TERRAIN ADAPTIVE SCANNING OF CONVENTIONAL MINE DETECTORS

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Abstract

The Canadian Centre for Mine Action Technologies[1] (CCMAT) was established in 1998 with the goal of developing technology for humanitarian demining. One component of the research program is the development of an articulated robotic scanner to allow conventional mine detectors to be mechanically scanned in a manner similar to the scan patterns of human operators.

The articulated robotic scanner (ARS) is a purpose built robotic arm designed to hold a mine detector payload (of up to 5 kg) and scan it over the ground. The arm control system includes terrain measurement sensors to allow the detector head placement to be adapted to follow the terrain profile. The ARS design employs five degrees of freedom to allow a local work area of approximately 2m by 0.5m to be scanned. Within design limits, the detector head can be "rolled" or "pitched" with respect to the horizontal plane, maintaining the head parallel to the local ground surface, if desired. Coupled with the motion of a host unmanned ground vehicle the ARS can scan any desired area; generating a spatially registered map of detector response.

The ARS design includes a second arm, with an additional degree of freedom, to mount the terrain height sensors. Height measurements are made by a combination of a scanning laser range finder and ultrasonic distance measurement devices.

The paper briefly describes the development of the arm system, discusses the performance of the arm system in trials to date and touches on some of the system integration and data interpretation issues remaining to be solved before the approach could be utilized in field operations.

Keywords: Demining, metal detector, area scan, robotic, tele-operation, humanitarian, vehicle mounted.

1. Background

A capability to automatically detect mines over large areas would make a significant contribution to mine action. Such a capability could be used in area reduction[2], actual mine clearance operations or in quality assurance[3]. Numerous vehicle mounted systems have been developed to meet this need[1, 2, 3], however, the focus of this work has largely been on detection of anti-vehicle land mines for military applications. Humanitarian demining operations face a significantly different set of issues than military countermine operations. Primarily, in demining operations, the focus is on the removal of all mines, including anti-personel mines, over a large area. In contrast, military operations often focus on providing safe lanes for vehicle traffic, ignoring anti-personnel threats and any area that isn't immediately useful.

The ARS concept was originally developed under the auspices of the countermine research program of Defence R&D Canada[4] and was subsequently adopted by CCMAT based on the assessment of a scoping study [5] which included an examination of the potential of scanning detector systems in a purely humanitarian demining context. The scanning system was aimed at duplicating the complex scanning capabilities of a human operator, yet provide for computer based processing of the detection information through real time measurement and control of the detector head position. This led to the development of the current articulated robotic scanner or ARS.

The ARS development was conducted under a series of contracts funded by the Canadian Centre for Mine Action Technologies and the Canadian Department of National Defence. The arm was developed by Engineering Services Incorporated(ESI) of Toronto, Ontario. Development of the concept started in 1996 and delivery of the current system was completed in February 2002.

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[2]preliminary investigation of an area suspected to be mined to verify whether it is mined and to better delimit the area that contains mines

[3]detection sweeps following a clearance operation to confirm the quality of the work

2. System Concept

The ARS relies upon a high resolution measurement of the terrain over which the detector is to be passed to allow the computation of a trajectory for the detector payload. The terrain measurement is achieved by a scanning laser rangefinder coupled with several ultrasonic distance measurement units. The ultrasonic units are used to provide for obstacle detection in directions that the laser doesn't scan and to provide height measurements in instances when the LRF fails to generate a measurement[4]. Figure 1 shows the configuration of the sensors. The laser range finder measures the distance from the sensors to the ground throughout an arc perpendicular to the motion vector of the arm. The spatial resolution of the range measurements varies due to the geometry of the sensors, but is nominally on the order of 10 mm. Two ultrasound sensors are placed on either side of the main sensor head providing single point distance measurements in the line of the detector head motion. These measurements do not have similar spatial resolution but partially compensate for dropouts in the laser measurements. Two additional ultrasound sensors are used for obstacle detection for the laser arm itself.

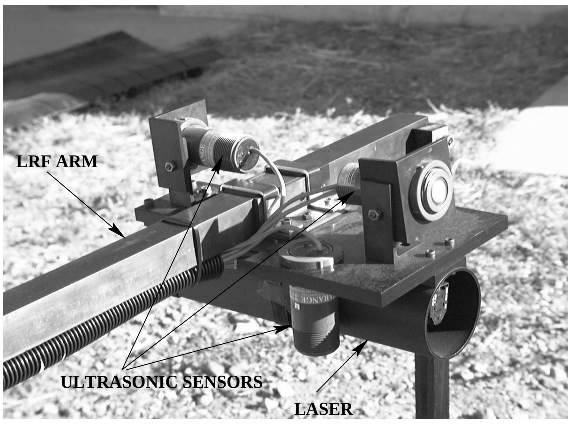

Figure 1: Terrain Sensor Configuration

A partial representation of the kinematics of the ARS can be seen in Fig. 2. The design includes two "arms"; one carrying the detector payload and the second (the LRF arm) mounting the terrain sensors.

The detector arm moves the detector payload in a circular arc about the shoulder joint (rotation q1) while the height of the detector is governed by rotation q2. The detector arm can be rotated (q3) to roll the detector and a linear actuator mounted on the arm (q4) allows the detector payload to be tilted in the "pitch" orientation. The upper arm

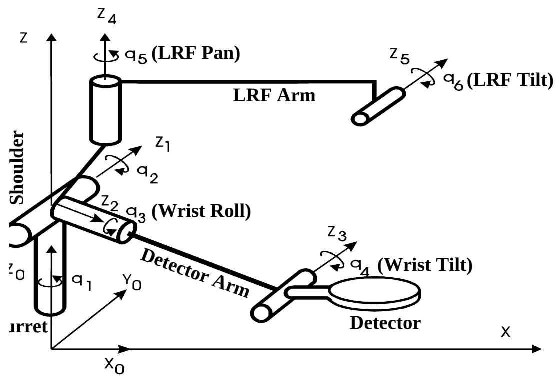

Figure 2: Robotic Scanner Kinematics

rotates with the shoulder; however this arm has an additional degree of freedom to allow the terrain sensors to "lead" the detector and to generate terrain measurements for the full width of the detector sweep.

This representation omits an additional degree of freedom which allows the shoulder to be translated in the longitudinal (x) direction. The entire shoulder / arm assembly is mounted on a platform coupled to a linear actuator that allows the shoulder to be moved forward by up to 0.5 m. This design allows the ARS to scan an area forward of its mount point that is approximately 2 m wide and 0.5 m deep (although highly non-rectangular).

In operation, the ARS is mounted on a vehicle. The vehicle and scanning system are then remotely operated by the system operator. The operator manoeuvres the vehicle to an area of interest and initiates a scan sequence. The vehicle remains stationary during a scan by the ARS and the data is telemetered back to the control station for display and interpretation.

A typical scan sequence would start with the detector head in a ready position, raised well off the ground. The laser scanner would then map a small area at one corner of the available scan area. The detector head is then lowered into this area and the laser scanning arm moved to lead the detector motion as the detector is moved to the opposite lateral extreme. The shoulder position is moved forward and the laser scanner moved to the opposite side of the detector head to again lead the detector motion. In the current software implementation, the computation of the detector trajectory is a real time process using only the height data from the area directly in front of the detector. Data from previous scans is not utilized. This avoids any issue of data misregistration should the orientation of the ARS change.

It should be noted that while the ARS includes

[4]primarily when the terrain surface generates a specular return as can be the case with standing water

the ability to operate in a terrain following mode, it is equally possible to sweep the detector head in a plane, should that be desirable for interpretation of the detector data. The plane can be computed based on the terrain measurements to provide the closest approach to a point of interest, or to maintain a nominal height above the local ground surface.

The ARS is designed to carry a payload of up to 5 Kg. For the purposes of the initial development and testing a Minelabs F1A4 detector is integrated. This detector is capable of generating a serial data stream representing its response, sampled with a period of 16 ms[5].

The control station receives time aligned detector data and joint position data. This is used to generate a spatial display of detector response versus position in the scan area. Combined with high resolution navigation data and motion estimates from the host vehicle, the detection data from multiple scans can be combined to provide a map of detector response over a broad area.

3. Trial Plan

The trials plan developed for the ARS system encompassed evaluating the performance of the arm in both a laboratory environment and in a limited range of outdoor environments. The principal objectives of the trials included:

- the ability of the laser scanner map building program to measure terrain features;
- the ability of the arm to control the detector head over terrain at realistic coverage rates; and,
- the ability of the arm control system to generate position information for point targets detected by the metal detector sensor.

The laboratory tests also provide an opportunity to verify all aspects of the integration between the ARS itself, the control system of the host vehicle and the control station. Integration issues include power consumption, time synchronization capability, command protocols, data protocols, and error reporting.

As an initial step to validating the utility of the ARS design, a variety of terrain types are used for trials including:

- sand
- broken or damaged pavement;
- gravel roads, both graded sections and sections subject to potholes, wheel ruts and washboard;
- coarsely mown grass or vegetated surfaces including examples with tracks, ruts and exposed rocks;
- surfaces with significant slopes or undulations; and,
- surfaces including obstacles such as marking stakes and trees that encroach on the scan area.

[5]due to limitations of the embedded controller used in the ARS the Minelab data is actually telemetered and recorded at a period of 33 ms

DoF	*Range*	*Referenced to*
q01	+78 to -88°	centreline
q02	5 to 35°	below horizontal
q03	+55 to -55°	horizontal
q04	+12 to -13°	horizontal
q05	+25 to -15°	lead / trail main arm
q07	0 to 500 mm	stowed position

Table 1: System Capabilities

4. Trial Status / Results

Trials of the ARS system are currently underway. Much of the laboratory testing has been completed and preliminary results are available. Initial laboratory testing was completed in a sand pit within a greenhouse complex. While much of the greenhouse structure is metal, it is sufficiently far away from the soil pits to provide an essentially metal free environment for the trials. Additional trials have been conducted in a conventional laboratory environment where the entire ARS assembly was raised and the detector was swept over a nonmetallic surface with wooden obstacles added as required.

The system capabilies are summarized in Table . For most of the trials performed to date the scan arc movement limits were limited to 40 degrees either side of centre. The nominal terrain offset used was 50 mm. The scan speed was 0.5 m/s[6]. The longitudinal position of the sweep arc was advanced by 30 to 50 mm between sweeps. For trials aimed at assessing the terrain following performance the detector position was advanced (in the x axis) at the end of a sweep in either direction, whereas, for trials aimed at collecting detector data the sensor head position was advanced following a sweep sequence in both directions.

Trials of the terrain following behaviour have been completed over a variety of surface profiles.

[6]this is the maximum sweep speed achieved during a scan. Acceleration profiles reduce the speed near the end of the sweep arcs

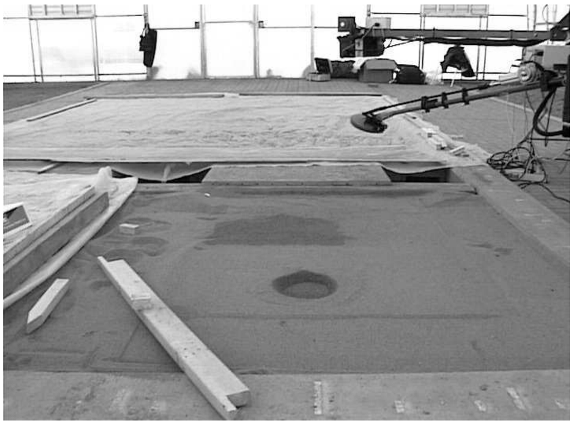

Figure 3: Example of Terrain Following Test

The initial trials were conducted in a sand soil with sand removed to form various surface profiles, including ruts and potholes. A photograph of a typical trial surface is included as Figure 3. The trials were generally successful with the detector able to follow most profiles attempted. While the performance of the ARS is currently adequate to support trials, some limitations of the current implementation have been identified. These primarily relate to the control algorithms driving the trajectory of the detector head. The current control strategy doesn't explicitly use the terrain measurements to form a terrain elevation map, but rather, uses the terrain data as a set point input to a relatively simple closed loop control strategy[7]. This limits the types of terrain that can be accommodated to those that are essentially "smoothly varying". Other issues with the current implementation relate to difficulties following terrain excursions near the edge of the scan path. This is due to initialization artifacts as the scan commences. None of these limitations is fundamental to the concept, but would require significant revision of the control software to fully exploit the mechanical capabilities of the system.

5. Example Detection Results

Detection data was collected for a variety of targets using the ARS. Tests included scans over both flat surfaces – in which the detector head was nominally in the same horizontal plane at all times – and over terrain features where the detector head followed the terrain profile.

Example plots of detector response versus detector position are included as Figures 4 and 5 as an intensity image. Both of these plots are derived from the same target[8], in the same position(equivalent to "pixel" 14,14 in the images). Figure 4 is derived from data collected as the detector head moves from right to left across the target and Figure 5 represents the response as the detector moves from left to right[9]. The differences between the two plots result from the time domain behaviour of the Minelabs F1A4. The detector has significant delay in the signal processing chain between the time the target enters the response zone and an output response. Further the detector exhibits an even longer decay time for the response. Human operators successfully compensate for, and even exploit, this behaviour in their use of the detector; however, it doesn't lend itself to straightforward spatial data interpretation. Despite the significant differences, it is still possible to localize the target from the combination of the two spatial data sets. The target location (for a point target) is essentially the point of symmetry between the two images. Display techniques to allow easy operator interpretation of the spatial result are being explored, but have yet to be finalized.

For comparison, Figures 6 and 7 show data collected with a larger target (a crushed aluminum pop can in this instance – centred at "pixel" 14,14). Localization is still possible, but the extent of the signature is so large it extends somewhat beyond the scan area of the ARS (at a single position). Other extended targets, such as larger pieces of scrap, loops of wire, metal anti-vehicle mines or larger EOD items can exhibit significantly larger spatial signatures. This emphasizes the requirement to being able to register data collected during multiple sweeps.

6. Future Work

Many aspects of the trial program remain to be completed. Controlled laboratory trials will be conducted against a variety of targets to collect a more complete data set to validate data visualization methods supporting target localization. This data set will also be exploited to develop concepts and techniques for interpreting data to infer target characteristics such as size, burial depth and material. Data interpretation may ultimately be automated, or it may remain as cues and guidance provided to an operator for manual interpretation.

The majority of the effort remaining to complete trials for the ARS is related to integrating the system onto a remotely operated vehicle and coupling the ARS control into the vehicle control and navigation systems. Mechanical integration

[7] in reality even the current control implementation is quite complex due to extensions required to accommodate the spatial extent of the detector head

[8] the target for these plots is a "clutter" example – a tab from an aluminum soft drink can

[9] the figures show the data with increasing longitudinal dimension down in the page. The ARS "shoulder" is at the top of the image; hence, "left and right" are reversed in the image

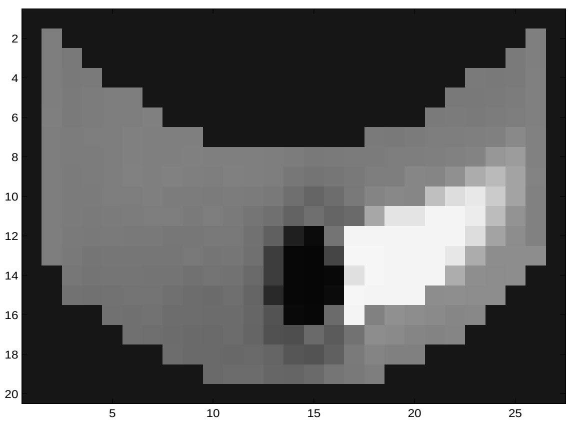

Figure 4: Detector Output Image (tab – Left Scan)

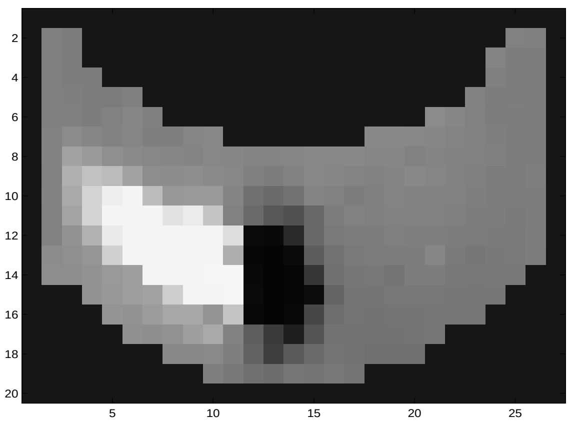

Figure 5: Detector Output Image (tab – Right Scan)

is complete and the ARS is shown on one of our research vehicles in Figure 8. Developing extensions to our existing vehicle control architecture and operator control station to support control of the ARS and display of the data is underway; however, the data display has not been validated as yet. The significant unknown in this regard is whether it will be possible to merge detection data from several passes of the ARS to form a spatial detection map over a larger area. This is required to localize targets near, or at the edge of, any given scan. While this is conceptually simple, and has been done in other systems for lower resolution data, the high spatial resolution of the data collected by the ARS will expose errors in position estimation to a great degree.

Once integration has been completed, trials will be conducted to investigate how best to exploit this class of system within a mine action environment and to fully define the potential utility of the system.

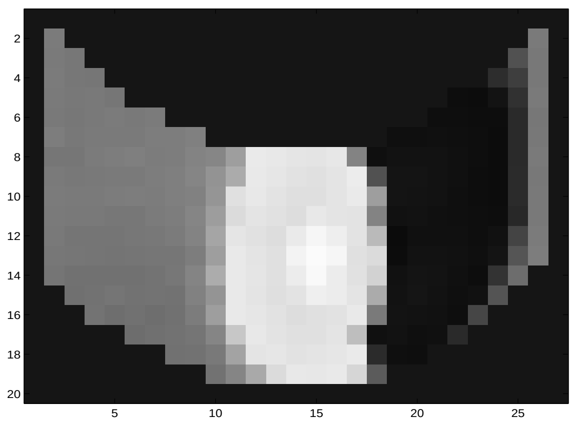

Figure 6: Detector Output Image (can – Left Scan)

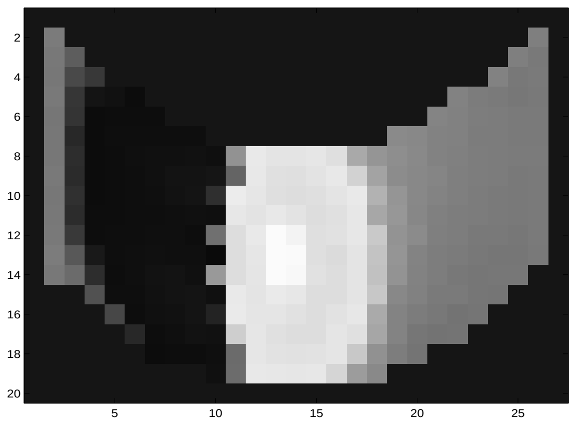

Figure 7: Detector Output Image (can – Right Scan)

Figure 8: ARS Mounted on "Scout" Remotely Operated Vehicle

7. References

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