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Map-Driven Platforms for Moving Sensors in Mine Fields

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Introduction

There is plenty of money being spent on demining research to develop instruments for sensing mines but not nearly so much on moving these sensors round a mine field. Project proposals and publicity material contain diagrams with sensor arrays hanging from all-terrain vehicles or helicopters with little detail about how these are to be driven.

This paper discusses two unconventional and complementary systems for sensor movement. The first platform is the Dervish, originally designed to bypass the problem of mine detection by deliberately rolling over them with mine-resistant wheels. The second uses carbon-fibre cables to set the position of a payload supported by a balloon. Some desirable features of a sensor platform might be as follows.

- Its should be automatically controlled to a precision comparable with the dimensions of a small mine from a distance further than the range of fragments from a larger one. This implies a precision of about 50 millimetres or less, with no people or expensive vulnerable parts within a hundred metres or more.
- Its typical forward speed should be compatible with the data rate from its sensors. This is likely to be much less than the design speed of conventional land vehicles, let alone aircraft.
- It should be able to move across steep, rough, soft or marshy ground avoiding obstacles such as buildings, walls, ditches and vegetation in a wide range of weather conditions, perhaps at night.
- Sensing should *not* have to wait for mines to be neutralised and the many false positives to be dealt with. This means that the platform should have either a high probability of not triggering mines or else of not being damaged by mine detonations. If this probability is not high enough, then the platform should be cheap enough to be regarded as expendable.
- It should provide power, communications, telemetry links and attachment points for a wide variety of sensor systems that may not yet be fully designed.
- It should have high manoeuvrability with a very small turning circle and be easy

to extricate from entanglements.
- It should be easy to transport over rough tracks, perhaps even by people on foot.

Platforms adapted from conventional ground vehicles will usually be too heavy and too fast. They have relatively large turning circles and need major modifications to their controls if they are to be operated remotely. A normal floor attempts but fails to contain blast and the skins are not thick enough to stop fragments. If sufficient armour is added the vehicles use lots of fuel and become heavy to move. Helicopters have very high running costs and cannot get sensors close to the ground.

The Dervish

The Dervish, shown in figure 1, is a three-wheeled vehicle with wheel axles pointing to the centre of a triangle. If all wheels were driven at the same speed then it would merely rotate about this centre and make no forward progress. However, carefully-timed, small, cyclical variations of wheel speed make the Dervish progressively translate in a chosen direction so that every point in its path is covered, *twice,* by a loading of about 90 kg in a pattern of overlapping circles as shown in figure 2. This should fire every functional anti-personnel mine but, because of the low weight, not normal anti-tank mines. The Dervish has a very open steel frame with all members oblique to the path of blast fragments. It effectively has a zero-radius turning circle. The wheels are made from Swedish Steel Hardox 400 excavator plate and can survive explosive charges larger than the largest anti-personnel mine in service. In a test with a 10kg charge, damage was confined to one corner and the axle and bearings from that test are still in use. The repair cost would be a few hundred dollars.

Figure 1. Carn Gibson with the Mark III Dervish, Edinburgh February 1999.

The Dervish drive uses three variable-displacement computer-controlled hydraulic pumps driven by a 340 cc Honda engine and controlled by a micro-processor to drive a Danfoss hydraulic motor at each wheel. We found that no conventional hydraulic pumps with displacement varied by swash-plates could be controlled to the precision needed and so we are using a design originally developed for renewable energy (Salter and Rampen 1993). This has electro-magnetically latched poppet valves to selectively disable each pumping cylinder. One data bit from the micro-processor is equivalent to an advance of 5 mm. The technology has now been licensed to Danfoss and we hope that this will allow a very large reduction in cost.

The rolling wheels of the Dervish are a very energy-efficient way of applying exactly the stimulus of the human feet for which the mine is designed. They do the minimum damage to fragile topsoil, less than the hooves of cattle. Repeatedly locking one wheel and driving the other two wheels spins the machine through 120 degrees about the locked one and allows rapid traverse at 5 kilometres per hour.

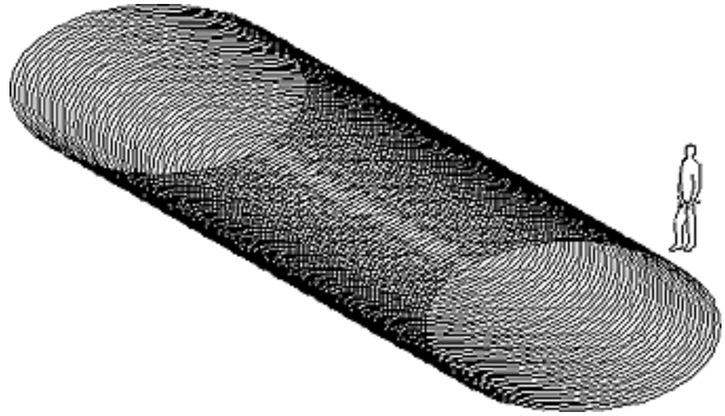

Figure 2. The overlapping circles of the Dervish track. Every point in the 5- metre wide path is covered twice by a load a little greater than that of a human foot.

In normal mine-detonating mode, the Dervish advances at about one metre a minute, a rate set by the requirement that there should be no mine-sized gaps between its wheel tracks. A possible change to the wheel design may increase this by a factor of three. With a 5 metre wide track this is equivalent to a coverage of 300 (perhaps 900) square metres per hour. Higher clearing rates, perhaps very much higher, could be used for sensors with a larger aperture than the present 20 mm wheel thickness. It may also be useful to do a fast, coarse scan of a mine-field to get a statistical sample of mine density and switch to a finer scan when mines are found. At present manual prodders can waste many man-months prodding areas without finding a single mine.

Navigation of the Mark III Dervish is by a local high-frequency radio system akin to the Decca technique but in command mode with local stations, (Salter and Gibson 1998, Salter 1999). The phases of unmodulated signals from two constant-frequency transmitters based safely outside the mine-field, as shown in figure 3, are compared with two signals from a control station. The Dervish motors are driven to keep a 90-degree phase shift between the pairs of transmissions. The addition or subtraction of phase at the control station drives the Dervish to a new point. If we regard the equal-phase lines as the strings of a net spread across the mine-field, the Dervish will always try to get to the nearest knot of the net. The phase-change commands have the effect of dragging the phase net over the ground with the Dervish (or a formation of Dervishes) following their knots. The final version of the electronics is now being tested.

Navigation data are taken from lines or scanning patterns drawn on a computer map. Software (to be described by DT. Sanella) converts Cartesian information in the HPGL format to the hyperbolic co-ordinates and then to the phase additions needed by the Decca system. The control computer has to know the positions of the control stations and

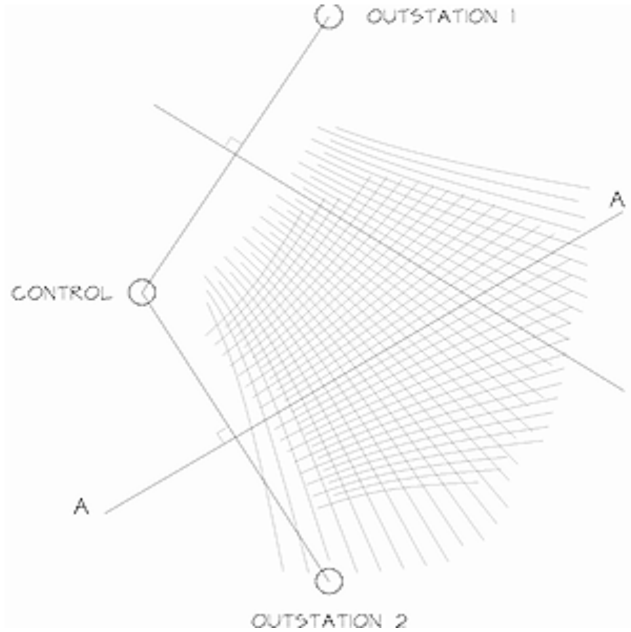

Figure 3. Lines of constant phase-shift are in general hyperbolic with the perpendicular bisectors of the base-lines between stations being a special case. A Dervish will move to the nearest intersection of two hyperbolae. Adding or subtracting phase to the signals at the control station has the effect of dragging the net and the Dervishes across the mine field.

the Dervish starting point, but from then on it behaves just like a pen-plotter with a 5 metre diameter pen drawing on a VERY large plotting area. If the positions of obstructions are known, clearance can continue through the night.

One limit to the resolution of the Decca system is the frequency stability of the transmissions: one part in a million is equivalent to a millimetre at a kilometre range. Reflection from nearby moving objects will induce secondary transmission paths that will also distort the Dervish track. For instance a human body at two metres would perturb the Dervish by about 50 mm with disturbance falling with the inverse square of distance. A rabbit at one metre disturbs the position signal by a millimetre. Moderate static distortions of the map geometry are quite acceptable. Detailed results will be reported shortly by JH. Dripps.

The rotary scan of a Dervish makes it particularly suitable as a sensor platform. We get 360-degree panoramic scans without having to provide any azimuth drive. We cover every area of the ground at least twice. We can look at objects from several directions. With enough data storage we can build synthetic apertures. The standard Dervish will come with one ordinary video camera looking outwards.

The Dervish can also carry a metal detector such as the Schiebel AN 19/2, in a thorn-resistant protective shroud with the sensor head just inboard of the wheel radius at 60 degrees from a wheel. We find that debris from surface mines is all thrown up in a cone with angle greater than 45 degrees so that equipment placed low will be safe from all except stake and tree mines. Data about the signal strength and position of metal fragments will be sent back to the control station and written into the navigation map along with the positions of mines that the Dervish has destroyed. A whisker contact with buildings and trees will be used to correct errors in the mine map. A tilt sensor will correct navigation for slope and hummocks and perhaps detect craters from old mine explosions.

We would like to test other sensors for non-metallic targets especially ones that respond to explosives in gram quantities. The ideal geometry would be for the sensor target to be about one metre outside the wheel radius but for the equipment to be housed in or below the engine bay. This would allow about a minute for data processing, giving the chance to decide whether we really do want to roll over a target such as a booby-trapped anti-tank mine. We would be grateful for suggestions and requirements from sensor designers.

As well as the three wheel pumps the Dervish has a fourth pump to provide 7 kilowatts of hydraulic power to a vegetation-clearing tool such as a single flail chain. Three machines can be stripped down packed in a one tonne van and assembled by a single person in 30 minutes with the minimum of tools. The separate parts can, if necessary, be carried on foot. A second version of the Mark III experimental unit would cost about $25,000 but in production we hope that costs would fall to those of a motor cycle of similar weight. This is far below the compensation costs for an injured deminer.

All our electronic equipment is fitted into steel tubes made from old nitrogen bottles with carefully-machined O-ring seals and uses military specification connectors. So far it has survived Scottish weather outdoors for 18 months and two winters with no problems.

Balloons

Although we believe that the Dervish will be a versatile platform for many conditions, particularly for the clearance of agricultural land, it cannot cross deep rivers, leap tall buildings (or even low ones) and its thin, blast-resistant wheels are unsuited to very soft ground. This has prompted us to work on a complementary design aimed purely at sensor movement with no mine detonation. It can satisfy many of the criteria listed in the introduction, and thanks to modern materials, even the ones concerning precision.

The initial design is based on a standard AB 3000 balloon manufactured by Cameron Balloons of Bristol, (Purvis 1999). It has a displacement of 85 cubic metres, can lift 44 kg, has stabilising fins, costs $10,000 and would last about three years in the conditions we should expect in a minefield. The size was chosen for initial study because balloon regulations in the UK require the presence of a licensed pilot on any balloon with lift above 50 kg. Many pilots weigh more than 50 kg so that there is a gap in available models above that size but no *technical* difficulty about making larger ones.

Safety-conscious balloonists prefer the use of helium for the lifting gas. I am advised that initial filling with helium will be about $4.50 per cubic metre at atmospheric pressure and that we should expect a leakage of about 10%, about $40 per week. Helicopters cost about $1000 an hour in the UK and perhaps five times as much in more difficult theatres. Brave, impoverished, non-smoking, electrically-grounded, outdoor deminers may find hydrogen attractive. We can generate it from water in remote places. Despite disturbing folk memories of the Hindenburg and R101 disasters we should have no anxiety. Hydrogen leaks disperse upward quickly and much more safely than the vapours of heavy gases that regularly destroy boats by collecting in their bilges. Furthermore the flame of burning hydrogen has very low radiation. The Hindenburg did cruise the world for many years in much greater safety than the aircraft of the period.

The cables of the balloon system are sketched in figure 4. The system uses one set of three, nearly horizontal, traverse cables to move the payload

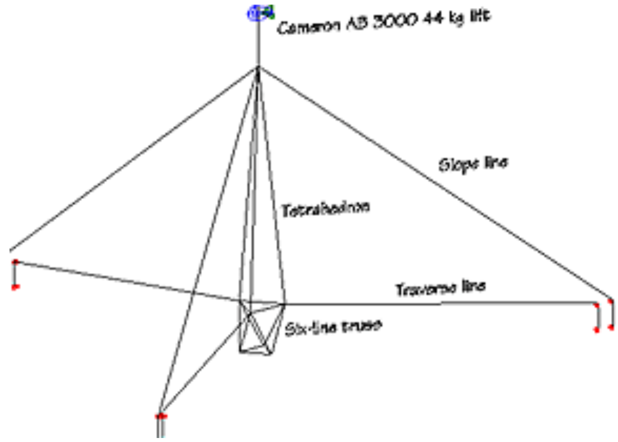

Figure 4. A perspective view of the control lines of the balloon system. Provided that all cables in the tetrahedron and six-line truss remain taut, they behave like a 'rigid' structure.

across the minefield and another set of three sloped ones to control its altitude. The design is greatly influenced by the requirement that no cable should ever go slack because of wind loading. The need to maintain tension in the sloped cables reduces the lift available for the payload from 44 to about 20 kg. The payload weight is about the maximum allowed for hold baggage of economy class passengers.

From the upper junction of the three sloped cables there are three lift cables that descend to the corners of a triangle forming a tetrahedron and making connections to the horizontal traverse cables. Below this triangle are six cables forming a truss to define the position of a light, rigid triangular frame to which the payload is attached. Provided that all cables in the tetrahedron and six-line truss are kept taut, they form a rigid structure on which we can calculate bending moments and deflections. The structure can be tilted until any cable approaches the vertical. The proportions of the trusses in figure 4 have been enlarged for clarity. They would be selected for a given mission so that the vertical dimension of the six-line truss clears the heights of houses and trees while the horizontal dimension is made less than gaps between them. Figure 5 shows a closer undistorted view of the arrangement near the payload.

Completed work to date is a Mathcad program that will calculate the cable diameters, stretch, winch specification, cable sag, resonant frequency, limiting wind conditions and balloon volumes for any size of field, payload and cable material properties. The following initial conclusions are based on the standard 44 kg balloon with winches 200 metres away from the centre of a triangular search area of just over 50,000 square metres.

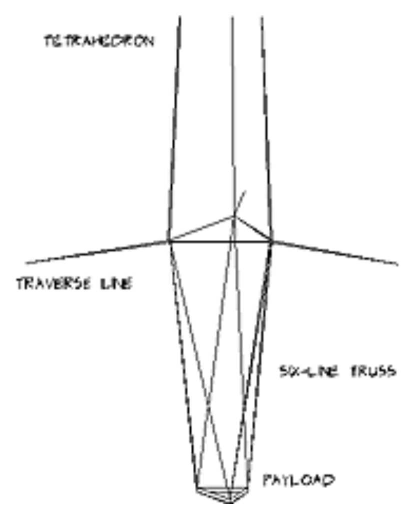

Figure 5. A less distorted view of the lines near the payload. The proportions of the six-line truss would be selected for a given mission to clear the highest obstacle and pass the narrowest gap.

A crucial choice is the material used for the lines especially the horizontal traverse ones. Despite a cost about four times that of glass fibre, which is widely used for tensile strength in electrical and fibre optic cables, the preferred material is carbon fibre. It is made by a process, known as pultrusion, in which a tow of fibres is pulled through a bath of acrylic resin and then through a die. It has a very much higher modulus, 140 E9 N/m2, to increase the natural frequency of the traverse system and a tensile strength of 1400 E6 N/m2, (Lambert 1999). A disadvantage is that it will snap suddenly if wrapped round too tight a bend. This means careful handling and large winch drums, several hundred times the diameter of the cable.

If we want a single slope-line to take the full balloon lift with a safety factor of two, the line diameter would be 0.9 mm. We would therefore use the next standard 1mm size for all lines. For the 50,000 square metre search area we need about 2500 metres weighing 3 kg and costing $1800.

The standing tension in the horizontal lines depends on linear density times the square of length divided by twice the sag. For the present search area the chosen sag is 0.64 metres. Sag introduces a change in separation of the ends amounting to 8/3 times sag squared over length. This seems surprisingly small, only 15 mm. At the centre of the mine-field natural frequency is just over 1 Hz and could easily be increased if we choose to spend more on larger diameter carbon cable. Human operators and automatic control systems can quite easily learn to drive systems with lower natural frequencies.

There is less concern about the natural frequency in the vertical direction because we can allow the payload to make a controlled-force contact with the ground which can also provide damping.

We can define an efficiency for the lifting mechanism as the ratio of the weight of the payload to the total airborne weight. For the 44 kg design the efficiency is just under one half. The amount of balloon lift wasted by the cable structure depends mainly on the need to resist wind loading. This rises with the square of balloon diameter while the lift rises with the cube. If the legal limits on balloon size are enforced less rigorously in mined countries we can certainly carry much heavier payloads, including perhaps deminers and their tools.

Wind problems

The entire structure and payload is at risk if ever a single member becomes slack. We must understand the effect of wind drag on the balloon. Good airship shapes have drag coefficients related to their frontal area of 0.05 at Reynolds numbers (referred to length) above 2E5. Spheres have a sharp drop in drag coefficient to just under 0.1 at Reynolds numbers of 3E5. We estimate that the Cameron design, which is not as slender as the best airship shapes, will have a drag coefficient of about 0.075.

The horizontal wind drag together with the buoyancy lift force will deflect the balloon tether through an angle from the vertical that can be calculated from the triangle of forces. The structure is safe if the tether remains inside a volume bounded by six planes in the form of an inverted six-sided pyramid with its apex at the junction of the slope lines.

The positions and inclinations of these planes can be determined as follows: three are continuations of the planes formed between the slope lines. This means that we do not want them to be too close to the vertical. The other three planes are each perpendicular to the slope lines and pass through the common junction point. This means that we do not want them too close to the horizontal. The best compromise depends on size of the search area relative to the triangle joining the winch points. For an equilateral triangle and side ratio of 0.7 the optimum slope is just over 40 degrees from the horizontal. This gives surprisingly high limiting wind speeds of 20 metres per second or 39 knots. This is quite a brisk wind, well above the cut-out speed for many designs of wind turbine. If necessary it may be possible to increase this by distorting the shape of the balloon profile to give it aerodynamic lift. The balloon would break a single cable at a wind speed of 41 metres per second.

Scan speed

There is no reason why the payload should not be scanned across the mine field at a good walking pace, say 2 metres per second and much faster, say the speed at which building site cranes are moved, in non-sensing mode. At 2 metres a second, a rather small mine sensor with an aperture of 100mm would cover a square metre in 5 seconds or 720 square metres per hour and would need 70 hours for the whole 50,000 square metre search area. However, there are many proposed sensor technologies that could use banks of sensors with much greater width and correspondingly higher productivity. A two-metre sensor width would cover the area once in only 3.5 hours. It is very likely that, when the sensor information has been written into the map, the demining supervisor would wish to scan some parts a second time.

It might be possible to exploit the resonance of the system and deliberately excite it by reducing tension in the traverse lines and applying oscillatory drives with controlled phase to the traverse winches. This would make the pay-load swing like a pendulum about the junction of the slope-lines. If we can start a rotation of the payload about the vertical axis, perhaps by an inertia wheel on the payload, we can keep it going as a parametric oscillation by correctly phased pulls on the three traverse lines so as to scan a sensor in azimuth. It would be necessary to have a separate measure of the pay-load position and rotation so that the read-out from the sensor could be logged at the right place.

Energy consumption

Calculations of the energy needed for altitude control are trivial but as we can plan search patterns to minimise vertical excursions the amounts are of little concern. A winch moving the payload horizontally will use energy equal to the distance moved times the traverse line tension which we can choose so as to balance economy with precision. It is theoretically possible to recover some of this energy from the other two winches but certainly not economical to do so. This means that the mechanical power used in moving round the minefield will be under two hundred watts, well below the rolling losses of a vehicle on soft ground. Winches could certainly be operated by muscle power but this would lose the disciplined precision we get from the combination of map-based search patterns, computers and Decca phase control.

Winch vehicles

The winches could easily be mounted to a roof rack on any road vehicle, but there are some other considerations. We want a vehicle that can move across uncleared mine fields without risk. It may need to do this with quite accurate navigation and no driver. It should be able to carry a gantry to lift cables clear of local obstructions. If we expect to increase payloads with bigger balloons the vehicle will need a wide wheel-base to give stability and should have a very stiff, or preferably no, suspension. It will have to have digital data links to the control centre. It will have to supply power to drive the winches and its communication electronics.

This description sounds very like that of a Dervish with a parallel rather than a 120-degree wheel plan.

The need for large drums to reduce bending stress in the carbon fibre leads to torques of a little under 100 Nm, rather high for electric motors but easily within the capability of Dervish hydraulics. It only needs two hydraulic valves costing about $70 each to divert oil from a Dervish wheel drive to a balloon winch. All the rest of the system can be used directly. Spares and maintenance training will be shared.

Deployment

Deployment of a balloon system will require planning, discipline and practice. We can expect that most mine-clearing activities will start from an access road. If a Tee-junction is not available we need to clear a roughly perpendicular path to form one to let the winch vehicles move apart.

Assume initially that the balloon is filled and held down by a single line. All three riser lines are wrapped on large spools which can be mounted like cine-film reels on shafts with a small, constant rewinding torque. This can conveniently be provided from a constant-current source of about one amp fed to DC permanent-magnet electric motors. The three slope-lines will be already wound on their winch drums. The winch vehicles are arranged in a circle round the balloon. Ends of all six lines are connected to the lower end of the single balloon line by a shackle like that used by mountaineers. The vehicles carrying the winches can move a short distance away to give separation between the lines. When the balloon is released it will unwind cable from both the tensioning drums and the hydraulic winches.

The amount of lift is controlled by the slope-line winches. It stops when all three riser lines have been wound off their drums. The drums carrying the carbon cables for the six-line truss are now fitted to the constant-torque spindles. The lower ends of the tetrahedron lines would each be joined to two top ends of the six-line truss lines and also to the inner ends of the three traverse lines, which can be pulled by hand off their winches. The balloon is then allowed to rise further with tension kept roughly equal between slope and traverse lines until the full lengths of the six-wire truss have been unwound. These are then connected, two to each corner of the triangular payload frame.

The payload can now be lifted so that it and the cables are safely clear of the ground. The winch vehicles can separate, paying out both slope and traverse lines as they go. This does not have to be done too accurately because the balloon can dip to compensate errors. The entire system can move from one search area to another, like a giant photographic tripod on wheels.

Navigation

The payload will be moved around the search area by co-ordinated movements of all six winches using information from search paths drawn on the mine-field map. We can use the same Decca system as for the Dervish but in a slightly different way.

We transmit exactly the same four frequencies from control stations but send signals back from the payload giving the output from the Decca phase–sensitive detectors. We use these two signals to adjust the phases of the transmissions so as to maintain 90-degree phase relationships at the payload. Knowledge of the cumulative phase changes gives a very accurate measure of the payload translation even if it has been disturbed by wind or winch excitation. Phase measurements from an aerial offset by half a wave-length from the spin axis give a direct reading of payload rotation. The narrow band-width of the Decca system gives it an excellent signal-to-noise ratio and we expect the transmission to be extremely reliable. However Decca is subject to multiple ambiguities, described as being in the right pew but the wrong church. If we do miss a wave-length we can reset the system using optical theodolite methods or proximity to pre–positioned markers in the mine-field.

Hazards

Balloons can easily avoid many obstacles that present great problems to vehicles and pedestrians but face a different set of difficulties. It is not possible to see a 1-mm diameter black cable against even a white background at a distance of more than 35 metres and so the support cables will be quite invisible from the edge of the mine-field and from aircraft. Low cable visibility does add some difficulty about manual control which we hope to solve with the recently available single-chip video cameras. We must avoid entanglements following a movement of the payload under overhanging branches. Balloons will need protection from extreme winds and lightning strikes. A winch vehicle cannot move under bridges or high-tension power cables. Air traffic controllers would not be amused by free-range balloons dangling hundreds of metres of cable, attached perhaps to winches or sensor packs. We may have to fit self-destruct facilities.

There will be times when the command links fail or a winch power source runs out of fuel. This would leave the payload stranded at some unpredictable height over the middle of the mine field. We can still recover it by having a hand-operated crank on each winch.

Other uses

Present metal detectors are not greatly advanced from the principles used by the original Polish technology from the 1930's. Deminers have already waited a long time for an improvement. It is useful to ask what else could be done with balloons if the wait is even longer. Opening up the third dimension presents many options despite limitations on the amount of force that can be used.

We can take close-up photographs to update maps. Sequences of pictures in different lighting conditions of melting frost, drying dew or patterns of parched grass are useful to archaeologists and may well provide information for deminers. We can see mines in trees. We can place navigation markers and radio repeaters. We can squirt paint at suspected mines. We can drop incendiary devices to burn off vegetation. We can drop grapnels to pull trip wires, remove cut vegetation or extricate robot vehicles. We can place counter-charges on mines and unexploded ordnance. We can drop acid-soaked quoits of limp glass-fibre to corrode through steel weapon casings. We can collect vapour samples. We can carry pigeons. (These can be trained to be many times better observers than US coastguards, have a longer attention span, cost less to feed and are much lighter, Sirois 1980). We can carry dogs, rats or cockroaches, all of which have a sense of smell many times more sensitive than any artificial nose.

Generals have always wanted to see the other side of the hill. Balloons make this cheap to do at any time and also give them the chance to do some gentle poking. If we use bigger balloons and get really confident about carbon fibres we can even hoist demining supervisors back to base for coffee-breaks.

Conclusions

The problem of moving sensors round a mine-field has been neglected. Most conventional vehicles have drawbacks of inappropriate speed and vulnerability to mines. It is important for productivity that the sensing task should not be delayed for every suspect target.

It would be useful to have outline specifications from sensor designers for weight, power-consumption, advance rate and communications bandwidth.

The two platforms described in this paper share a great many areas of technology including navigation, command electronics, path generation and even hydraulics.

As well as avoiding the disposal problems of anti-personnel mines, the Dervish can carry a metal detector, a vegetation clearing-tool and many other kinds of sensor. It will be able to write sensor information back on the mine map.

Balloons can carry payloads weighing about half their lift. The mass-produced Cameron AB 3000 can carry the hold-baggage weight of an economy-class airline passenger. This should be enough for many sensor techniques.

Balloon platforms do no damage to crops, do not produce pollutants to confuse chemical sensors or dogs. They are acoustically silent and can time-share the electromagnetic spectrum if necessary.

While there may be regulatory difficulties there are no technical problems about carrying much heavier payloads including people and quite heavy tools. These could perform many useful functions in demining. The present Dervish hydraulics could be used for much bigger balloons and the present Dervish could easily be adapted for use as a winch vehicle.

Search areas can be as much as 50,000 square metres and be swept in as little as 4 hours with a two-metre wide sensor. Costs per square metre and operating hour appear very attractive.

Carbon fibre lines are essential for stiff positioning but must be treated carefully, with no sharp bends, and always kept on large drums with controlled tension during deployment.

Natural frequencies of the sensor platform can be above 1 Hz and could reach 2.5 Hz if we pay for increased line diameter.

Vertical slope lines must be kept taut despite wind loads. This can be done in wind speeds up to 20 metres per second.

Energy consumption is very low especially if repeated changes in altitude are avoided.

There is anecdotal evidence from World War II that female barrage-balloon operators grew very fond of their equipment, becoming deeply distressed if a balloon suffered damage from enemy gunfire. The author finds that, even on a short acquaintance, he shares this affection.

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(Chapter 11 deals with taut wires.)

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The project has benefited from the voluntary work of a number leading engineers: Jimmy Dripps, and Hugh MacPherson of Spectral Lines have built the high frequency Decca system. Keith Manning and Don Sanella are writing control software.

Present UK Ministry of Defence rules (at present under review) forbid support for humanitarian mine clearance but this regulation has been observed with a considerable degree of elasticity in several ways that need not be precisely detailed. I can however record my thanks for frequency allocations.

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