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DESIGN OF AN AUTONOMOUS EXTERIOR SECURITY ROBOT

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Abstract

This paper discusses the requirements and preliminary design of robotic vehicle designed for performing autonomous exterior perimeter security patrols around warehouse areas, ammunition supply depots, and industrial parks for the U.S. Department of Defense. The preliminary design allows for the operation of up to eight vehicles in a six kilometer by six kilometer zone with autonomous navigation and obstacle avoidance. In addition to detection of crawling intruders at 100 meters, the system must perform real-time inventory checking and database comparisons using a microwave tags system.

I. Introduction

High dollar and sensitive assets stored within U.S. Government warehouses, ammunition bunkers and storage yards are vulnerable to a skilled intruder attempting to steal, sabotage, embarrass, terrorize or exploit the U.S. Government during peacetime. Targets range from classified documents, electronic equipment, personnel and small arms to nuclear and chemical material.

General Accounting Office (GAO) report NSIAD-92-60 notes that the Department of defense (DoD) is losing millions of dollars of inventory per year and conducts physical inventory audits that vary by several billion dollars from year to year. This problem is being exasperated by the reduction of security and inventory personnel due to the downsizing of the DoD budget. A highly secure autonomous intrusion detection systems (IDS) using robotic technology would protect these assets in addition to performing a physical audit of inventory on a daily basis.

This system called the Mobile Detection, Assessment and Response System, or MDARS, consists of two parts - an autonomous interior security robot and an autonomous exterior robot. In October of 1993 Robotic Systems Technology (RST) was awarded a three year contract by the Program Manager for Physical Security Equipment, located at Ft. Belvoir, VA, to develop and demonstrate an autonomous exterior security robotic system called MDARS-E.

II. Operational Environment and Concept

The MDARS-R system will be required to operate within fixed areas such as storage yards, office parks, dock facilities and air fields, both within and outside the Continental United States. Majority use will be in areas that are semi-structured with clearly defined boundaries. Within these areas will be structures of many shapes and sizes. The system will be required to operate on concrete and blacktop roads, crushed stone roads, or semi-flat rough terrain, and have the ability to cross railroad track or other small obstacles. Most of the areas will be limited access areas, with only security vehicles allowed after duty hours. Operations will be 24 hours a day in fog, rain and snow conditions.

Up to eight MDARS-E will be operating simultaneously in a six kilometer by six kilometer area or zone. This area will consists of a mixture of different storage bunkers and facilities and warehouse areas. Following a random path, a system will be autonomously looking for intruders or performing barrier and/or inventory assessment on the storage facilities.

During this time, video and status data will be continuously relayed back to the control station for potential collection, however the operator will not be actively involved with any of the systems. His job is to respond only if an anomaly is detected. Once an anomaly is detected by the system, the operator is alerted. He will then take over control of the system via teleoperation for final assessment. If he decides that a false alarm situation occurred, he will put the system back into automatic mode. However, if a real problem is detected, the operator can use the MDARS-E vehicle to respond to the threat or he can send in a manned patrol unit.

III. Requirements

The MDARS-E Requirement document and

the draft Concept of Operations paper define the following requirements for the MDARS exterior system :

- Simultaneous autonomous operation of up to eight MDARS-E systems within a six kilometer by six kilometer zone.
- Be able to travel both random and deterministic paths on road and rough terrain.
- Have a navigation system accurate to less than 0.3 meters within the six by six kilometer zone.
- Normal operating detection speed of 5 kilometers per hour (1.4 meters per second). Maximum teleoperation response speed of 25 kilometers per hour.
- Detection of crawling and/or running intruder from 2 to 100 meters over a 360 degree horizontal field of view.
- Probability of intruder detection between 90 to 95 % with no more than one nuisance/false alarm per platform per eight hour shift.
- Have an intruder detection system capable of penetrating smoke, fog, dust and precipitation.
- Provide an alarm if vehicle is tampered with.
- Operate on 10 degree slopes.
- Diesel primary motive power.
- Provide video, status, and command data to the main control station using a non-jammable, non-detectable communication link.
- Automatically avoid obstacle or prevent running into obstacles with a desired 100% assurance rate.
- Provide self-contained power capability for a minimum of eight hours continuous mobile operation.
- Be able to operate in an environment which contains fixed IDS sensors. Operate also in conjunction with the MDARS interior systems.
- Have a full teleoperation mode that will allow the operator to perform assessment and respond to threats.
- Be able to automatically query and update lock status on ammunition bunkers using a microwave detection system on a real-time basis.
- Be able to automatically collect inventory data of bunker contents using microwave tag collection system and compare to known inventory on a real-time basis.
- Be able to autonomously check the status of fixed barriers such as doors or fences.
- Have ability to detect exterior fires.
- Provide continuous video to the operator control station from all eight system for potential simultaneous recording and data collection.
- Provide bi-directional audio information.
- Be designed so that production cost in lots of 200 is approximately $150,000 per platform.

IV. Preliminary Design

Currently RST is involved in the preliminary design stage with. For design purposes, the system has been broken into seven different areas. These areas are:

- Navigation
- Obstacle Avoidance
- Intruder Detection System
- Lock/Inventory Monitoring
- Communication
- Vetronics/Platform
- Command and Control

Our approach in all of these areas is to have a primary and secondary method to ensure mission success. Candidate solutions are discussed in the following sections.

Navigation

The navigation system will depend on two primary position approaches - a highly accurate low-cost Radio-Frequency (RF) locating system using 3 fixed base stations and vehicle dead reckoning. The output of both of the system will be fed into a Kalman filter to obtain an absolute position less than 0.15 meters over the six by six kilometer zone.

Using a infogeometric code division multiple access RF spread spectrum system, we will be able to obtain accurate position and bearing data - in essence a virtual navigation sensor. In order to ensure constant communications with the RF locating systems, we will operate on three simultaneous, redundant spread spectrum frequencies - 50 Khz, 1920 Khz, and 2400 Khz. This approach will make our system virtually unjammable and unbreakable with encrypted codes. Another advantage of the system is that every vehicle knows the position of every other vehicle at all times.

RST's software navigation methodology approach is to use position measurement data to provide position matching to a digital map. This map, in addition to terrain and path data, will contain location of expected landmarks, microwave tags, obstacles, and any other important items (this map will be used to control both navigation and detection/assessment behaviors of the system). This data will be incorporated using a combination of proven navigation software methodologies that has developed and demonstrated on the MDARS interior platform. These concepts include: Virtual Paths, Fuzzy Fit, and Event Driven Reentrant Behaviors.

Virtual paths is the division of routes into short, concisely defined, and easily modified path segments that are combined to form complete route programs which allow the vehicle to navigate between any two points in the system. Each path segment contains all the navigation, control, and personality data required to permit the robot to perform its mission along the segment.

Our unique fuzzy logic algorithms extend fuzzy logic to include the concept of two dimensional degrees-of-membership. Using these techniques, sensor inputs are automatically tested against a position estimation and confidence. Data is accepted (or believed) in proportion to its level of agreement. Using this technique, past sensor readings are automatically integrated with new data with the result being that the vehicle exhibits smooth, accurate, and purposeful control even in the presence of erratic navigation sensor data.

Under the virtual path approach, the vehicle attempts to close on and navigate along a precise path. To accomplish this, the vehicle must use event driven reentrant behaviors to change behaviors as the result of both expected and sometimes unexpected events. An example of an expected behavioral change would be the beginning of a turn to join smoothly with the next path segment. An example of an unexpected event would be the required circumnavigation of an obstacle.

Another recent navigation methodology development is a clean and simple technique that permits the vehicle to change behaviors while maintaining the context of each behavior for possible reentrance. For example, when a vehicle has finished a circumnavigation maneuver, it can return to the normal routine of collecting and processing navigation data without the loss of previous landmark information.

Obstacle Avoidance

Because of the high reliability required for the obstacle avoidance (OA) system, we are planning to use three different sensor methods. The first approach is a vision based system using a front facing stereo camera arrangement for object detection. The image processing of this data will be handled through time-sharing the same electronics designed for the Intrusion Detection System image processing (see next section).

The second method is the use of an array of ultrasonic sensors in the front of the vehicle. One low cost concept that we are currently exploring using three transmitting sensors and a single receiving sensors. With the proper signal processing, we will be able to derive a 3 dimensional acoustic image out to 10 meters with spatial resolution of around 3 inches. This approach would provide 100 degrees of horizontal and vertical coverage.

Finally we are examining several low cost radar systems that are currently on the market. Final selection will be made after a full evaluation on our remote controlled testbed.

Intruder Detection Systems

The primary IDS system will be vision based using a thermal imager (FLIR) and a pair of image intensified Gen 3 cameras specially arranged to reduce the motion parallax problem. Using a stop and stare technique with a rotating mirror, we believe that this configuration will allow the detection of both running and crawling intruders while the vehicle is moving. We will be looking for motion, color cues, thermal hot spots, shapes and the presence of object in clear areas. As the backup method, we are examining several concept including an unique pulsed radar technique and a scanning laser system.

David Sarnoff Labs has pioneered the development of pyramid (wavelet) technology for computer vision. The pyramid is a multi-resolution image representation that provides a framework for implementing fast algorithms for motion, stereo, and visual search tasks. The pyramid/wavelet representation also facilitates object recognition by isolating key features based on scale, orientation, and texture or spatial/temporal pattern characteristics. The use of pyramid technology can provide enhancements in system speed (or reductions in system size and cost) by factors of 1000 or more compared to conventional approaches. This technology makes it possible, for the first time, to build a sophisticated vision system for real time applications using modest hardware.

The video processing functions provided are summarized in Table I. The test system is designed to support multiple vision functions simultaneously. Most functions will be processed at full video rate, 30 frames per second. Stereo and motion vision processing functions share hardware modules so these functions will normally be performed in alternate frame times, each at 15 frames per second.

The prototype vision system consists of a set of custom processing modules mounted on approximately 6 VME boards. It will be housed in a box measuring roughly 15 by 15 by 10 inches (without power supply), and will consume roughly 120 watts of power. Both size and power will be reduced significantly in future implementations of this system.

The vision system is capable of processing data from three camera channels at once, and it can switch between cameras on a frame by frame basis. For example, the system might process the FLIR camera and two stereo cameras during one frame time, then switch to the three channels (RGB) of a single color camera the next frame time.

The vision system is organized in a parallel pipeline architecture. The processing modules are connected to a specially designed backplane that can transfer images along 32 separate pathways simultaneously. The vision functions (motion, stereo, etc.) are implemented as software programs that control the flow and processing of image data. The system includes three digital signal processing (DSP) units and a microprocessor for control and analysis. An external disk is used to store reference images and other data. A display module is provided to overlay graphic information on displayed video. This is used both in system development and in presentation of information to a human operator.

This vision system design contains the flexibility to upgrade or replace vision functions through modifications to the software programs and through the addition of new processing modules.

The design of the video processing system proposed for MDARS testing is based on a moving target indicator (MTI) system built by Sarnoff for the Army Mission Command and delivered in June, 1992. It was designed to detect and track moving targets from a moving platform. While still under test and evaluation at MICOM, this system has already proven remarkably capable and can detect even small or camouflaged targets while the camera is moving. The MTI system is a prototype built on two custom 9U VME boards. Total parts cost is roughly $12,000, and power consumption is 120 watts.

The MDARS vision system will be an improvement of the MTI design in four important respects. First, the system speed will be increased so that it can perform motion analysis at 30 frames per second (the MICOM MTI system processes 15 frames per second). Second, the processing modules will be modified slightly to support stereo as well as motion analysis. The same processing modules perform electronic image stabilization and registration to reference images . Third, further modest additions will be made to the processing capabilities to support the other vision function (e.g., color and texture). Finally, a new backplane will be added to support flexible data communications.

Table I Functions of the Video Processing System

Vision Functions	MDARS Task Served	Specifications
Motion Vision (stationary)	To detect moving objects while the MDARS vehicle is stationary and the cameras are panning. This is required for detecting intruders.	• can detect camouflaged objects • can detect small or distant objects (one or two pixels in size) • 30 frames/second
Stereo Vision	To determine the distance to objects and the orientation and shape of the road surface. This is required to determine distance to moving objects, to determine whether they are within a secured area, and to estimate their size. It is also required to detect objects or ditches in the path of the vehicle while driving off road (pursuit mode).	• 10 to 30 stereo frames per second • 1/10 pixel disparity precision
Registration to Reference Images	To detect minute-to-minute or day-to-day changes in a scene. This is required to detect intruders who stand still when cameras are directed towards them, and move between camera scans. It is also needed to monitor stored inventory for tampering or loss.	• images aligned to 1/20 pixel • compensates for errors in camera positioning • 30 frames/second
Electronic Image Stabilization	To compensate for erratic camera motion as the vehicle moves over rough terrain. This is required for human viewing in the teleoperation mode, and for computer vision to maintain frame to frame correspondence.	• compensate for image translation and rotation • 1/20 pixel precision • 30 frames/second
Pattern Vision	To determine object shape. This is required for discriminating between humans, vehicles, and animals when they are detected as moving objects in a scene.	• 10 frames/second
Landmark Recognition	To identify visible landmarks such as buildings, trees, poles. This provides data for refining estimates of the vehicle's position based on stored maps. It also guides the vehicle to standard observation points for observing inventory using reference images.	• accurate to 1 foot • less than 3 seconds per position update
Color	To classify objects based on color. This improves reliability of target detection and discrimination. It also improves the system's ability to detect obstacles in the road.	• generates a set of compact color maps • 30 frames/second
Texture	To detect irregular patterns in the road that may signify obstacles or a rough surface. This is required for driving on rough terrain.	• generates a set of compact texture maps • 30 frames/second
Detection on the Move	To detect intruders while the vehicle is moving. Primarily a software improvement over fixed motion detection	• can detect while vehicle is moving • 30 frames/second

Lock/Inventory Monitoring

The RST contract requires the MDARS -E system to interface to the U.S. Army developed RF secure lock system and the RF inventory tag system. Jointly, the MDARS interior and exterior program will develop a common database structure for cataloging and up-dating inventory as information is gathered in real-time.

Communications

The same RF system used for navigation location will also provide the transmission medium for video and command and status data. Each of the three frequency used will have the capability to transmit 256 kbits of information. The 50 Khz channel will be the primary data link due to its non-line-of-sight ability. The other two line of sight channels will be backup in case of jamming or other interference.

We will use real-time data compression techniques to reduce the black and white video image to under 256 kbits per second. Command and status data will be transmitted in a bi-directional 4800 baud channel. Audio data will be overlaid with the video during the compression process using multi-media technology.

Vetronics/Platform

Current plans are to build a hydrostatic driven six wheel, all wheel drive platform. This platform will be 84 inches long, 51 inches wide and 30 inches tall with a center of gravity that will allow it to operate on 40 degree sideslopes. Each wheel will have independent suspension for maximum rough terrain capability. A diesel engine driving a hydrostatic propulsion system offers several advantages over a convention mechanical drivetrain. These are:

- The diesel engine operates at a constant speed within its optimal power range. Because the speed is constant, it is easier to shock isolate the engine vibration and to reduce engine noise.

- Electronic vehicle control is only two wires to a flow control valve and two wire to the valve controlling the ackerman steering system.

- Individual wheel motors lowers the center of gravity and pushes weights to the outside edges of the platform, making it more stable on sideslopes. Conversion to an all electric drive is easy with the replacement of the hydraulic motors with electric motors if desired.

- Hydraulic components are proven technology, rugged, immune to dust and low cost.

The basic vehicle electronics will be VME based. Our design will use the Controller Area Network (CAN) local area network for communication between subsystems. Software programming will be initial done using the "C" language and VxWorks, with eventual conversion to ADA by the third year.

Command and Control

The command and control station is being developed under the interior MDARS program. This console control up to 8 interior systems, 8 exterior systems and interface with any fix sensor system.

Electronics in the control station will allow for data recording of status and video data from all 16 system simultaneously. This data will provide an historical record of events and will assist the operator in the manual assessment part of his job.

V. Conclusion

The program schedule defines three major milestones. In January, 1994, RST will demonstrate key technology components in a standalone fashion. In January of 1995, RST will demonstrate two fully working systems at our facility. During the last 12 months, we will install and test the systems at a military site. During this 12 month period we will also be allowed to modify systems hardware and software components if required. At the end of this period, a formal acceptance test will be used to validate the exterior MDARS concept.