcome this problem if we insert known targets into the suspect land before or during the clearance process such that these will be detected as a result of the clearance process. Although this is not a direct measurement of missed mines, we can devise the targets such that they are more difficult to detect than the mines and we can insert enough for the measurement to be statistically significant.

There are two aspects of mine clearance quality which can be measured in this way:

- Whether deminers miss areas of ground
- Whether deminers maintain the required detection depth

Different target strategies are needed for these aspects. Shallow targets which can be easily detected will help to confirm that all the ground is being checked. Deeper targets which are more difficult to detect will tell us if we are maintaining the required clearance depth.

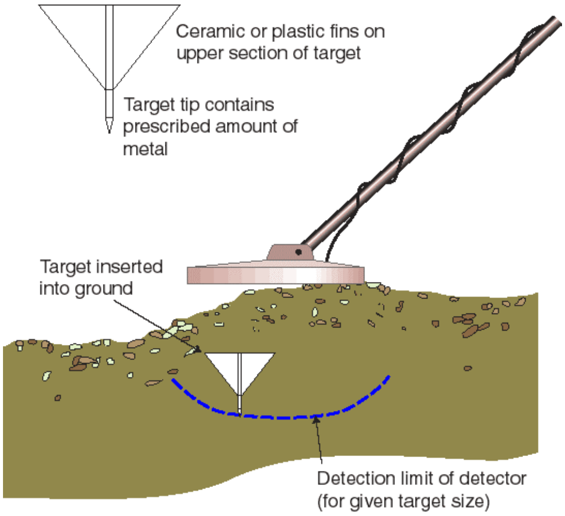

Figure 1: Target for measuring detection probability. Target can be detected by probing or metal detector.

Take, for example, the metal detection & prodding process of demining. (See later sections for discussion of dog techniques.) This is widely used in many countries. Small targets, as shown in figure 1, can be inserted into the ground. The upper part of the target is large enough to be detectable by probing, though it is smaller than mines are so that the detection probability is less than for mines. A piece of metal is built into the base of the device so that it can be detected by metal detectors, but is more difficult to detect than the mine with the least amount of metal found in the region when buried at the maximum specified depth. The target would be harmless to the environment if it is not detected during clearance. The positions of the targets would be known to the test administrator beforehand, but not to the deminers performing the work.

At demining sites where each metal target is visually investigated (ie excavated and checked) simple metal targets can be used, without the fins shown above.

This method represents a significant improvement over searching for missed mines.

i) The number of targets can be large enough to produce a statistically significant result without increasing demining costs significantly.

ii) The procedure can be used internally by a demining organisation (even down to team or platoon level) to improve its techniques, or equally by an independent agency to monitor demining standards.

iii) While the discovery of each target causes extra work for a deminer, the number needed can be quite small compared to the number of false alarms usually found in minefields.

iv) Feedback to the deminers is almost immediate so that field procedures can be altered if targets are being missed by deminers. Targets must be numbered and their positions recorded so that individual deminers can monitor their performance.

v) As experience increases, deminers will have more confidence in their work if they know they are meeting appropriate standards.

vi) Finally, the different targets need to be used for different types of mines. If the risk of finding minimum metal mines is extremely low, then targets with a higher metal content could be used. This should allow demining procedures to be adjusted to the nature of the task with the confidence which direct measurement provides.

We shall now discuss some practical ways for inserting known targets into the minefield to measure detection probability.

3.3 Inserting targets

For the conventional metal detection and prodding process used in most countries, targets can be inserted into the ground using a number of techniques:

a) Skilled and experienced deminers administering the test can enter uncleared areas using metal detectors and temporary markings. Since a network of safe lanes is needed for any mine clearance task, targets can almost always be inserted only a short distance from existing safe lanes.

b) Mine resistant vehicles could be used (if available) to access uncleared land, with a target insertion device powered by the vehicle. The target is designed such that insertion leaves minimal evidence on the surface of the ground. However the tracks left by the vehicles may be visible for some time afterwards.

c) If the vegetation has been cleared by a machine, the targets can be inserted as the vegetation is cut.

d) Targets could be inserted by a portable, remotely operated machine in areas where vehicles cannot access the uncleared areas. Access is available from the safe lanes normally prepared in any demining operation.

Of course, with methods b) c) and d) there is a small risk that a target will be inserted directly over a mine, setting it off. This must be taken into account in designing the insertion equipment. The insertion device should not generate enough force to set off an anti-vehicle mine.

The insertion device will inevitable leave some trace that a target has been placed in the ground. However, this should normally be invisible, even in thin vegetation.

Some terrain types pose greater problems.

Inserting targets like the one shown in figure 1 into very hard or stony ground (common in Afghanistan) is practically impossible. However, in Afghanistan all metal pieces are removed from the minefields so the top part of the target could be omitted and just the metal target inserted. Experiments in Pakistan have shown that this is a practical alternative.

Very thick vegetation which is currently cleared by hand, or steep slopes may make access for target insertion almost impossible. In these circumstances an alternative approach could be used. Targets could be inserted into small sections of *cleared* areas and clearance repeated on these areas. This would not be as realistic as using targets in uncleared areas, and would cost some additional time, but would still provide some assurance that the detection process is adequate. In this case it would be feasible to ensure there is no evidence of target insertion visible.

3.4 Measuring outcomes for dogs

The discussion, so far, has concentrated on measuring the detection probability outcome for manual demining: metal detection, probing and prodding in different combinations. The targets are designed to be detected in these ways. Clearly, different measurements of outcome are needed for dogs and machines.

In essence, a dog is used to find the 'first' explosive vapour traces in a defined area. In Croatia, a 10 metre square box is the defined area. Once a single explosive target has been detected by a single dog, the box is searched using manual demining methods. Two dogs must check a box without indicating explosive for the box to be declared safe. In Afghanistan, a dog indication initiates a manual search of a 2 metre square zone around the indication. Again two dogs must traverse each search area (8 metre wide rectangles) along lines about 60 cm apart for the area to be declared safe.

Tests in Bosnia have shown that dogs do not indicate explosives all the time. On one particular test site set up by Norwegian Peoples Aid near Sarajevo, on a hillside with heavy clay soil, dogs have even failed to find slabs of TNT buried with one corner exposed to the air. This suggests that the amount of explosive vapour in the air and the dog's ability to sense it may be affected by several factors:

i) Amount, type, age of explosive, impurities with explosive (mine factors)

ii) Depth below soil surface and length of time in soil (placement factors)

iii) Soil permeability to vapour and moisture (soil physics)

iv) Soil particle adsorption and biochemical absorption of explosive vapours (soil chemistry)

v) Water flow over and through soil, and explosive solubility in water (soil hydrography), soil surface slope.

vi) Rainfall, wind. (Climate effects)

vii) Surface vegetation which may store explosive vapour in roots and/or transport vapour to surface leaves. Also distracting scents emitted by surface vegetation or soil organisms (could be seasonal or diurnal). (Surface vegetation effects)

viii) Surrounding vegetation which may store explosive vapour in leaves or emit distracting scents (could be seasonal or diurnal).

ix) Site contamination by humans or animals.

x) Dog or handler behavioural issues, sensitivity to climate or terrain factors.

These can be grouped as follows:

a) Factors which determine available concentration of vapour in the air above the soil.

b) Factors which determine how easily the dog can sense the vapour which is present.

Type a) factors will also affect any explosive vapour sensor which might be developed. Type b) factors would not necessarily affect such a sensor, but there are likely to be other type b) factors (of limited degree hopefully) which will affect any given type of sensor.

The closest analogy to the 'known target' measurement method, then, is to insert targets containing known amounts and types of explosive into safe ground as close as possible to the working area for the dogs. Precautions will be needed to ensure that human or machine scents do not contaminate the targets. The targets will have to be left for long enough so the dogs cannot sense ground disturbances. The dogs can then be tested on these known targets before or after clearing boxed areas.

Methods along these lines are already being used by some companies in Croatia (ABC for instance).

3.5 Measuring outcomes for machines

Mechanically assisted demining, as currently applied in Croatia and Bosnia, uses machines for either ground preparation (vegetation cutting) or ground beating or milling. In the former case, mine detection outcomes are not relevant because dogs or manual demining are used subsequently. A vegetation cutting machine may be useful for inserting known targets into the ground, as noted earlier.

A ground milling machine is designed to break up mines and render them harmless. Their use is controversial because they do not destroy and neutralise all devices under all conditions. Depending on the design, they may bury dangerous devices deeper than before.

Ground beating flails have been used for cutting vegetation, but they are also effective in activating or breaking up mines.

Apart from cutting vegetation, a machine is, in essence, reducing the risk of using the land it processes. By activating, destroying or disrupting mines, the machine eliminates some or all of the hazards to people.

What then, is an appropriate outcome measure for mechanical demining? It can be argued that risk reduction is the most appropriate outcome. By using appropriate sampling techniques, this could be measured and quantified. If we then look at demining as a risk reduction process in itself, we could then easily build in measures of machine performance. However these issues are well beyond the scope of this paper.

For the time being, manual demining or dogs are always used after mechanical clearance. Therefore, methods for measuring performance in these methods will cover the issue of mechanical clearance.

4 Initial Experiments

We performed some experiments to explore some of the problems which might arise in using known targets. This led to a small simulated field test performed by two Afghan deminers in Islamabad, Pakistan, on very hard ground conditions similar to Kabul and many other parts of Afghanistan (Trevelyan 1999a). The test results were surprising and interesting.

Hameed and Ali Research Centre staff prepared a 6 metre by 3 metre test area and located 8 unidentified metal targets in the ground before the test. They used a standard Schiebel metal detector on issue to Afghan deminers.

41 numbered targets were inserted into a test area 3 metres by 6 metres. The target positions were planned by a computer program such that the positions were random and the depths also random, but with a special distribution to resemble the distribution of metal fragments and mines. Most of the targets were shallow, with a significant number at depths ranging up to the maximum detection depth of the detector. The

targets were pieces of 3mm thick mild steel 25 mm square, inserted into the ground with a simple tool such that no trace of the insertion was apparent to the deminers. The ground was very hard with stones, and we were surprised that a 2 kg hammer and simple insertion tool worked so well.

The maximum detection depth for the targets was measured independently. A target was suspended inside a vertical plastic tube forming a well about 300 mm deep. The target was raised or lowered until it was only just detectable with the Schiebel detector.

The deminers were asked to mark clear the test area using "normal" working procedures. At first they were not working carefully, as they thought the area was not dangerous. They were asked to consider it as dangerous, and then appeared to follow well-controlled procedures. Casual discussions with the deminers confirmed that they were following normal field procedures, but not all aspects of the SOP's. However, the trial results revealed many serious mistakes.

4.1 Summary of Results

The trial procedure was followed successfully, but several detailed aspects need careful attention. One recording mistake was discovered. The target depths were different to those originally intended. The deminers found 12 metal items which were not test targets. The test was administered by staff with training and background comparable to demining team supervisors.

The trial revealed several procedural failures by the deminers. Four targets were missed out of 41 inserted into the test area. Three of these were much shallower than the maximum detection depth. One was near the surface and should have been easily detected. However this was located at the end of the first day's work, and was missed the next day. One target at the edge of a lane was missed on the first day, but found on the second day. The targets contained significantly less metal than a PMN mine (the most common in Afghanistan).

The extent to which the trial revealed procedural failures was surprising, given the relative simplicity of the trial procedure, and the obvious nature of the test targets. The deminers had 16 years experience between them, and seemed to be following procedures carefully.

The map (figure 2) shows the sequence in which targets were discovered. It reveals poor control of lane width (which should be 1 metre) and other more subtle failures. For instance, after target 42 was found by Deminer A, Deminer B went forwatook over and found target 44. After he had completed his 20 minute spell, Deminer A resumed and found target 41, well behind target 42. This seems to suggest that their control over the ground marking was poor, particularly when handing over to each other. The two deminers do not normally work together though.

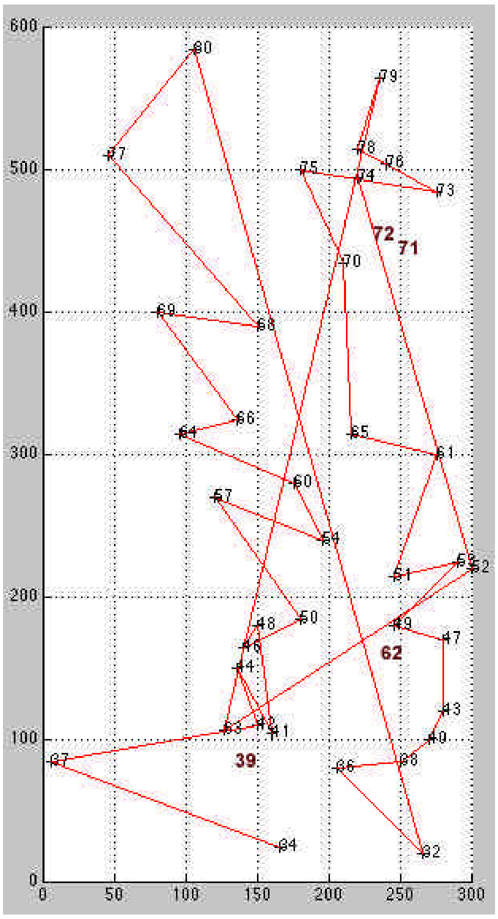

Figure 2: Map of trial with deminers showing sequence in which test targets were found. Targets 39, 71 and 72 were missed and were well within the maximum detection depth. The sequence reveals many errors (refer to text).

Interestingly, the deminers found several deep targets on the second day. However, these were close together and may have produced a stronger signal, almost continuous. Interestingly there is no strong relationship between the depth of the target and the time required to find it. This may be explained by variations in the ground conditions.

This test was only intended to explore some of the practical difficulties with this method for quality measurement. It has shown that this test could have several applications.

First, the test could be used as an 'examination' for training courses as it tests not only the individual deminers but also their teamwork and coordination.

Second, the test can be used (perhaps on a larger scale) for assessing demining teams, even if administered on safe ground. If a demining team performs well in the test, but works at a rate far less than they achieve in the field, one could question their quality performance at the higher working speed. Alternatively, one could insist that the test be completed within a standard time corresponding to their rate of progress in the field.

Finally, the testing technique could be a valuable approach for evaluating metal detectors. Current approaches for metal detector testing seem to be rather 'ad-hoc' and a more systematic approach could be valuable.

5 Target Detection Probability

5.1 Measuring Area Coverage

One obvious way in which mines can be missed is that certain areas of ground are not checked by the deminers. Analysis of demining accidents suggests that mines close to lane boundaries are more likely to be missed, for example.

Inserting shallow targets into the ground in a manner similar to the trial described in the previous section will help to monitor this. Clearly, the more targets inserted, the more likely they will reveal areas not covered by the deminers. However, the work required to insert the targets and record the results increases in proportion.

Since it is not feasible to insert large numbers of targets, we cannot be certain that we will detect small areas which may be missed by deminers. Therefore, we need to examine the theory of random events to understand what it is possible to measure using this kind of approach.

5.2 Random Events

The previous discussion suggests that by counting the number of known targets recovered during mine clearance, relative to the number originally inserted, we can measure the target detection probability resulting from the mine clearance process. In this section, we look at quantitative methods to decide how we can set statistical requirements so we can have confidence in the measurement.

We assume that finding a target is a random event with a probability P. For instance, if P is 0.1, the probability of the event occurring in any test is 1 in 10.

We can simulate random events using a standard computer package such as MATLAB. The function 'rand' generates a uniformly distributed random number between 0 and 1. By selecting a portion of this range of size P and calling this function repeatedly, we can simulate an event with probability P. If the value provided by the random number generator falls within the range, the event is deemed to have occurred.

We could also approach this analysis using the mathematics of the Poisson distribution. However, the simulation approach is equally valid, and perhaps easier to follow.

Let us assume that P_d is 0.04, for example. If we repeat the experiment 500 times, we would expect the event to occur 20 times (ie 500 multiplied by the probability 0.04). This is similar to tossing a coin where the probability of 'heads' is 0.5. If we toss the coin 500 times, we would expect it will land heads up 250 times. Of course, this rarely occurs: on one day we might get 279 heads, another day we might get 223, another day we might get 243 and so on. In other words, the actual number of times a random event occurs in a given number of trials will vary.

We want to understand the likely distribution of results in such trials. Figure 3 shows the result of simulating the simple experiment (ie 500 tests of an event of probability 0.04) repeated 2500 times.

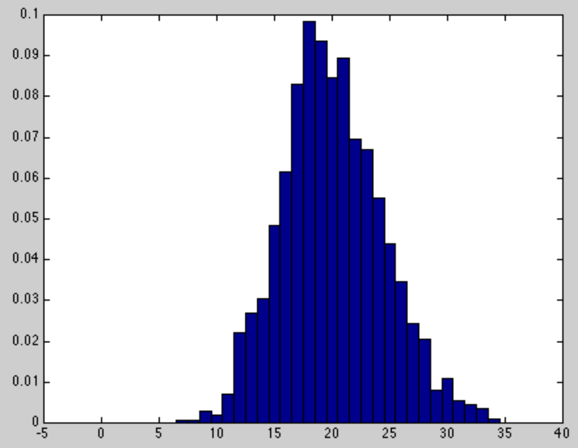

Figure 3: Histogram result from 2500 simulated experiments when we expect a random event ot occur 20 times. Most of the time, the count is between 12 and 27, but is as low as 6 and as high as 34. The vertical axis has been divided by the total number of trials to normalise the graph.

The methematical distribution is called a 'Poisson' distribution and is a key concept in statistical quality control theory.

5.3 Statistical Confidence

In a practical situation, we will count the number of targets found, and we need to estimate the detection probability which is unknown. Let us now assume that we run one experiment like the one described above, but we don't know what the probability *P* of the event occurring: we will use the result of the experiment to estimate *P*.

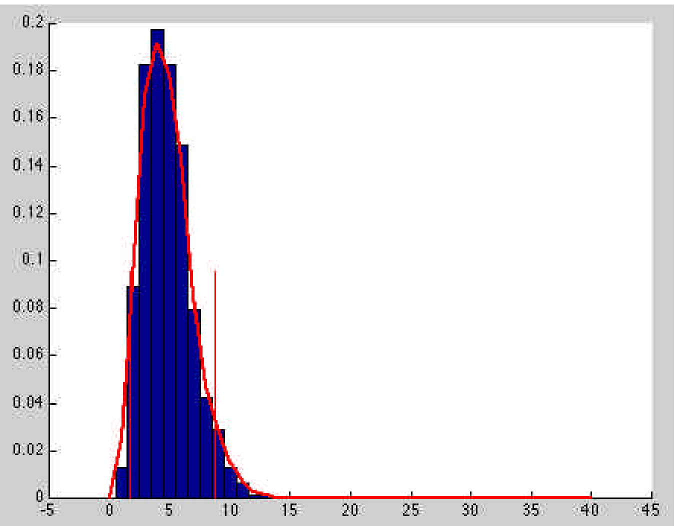

Figure 4: In 40 tests, the random event occurred 4 times. From 2000 simulations of this test, we construct the distribution above which shows the probability that this result could have occurred when the expected value was 0, 1, 2, 3, 4 … etc.

We can simulate the experiment a very large number of times to determine, for expected outcomes of 0 to 40, the chances that the result turned out to be 4. Needless to say, if the expected outcome is zero (i.e. *P* is zero) the result 4 does not occur at all. If the expected result is 10, the result 4 only occurs a very few times.

Thus, from all this data we can decide how high or low *P* could have been to give the result of 4. Here we have to decide how certain we want to be. Let's suppose we are happy with 95% certainty. (100% certainty is unrealistic). The vertical red lines in figure XX show the 95% confidence limits (1.6, 8.8 respectively). These tell us that we can be 95% certain that *P* was less than 8.8/40 (0.22) and we can be 95% certain that *P* was greater than 1.6/40 (0.04).

If we wanted to be more certain, we can use the same data , but we can find where the 99% confidence limits are. These turn out to be 0.02 and 0.27 respectively.

5.4 Detection depth

We can now apply this type of thinking to the problem of detection depth. This is a different problem to that of detecting missed areas. Here we are concerned ensure that we can reliably detect mines to the specified depth.

So far we have only discussed 'random events' without considering the problems of detection. A metal detector has a limited detection depth determined mostly by the target size, coil diameter and the sensitivity of the electronic circuits. The following graph illustrates the effect of target depth on signal strength: increasing the target depth by about one third the coil diameter reduces the signal strength by about 10 times.

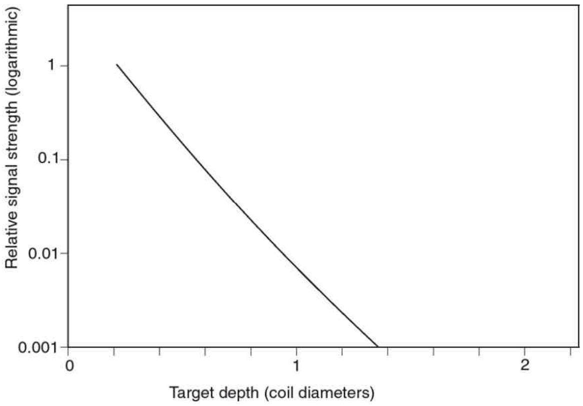

Figure 5: Effect of target depth on signal strength (calculated) for a certain metal detector.

We can, therefore, suggest that a graph of target detection probability and target depth (for a given type of target) should look like the following graph.

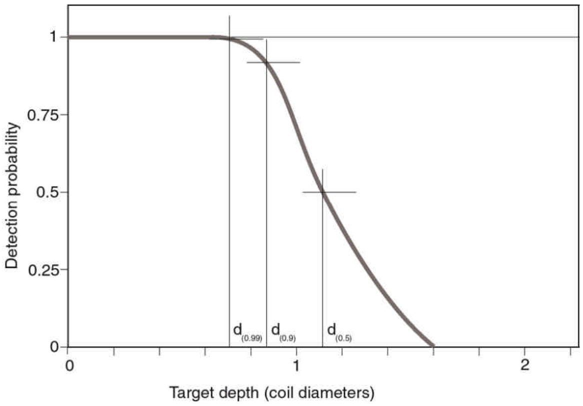

Figure 6: Target depth and detection probability for a given type of target (suggested).

The steep reduction in detector sensitivity with depth will result in a sharp decrease in detection probability with depth. The graph shows that (for this particular notional target) detection is almost certain at depths less than $d_{(0.99)}$. Why is there not a sharp cut-off at the maximum detectable target depth? The reason for this is that we have included the effects of different operators in this concept of detection depth. An operator has to swing the detector head slightly above the ground level, the ground is uneven, and the detection depth depends on the position of the target relative to the coil as well (see figure 1 earlier in the paper). A substantial series of measurements will be needed to quantify this graph for particular detectors.

The characteristic curve will also depend on ground conditions, the orientation of the mines, and other effects. Testing is needed, again, but these are secondary effects as we shall see.

Although the graph has been constructed for metal detectors, a similar graph could be constructed for the probing method of mine clearance which is used when there are too many metal fragments for metal detectors to be effective.

A further point is that we are not (in this case) able to detect this kind of mine reliably with this detector at depths greater than 0.6 coil diameters. Note that this figure is notional: the characteristic curve is an educated guess at the moment which needs to be substantiated with experiments.

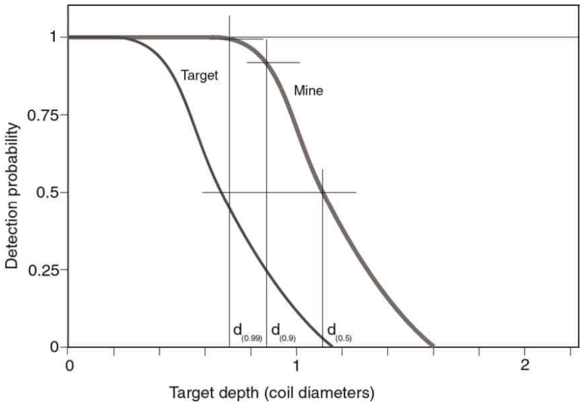

Figure 7: Target depth and detection probability for a target and a mine of given types.

The next graph (figure 7) shows, in addition, an estimate of the detection probability for different depths of a target designed to be harder to detect than the particular kind of mine we have chosen. The detection probability of the target is only about 0.5 at a depth of 0.6 times the coil diameter implying that we will miss half the targets if they are placed at this depth.

Let us now assume that we insert 40 targets into the ground at 0.5 times the coil diameter, at which the detection probability is about 90%.

Let us suppose that during clearance, we manage to find 25 targets which is substantially less than the 36 out of 40 predicted. What conclusion can we draw from this?

From our statistics calculations (similar to those discussed above) we can conclude that the detection probability lies between 0.43 and 0.71 (95% confidence limits). Looking at the graph in figure 7 above, we can see that the if the target detection probability were about 0.43, the mine detection probability would be about 0.99. Thus, we can use this method to estimate the detection probability for the mines, even though we do not know how many mines there are.

If we found 36 out of 40 targets as predicted, the 95% confidence limit gives a target detection probability of 0.78. The graph shows that this is well within the 'certainty' range for mine detection.

Since we took care, in the first instance, to place the targets at a depth at which the detection probability is 90%, why would the number of targets found be significantly less than 36 out of 40? This reduction in detection performance could reflect ground conditions, failures by deminers to follow procedures, or one of many other possible factors. However, by designing targets in the manner suggested, the effect on mine detection performance will be similar to the measurable effect on target detection performance. Therefore we can conclude that if target detection performance is degraded, mine detection performance will also be degraded.

However, if there are mines deeper than the 99.9% detection depth for the detector we are using, then we will certainly miss some of them. The proportion we miss will depend on how deep they are. The quality measurement method we are proposing here will only ensure that the demining performance is as good as it can be, given the performance of the detection equipment.

5.5 How many targets are needed?

Doubling the number of targets from 40 to 80 has a slight effect. Assuming that we find 46 out of 80 targets (corresponding to 23 out of 40 above), the lower 95% confidence limit on detection probability is 0.46 (instead of 0.43). Therefore we have a slight improvement in measurement accuracy at the cost of doubling the effort in laying targets, finding them, and recording them.

If we use only 20 targets, the lower confidence limit turns out to be 0.37 which is a significant reduction in certainty. Therefore, one can conclude that about 40 to 50 targets are needed for reasonably accurate measurement. However this result depends on experiments which will hopefully confirm the detection probability characteristics we have assumed for this analysis.

5.6 A post-script on 99.6% clearance - what can we measure?

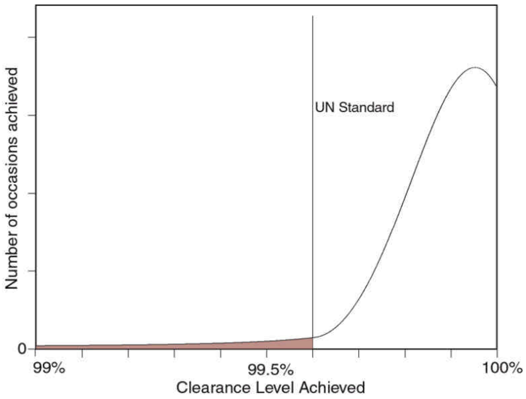

Figure 8: Achieving 99.6% clearance performance?

Figure 8 illustrates what we would hope is current achievement in mine clearance performance: the clearance standard approaches 100% even though we cannot actually measure this. On some occasions mines are missed and we discover this when deminers have accidents or when civilians use the land later. Given that typical minefields contain no more than 20 - 50 mines in many theatres, a single missed mine significantly reduces clearance performance. This shows as the long shaded tail in the distribution of results shown above. Needless to say, the 'normal' performance has to be much better than 99.6% to achieve the UN standard more than 95% of the time.

Typically, some form of independent quality control check will be performed on 10-20% of the minefield area, either by team supervisors or an independent agency. (We also know that some deminers use their detectors to check their lanes as they walk to and from their work.) What can random event statistics tell us about the effectiveness of this kind of quality control check?

Just as an example, us assume rather pessimistically that deminers clear with 99% effectiveness, and we use a 10% quality control check with 50% detection rate in the quality control checking. The reduced detection rate in quality control reflects the likelihood that most of the easily detectable mines will have been removed by the deminers.

How many times would we expect to find missed mines, given 50 AP mines cleared in each minefield of about 50,000 sq metres on average? (typical Afganistan figures). How much does the quality control process cost? We don't have complete answers, so this analysis is simply a preliminary check which needs further substantiation.

Given 100 minefields with these average characteristics, we would expect 1% of 5000 mines to be left behind (50 mines). We would expect quality control clearance on 10% of the minefield area, to be performed by an independent agency. They will need to clear 5,000 metres of each minefield again. Given the notional detection rate, we would expect to find 2 or 3 mines in the quality control checks. We do not currently have information on the actual number of missed mines found currently in

Afghanistan, but this example illustrates the current problem of quality control. Very few mines may be found, but the clearance rate still falls short of the required standard.

The cost of this is considerable. Assuming metal detectors are used, and all metal found by deminers is removed from the minefield, the quality control checks can be done faster than the original demining. Appendix 1 presents some modelling results from Afghanistan which suggest that rates of 10 to 30 sq metres per 2 man breeching party per hour could be expected. Assuming a median rate of 20 sq metres per hour, the 500,000 sq. metres will take about 25000 hours of work for 2 man breeching parties. In Afghanistan, where a team with 12 breeching parties costs about US$120,000 a year to support (or about US$100 per hour in the field), this will cost about $208,000. We have not allowed here for increased overhead costs in quality control work, where teams would be deployed only for a short time at each minefield.

Let us now assume that we use 250 known targets on average for each minefield. In our preliminary tests we have shown that it takes about 8 man-hours to set about 40 targets. Let us allow twice this time for field conditions, at a cost of about US$5 per hour for supervisory level staff (including all support costs), this will cost an extra $2 per target set in the ground, recovered, and recorded, or about $500 per minefield, or $50,000 for the notional 100 minefields we assumed before.

With 200 targets we can confirm 99% area clearance with a confidence level of about 90%. The 50 remaining targets can be used for confirming depth of clearance.

If the estimates discussed briefly here are supported by more careful analysis, we can see that the proposed method using known targets costs a fraction of the current methods. It also provides immediate feedback, a more statistically reliable measurement method than the current methods, and could significantly enhance safety in mine clearance operations by revealing procedural failures in the field while the work is being done.

5.7 Further research is needed

For this method to be useful in practice, we need to perform numerous measurements to confirm the target detection performance of typical metal detectors and the effects of depth, soil conditions, vegetation and target size. Similar studies are needed for probing techniques.

It would be very useful for similar studies to be conducted with mine detection dogs. However, with much more uncertainty on what the dogs actually detect, and how they manage to do it, developing suitable targets will be more difficult.

We also need to research quality control aspects of the test itself. This means establishing reliable and error-free procedures for administering tests of this kind so that typical human errors are detected or corrected to minimize any inaccuracies in the measurements.

Some examples of procedural errors are evident from the experiments we have already conducted. Target numbers can be mis-read and recorded incorrectly. There are standard techniques to detect this: if target numbers are designed with redundant digits, the undetected reading and recording errors can be almost eliminated. Missing targets need to be checked: if the targets cannot be found at the location they were supposed to be inserted then they are not counted as targets missed by deminers.

We need to develop simple and safe techniques for inserting targets into mined areas.

6 Conclusions

We have demonstrated that using known targets to measure demining qualilty is likely to be more cost effective than the current methods of quality assurance in which a proportion of land cleared is checked with the same or a different demining technique.

The proposed method is more statistically reliable, and can provide immediate feedback to the deminers in the field if they miss targets.

The method requires simple equipment and can be administered by typical field level supervisory staff.

Any new standard based on this method has to allow for the necessity of designing targets and test procedures which are adapted for specific minefield conditions and operating procedures.

7 Acknowledgements

The major part of the funding for this research comes from the Night Vision and Electronic Sensors Directorate, US Army Fort Belvoir and private donations. The author acknowledges the contributions of many people to this work, particularly staff of the mine action centres for Afghanistan, Cambodia, Bosnia-Herzegovina and Croatia. Thanks are also due to his colleagues Dino Busuladzic, Saad Soliman, and Sabbia Tilli for support and field data. Thanks to many people in the demining community for helpful suggestions and comments. Thanks also to Samina Yasmeen for reviewing the arguments central to this paper.

8 References

Blagden, P. (1999) Personal communication. Director, Geneva International Centre for Humanitarian Demining.

Trevelyan, J. P. (1999) Report on Initial Demining Quality Tests. Hameed and Ali Research Centre, Islamabad, Pakistan.
Available from http://www.mech.uwa.edu.au/jpt/demining/.

XXXXX - Reference on quality control and inspection methods and Poisson distribution mathematics.

Trevelyan, J. P. (1998) Modelling minefield clearance statistics, Technical Report: Department of Mechanical and Materials Engineering, The University of Western Australia, Nedlands 6907, Australia.

Appendix 1:

Predicting clearance rates from Afghan minefield clearance statistics

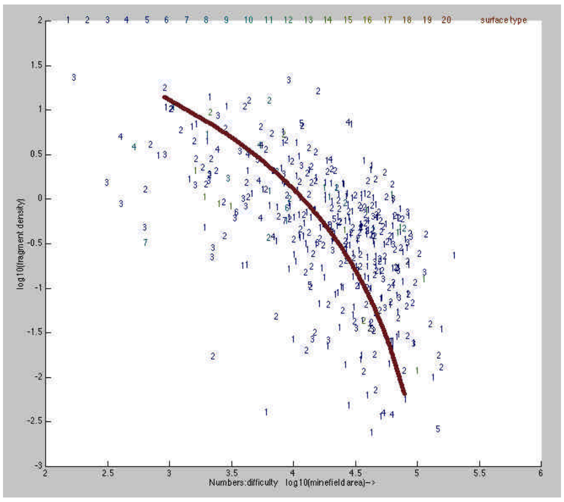

Figure A1: Logarithmic graph showing distribution of minefield fragment density and minefield size in Afghanistan (1992 - 1997 statistics for manual clearance in soft ground areas: hard ground shows almost identical data). The dark line is a visual estimate of the trend.

The best fit we obtained for predicting clearance rates in Afghanistan was a nonlinear logarithmic fit from which the clearance time for nearly all minefields is within a factor of two of the statistical estimate (Trevelyan 1998). Given a fragment density for a test, say 3 fragments per square metre, this corresponds to a typical minefield area of about 5000 sq. metres.

The model predicts the following clearance rates :

> Area = 1000, frag = 3000, hard ground:
> 5.6 sq metres per hour per breeching party (2 men)
>
> Area = 5000, frag = 15000, hard ground:
> 9.3 sq metres per hour per breeching party (2 men)

For quality control checks, assume minimal frag (say 1 fragment for 10 square metres) to predict a clearance rate:

> Area = 1000, frag = 100, hard ground:
> 10.4 sq metres per hour per breeching party (2 men)
>
> Area = 5000, frag = 500, hard ground:
> 31.3 sq metres per hour per breeching party (2 men)

Appendix 2: Some factors which affect the quality of mine clearance

Variable	Units or Definition	Measurable? If so how	Controllable?	Effect on outcome (missed mines)	Effect on outcome (production rate per day)
Process: Vegetation Cutting					
Vegetation type - grass, brambles, scrub, bushes, trees, vines, jungle, bamboo	Description	Photography, video camera	Not unless mechanized removal is possible. Seasonal vegetation can be controlled by choosing appropriate time of year.	None except possibly for trip wires which are harder to see.	The main effect in many countries. If vegetation has to be removed by hand, prodding may take twice as much time.
Stacking density - cu m per square metre when cut	Cu metre	Photography, video camera	Style of cutting	None	Reduces production rate - more stacking time needed and possible burning later
Wood hardness		Specialised tests	No	None	Increases cutting time, reducing production
Ground slope, surface	degrees	level, measuring tape	No	Awkward slopes or terrain may reduce safety	Likely to reduce production rate
Speed of clearance	sq m per hour	Video surveillance, paper records	Appropriate season	Thick vegetation makes mines harder to see and detect	Directly in proportion
Process: Probing					
Probing rate	No. of probes per unit time	Sensor in handle, electronic read-out	operator	none	Directly in proportion
Side-separation distance	mm	Video surveillance?	operator - can use marked rod as a guide, depending on SOP	can miss mine if too great	Inversely in proportion
Lane coverage	percent overlap	Video surveillance (hard)	operator, use of lane markings, SOP	can miss mine if not controlled carefully	Overlap is wasted production - needs to be minimized.
Length of work spells	minutes	Paper records	regulations, SOP	20 minute spells for maximum vigilance, longer spells may affect results	None
Elapsed time	hours	Paper records	regulations, SOP	Operator fatigue may affect result	Directly in proportion
Angle of probing	degrees	Surveillance?	operator, SOP	Penetration depth reduced if angle too low -> possible to miss mine, danger of activating mines if too high	None
Insertion distance	mm	Electronic sensor, video surveillance	operator, SOP, depends on ground hardness	Penetration depth directly affected - will miss mine if too small.	None
Insertion force	Newton	Force transducer in handle	operator, can be assisted by mechanical device in handle (or electronic sensor)	Can activate mine if too high. Low insertion force may reduce penetration depth -> missed mine.	None
Ground hardness	Resistance to object being pushed into soil.	Penetrometer	Not normally, can spray water to soften ground	Reduced penetration in hard ground -> may miss mines. However, risk of activating mine less in hard ground.	None
Ground contamination - stones, rubble, rubbish	none	Take sample, remove and record contaminants	No	None if SOP followed and all items inspected visually - otherwise may miss a mine, particularly if under rubbish.	Time needed for investigation reduces production
Depth of mines	mm to top of mine	When mines found, paper records	No	Mines will be missed if they are too deep. However risk of activating mine decreases with depth.	None

Appendix 2 Process variables in demining

Variable	Units or Definition	Measurable? If so how	Controllable?	Effect on outcome (missed mines)	Effect on outcome (production rate per day)
Process: Prodding or Excavation					
Depth of prodding	mm	Paper records	Operator, SOP	Unlikely to miss mine, but danger of activating mine while prodding near top of mine.	Inversely in proportion
Prodding rate	cu. m per hour	Video surveillance, paper records	Operator	May activate mines if working too fast	Directly in proportion
Lane coverage	percent overlap	Excavated ground clearly shows area processed	operator, use of lane markings, SOP	can miss mine if not controlled carefully	Overlap is wasted production - needs to be minimized.
Length of work spells	minutes	Paper records	regulations, SOP	20 minute spells for maximum vigilance, longer spells may affect results	None
Elapsed time	hours	Paper records	regulations, SOP	Operator fatigue may affect result	Directly in proportion
Ground hardness	Resistance to object being pushed into soil.	Penetrometer	Not normally, can spray water to soften ground	More effort needed in hard ground with higher risk of activating mine.	Time needed to excavate hard ground affects production
Ground contamination - stones, rubble, rubbish	none	Take sample, remove and record contaminants	No	None if SOP followed and all items inspected visually - otherwise may miss a mine, particularly if under rubbish.	Time needed for investigation reduces production
Depth of mines	mm to top of mine	When mines found, paper records	No	Mines will be missed if they are too deep. However risk of activating mine decreases with depth. Accidents can occur if deminer stands in bottom of excavation and mine is just below, undiscovered.	None

Appendix 2 Process variables in demining

Variable	Units or Definition	Measurable? If so how	Controllable?	Effect on outcome (missed mines)	Effect on outcome (production rate per day)
Process: Metal Detection					
Speed of sweep	mm/sec	Video surveillance with test target	Operator training, SOP - MD could make rythmic sound to guide operator	May miss mines if too fast	Directly in proportion
Gap between sweeps	mm	Ground marker, video surveillance with test target	Operator training, ground marking could help. Use of wooden guide rod helps in come environments	Will miss mines if gap between sweeps too great	Directly in proportion
Length of sweep, overlap	mm	Ground marker, video surveillance with test target	Operator training, ground marking helps. Use of wooden guide rod and lanke markings essential	Will miss mines if sweep length too short, no overlap	Slightly inverse proportion
Sensitivity		Minimum size of detectable target at ground surface level, max depth at which standard test piece detectable.	Switch or rotary knob setting on some models, others do not have control. Deminers need careful training to use this.	Will miss mines if sensitivity too low.	Will reduce production rate if too sensitive and false alarm rate rises.
Coil size	mm	Maximum depth at which test target detectable, ruler	Usually coils are not interchangeable in mine detectors. Gold prospectors often require several different coils.	Will miss mines if depth insufficient (with small coil)	False alarm rate may be increased if metal contamination exists 200 - 300 mm below surface.
Detection cone shape		Special test rig needed	Fixed in service	Will miss mines if effective width of cone is too small at maximum detection depth.	May reduce production if gap between sweeps has to be reduced to avoid missing deep mine-like targets.
Height above ground for search head	mm	Visual, ruler, video	Operator, SOP	Will miss deep mines if too high above ground	May reduce production if gap between sweeps has to be reduced to avoid missing deep mine-like targets.
Ground interference		Measure on metal-free ground	Some detectors can eliminate this with automatic or manual compensation. Depends on ground conditions.	Ground interference noise may confuse operator, possibly leading to missed mines.	If operator is not confused, production rate is higher.
Metal content of mine	composition, weight, size	Inspection of mine after disarming (if possible)	No	Minimum metal mines can easily be missed.	If detector is sensitive enough to detect minimum metal mines, false alarm rate may be higher.
Depth of mines	mm to top of mine	When mines found, paper records	No	Mines will be missed if they are too deep. However risk of activating mine decreases with depth.	Deeper mines (and false alarms) require more time for investigation.
Process: Lane and Perimeter Marking					
Ground hardness		Penetrometer	No but water can be sprayed to soften ground in some areas	Mines may be missed if ground marking is not accurate because marker posts cannot by driven in at correct locations	Accurate marking will minimise need for overlap, increasing production
Distance between marker posts or stones	m	Paces	SOP	Mines may be missed if ground marking is not accurate because marker posts or stones are too far apart	Accurate marking will minimise need for overlap, increasing production. However, using more posts or markers increases costs and time needed for marking.

Appendix 2 Process variables in demining

Variable	Units or Definition	Measurable? If so how	Controllable?	Effect on outcome (missed mines)	Effect on outcome (production rate per day)
Process: Mine Dog area reduction					
Mood of dog and handler		Subjective assessment		Will miss mines if dog and handler are not working well together.	
Vegetation type - grass, brambles, scrub, bushes, trees, vines, jungle, bamboo	Description	Photograph, description, height estimate	Only if mechanical clearance available - If vegetation seasonal, can choose season when vegetation low.	Dog cannot enter thick vegetation, may get lead tangled on bushes. Strong scents from some plants at particular times may mask explosive vapour.	Work may not be possible
Interference from false scents		Unknown	Unknown	False scents may mislead dog.	Slight - dog may work slower
Mine type, explosive		Record when found	No	May miss mine if dog not trained for explosive used	No effect
Mine age	years	Estimate when found	No	Unknown	Unknown
Length of time mine has been in place	years	Estimate when found	No	May be easier to find mines which have been lying for longer time	Unknown
Soil characteristics	various	Laboratory tests, maybe specialised test equipment can be made to measure vapour pressure with standardised target in soil.	No	Soil may adsorb explosive vapour strongly, also water way carry vapour away. Soil structure will affect rate at which vapour leave soil. These factors may cause dog to miss mine.	Unknown, dogs probably work slower if vapour harder to detect
Terrain		Photograph, description	No	Unknown	Unknown
Slope	degrees	Level, tape measure	No	May affect vaopur movement or make it difficult to keep dog on track across area to be checked -> missed mines.	Unknown
Weather	degrees etc.	Thermometer, hygrometer, wind speed meter	Only by selecting time of work	Affects vapour movement and dog behaviour - may result in missed mines.	Delays will reduce production if deminers, dog and handler have to wait on site.
Time of day	hours	Watch	Choose working times	May affectother factors such as strong scents from seasonal flowers	
Process: Mechanical vegetation removal					
Vegetation type - grass, brambles, scrub, bushes, trees, vines, jungle, bamboo	Description	Photography, video camera	No	Little effect unless ground is strongly disturbed making mines more difficult to detect	Depends on vegetation type and ground conditions
Stacking density - cu m per square metre when cut	Cu metre	Photography, video camera	Style of cutting	None	May choke machine if vegetation does not mulch easily
Wood hardness		Specialised tests	No	None	Increases cutting time, reducing production
Ground slope, surface	degrees	level, measuring tape	No	Awkward slopes or terrain may reduce safety	Machine may not operate if slope too great or terrain too rough, or ground too soft and slippery
Weather	degrees etc.	Thermometer, hygrometer, wind speed meter	None other than choosing timing	unknown	Appropriate season and weather conditions - probably helps if relatively dry when cutting.
Speed of clearance	sq m per hour	Video surveillance, paper records	Operator control	unknown	Directly in proportion