Real-world issues in warehouse navigation

H.R. Everett, D.W. Gage, G.A. Gilbreath, R.T. Laird, R.P. Smurlo

RDT&E Division, Naval Command Control and Ocean Surveillance Center
NCCOSC RDTE DIV 531, San Diego, CA 92152-7383

ABSTRACT

The MDARS security robotics program has successfully demonstrated the simultaneous control of multiple robots autonomously navigating within an industrial warehouse environment. This real-world warehouse system installation required adapting a navigational paradigm designed for highly structured environments such as office corridors (with smooth walls and regularly spaced doorways) to a semi-structured warehouse environment (with few walls and within which odd-shaped objects unpredictably move about from day to day). A number of challenges, some expected and others unexpected, were encountered during this transfer of the system to the test/demonstration site. This paper examines these problems (and others previously encountered) in the historical context of the ongoing development of the navigation and other technologies needed to support the operations of a security robotic system, and the evolution of these technologies from the research lab to an operational warehouse environment. A key lesson is that a system's robustness can only be ensured by exercising its capabilities in a number of diverse operating environments, in order to (1) uncover latent system hardware deficiencies and software implementation errors not manifested in the initial system hardware or initial development environment; and (2) identify sensor modes or processing algorithms tuned too tightly to the specific characteristics of the initial development environment.

1. BACKGROUND: THE MDARS PROJECT AND SYSTEM ARCHITECTURE

The Mobile Detection Assessment and Response System (MDARS) is a joint Army-Navy development effort to provide an automated intrusion detection and inventory assessment capability for use in DoD warehouses and storage sites. The program is managed by the Physical Security Equipment and Management Office at Ft. Belvoir, VA, with overall technical direction provided by the Naval Command Control and Ocean Surveillance Center, Research Development Test and Evaluation Division (NCCOSC RDTE DIV, or NRaD). The MDARS goal is to provide multiple mobile platforms that perform random patrols within assigned areas in order to: (1) detect anomalous conditions such as flooding or fires; (2) detect intruders; and (3) determine the status of inventoried items through the use of specialized RF transponder tags. A separate exterior development effort[1] addresses the requirements of outdoor DoD storage sites; this paper is concerned strictly with the MDARS Interior system and its operation in typical industrial warehouse environments.

The design of the MDARS system is driven by a number of characteristics of the application domain: (1) MDARS must function as a key component of a complete security system that also includes fixed detection capabilities and human security guards; (2) the patrol coverage of a large number (expandable up to 32) of mobile robotic platforms must be controlled and coordinated to minimize opportunities for undetected intrusion, even by insiders; (3) both the interior warehouse and exterior storage site environments require navigational capabilities intermediate between those of an unknown and dynamic environment (e.g., battlefield) on the one hand, and a completely structured and static environment (e.g., hospital corridors) on the other.

At the highest level of system description, the two areas of the design that particularly reflect the requirements of the MDARS application are: (1) the distribution of processing functionality, especially navigational planning; and (2) the choice of sensors and processing techniques to support vehicle navigation in the semi-structured environments.

The mappable nature of the environment, the relatively low frequency of exception conditions, the need to achieve coordinated coverage of multiple platforms, and the requirement to simultaneously support up to 32 platforms suggested a navigation approach based on centrally planned routine patrol routes, with any deviations handled on an exception basis. This feature is implemented in MDARS via the Multiple Robot Host Architecture (MRHA), in which a LAN interconnects a Supervisor computer, a pool of centrally located Planner/Dispatcher computers, one or more (human guard) Operator

Stations, and a Link Server (to route messages to and from the robots via RF modems). When a robot becomes idle, the Supervisor assigns a Planner/Dispatcher from the pool to plan and download a new path. The robot then autonomously executes the set of commands until completion or until an exception condition is encountered, whereupon the process repeats. Meanwhile, the Planner/Dispatcher is released back to the pool for allocation to another platform, so that a small number of Planner/Dispatchers can handle a large number of robots. When an event is deemed to require the attention of a human operator, the Supervisor assigns an Operator Station, which displays the appropriate information to the guard and provides an interface for command entry. Details of the MRHA architecture can be found in recent papers[1,2,3] by Everett et al.

2. BASELINE NAVIGATIONAL CAPABILITIES

The navigational capabilities of the MDARS Interior vehicle build upon those incorporated in the Cybermotion *K2A Navmaster* mobility platform -- preplanned *virtual paths* are downloaded to the platform for execution in various possible guidance modes. Cybermotion's *virtual path planning* has been supplemented in MDARS by NCCOSC-developed *unrestricted path planning.* When an obstacle is detected in the intended path by the robot's array of acoustic and infrared sensors, the robot halts and notifies the MDARS Supervisor computer, then sends its history buffer of recent sensor data to an assigned Planner/Dispatcher, which in turn uses it to plan an alternate "unrestricted" path to avoid the obstacle. The details of how this process is supported by the MRHA architecture are contained in the references.[1,2,3,4]

The primary movement command in Cybermotion's virtual path programming is the RUN instruction, which has as its arguments the coordinates of the desired destination and the desired target speed. Given only the RUN instruction, a vehicle will turn toward the destination and accelerate to the prescribed speed. Using a ramped velocity profile, the vehicle will then slow in order to reach a smooth stop at the destination. (The derivative RUNON command operates like RUN except that a smooth transition is made to a following RUN or RUNON command, rather than stopping at the destination.) A *K2A* platform with no sensor will execute a RUN or RUNON solely through odometry: every time the vehicle moves a fraction of an inch, the algorithm reads the drive and steering encoders, calculates the relative translation, and updates the vehicle's current position estimate.

The *Navmaster* adds to the *K2A* mobility base a sensor turret with RF data link, sonar system, and docking beacon. This sensor suite allows the vehicle to correct its position and heading estimates on-the-fly. This is triggered by preceding a RUN or RUNON instruction with a WALL, HALL, or APPROACH instruction. The WALL instruction causes the vehicle to monitor the relative range of a WALL on either side of the vehicle and parallel to its intended path. As the RUN executes, range points are collected along the wall. If these range points fit a straight line within programmable limits, corrections are made both to the heading and to the position along the axis perpendicular to the wall. HALL looks for walls on both sides simultaneously. APPROACH corrects the vehicle's dead-reckoned position as it approaches normal to a wall. Virtual paths may be programmed in text, or may be automatically generated by drawing paths on a CAD map of a building[4].

Figure 1. Photograph of the current MDARS-I vehicle configuration in the Camp Elliott warehouse test site.

3. NAVIGATIONAL ENHANCEMENTS FOR THE WAREHOUSE ENVIRONMENT

Cybermotion's wall following (WALL and HALL) navigational modes were developed initially for environments similar to office spaces, with many flat walls that allow continuous closed-loop correction of odometric errors. Because the warehouse environments in which MDARS Interior will be installed will not in general have such wall areas, a supplementary navigational re-referencing scheme is needed.

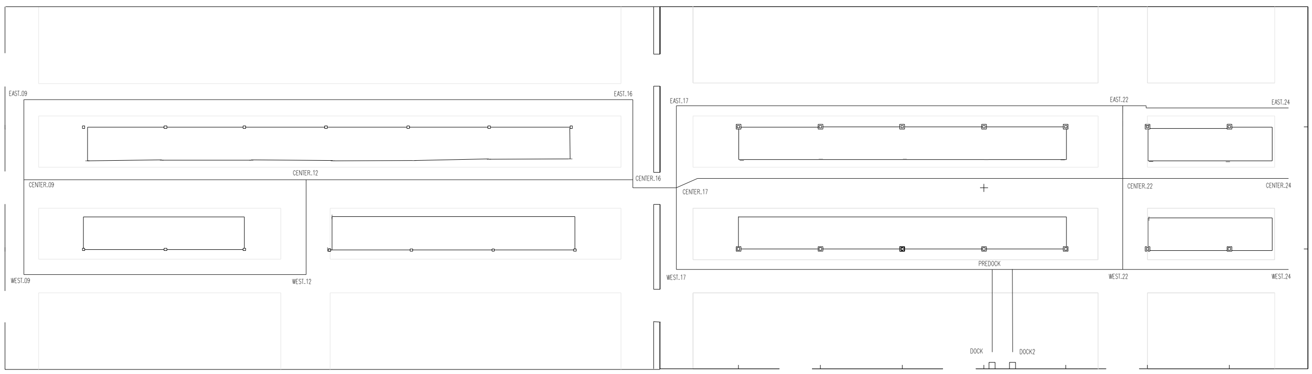

Figure 2. Map of MDARS Interior test/demonstration warehouse site at Camp Elliott in San Diego, CA. Long storage racks supported by posts are surrounded by rectangles that mark the boundary between the areas within which storage items may be placed and the allowed robot (and forklift) operating area which includes the network of interconnected virtual paths.

Many different solutions have been proposed (and a significant number actually implemented) to the problem of determining a robot's actual position within its operating area. The approaches differ greatly in accuracy, operating area size and characteristics, and costs in terms of requirements for sensors, processing, communications, and installation complexity. Typically some sensor is used to measure either the distance and/or the bearing to some chosen objects in the environment. Objects with desirable characteristics may be deliberately emplaced at surveyed locations, or existing objects may be used opportunistically. The objects may participate in the sensing process either actively or passively. The sensing system may involve ultrasonics, visible or IR light, or RF. Here are a few examples:

- An ultrasonic vehicle location system[5] developed at Tulane University employs a transmitting ultrasonic transducer mounted on the vehicle (a *TRC Labmate* is currently used) and a geometric array of receiving transducers mounted on the ceiling of the robot's 9 foot by 12 foot operating area. Sophisticated envelope-peak phase detection and compensation for temperature and humidity variations provide a .001 inch position accuracy at 100 Hz.

- Harris Technologies' Infogeometric System[6] employs a network of intelligent code-division-multiple-access (CDMA) spread spectrum RF devices (both mobile users and fixed reference units) that self-organize in order to provide data communications and distributed sensor data fusion as well as associative location and orientation tracking and network level autocalibration. The navigation function is essentially analogous to a scaled-down Loran system.

- MacLeod Technologies' CONAC System[7] employs a vehicle-mounted laser spinning at 3000 rpm and an array of photosensors fixed at known locations. The precise times of laser beam detection are then centrally processed to yield vehicle position and heading at a 25 Hz rate, with sub-cm accuracy. This scheme has been demonstrated controlling both an RC toy car in a parking lot and a Dodge Caravan traveling down a highway at 50 mph (not at the same time).

Everett[8] provides a comprehensive overview of acoustical, optical, and RF position-location techniques and available systems.

The navigational re-referencing technique implemented on the MDARS Interior vehicles, *lateral post detection*, is a hybrid scheme combining: (1) IR proximity sensors that determine the presence of a cooperative target of known location at a precisely determined bearing, with (2) ultrasonic range sensors that determine the distance to the object. The scheme is inexpensive in terms of both sensor hardware and processing power requirements, and fits smoothly into the Cybermotion *virtual path planning* structure.[8]

Short vertical stripes of 1-inch retroreflective tape are mounted on various immobile objects (usually structural support posts) on either side of a virtual path segment. The X-Y locations of these tape markers are encoded into the virtual path program as parameters (distance along the path where the stripe should be detected, and lateral distance expected from path to stripe) for a new STRIPE navigational mode implemented by Cybermotion on the *Navmaster* robot. Installation of the tape takes only seconds, and there is little chance of damage to the unobtrusively flat tape from passing forklifts.

A Banner Engineering *Q85VR3LP* retroreflective IR proximity sensor is mounted on each side of the *Navmaster's* turret, pointed perpendicular to the robot's direction of travel. As the robot passes the stripe, the sensor triggers a "snapshot" virtual path instruction that records the current side-sonar range values. The longitudinal position of the platform is updated to the known marker coordinate, while lateral position is inferred from the sonar data, assuming that both values fall within specified tolerances. Figure 3 depicts the geometry of the scheme in operation.

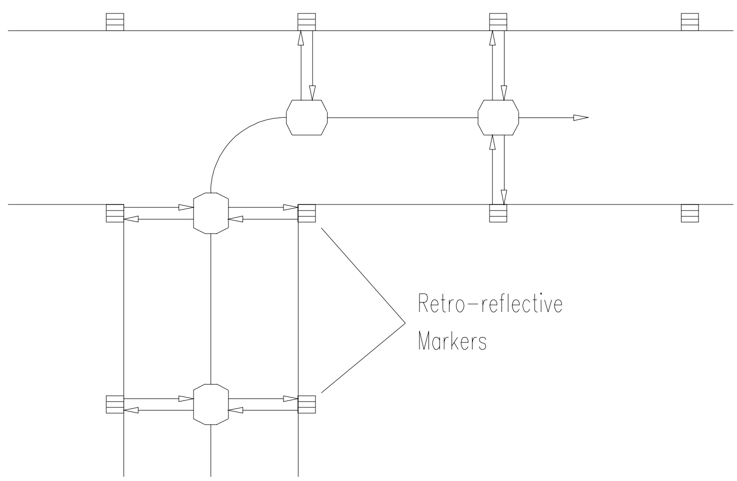

Figure 3. Circularly polarized retroreflective proximity sensors are used to locate vertical strips of retroreflective tape attached to shelving support posts in the Camp Elliott warehouse installation of the MDARS security robot.

The accuracy of the longitudinal (marker) correction is much higher than that of the lateral sonar readings, since the circularly polarized Banner sensor responds only to the presence of a retroreflector and ignores reflections from even highly specular surrounding surfaces, while the ultrasonic energy from the sonar will echo back from any reflective surface encountered by its relatively wide beam. While protruding objects in the vicinity of the tape (not unexpected in a warehouse environment) result in a shorter measured lateral range value, the long-term effect on X-Y bias tends to be averaged out.

This lateral post referencing concept was implemented on the MDARS unit in May 1994 and tested in an operational warehouse environment at Camp Elliott in San Diego, CA. The *Navmaster* robot was run continuously back and forth along a 150 foot path, with 7 tape markers set on posts 20 feet apart. No other navigational referencing instructions were contained in the path program. Initial heading and location errors were quickly nulled out after the second or third post was detected, and accumulated errors remained essentially insignificant for the remaining length of the path. Each time the robot reversed course at the end of a run, some noticeable heading error was introduced, but the error was then quickly eliminated as lateral-post updates were processed on the return leg. Introduction of objects protruding as much as 16 inches into the aisle immediately adjacent to the retroflective tape caused the expected shift in the actual path followed, but introduced no instabilities in the overall path-following process.

4. A NEW ENVIRONMENT BRINGS "NEW" PROBLEMS

The transfer of the lateral post scheme to Camp Elliott was not immediately successful, however. Several completely unanticipated and unrelated problems appeared during initial testing at the warehouse, even after complete subsystem checkout and integration in the laboratory. In this section we will place these problems in the historical context of other issues encountered while moving a robot to a new operating environment, over more than a decade of development of MDARS and its precursor security robots, ROBART I and ROBART II.

4.1 Pre-MDARS security robot development

Generally regarded as the world's first autonomous security robot, ROBART I was developed in 1982 at the Naval Postgraduate School[9]. While rich in collision avoidance sensors, this research platform had no sense of its absolute location, and was thus strictly limited to navigating along reflexive patrol routes defined by the relative locations of individual rooms, while periodically returning to a recharging station by homing on an IR beacon.

The second-generation follow-on to ROBART I was ROBART II (figure 4), which incorporated a multiprocessor architecture and augmented sensor suite in order to support enhanced navigation and security assessment capabilities. The addition of a world model allowed ROBART II to: (1) determine its location in world coordinates, (2) create a map of detected obstacles and (3) better perform multisensor fusion on the inputs from its suite of security and environmental sensors.[10] ROBART II was transfered to NRaD (then NOSC) in 1986, and used as a testbed for the development of obstacle mapping and other sensor fusion and navigation capabilities.

Figure 4. ROBART II. Second generation security robot constructed between 1982 and 1986.

Problem: When ROBART II was first moved from a small laboratory space to a large test bay in January 1990, a software data conversion rollover error that occurred whenever the sonar range was greater than 34 feet was uncovered. This software flaw had lain undetected for over 3 years, even under heavy use, due to the constricted confines of the original lab space. When the problem finally did manifest itself, the true nature of the bug was not correctly analyzed until after several other suspected causes were systematically eliminated: low battery voltage, electrical supply noise, acoustic interference between sensor transducers, and even confusion by chirping crickets.[11]

Problem: When ROBART II was later relocated to a new laboratory building in mid 1993, the performance of its reflexive teleoperation mode[12] (in which a human operator's teleoperation inputs are modulated by inputs from collision avoidance and other sensors) was observed to be substantially degraded: the robot would approach much closer than intended to a wall before turning away. This problem occurred because the surface of the wall of the new laboratory had much less texture than that of the space in which the behavior had been developed and tuned; the reduction in diffuse reflection meant the ultrasonic and near-IR sensors employed did not detect the presence of the wall until it was much closer.

4.2 MDARS -- laboratory experience

Beginning in 1989, the security robotics technology base developed on the ROBART testbeds was transitioned to the MDARS Interior engineering development effort. Obstacle detection sensors and *unrestricted path planning* algorithms that permit a robot to avoid collisions and to automatically move around detected obstacles were ported to the Cybermotion *K2A Navmaster* robot.

Problem: An array of ultrasonic sensors aligned 7 degrees below the horizontal was incorporated to detect obstacles on the floor in front of the robot. When this system was delivered to another government laboratory for test and evaluation, it was discovered that sonar returns from harmless expansion joints in the concrete floor were being misinterpreted as obstacles; the smoother floor of the original lab space had resulted in completely specular reflection. The solution was to fabricate new mounting plates for the sensor array, eliminating the downward pitch. While this simple relocation of the transducers effectively eliminated the problem of spurious returns from the floor cracks, it also reduced the robot's capability to detect low-lying obstructions.

4.3 MDARS -- warehouse experience

We return now to the 1994 installation of MDARS in the warehouse at Camp Elliott.

Problem: Following complete checkout in the MDARS development laboratory at NRaD, the lateral post detection software was ported to another *Navmaster* platform at the Camp Elliott warehouse site. It turned out that this robot's mobility base was not well aligned, so that its execution (with no sensor input except odometry) of a RUN command deviated significantly from a straight line, by as much as 1.5 - 2 feet over a travel distance of 20 feet (Cybermotion calls this *precession*). This hardware problem had not been previously detected because, in wall-following (WALL) mode, the robot used a steady stream of wall-distance measurements to constantly correct the error. Because the lateral post detection method used only <u>intermittent</u> fixes to correct the odometry-derived position estimate, the fact that the robot failed to hold a constant heading resulted in a lateral divergence that eventually became so large the displacement exceeded the range of the proximity sensor, and the platform subsequently became "lost." This problem was of course easily solved by employing a properly calibrated mobility base.

Problem: One completely unexpected development was that the warehouse exhibited several locations where the RF communications link between the robot and control station's Link Server became very unreliable. Systematic mapping of RF signal levels indicated wide variation, including areas of very low signal strength (see figure 5). When the robot entered one of these RF nulls, the Arlan RF units (which provide the user with a 9600-bps serial channel, using transparent packetization, error detection, and retransmission) would automatically retransmit packets until they got through. This retransmission was transparent to the higher level processing, except that the higher level protocol's one-second timeout would occasionally be exceeded, resulting in the retransmission of a complete message. Because the character-oriented data stream was protected by only a simple 8-bit checksum, the higher level processing would occasionally accept improperly combined message fragments as a valid message, resulting in the trashing of various status bits (incorrectly indicating a low battery condition, presence of an intruder, a fire alarm, etc.). In one case, a minor communications error led the system to initiate a sequential interrogation of 2000 nonexistent inventory tags. This problem has been addressed by moving to a greater bandwidth Arlan RF Ethernet implementation and a more robust CRC in the higher level protocol.

Problem: Improper alignment of individual LEDs in the IR docking beacon on the robot resulted in a small gap in the intended 180-degree beam coverage. Since the docking software was written with the assumption that an interruption of the beam meant a person was blocking the path, it waited for the person to move out of the way -- in this case indefinitely. The LED-alignment problem had not been detected in the laboratory because the robot had never approached the beacon from the "gap" angle (i.e., the robot was always within a smaller ellipsoid of uncertainty when it initiated a docking action). This problem was solved by realigning the beacon to eliminate the gap in its coverage.

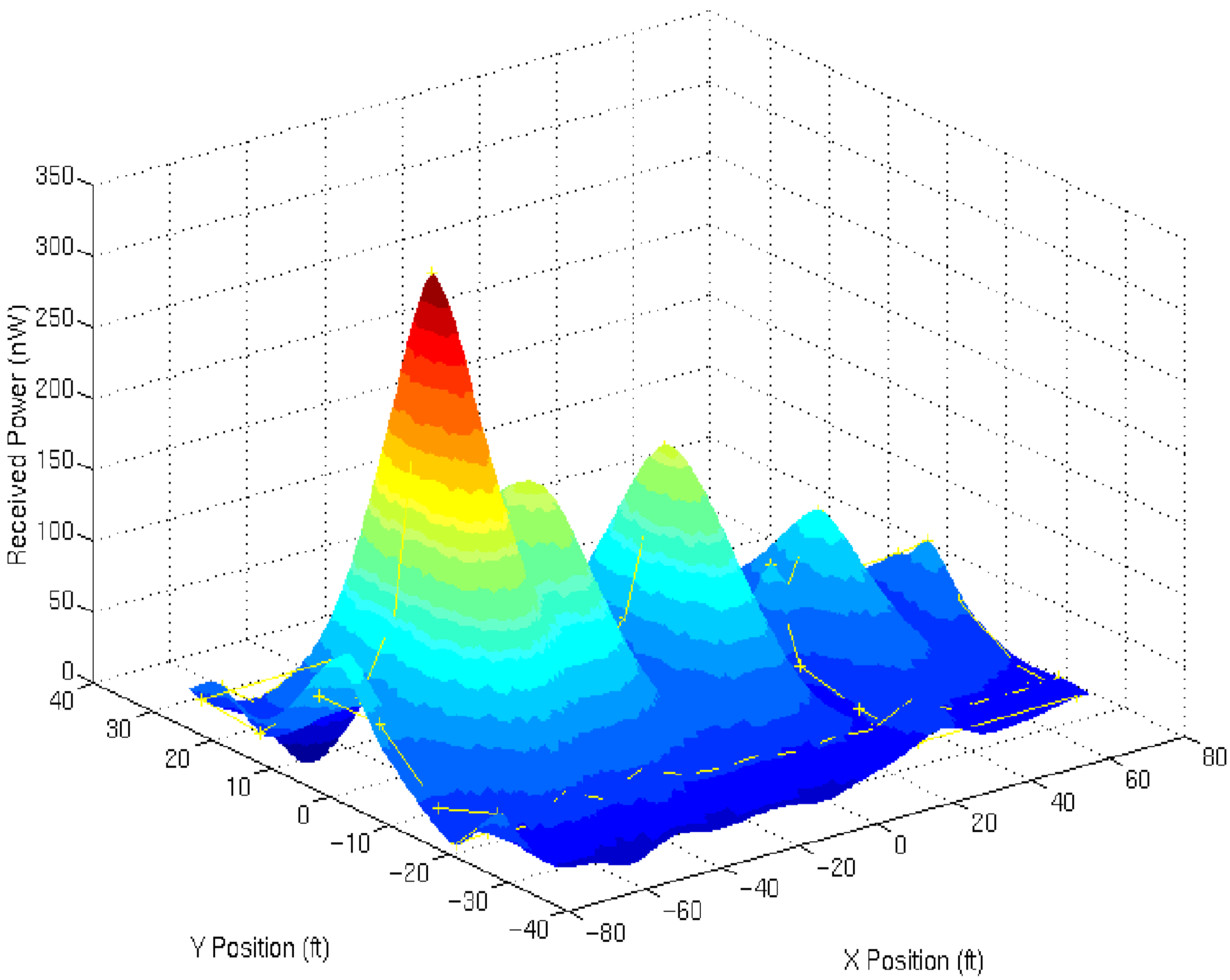

Figure 5. Survey of RF signal levels measured in Camp Elliott warehouse.

Problem: The IR docking beacon at Camp Elliott was initially installed near a west-facing exterior doorway. It was soon discovered that the late afternoon sun completely saturated the photodetectors used in the docking process, and the docking station had to be moved. All previous charger locations in the development environment had been along interior walls free of optical interference.

Problem: Because it was recognized from the beginning that MDARS robots would have to share their warehouse operations area with forklift operators and other human workers, reasonable precautions were taken to prevent accidents. Whenever a robot approaches the passageway between the two bays (see figure 2), a flashing light mounted in a highly visible location above the door is activated to alert forklift operators who might be working nearby. Unfortunately, human operators do not necessarily heed such warnings; in fact, in October 1994, a speeding forklift operator spilled his entire load in an emergency stop that narrowly avoided a collision with a robot approaching from the "blind" alley to his right. The virtual path structure within the warehouse has now been edited to prohibit the robot from approaching this virtual node from the side corridors, thus assuring that the forklift driver can see the robot directly ahead as it makes its way towards him down the central corridor.

5. DISCUSSION AND LESSONS LEARNED

5.1 General lessons learned

Our purpose in enumerating these problems is to point out that the process of moving a mobile robotic system from one operating environment to another, especially when moving from a deliberately benign laboratory development environment to a more complex and less structured environment more representative of real-world operations, is one in which unanticipated problems are the rule rather than the exception. The causes of the problems described above fit into a number of different categories:

- Hardware deficiencies not manifested on the initial system hardware;
- Hardware deficiencies not manifested in the initial development environment;
- Software implementation errors not manifested on the initial system hardware;
- Software implementation errors not manifested in the initial development environment;
- Sensor modes or processing algorithms tuned too tightly to specific characteristics of the initial development environment; and
- Subtle interactions between multiple hardware and software components, leading to unexpected breakdowns.

While a human's perceptual capabilities are powerfully adept at characterizing both the similarities and differences between various features of his/her environment -- at detecting both the general rule and the specific exception to it -- a robot's sensory inputs are far more limited, and it can interpret these inputs only up to the limits of its model of its environment.

A robot's software implicitly embodies a world model derived from -- but infinitely simpler than -- the world model present in the mind of the software designer. The designer may deliberately work to capture certain specific aspects of the world in the robot's "brain," while other aspects may creep in as unintended consequences of various software design decisions. Some problems arise when the robot's implicit world model is not rich enough to support the behaviors required by the application. Many others result when the designer simply fails to understand the limits of his robot's world model -- which aspects of his own world model have been implanted in the robot, and which have not. If a complex robotic system is to operate robustly, the model must take adequate account of the relevant dimensions of variability of the environment, as they will be reported by the sensor subsystems. A rough floor is still a floor, and you can drive over it; a low-lying obstacle is still an obstacle, and you can't drive over it. The sensors and perceptual software that build a robot's world model have to be able to draw such distinctions.

Well-implemented adaptive behavior in a robot (such as Cybermotion's wall-following mode) can bring along the downside risk of actually *masking* a hardware or software fault that may then manifest itself later at an unfortunate time. One possible solution to this problem is to instrument adaptive behaviors in order to monitor their adaptation modes -- to install "intelligence" analogous to that of the human driver who, while driving straight down the highway, notes the fact when his car's steering constantly "pulls left." Cybermotion is currently in the process of doing just that with their closed-loop navigation modes.

Behavioral robustness is required if mobile robots are to find viable markets. Robots must be mass producible, rather than handcrafted, and they must function acceptably over as wide a range of environments as possible without excessive manual tuning. Thus the designer of mobile robot hardware and software must accommodate the full range of variability within manufacturing processes and within target operating environments.

5.2 Specific lessons for MDARS

The MDARS Interior system is currently slated to be installed at an operational DoD warehouse for Early User Evaluation (EUE) in late 1996. Based on our previous experiences in transfering ROBART and MDARS robots to new environments, as described above, it is clearly prudent to anticipate that yet additional problems will be encountered in navigating the robot through this new warehouse. It makes sense to try to identify strategies that can reduce the technical, schedule, and cost risks to the MDARS program as the system is installed at the EUE location. For example:

- Carefully survey the site in advance of installation in order to identify environmental factors that might affect navigational performance. Are the posts supporting the storage racks 30 feet apart instead of 20? What are the reflective characteristics of floors and walls to both ultrasonic and IR? Do the standard operating practices of the human co-workers seem to pose any special challenges?

- Exercise the MDARS system in as many diverse environments as possible prior to EUE, in order to detect and correct additional latent flaws before moving to the EUE site.

- Anticipate that, despite our best efforts, real-time navigational re-referencing along the patrol route may occasionally fail, resulting in the robot becoming lost. Develop in response a general purpose automatic procedure that can be executed in order to re-establish the robot's absolute position.

The basic approach for such a navigational recovery procedure can be easily outlined, as follows. Start with the recognition that the robot can't get too lost over a relatively short period of time (i.e., it may be disoriented to the extent it cannot complete the assigned virtual path, but its position is still within some bounded ellipsoid of uncertainty). Starting with this knowledge of the robot's approximate position, the semi-structured nature of the warehouse aisles can be exploited to effect a recovery maneuver. For example, a static interpretation of surrounding sonar data can be used to generate a preliminary move to the perceived center of the aisle. Reflexive "tunnel navigation" can then be invoked to cautiously maneuver the platform along the longitudinal axis of the aisle at reduced speed while searching for definitive reference landmarks.[12] The robot's actual heading and X-Y position remain ambiguous during this maneuver, but the onboard sonars can be used to keep the platform generally centered between the perceived clutter on either side of the aisle.

Magnetic heading from an inexpensive fluxgate compass can potentially aid this process, and in worst-case scenarios ensure the robot is moving down the aisle in the desired direction. Retroreflective stripe markers would then be processed in conventional fashion to re-reference the platform, assuming the corrupted dead-reckoning solution is not off by more than the typical 20-foot stripe-separation distance. A more robust (and expensive) sensing approach would involve a rotating laser scanner to detect in-plane retroreflective targets, the advantage being a more tolerant acceptance window due to longer effective range and the 360-degree field-of-view. If laser range information is subsequently available, triangulation techniques could also be used to establish actual platform heading and position. Yet a third possible alternative would involve reflexive aisle transit to the first encountered intersection, followed by a static ultrasonic position-location action using the four corner shelf-support posts as definitive targets.

5.3 Coexistence of mobile robots and manned vehicles

The large number of robots performing industrial tasks such as welding, painting, and spraying in operational factory environments has generated a base of experience in the coexistence of human factory workers and industrial manipulators. The key concern with a powerful manipulator is the safety of workers entering its workspace to perform tasks such as feeding materials; fortunately, the limits of the workspace are static and access can be easily controlled. For mobile robots, on the other hand, the workspace is neither static nor (in many cases) physically constrained. While a robot mailcart equipped with good bumpers repeatedly following an installed guidepath at 1 mph does not pose a significant threat to the safety of the people walking the corridor (nor do they pose a threat to it), the initial MDARS experience demonstrates vividly that a larger, heavier mobile security robot autonomously patrolling a warehouse in which potentially inattentive forklift operators are moving quickly about poses issues of safety for the robot as well as for the humans involved.

Beyond simple safety, the activities of humans in the warehouse unpredictably reconfigure the robot's environment as cartons and pallets are moved about daily, somewhat complicating the navigation task and making the role of the MDARS operator (guard) all the more important as the assessment engine of last resort. Finally, the need to cultivate acceptance of robots by human co-workers is clear if they are to operate successfully in the same space, since any seriously adversarial situation between robot and human co-worker will eventually be manifested as a system malfunction.

6. SUMMARY

Transplanting a mobile robot system from the benign laboratory environment in which it was initially developed to a semi-structured test and demonstration environment is seen to be a challenging process, but one which is necessary for the successful development and validation of robust navigational capabilities. The MDARS Interior security robot system has successfully made this transition as the latest in a series of steps that will eventually see it performing security patrols in operational DoD warehouses. The lessons learned to date will be exploited to improve the chances of success as the MDARS system is transfered to successively more demanding environments.

7. ACKNOWLEDGEMENT

This work has been performed under the Mobile Detection Assessment and Response System (MDARS) project, managed by Mr. Jerry Edwards of the Physical Security Equipment and Management Office (PSEMO) at Ft. Belvoir, VA.

8. REFERENCES

1. T.A. Heath-Pastore, H.R. Everett, "Coordinated Control of Interior and Exterior Autonomous Platforms," *ISRA '94, Fifth International Symposium on Robotics and Manufacturing*, Maui, HI, August, 1994.

2. R.T. Laird, H.R. Everett, G.A. Gilbreath, "A Host Architecture for Multiple Robot Control," *Proceedings of the ANS Fifth Topical Meeting on Robotics and Remote Systems*, American Nuclear Society, Chicago, IL, (1993).

3. H.R. Everett, G.A. Gilbreath, T.A. Heath-Pastore, R.T. Laird, "Coordinated Control of Multiple Security Robots," *Proceedings of SPIE Mobile Robots VIII*, Boston, MA, September 1993.

4. J. Holland, H.R. Everett, G.A. Gilbreath, "Hybrid Navigational Control Scheme for Autonomous Platforms," *Proceedings of SPIE Mobile Robots V*, Boston, MA, November 1990, pp. 291-298.

5. J.F. Figueroa, A. Mahajan, "A Robust Navigation System for Autonomous Vehicles Using Ultrasonics", *Control Engineering Practice*, Vol 2, No. 1, pp. 49-59, 1994.

6. J.C. Harris, "An Infogeometric Approach to Telerobotics", *Proceedings of 1994 National Telesystems Conference*, San Diego, CA, 26-27 May 1994.

7. E.N. MacLeod, M. Chiarella, "Navigation and Control Breakthrough for Automated Mobility", *Proceedings of SPIE Mobile Robots VIII*, Boston, MA, 9-10 September 1993, Volume 2058, pp 57-68.

8. H.R. Everett, *Sensors for Mobile Robots: Theory and Application*, AK Peters, Ltd., Wellesley, MA, draft copy, July, 1994, (available Spring 1995).

9. H.R. Everett, "A Microprocessor Controlled Autonomous Sentry Root", Masters thesis, Naval Postgraduate School, Monterey, CA, October 1982.

10. H.R. Everett, G.A. Gilbreath, T. Tran, J.M. Nieusma, *Modeling the Environment of a Mobile Security Robot*, TD 1835, Naval Ocean Systems Center, San Diego, CA, June 1990.

11. Ibid, pp 16-18.

12. H.R. Everett, R.T. Laird, "Reflexive Teleoperated Control," *Proceedings of AUVS-90*, Dayton, OH, July 1990, pp. 280-292.