An articulated robotic scanner for mine detection - a novel approach to vehicle mounted systems

Y. Das[a], K. Russell[a], N.Kircanski[b] and A.A.Goldenberg[b]

[a]Defence Research Establishment Suffield,
Box 4000, Medicine Hat AB, Canada,T1A 8K6

[b]Engineering Services Inc.,
5 King's College Rd, Toronto, ON, Canada, M5S 3G8

ABSTRACT

Conventional vehicle-mounted mine detector systems employ an array of sensor elements to achieve a detection swath (typically 2 - 4m wide). Some systems employ more than one type of sensor technology. These systems, while being very useful, are often expensive, complex and inflexible. A human operator, on the other hand, sweeps a mine detector from side to side while moving forward to cover ground. The operator can follow the ground profile with the detector head close to the ground without hitting the ground or any objects on it. She can also vary the width of sweep to suit a particular situation, and is usually not limited by terrain. In this paper we present the concept and early prototype of a system that incorporates the advantages of the two methods described above while minimising the disadvantages of both. For example, it will have the flexibility of a manual system with the rapid and safer mechanized scanning of the vehicle-mounted systems but at a reduced cost, size and overall system complexity, when compared to existing approaches. Our approach uses an articulated robotic device capable of automatically moving mine detection sensors over natural ground surfaces including roads and tracks in a manner similar to a human operator. The system can also easily be used to place a confirmatory point sensor at a specific location if needed. The early prototype, which incorporates only a metal detector for a mine sensor, implements ground following by using a laser range finder and four ultrasonic sensors.

Keywords: landmine detection, vehicle mounted mine detection, robotics, metal detection, sensor platforms

1. INTRODUCTION

There is a need for landmine detection equipment that can sweep large surfaces such as roads at a reasonable speed with a reduced logistic burden and hazard level. In response to this need, various vehicle-mounted systems have been developed over the years worldwide.[1–6] Under the US Army's Vehicle Mounted Mine Detection/Ground Standoff Mine Detection System Advanced Technology Demonstration (VMMD/GSTAMIDS ATD) program five vehicle-mounted systems[7] from different companies were

Further author information:(Send correspondence to Y.D.)
Y.D.:E-Mail:Yoga.Das@dres.dnd.ca; T/F:+[1](403)-544-4738/4704
Supported by the Defence Research and Development Branch, National Defence, Canada, Project 2MB

recently tested. Examples of recent Canadian vehicle-mounted systems are: (a) Remotely Operated Metallic Mine Detector System (ROMMIDS) developed in early 1993 under Project JINGOSS[1]; (b) Improved Landmine Detection System (ILDS) which is a multisensor, teleoperated system was completed in 1998.[2,3] All these conventional vehicle-mounted systems usually employ an array of sensor heads to achieve the required detection swath. For example, the ILDS uses 24 metal detector coils to cover a 3 m swath. It also uses 3 Ground Probing Radar (GPR) modules, each consisting of a number of transmit/receive antenna pairs, to achieve the required coverage. On the other end of the spectrum is the handheld detector that is manually swept from side to side by an operator as she moves forward to cover ground.

The manual method is slow, hazardous, manpower-intensive, and stressful to the operator who, as a result, can perform this task only for short periods at a time. As well, the task is monotonous and at times errors result due to operator inattentiveness. On the other hand, the conventional vehicle-mounted solutions, while being preferable for certain applications, are often expensive, complex and inflexible. For example, a system employing a 4-m wide array cannot be easily adapted in the field to traverse a narrower road if needed. As well, sensor height above the ground is usually fixed, resulting in non-optimal use of a sensor to the extent that it may miss a landmine that it could otherwise detect if the sensor height was controllable. In this paper we will discuss an approach which incorporates the advantages of manual and vehicle-mounted operations described above while minimising the disadvantages of both. For example, the proposed system will combine the flexibility of a manual system and the rapid and safer mechanized scanning of vehicle-mounted systems but at a reduced cost, size and overall system complexity. In this paper, our primary aim is to present the concept and briefly describe the first prototype in very general terms. An analysis of kinematics of the scanning arm as well as other engineering details of implementation can be found in the appropriate references.[8,9]

2. CONCEPT

Our approach uses a generic robotic device capable of autonomously moving a mine detection sensor over natural ground surfaces including roads and tracks in a manner similar to a human operator. Such a device, operated remotely, will increase the safety of the personnel performing mine detection. As well, this will provide a more flexible and less expensive way of sweeping surfaces such as roads and fields than systems which employ a static array of a large number of sensor heads. Our system can also be used to place a confirmatory point sensor at a specific location if needed. One example of such a sensor is the Thermal Neutron Activation (TNA) sensor used in the ILDS.[3]

A human operator sweeps a mine detector from side to side as she moves forward to cover ground. She holds the detector head close to the ground at a continosly adjustable height without hitting the ground or any objects on it. If required, she can pass the detector head a number of times, in a number of directions, over the same piece of ground to confirm a detection. She can vary the width of sweep, at will, to suit a particular situation, and is usually not limited by terrain. Our aim is to emulate these attributes as closely as possible by using a robotic system. Some of the attributes of our proposed system are summarized below.

- The robotic arm system which sweeps the sensor(s) over the ground can be mounted on almost any vehicle, and can be moved easily from vehicle to vehicle. The autonomous sweeping process aims to emulate the actions of a human operator as much as possible. The vehicle carrying the arm can be teleoperated or manually driven. These features will enhance the flexibility of vehicle-mounted detection operation.

- Our approach replaces an array of sensors (as used in conventional vehicle-mounted mine detector systems) with a single sensor that moves and provides similar coverage. Cost, size and overall system complexity are reduced, albeit, with minor increase in mechanical complexity.

- A small sensor head (as opposed to an extended array) follows the profile of a road or a natural surface in realtime. While scanning, the detector head can approach the surface as close as desirable without actually touching it. This results in the optimal use of a sensor. Besides improved safety, not contacting the ground with the sensor will result in significantly reduced sensor noise caused by ground-induced vibrations.

- If more than one sensor type were to be used, the approach will allow simplified collocation of different sensors, thus making the data correspondence and fusion problem in a multisensor system simpler than in a conventional vehicle-mounted system.

- The system can be used as a data gathering tool where precise positioning of a sensor head and association of sensor data with sensor position in an earth-fixed co-ordinate system are needed. This data collection and association can be done dynamically, if desired, to produce ground-referenced signal maps as the sensor head(s) is swept. Precise and repeatable sensor positioning will help develop or make practical sophisticated signal processing algothims (e.g., synthetic aperture GPR processing) aimed at detection and location of buried targets.

- Compared to conventional systems, our approach will allow convenient scanning of verges of roads and better off-road performance.

- The approach can be used to provide convenient platform for deployment of detector systems that are considered too big for manportable operation and too small to warrant full-fledged vehicle-mounted operation. One example of such a system could be an Nuclear Quadrupole Resonance (NQR) detector. As well, because of teleoperation, systems that are potentially hazardous, such as those using X-ray and radioisotope sources can also be safely used.

- Although some vehicle-mounted systems are protected against conventional antitank mines, they still may require a precursor vehicle to neutralize antipersonnel and tilt-rod mines. For example, the deployment concept of the Canadian ILDS calls for a protection vehicle to precede the detection system. For the system proposed in this paper, the requirement for such protection will be much reduced primarily because mines will be detected ahead of the vehicle without the sensor contacting the ground.

3. IMPLEMENTATION

A photograph of the robotic scanner mounted on an off-the-self teleoperated EOD vehicle (MR-1 from ESI) is shown in Fig. 1. A schematic illustration of the various degrees of freedom of the scanner is shown in Fig. 2. A close-up photograph showing the motors and actuators used to implement the required degrees of freedom is included Fig. 3 while details of the auxilliary sensors on the LRF arm are shown in Fig. 4. The system consist of the following major components.

1. A **scanning mechanism** consists of two “arm-like” devices - the detector arm and the Laser Range Finder (LRF) arm. The detector arm which has 4 degrees of freedom carries the mine detector which in this case was a Minelab F1A6 metal detector (Fig. 1 and Fig. 5) with digital output.

   The LRF arm is used (Fig. 4) to carry all the auxilliary sensors which in this case are the laser range finder and the ultrasonic distance sensors. The laser range finder which is aimed downwards at the ground provides instantaneous distance to points on the ground surface. Two of the four ultrasonic distance sensors are also pointed towards the ground to measure the distance to the ground, while the remaining two are pointed in the lateral directions to obtain information needed to avoid obstacles on the sides of the arm. In the present implementation, the scanning mirror of the LRF was locked in place thus limiting the “terrain mapping” to a ground-height profile along a line determined by the path of the LRF arm. The ultrasonic sensors pointed at the ground were used as an alternate to the LRF and not, as it is planned for future implementations, as complementary sensors providing a degree of redundancy and enhanced reliability. Object avoidance using the side-looking ultrasonic sensors was also not implemented in this version. These restrictions allowed the development of a simple (proof of concept only) strategy to control the mine detector's height above ground so as to follow the local terrain profile in an autonomous manner. The orientation of the mine detector head (roll and tilt) will also be controlled in future versions, through the use of 3-D terrain mapping.

2. The scanning subsystem is attached to a **prime mover** or a load-carrying platform. It could be a truck, a tracked or wheeled EOD robot, a legged robot or any other vehicle which can carry the electronics, computer, and power payload needed for scanner control, data acquisition and communication with the control station.

3. The LRF and the ultrasonic range finders and their associated electronics comprise the **auxilliary** sensor subsystem which is used to gather terrain information. Other auxilliary sensors such as video cameras, radar range finders and so on might also be considered for future implementation.

4. The **primary** sensors perform the mine detection task. Although only a metal detector with digital output is used in the present version, any other suitable detector or a combination of detectors (a metal detector and a GPR, for example) could also be used.

5. A **control station** communicates with and displays data from the above subsystems through a hard-wired or radio telemetry link. Although some aspects of the system are (semi)autonomous, such as the control of scanning of the detector head, the prime mover is teleoperated at this time. The control station is also used as a data gathering tool. A description of the control station and teleoperation of the vehicle are outside the scope of this paper.

The present version of the scanning process proceeds as follows: After the system is initialized and a homing process is performed, the vehicle is moved to the location to be scanned and the automatic scanning mode is activated. The arms are moved to one end of the arc to be scanned and the metal detector head is lowered to the desired scanning height (typically 5 cm). The scan starts by positioning LRF arm slightly ahead in the direction of intended travel of the detector arm with the angle between the two arms set at $15°$. Data from the LRF which moves “ahead” of the detector is analysed to estimate local terrain parameters such as ground elevation. This information is used to control the vertical position of the metal detector head. The lateral motion of the detector is controlled according to a trapezoidal acceleration profile (i.e., the arm is linearly accelerated to a constant velocity and then linearly decelerated). When the arms reach the end of the arc they stop, the LRF arm moves over the detector arm and positions itself slightly ahead (15°) of the detector arm (i.e.,in the direction opposite to that of the previous scan), and the scanning process is repeated but this time in the opposite direction. This autonomous side-to-side scanning will be repeated continuously. In our present implementation, forward ground coverage, that is, scanning in the direction of motion of the vehicle is provided by vehicle forward motion, resulting in lack of precise control in this direction. In future implementations, an additional degree of freedom allowing limited but precise movement of the detector in the forward direction will be added. The preferred operational mode of the system in this case will be "stop" and "go", where the forward motion is realized by the prime mover and while the system is stationary, the detector head will scan a selected small area. This area, whose size would be selectable, would typically be 2-3 m cross range to vehicle motion by 1 m along vehicle motion. The vehicle will then be moved ahead to new spot. Other modes of operation are also possible.

The current side-to-side scanning speed is variable in the range 0 to 1.4 m/sec and the arms can scan over an angle of 160° in front of the vehicle. Position information from encoders in the robot joints are used to establish correspondence of sensor data (such as metal detector output) with sensor-head position in a suitable reference frame, which is currently fixed to the vehicle. In the future data will be related to an earth-fixed reference system by acquiring vehicle navigation information. This will allow the production of geo-referenced signal strength maps and target locations. The process of data correspondence can be extended to multisensor systems to facilitate data fusion.

4. TESTS AND RESULTS

Only preliminary tests of a qualitative nature were done with this first prototype with the goal to assess the feasibility of the basic concept of scanning various surfaces. Tests were done both in the laboratory and outdoors while the data collected consisted mainly of video tape recordings of the arm and vehicle movements. In the laboratory, the system was required to scan over artificial surfaces and objects of varying complexity, which included cardboard, wooden surfaces, pieces of sod and so on. Different surface profiles, from flat to smoothly varying, were simulated. The detector head was able to follow these surfaces at a standoff of about 5 cm quite satisfactorily provided there were no abrupt (e.g., step) change in surface height. Future versions, implemented with 3-D terrain mapping, will be better able to negotiate step changes in surface profiles.

Outdoors, the prototype was used to demonstrate automatic sweeping over various natural surfaces during a two-day test under bright sun. The system satisfactorily followed flat and smoothly undulating gravel and dirt road surfaces, natural prairie covered with grass upto 15 cm tall, small mounds of dirt and gravel (typically 15 cm high and 30 cm base diameter), and a mud puddle. As expected from results indoors, the system could not negotiate sharp changes in terrain profile. As well, a standing water puddle caused the LRF to produce false readings and as a result the detector head struck the puddle.

Future work will be aimed at developing more robust terrain sensing techniques and control strategy so that the system could be used to scan a much wider variety of practical terrain.

5. SUMMARY AND FUTURE WORK

A new concept of vehicle-mounted operation of landmine detectors has been introduced. The concept which combines the flexibility of a manual system with the rapid and safer mechanized scanning of vehicle-mounted systems, with the advantage of reduced cost, size and overall system complexity. The idea was implemented using an articulated robotic scanner with enough degrees of freedom to follow the contour of various natural surfaces at a short (typically 5 cm) standoff. A simplified prototype was built which used a metal detector to demonstrate the concept. This system used a laser range finder and ultrasonic sensors to determine terrain profile parameters which were used to control the trajectory of the detector head. Although the basic concept was successfully demonstrated using the first prototype, a number of deficiencies, as discussed in previous sections, were apparent. Further development of the system is required before it becomes ready for practical deployment. Planned future work include the following:

- Currently, "terrain mapping" is limited to a ground-height profile along a line determined by the path of the LRF arm. In future implementations the laser beam will also be independently scanned to produce 3-D depth map of the terrain. In addition, the ultrasonic sensors pointed at the ground will be used as complementary sensors providing a degree of redundancy and enhanced reliability of terrain parameters. Object avoidance using the side-looking ultrasonic sensors may also be implemented.
- Develop more sophisticated and robust strategies to control detector head trajectory as well as its orientation (roll and pitch) based on 3-D terrain information. This work will involve developing suitable perception and path planning models.
- Scanning in the direction of motion of the vehicle is currently provided by vehicle forward motion. An additional degree of freedom allowing limited (typically 1 m) but precise movement of the detector in the forward direction will be added.
- In the present implementation, detector data and position information are referred to a co-ordinate system fixed to the vehicle. In the future, vehicle navigation information will be used to refer all measurements to an earth-fixed co-ordinate system.
- The addition of other mine detecting sensors, such as a GPR, will also be investigated.

Other terrain mapping techniques such as forward-looking optical stereo imaging should also be researched as a long term objective.

REFERENCES

1. A.Carruthers, R.Eirich, Y.Das, and A.Kramer, "Project JINGOSS – a tele-operated metallic mine detector (U)," in *Proceedings of the Knowledge-Based Systems and Robotics Workshop*, H.Merklinger, M.Farooq, P.Roberge, J.J.Grodski, and G. R. D. (Ret.), eds., pp. 283–291, (Ottawa , Ontario, Canada), November 1993.
2. J.E.McFee and A.Carruthers, "A multisensor mine detector for peacekeeping – Improved Landmine Detector Concept (ILDC)," in *Detection and Remediation Technologies for Mines and Mine-like Targets*, A.C.Dubey, R.L.Barnard, C.J.Lowe, and J.E.McFee, eds., *Proc.SPIE* **Vol.2765**, pp. 233–248, (Orlando, FL, USA), 9–12 April 1996.
3. J.E.McFee, V.Aitken, R.Chesney, Y.Das, and K.Russell, "A multisensor, vehicle-mounted, teleoperated mine detector with data fusion," in *Detection and Remediation Technologies for Mines and Mine-like Targets III*, A.C.Dubey, J.F.Harvey, , and J.T.Broach, eds., *Proc.SPIE* **Vol.3392**, pp. 1082–1093, (Orlando, FL, USA), 13–17 April 1998.

4. B.M.Cain and T.V.Meidinger, “The Improved Landmine Detection System,” in *The Detection of Abandoned Landmines: A Humanitarian Imperative Seeking a Technical Solution, EUREL International Conference* **Publication Number 431**, pp. 188–192, (EICC, Edinburgh, UK), 7–9 October 1996.
5. T.Hanshaw and D.M.Reidy, “Operational Standoff Mine Detection: Its Technology and Application,” in *Detection and Remediation Technologies for Mines and Mine-like Targets II*, A.C.Dubey and R.L.Barnard, eds., *Proc. SPIE* **Vol.3079**, pp. 432–442, (Orlando, FL, USA), 21–24 April 1997.
6. T.J.Gorman, “Analysis of sensor integration of the integrated ground mobile mine detection testbed (IG-MMDT),” in *Detection and Remediation Technologies for Mines and Mine-like Targets II*, A.C.Dubey and R.L.Barnard, eds., *Proc. SPIE* **Vol.3079**, pp. 443–451, (Orlando, FL, USA), 21–24 April 1997.
7. F. Rotondo, T. Altshuler, E. Rosen, C. Dion-Schwarz, and E. Ayers, “Report on the Advanced Technology Demonstration (ATD) of the Vehicular-Mounted Mine Detection (VMMD) Systems at Aberdeen, Maryland, and Socorro, New Mexico ,” IDA Document D-2203, Institute for Defense Analyses, 1801 N. Beauregard Street, Alexandria, Virginia 22311-1772, October 1998.
8. Engineering Services, Inc., “OPERATOR'S AND MAINTENANCE MANUAL (Development of a Robotic Scanner for Mine Detection),” Final Report (Part 1 of 7), Contract No.W7702-6-R625/001/EDM, DRES CR 1999-01, Defence Research Establishment Suffield, P.O. Box 4000, Medicine Hat, AB, Canada, December 1998.
9. Engineering Services, Inc., “CONTROL ARCHITECTURE MANUAL (Development of a Robotic Scanner for Mine Detection),” Final Report (Part 3 of 7), Contract No.W7702-6-R625/001/EDM, DRES CR 1999-03, Defence Research Establishment Suffield, P.O. Box 4000, Medicine Hat, AB, Canada, December 1998.

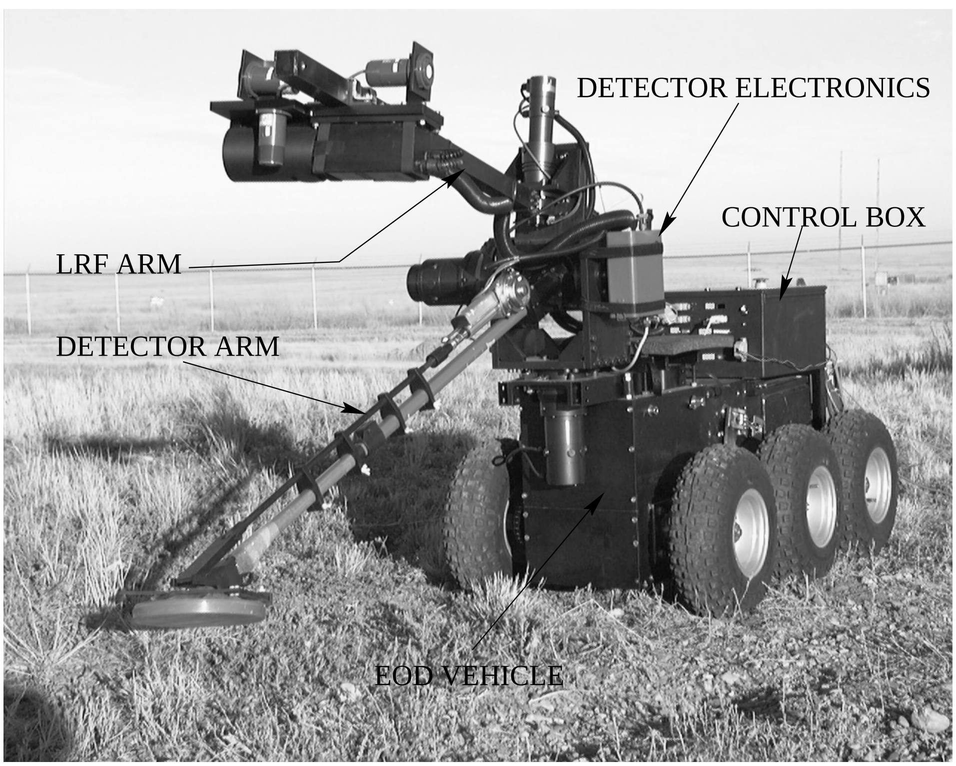

Figure 1. Robotic Scanner mounted on a teleoperated EOD vehicle

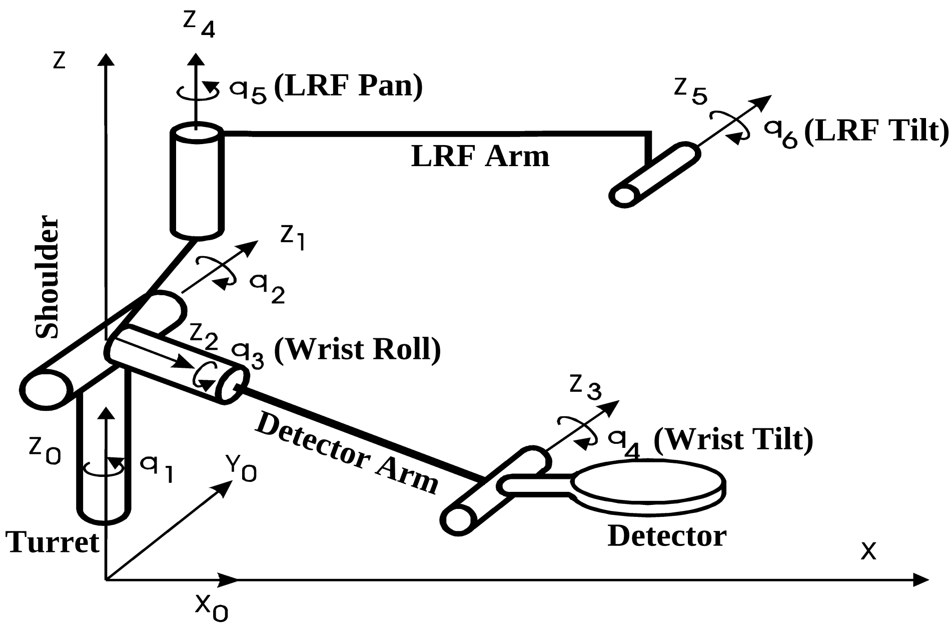

Figure 2. Kinematic scheme of the robotic scanner. The ultrasonic sensors are fixed to the LRF arm and are not shown in this illustration.

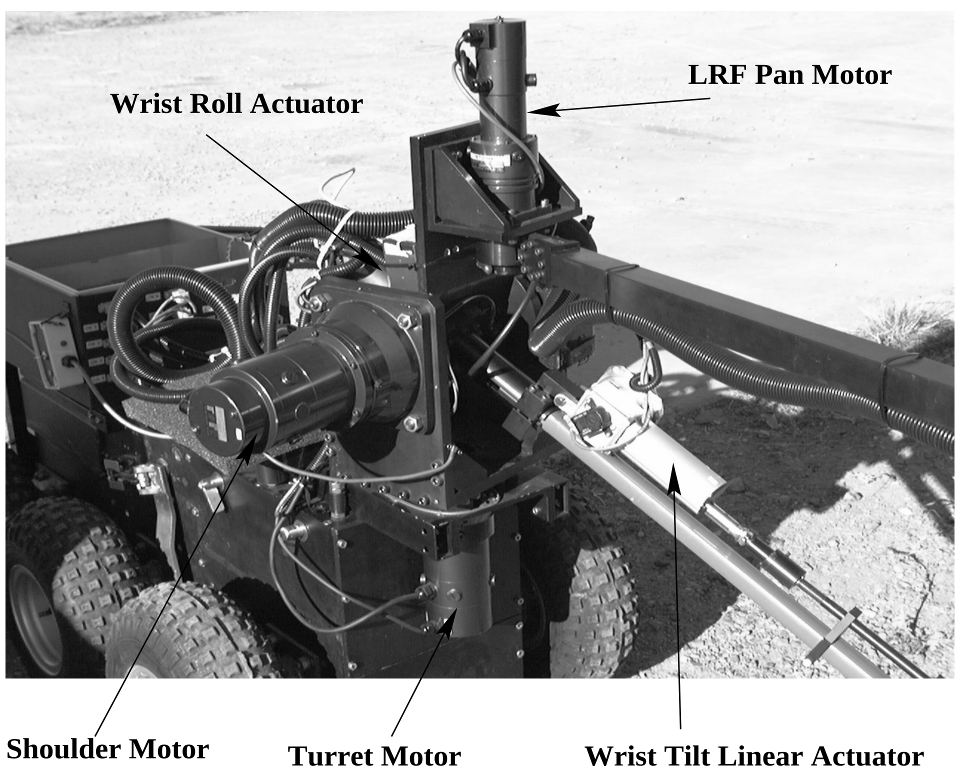

Figure 3. Robotic Scanner main actuators

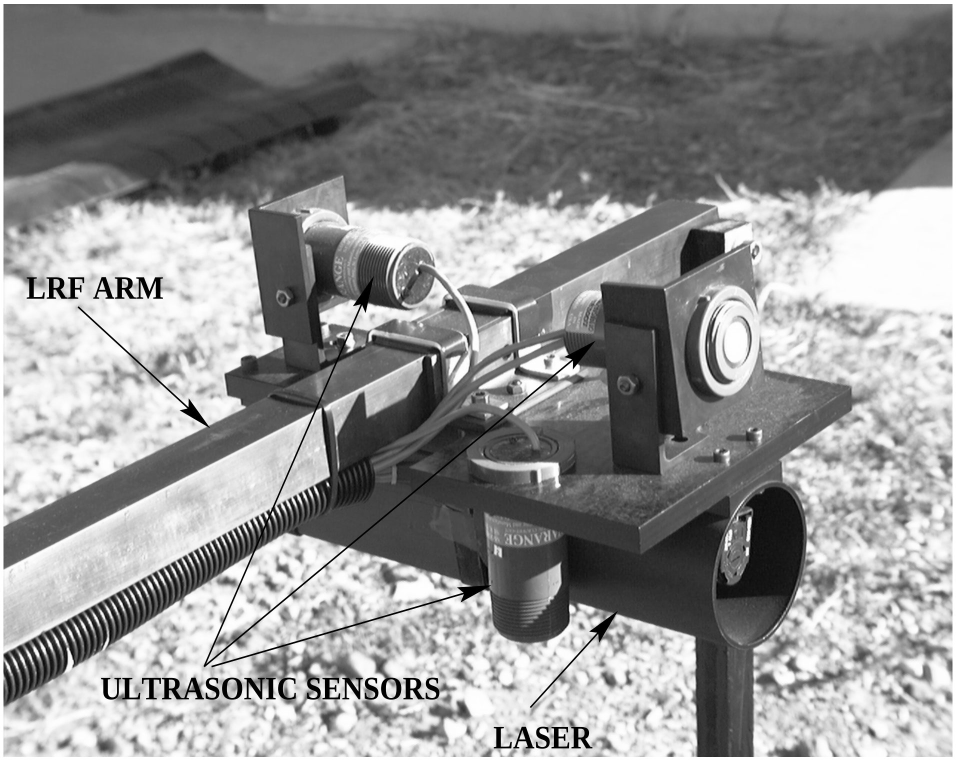

Figure 4. Sensor Heads at the end of the LRF Arm. 3 out of 4 ultrasonic sensors are visible.

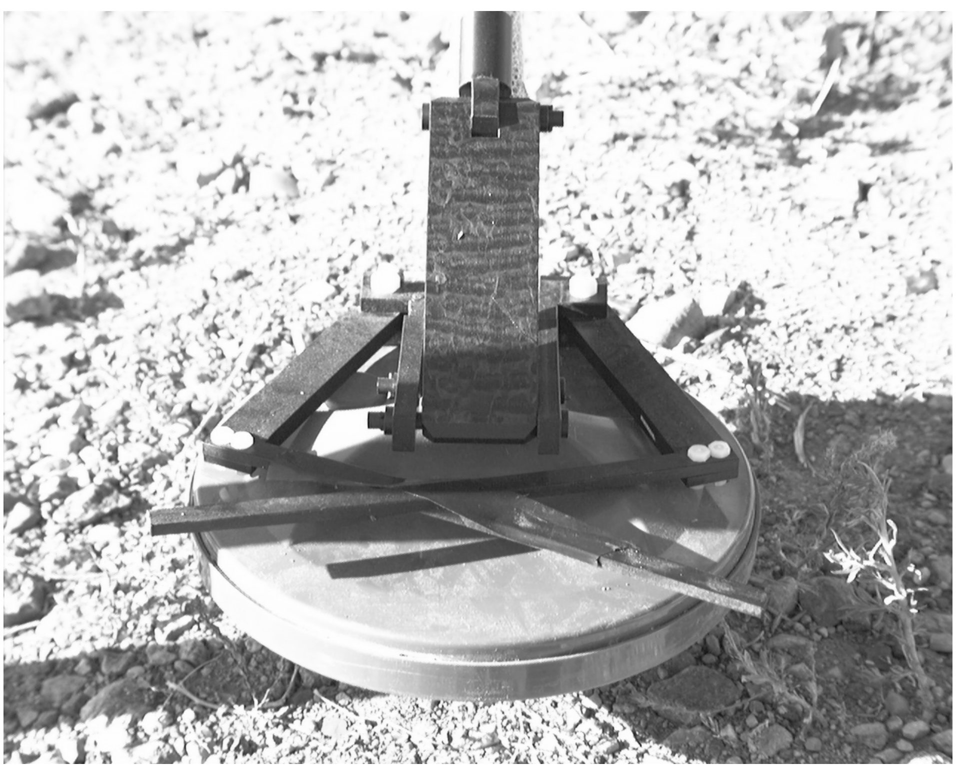

Figure 5. Mine detector head scanning the terrain