Hand-Held Force Probing Experiment

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1 Introduction

The purpose of this document is to to specify and comprehensively describe the first of a series of experiments in a project to assess the applicability of force sensing for landmine detection. This experiment forms an integral part of the first phase of the project which involves constructing a hand held ground penetrating probe capable of sensing and relaying information on the reaction, axial force as it is inserted into the ground. The series of tests described for this experiment were conducted by the authors on the sixth and seventh of May, 1997.

The aim of this document is to describe the experiment conducted during the first phase and relate this work to the research project as a whole. The motivation and requirements specification for the experiment will be presented and the experimental aims defined followed by a description of experimental procedure. This includes descriptions of the apparatus used and procedure taken during the experiment. The results of the experiment will then be presented and conclusions will be drawn from these.

2 Experiment Requirements Specification

2.1 Motivation

The aim of the research is to investigate the feasibility of automating the probing action undertaken by human workers for humanitarian de-mining operations. The first phase of the project involves developing a hand held probe, similar to those used for land mine detection, which can measure and record the reaction force experienced while the probe is inserted into the ground.

2.2 Aims

The objective of the experiment was to use the hand held probe fitted with a force sensing device in order to gain a better understanding of the forces involved while probing for buried objects. The aim of the experiment was to investigate if axial force data obtained from inserting a probe into the ground could provide sufficient information to allow for the detection of buried objects with a view to future identification.

3 Experimental Procedure

3.1 Apparatus

The equipment used during the experiment are described below:

Hand-Held Probe This was manufactured according to the design shown in figure 1 and is pictured in figure 2. The probe, constructed of stainless steel, consists of a 280mm pointed probe attached to a 110mm handle. The base of the handle contains a cut-out

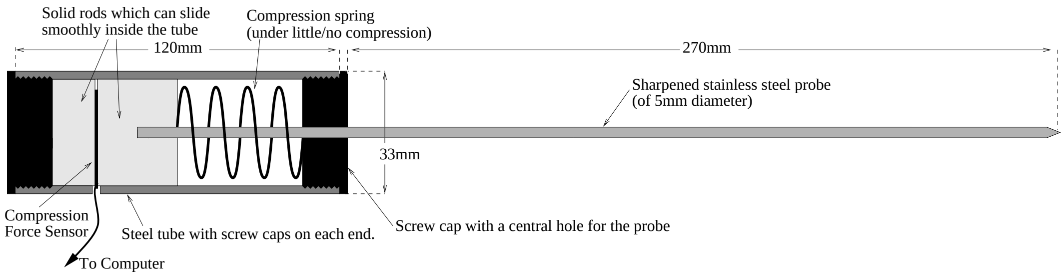

Figure 1: The design drawing for the hand held probe

section which allows a force sensor to be inserted between two solid steel rods. The pointed probe is securely attached to the upper rod thus, any reaction force exerted on the probe tip or along its length will be experienced between the two rods secured inside the handle. These rods provide a smooth surfaces between which the force sensor can be inserted. This ensures that the force is evenly distributed across the surface of the force sensor which is required to obtain accurate readings. The probe is constructed to be strong enough so that it does not suffer any deformation or excess bending when the operational forces are exerted on its tip.

UniForce^{TM} Sensors This thin sensor exhibits changes in electrical resistance when a load is applied perpendicular to its surface. As can be seen in figure 3, the force sensing area, a circle 7mm in diameter, is at the tip of the sensor. These sensors are available in different ranges. A sensor able to detect a range of forces up to 220 Newtons was used for the duration of the experiment.

The sensor was directly connected to a PCMCIA expansion card which was in turn inserted into a PC laptop executing software supplied by UniForce. The software provides a graphical representation of the forces present at the sensor and has an event recording feature which allows for a sequence of force measurements to be saved to a file. This feature was used during the experiment with the data capture rate set at $20Hz$.

The sensor system provides an integer output in the range of 0 to 255 depending on the load exerted on the sensor. A calibration procedure is provided by the software, however, this feature was not used and the sensor output was converted into Newtons based on the sensor specifications, that the force rating is approximately that which is required to load the sensor to 90% of full load. Therefore 220 Newtons corresponded to an output reading of 230.

The performance of the force sensor was considered adequate for this experiment which was primarily concerned with gaining a feel for the forces involved in manual probing and

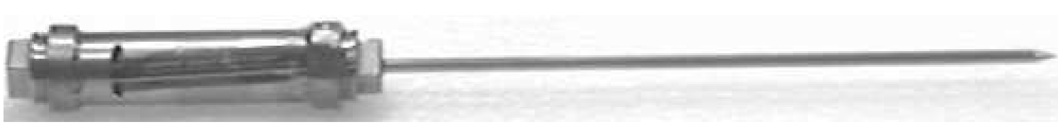

Figure 2: The hand held probe with force sensor

Figure 3: The UniForce sensor

comparing results for different ground conditions. The following data on the accuracy of the sensors was gained from the accompanying documentation (uniforce, 1995) The sensitivity of the sensors varies according to temperature and they will experience up to 1% difference in reading per degree Fahrenheit in temperature change. The resistive output of the sensor is non-linear particularly in the first one tenth to one third of the force range; the operating range for this experiment. The force sensor only is repeatable to within $\pm 5\%$ of full range. The force sensor also suffers from drift of approximately 1.2% of full scale over a minute and 8.8% over an hour. Each experiment took between ten and fifteen minutes to conduct. None of these specification considerations were taken to account during the experiment.

The sensor is a resistive device, sensitive to the how it is driven. The sensor used during this experiment was driven by a laptop PC via a PCMCIA card. It was noticed that when the PC was powered from a external power source, this caused considerable fluctuations in the sensor output even when there was no change in the applied load. Therefore, while recording data, care was taken to ensure that the PC was always powered from its internal battery source which provided a much more consistent and stable reading.

Test Objects A small selection of objects were used to simulate different buried materials.

Simulated plastic anti-personnel mine This object was constructed from three flower pot bases inserted into one another for increased rigidity as pictured in figure 4. These formed a cylinder $130mm$ in diameter and $30mm$ in depth. The object resembles anti-personnel mines commonly found in areas needed to be cleared for humanitarian purposes (Foss & Gander, 1990-91; Craib, 1996).

Wooden block The purpose of using this object, $45 \times 70 \times 130mm$, was to investigate if there were any differences in the force signatures when the probe detected a wooden compared to a plastic object.

Stone The purpose of burying an irregular shaped stone of approximate dimensions $110mm \times 90mm \times 70mm$, was to determine whether or not object of different material provided differences in their force signatures when encountered by the probe.

Test Terrains A number of terrains were used during the experiment to provide a range of test conditions. In order to provide a controlled environment, most of the experiments were conducted indoors using a rubbish bin filled with loose soil. In order to compare the force signature of different ground conditions, subsequent experiments involved inserting the probe into turfed, flat ground, a turfed mound and a flower bed.

Figure 4: The simulated plastic anti-personnel mine

3.2 Preliminary Tests

Preliminary tests were conducted in order to verify the operation of the probe and sensor configuration. They involved inserting the probe into loose soil and observing the resultant forces. These tests revealed that of the sensors readily available to us the force sensor of range 220 Newtons was best suited for our investigations and that a data acquisition rate of $20Hz$ provided sufficient resolution.

3.3 Object Detection

The probe was inserted into the rubbish bin filled with loose soil so that it encountered: 1) no object; 2) the simulated plastic mine; 3) the wooden block and 4) the stone. These tests were intended to reveal differences between the force profiles when the path of the probe was and was not blocked by an object.

The configuration of the experiment is pictured in figure 5 which shows the location of the objects prior to them being covered in soil and the test terrain. The objects were buried to a vertical depth of approximately $25mm$. Each test involved inserting the probe at an angle of 30^o to the horizontal at a constant velocity of approximately $45mms^{-1}$. If an object was detected, the pressure applied by the investigator would be increased. The probe was also inserted vertical into the test terrain in order to ascertain whether the angle of insertion effected the reaction force profile.

The plot in figure 6 shows the results from tests where the probe was inserted fully into the soil at and angle of 30^o to the horizontal and vertically. These results show the increase in the force due to increased friction against the sides of the probe as it is inserted further into

Figure 5: The position of the objects prior to being buried

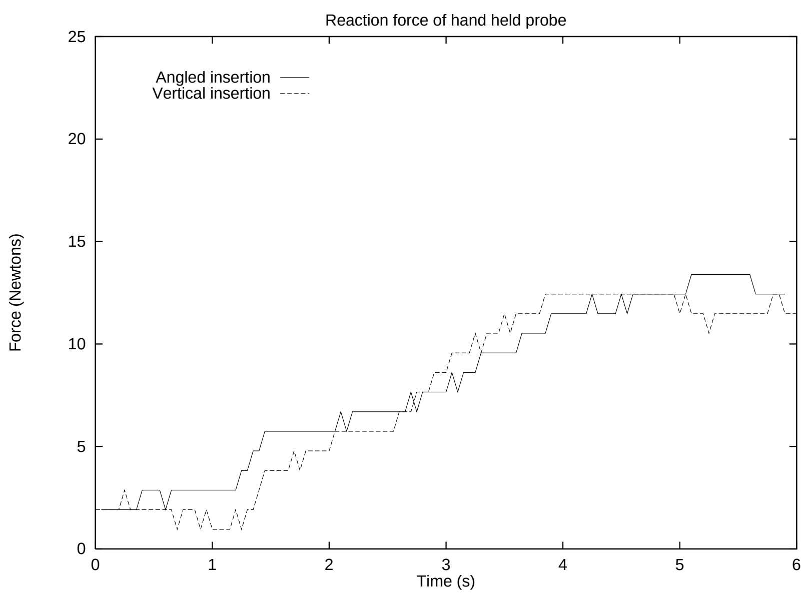

Figure 6: Results from the tests comparing the vertical and angled insertion of the probe with no obstructing object. These demonstrate that there is no significant difference in the reaction force regardless of the angle of insertion.

the ground They also demonstrate that there is no significant difference between the reaction force whatever the angle the probe is inserted into the ground.

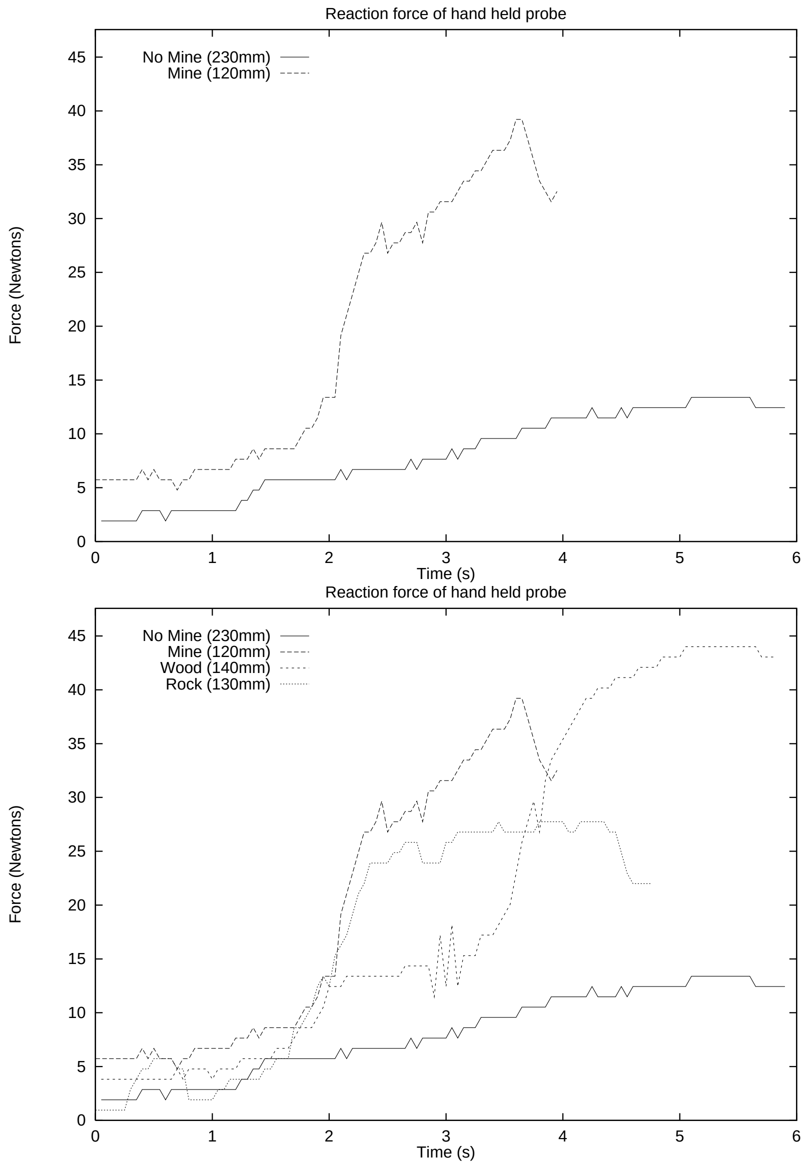

Figure 7: Results from the object detection tests. The first plot highlights the difference between the situations where the path of the probe is unobstructed and blocked by the buried simulated landmine. In the second plot the traces for the other buried objects are added which demonstrate that there is no significant differences in the reaction forces for different materialed objects.

The results obtained from the tests with buried objects, plotted in figure 7, show a significant increase in the reaction force along the insertion axis as the object was detected and increased pressure was applied by the human prober. The first plot highlights the difference in the force signatures when the probe is obstructed by a buried object and when there is no obstruction. It can be seen that for the first $1\frac{1}{2}$ seconds, insertion depth of approximately $100mm$, both plots increase linearly at a rate of 2 Newtons per second. At the point where the probe tip makes contact with the buried object, 2 seconds into the test, there is a marked increase in the corresponding plot due to the prober applying an increased force while the plot corresponding to no object being detected continues to increase linearly.

The second plot in figure 7 demonstrates the similarities between the force signatures for different buried objects. When all three objects are encountered, there is an increase in the reaction force as additional pressure is applied by the prober. This is in contrast to the plot where no object was encountered which continues to increase linearly as the probe is inserted further into the ground.

These plots also highlight some of the inadequacies of the UniForce sensors. Their low repeatability is demonstrated in the first plot where prior to insertion, one plot gives a reading of 2 Newtons while the other, under the same conditions gives a reading of 6 Newtons. It should also be noted that since these test were conducted by a human prober, the insertion velocity could not be guaranteed to be consistent for each test, therefore, the time scale provides an approximation of the insertion depth of the probe.

Observations made during the experiment revealed that the human prober could easily identify the moment at which the tip of the probe came into contact with a buried object. It is known that experienced probers are able to distinguish between objects of different material. Novice probers which conducted the experiment could not, however, distinguish between objects of different materials when they were buried. A slight difference in the noise and vibration was noticed when the probe was struck against unburied objects. The different vibration patterns of materials have been exploited by some researchers in this field for object recognition (Communications *et al.*, 1995; Greiner *et al.*, 1995).

Different angles of the object surface could also be detected by the human prober. This was particularly evident when encountering the simulated plastic mine at an oblique angle where a resultant reaction force, a combination of frictional forces and a reaction force perpendicular to the surface of the object at the point at which it was touched, could be felt by the prober as the applied force was increased. It was noticed that as the applied force was increased along the Z axis, an increased force would be sensed along the X axis. This is illustrated in figure 8.

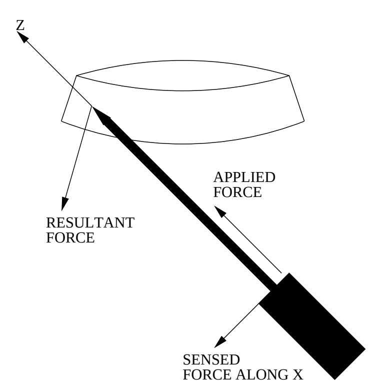

Figure 8: The resultant force and sensed force along the X axis when an object is encountered at an oblique angle.

3.4 Visually Recorded Probing

The purpose of the second set of tests in the experiment was to demonstrate more clearly the relationship between the inserted depth of the probe and reaction force. To this end, information on the insertion depth of the probe was captured in addition to the force profile. It was decided to concentrate on comparing the results from tests with and without buried objects blocking the path of the probe.

The apparatus was configured similarly to the previous tests with the probe inserted at an angle of 30^o to the horizontal. Tests were conducted with and without the simulated plastic mine blocking the path of the probe. In order to obtain information on the insertion depth and velocity of the probe, these runs were videoed by an overhead camera. The video was then captured at a rate of 20 frames per second and stored in a digital format on a PC for easier manipulation. In order to synchronise the video and force sensing information, the probe was pressed against a hard surface and then removed suddenly. The sudden movement on the visual data coincided with a sudden drop in the force data and allowed for the visual and force data to be synchronised. Since both were stored at a rate of $20Hz$, each video frame could be corresponded directly to force sample.

In order to retrieve probe depth information from the video data, the video was processed by software which allowed for it to be replayed one frame at a time. By manually measuring the visible length of the probe from the base of the handle to the insertion point in the soil for every five frames, the rate at which the probe was being inserted could be determined. Relating the measured full length of the probe on the video to its known actual length allowed for the video data to be translated into the actual insertion depth of the probe for each video and force sample.

The two set of results from these tests, the top two plots in figure 9 provide a more accurate picture of how the reaction force increases as the probe is inserted into the ground. The Y scale for these plots correspond to both the reaction force in Newtons, experienced by the probe and the inserted depth of the probe, in centimeters, at any instant during the test. In the first plot, where no buried object is detected, the force increases linearly with the inserted depth. This is in contrast with the second plot where the inserted depth reaches $11cm$ which signals that the object has been detected and there is a marked increase in the reaction force as more pressure is applied by the prober.

The middle two plots in figure 9 show the relationship between the insertion velocity and reaction force. According to the laws of friction, the reaction force is directly proportional to the velocity, the plot where no mine was present, however, does *not* illustrate this. Even though the velocity remains constant there is a significant increase in the reaction force as the probe is inserted into the soil. From the situation where the path of the probe is blocked by a buried object, it is can be seen that the point at which the velocity is reduced to zero, when the object is hit, corresponds to when there is an increase in the reaction force as the probe is pushed against the object.

The bottom two plots in figure 9 illustrate the contrast in the situations where a buried object was and was not detected when both the force and depth data are combined. In the situation where no buried object was detected there is little deviation in the data from the zero point. In the case where an object was detected, however, there is a significant increase

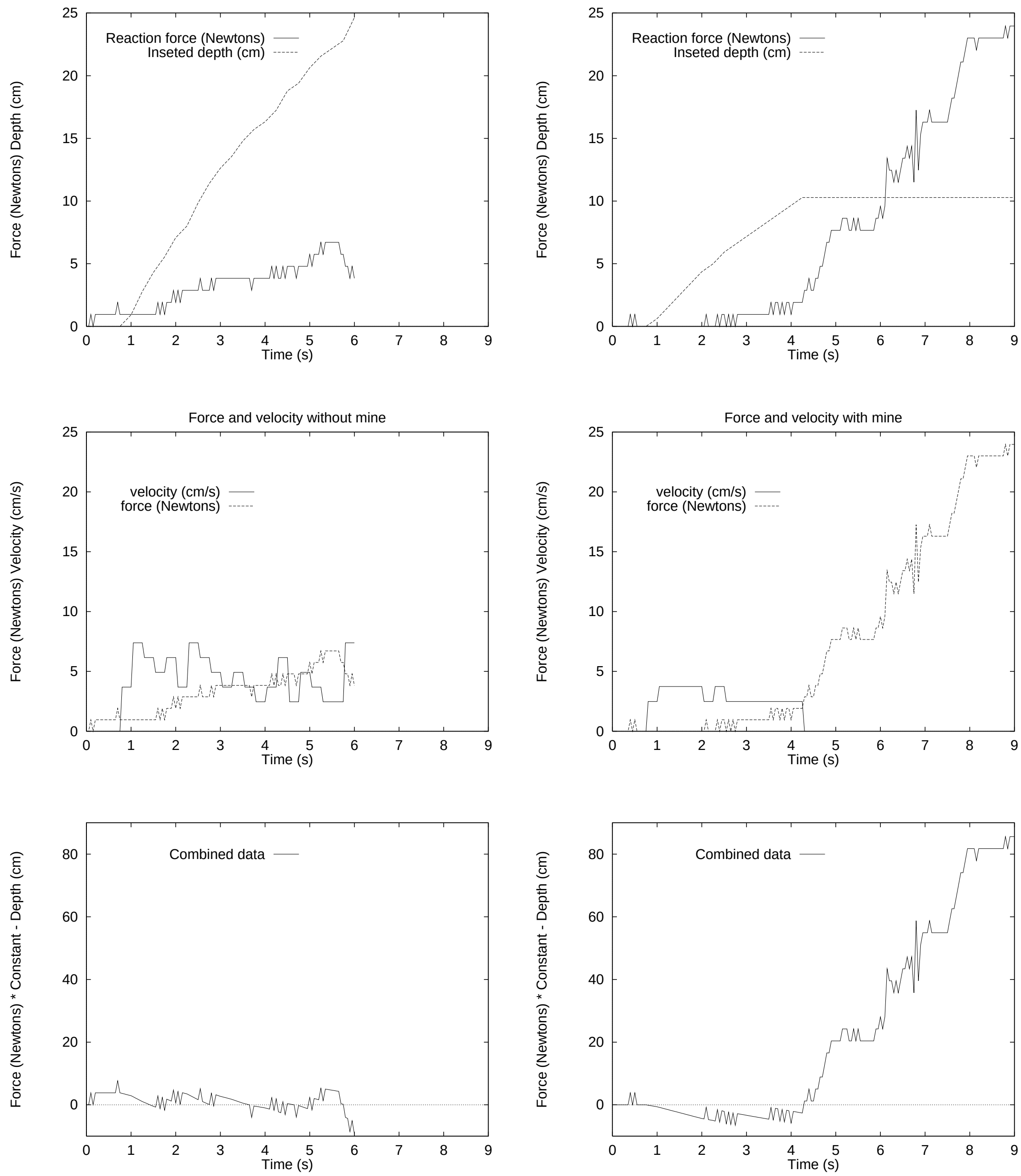

Figure 9: Results from the visually recorded tests. The plots on the left illustrate the results form the test where the path of the probe was not blocked while those on the right represent the data from the test where the path of the probe was blocked by the simulated mine. The upper plots illustrate the relationship between the insertion depth and reaction force. The middle two plots illustrate the relationship between the insertion velocity (time derivative of the depth) and reaction force. The bottom two plots are an attempt to fuse the depth and force data. The data was combined using the formula $(ReactionForce \times 4) - InsertedDepth$

in the combed data at the point where the path of the probe is obstructed.

3.5 Comparison of Terrains

The final set of test in this experiment were intended to relate the findings of the previous tests to external, less controlled ground environments. The probe was inserted a number of times into different outdoor terrains found in the close vicinity of the laboratory. These included a turfed, flat playing field, a turfed mound of earth and a flower bed. The probe was inserted manually at an angle of 30^o and at a constant velocity of approximately $40mms^{-1}$.

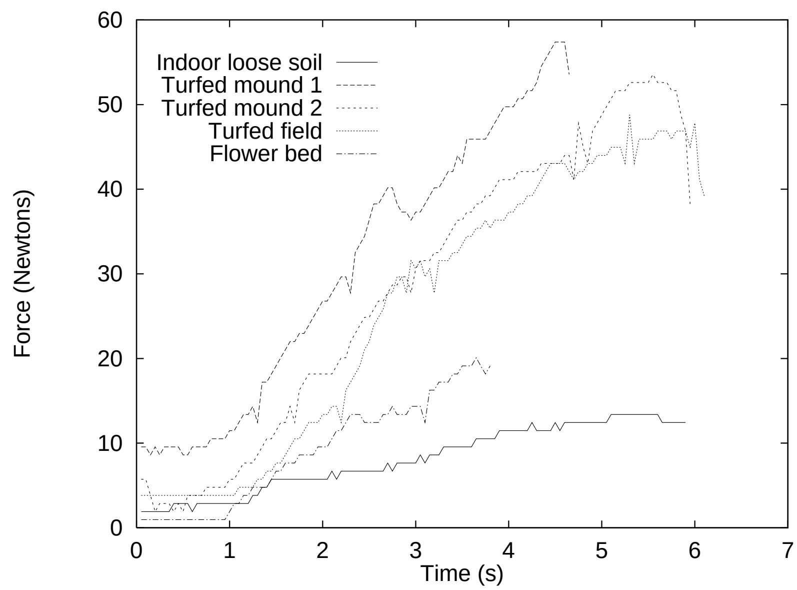

Figure 10: Results for the terrain tests. These demonstrate that the force required to insert the probe varies significantly for different types of terrain. The force required for the turfed mound (dry, settled ground), is five times greater than that required for the loose soil.

The results from a range of runs, shown in figure 10, illustrate the force characteristics as the probe is inserted into different terrains. All tests resulted in an approximate linear increase in reaction force as the probe was inserted but there were significant differences in the rate of change of force. For the indoor loose soil the increase was modest at an approximate rate of 2 Newtons per second. The flower bed's rate of increase was 7 Newtons per second while the plot for the turfed field indicates a rate of 10 Newtons per second. The plots for the turfed mound indicate a rate of increase of approximately 12 Newtons per second. These results reflect the increased resistance of the different types of terrain to the probe. Packed, dry ground provided significantly more resistance requiring the investigator to apply a much greater force in order to insert the probe.

Some of the plots illustrate the force experienced by the prober. During these runs it was noticed that the force required to inset probe into these ground conditions were not as smooth and linear as for the indoor simulated environment. Various small objects could be detected and, as the force was increased to overcome these and, once negotiated, the increase in the applied force resulted in the probe being surged forward at an increased velocity into the ground. At 3 seconds into the first test on the turfed mound the prober encounters a small obstacle, indicated by the peak in the trace. The additional force applied by the prober moves this obstacle out of the path of the probe, illustrated by the drop in reaction force, and results in the probe being surged forward a short distance until the opposing force of the ground reaches the applied force and control of the inserting velocity is regained.

4 Conclusions

The experiment provided useful information regarding our investigations into the use of force sensing for humanitarian de-mining. The conclusions drawn from the experiment are summarised below.

- The first set of tests demonstrated that there is no significant differences in the reaction force whatever angle the probe is inserted at into the ground.
- The first two set of tests demonstrated that there is a significant difference between the force signatures when the path of the probe is not blocked by the object and when a buried object is detected. The former provided a linearly increasing force as the probe was inserted while the latter showed a sharp increase in the reaction force when the object was encountered. When the insertion depth information was combined with the force information the difference between the two situations was even more pronounced with the sudden increase in force corresponding with the probe being blocked by the object and not inserted further into the soil.
- It was found that there were no significant differences in the axial force when objects of different material were encountered. It was also found that novice probers could not distinguish between buried objects of different material.
- A translational forces experienced by the investigator when the probe encountered the object surface at an oblique angle could, if properly measured, provide information on the angle of the mine surface at the point of contact or on the material of the object.
- Results from the final set of test, probing different external terrains, provided evidence that the reaction force increased linearly with depth for a wide range of terrains. They also demonstrated that there was a large difference in the force required to push the probe into various soil conditions. These ranged from axial force of around 10 Newton for loose soil to 50 Newtons for dry, packed ground.

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