# An automated security response robot

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## ABSTRACT

ROBART III is intended as an advanced demonstration platform for non-lethal response measures, extending the concepts of reflexive teleoperation into the realm of coordinated weapons control (i.e., sensor-aided control of mobility, camera, and weapon functions) in law enforcement and urban warfare scenarios. A rich mix of ultrasonic and optical proximity and range sensors facilitates remote operation in unstructured and unexplored buildings with minimal operator supervision. Autonomous navigation and mapping of interior spaces is significantly enhanced by an innovative algorithm which exploits the fact that the majority of man-made structures are characterized by (but not limited to) parallel and orthogonal walls.

Extremely robust intruder detection and assessment capabilities are achieved through intelligent fusion of a multitude of inputs from various onboard motion sensors. Intruder detection is addressed by a 360-degree staring array of passive-infrared motion detectors, augmented by a number of positionable head-mounted sensors (i.e., sonar, microwave, video). Automatic camera tracking of a moving target is accomplished using a video line digitizer. Non-lethal response systems include a six-barreled pneumatically-powered Gatling gun, high-powered strobe lights, and three ear-piercing 103-decibel sirens.

This paper presents a comprehensive overview of ROBART III's supervised autonomous navigation, intruder tracking, and non-lethal weapon and control systems.

**Keywords**: security, robot, response, navigation, exploration, non-lethal, weapon, beam-splitting, sonar

## 1. INTRODUCTION

From a navigational perspective, the type of control strategy employed on a mobile platform runs the full spectrum defined by *teleoperated* at the low end through fully *autonomous* at the upper extreme. A *teleoperated* machine of the lowest order has no onboard intelligence and blindly executes the drive and steering commands sent down in real-time by a remote operator. A fully *autonomous* mobile platform, on the other hand, keeps track of its position and orientation and typically uses some type of world modeling scheme to represent the location of perceived objects in its surroundings. A very common approach is to employ a statistical certainty-grid representation, where each cell in the grid corresponds to a particular "unit square" of floor space (i.e., a three-inch square, a six-inch square, depending on the desired map resolution)[1]. The numerical value assigned to each cell represents the probability that its associated location in the building is occupied by some object, with a value of zero indicating *free space* (i.e., no obstacles present).

The existence of an absolute world model allows for automatic path planning and execution, and for subsequent route revisions in the event a new obstacle is encountered. Unfortunately, the autonomous execution of indoor paths generally requires *a priori* knowledge of the floorplan of the operating environment, and in all cases the robot must maintain an accurate awareness of its position and orientation. Differential GPS has come a long way recently in satisfying this latter referencing criteria for outdoor applications, but is of no help indoors due to signal blockage by the building structure.

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Accordingly, traditional autonomous navigation techniques are of limited utility for applications where the requirement exists to enter previously unexplored structures of opportunity as the need arises.

Teleoperated systems, on the other hand, permit remote operation in such unknown environments, but conventionally place unacceptable demands on the operator. For example, simply driving a teleoperated platform using vehicle-based video feedback is no trivial matter, and can be stressful and fatiguing even under very favorable conditions. Experience gained through actual use (by law enforcement and military personnel) of conventional teleoperated devices with minimal onboard intelligence has revealed other shortcomings from a man/machine interface point of view. Simply put, if a remote operator has to master simultaneous manipulation of three different joysticks (i.e., one for drive and steering, another for camera pan and tilt, and possibly yet a third for weapons control), the chances of successfully performing coordinated actions in a timely fashion are minimal.

Easing the driving burden on the operator was a major force behind the development of the reflexive teleoperated control scheme employed on ROBART II (Figure 1), a prototype security robot capable of both teleoperated and autonomous operation. The robot's numerous collision-avoidance sensors, originally intended to provide an envelope of protection during autonomous transit, were called into play during manual operation as well to greatly minimize the possibility of operator error. The commanded speed and direction of the platform was suitably altered as needed by the onboard processors to keep the robot traveling at a safe speed and preclude running into obstructions. Work on ROBART III (Figure 2) currently seeks to extend this reflexive-teleoperation concept into the realm of sensor-assisted camera and weapons system control, as will be discussed further in the following sections.

**Figure 1.** ROBART II (1982-1992) served as a development platform for reflexive teleoperated control of platform and camera motion.

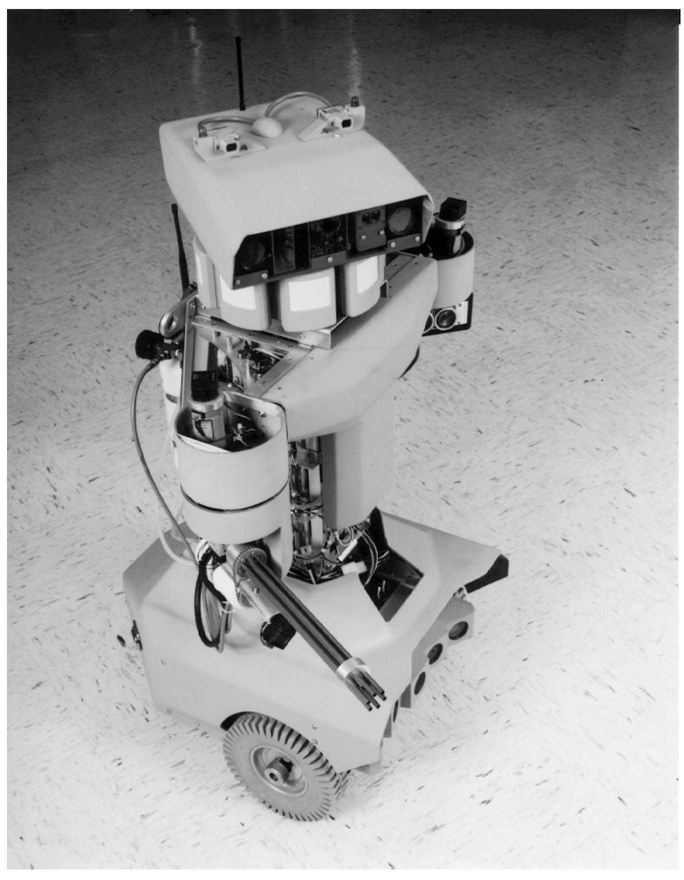

**Figure 2.** ROBART III (1992- ) extends this reflexive teleoperation concept to include automated weapon control for an intelligent response robot capable of entering unexplored structures.

## 2. NAVIGATION AND COLLISION AVOIDANCE SENSORS

A combination of Polaroid ultrasonic sensors and optical proximity and ranging sensors are strategically located to provide full collision avoidance coverage in support of the advanced teleoperation features[2]. A 16-channel multiplexer based on the bi-directional LH1500 solid-state relay is used to sequentially select individual sonar transducers for connection to a single Polaroid 783821 ranging module. Eleven of the sonar transducers have been installed to date: two head-mounted sensors, a five-element forward-looking array on the front panel of the mobility base, and one forward and one rear facing sensor on each shoulder pod (four total). Two Banner SM312D near-infrared proximity sensors are located on the top of the head for collision avoidance purposes, while a longer-range SM912D unit is located behind the face plate, intended primarily to assist in locating openings in doorways. A Hamamatsu near-infrared range finder mounted on the left shoulder pod is scanned to precisely determine the location of the left and right door edges. Two side-looking Electro Corporation piezoelectric PCUC-series ultrasonic proximity sensors operating at 215 KHz are used primarily for wall following. An array of twelve Sharp GP2D12 near-infrared triangulation ranging sensors located in the shoulder pods and base are used for high-resolution environmental awareness in close proximity to the robot (i.e., less than 30 inches).

### 2.1 Obstacle detection

ROBART III uses a very simple but effective ultrasonic obstacle detection method which makes use of *beam-splitting* techniques to increase sensor resolution. Effective beamwidth introduces some uncertainty in the perceived distance to an object from the sonar transducer, but an even greater uncertainty in the angular resolution of the object's position. For discrete targets, improved angular resolution can sometimes be obtained through beam splitting, a technique that involves the use of two or more transducers with partially overlapping beam patterns[3]. Figure 3 shows how for the simplest case of two transducers, twice the angular resolution can be obtained along with a 50-percent increase in coverage area. If the target is detected by both sensors A and B, then it (or a portion of it) must lie in the region of overlap shown by the shaded area. If detected by A but not B, then it lies in the region at the top of the figure, and so on.

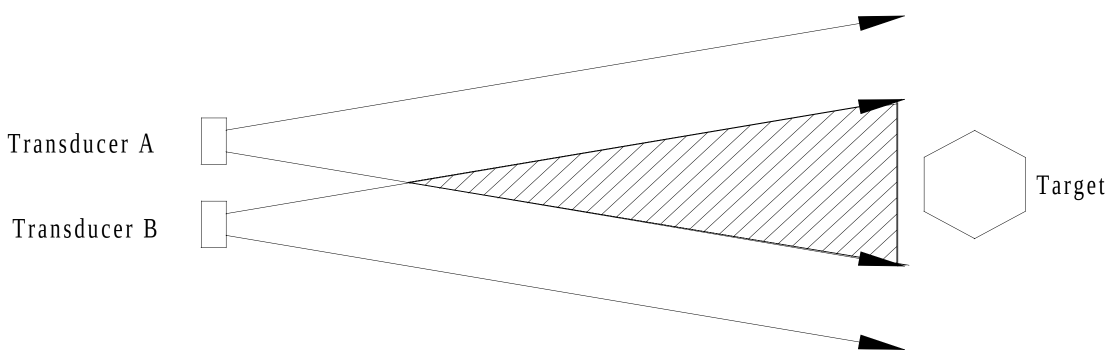


**Figure 3.** Example of beam-splitting technique using two sonar sensors.

ROBART III's sonar transducers are configured for maximum beam overlap through use of a concave (versus convex in the case of ROBART II) sonar fan out (see Figure 4). In this fashion, the most critical region directly in front of the robot can have up to seven transducers with overlapping beam patterns. The use of a concave array also minimizes vulnerabilities due to the *dead-zone* associated with minimum effective range for those transducers aligned in an off-centerline configuration (i.e., transducers 0, 1, 3, and 4). For example, transducers 1 and 3 are offset 15 degrees in alignment towards the center of the robot. This means that sonar transducer 1, mounted on the right side of the robot, faces toward the left and sonar transducer 3, mounted on the left side of the robot, faces towards the right. Coordinated assessment of triangulation pairs (i.e., sensors 0 and 5, sensors 4 and 6) can provide additional enhanced angular resolution on the location of a discrete object, allowing for more precise maneuvering in congested environments.

The current collision avoidance algorithm considers just one snapshot of sonar data at a time, with previous readings discarded (i.e., no onboard mapping). A number of quick calculations are performed to determine the best avoidance maneuver on the fly. (A more sophisticated polar histogram approach is also under development[4]). Sonar range data from transducer 2 (the center-most transducer in the concave array on the front of the mobility base) is first examined for potential obstructions in the robot's intended path of travel. If the range reading is greater than 5½ feet, the search is widened to check for a potential obstacle* detected by the remaining sonar transducers in the array. Next, sonar transducers 14 and 15 (both forward-facing and head-mounted) are checked for any significant range difference. If there is no noticeable discontinuity in range between these two transducers, the robot continues forward, fairly confident there is no object in its path. If a difference of two or more feet is detected between the two sonars, further assessment is done to determine from which side the potential obstacle is approaching. Currently only four possible decisions are made based on the assessment results: 1) continue forward if the two range readings are greater than the minimum threshold (potential obstacles are still far enough away); 2) turn right if sonar transducer 15 is within the minimum threshold; 3) turn left if sonar transducer 14 is within the minimum threshold; or 4) continue forward if both sonars are within the minimum threshold (i.e., sonar 2 sees through a door opening while the two head-mounted sensors detect the left and right door edges). If the robot is still moving forward, it then begins to widen its search for potential obstacles on either side of the robot. The search is then expanded to include sonar transducer combinations 1 and 3, 0 and 4, and 5 and 6.

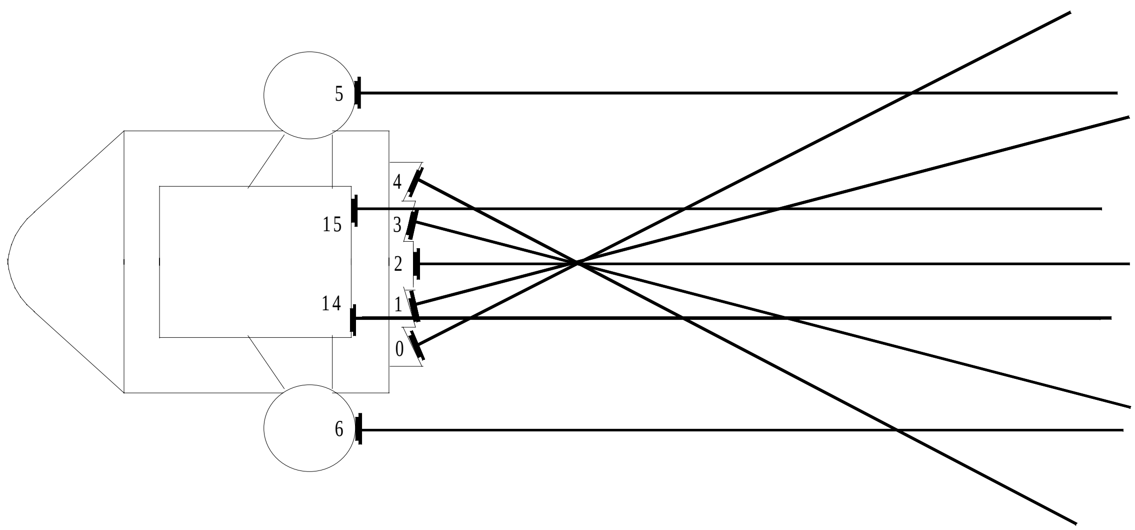


**Figure 4.** Top view of sonar configuration with beam centerlines (30-degree effective beamwidth) shown. Overlapping beam patterns allow for beam-splitting techniques to increase angular resolution.

Shoulder- and base-mounted Sharp triangulation ranging sensors (model GP2D12) are used to double check sonar data for any obstacle that comes within two feet of the robot or falls in one of the sonar blind spots. The outputs of these optical sensors are analyzed in much the same way as the ultrasonic range data. A Banner SM912D near-infrared proximity sensor located behind the face plate double checks all forward motion for a missed obstacle.

## 2.2 Entering doorways

In addition to detecting potential obstructions, some of these non-contact ranging sensors are also used to seek out in advance appropriate portals of passage (i.e., doorways) to facilitate optimal approach and subsequent safe penetration. ROBART III is relatively wide at 26 inches compared to the two previous research prototypes ROBART I[5] (at 15 inches) and ROBART II (at 17 inches). With most interior doors providing a typical opening of 36 inches or less, entering doorways can be quite a challenge, as this wide girth leaves a meager 10 inches (or possibly less) of clearance. With ROBART III absolutely centered during doorway traversal, a best-case separation of only 4 to 5 inches is measured from the left and right door jambs to each of the robot's shoulder pods. Because of this, it is critical that the robot enter a doorway with both optimal alignment and centering to avoid damaging the pod-mounted Gatling gun or Hamamatsu range finder.

In support of this goal, nine collision avoidance sonar sensors are first used to look for the door opening at an estimated approach distance of six feet. The robot proceeds towards the open door, using the collision avoidance algorithm, slowing

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* The term "potential obstacle" is used due to the questionable accuracy of sonar transducer data because of noise, poor directionality, crosstalk, and specular reflections.

down as the minimum sonar range dictates. The standard collision avoidance algorithm performs nicely in this mode since the task of entering a doorway decomposes into avoiding two obstacles on the left and right (door jambs) while staying in an open passageway (door opening).

Sonar transducer 2 will penetrate the door first at an approximate range of four to five feet depending on how centered the robot is in front of the door. Next, sonar transducers 1 and 3 should give nearly identical and progressively decreasing range readings while moving forward towards the door opening. The beams associated with these two transducers will penetrate the door opening at a range of two to three feet, with sonar transducers 0, 4, 5 and 6 each penetrating the door between 1 and 2 feet out, again depending on robot alignment with respect to the door.

To ensure optimal alignment, the pod-mounted Hamamatsu near-infrared range finder is swept back and forth in azimuth to look for range discontinuities associated with the vertical door jambs as the robot closes within six feet of the anticipated door location. This scanning allows the robot to determine the location of the left and right door edges and steer towards the center of the door. This back-and-forth scanning of the door opening continues until the robot comes to within 18 inches of the door. At this close distance the triangulation range finder, which is mounted on the left shoulder pod, has a difficult time getting an accurate edge-detect fix on the right door jamb. The edge-detection algorithm shifts into a dither mode and stays locked onto the left door jamb only, guiding the robot through the door opening. But since the edge detection function degrades with the change of perspective associated with doorway closure, and the sensor can only see one door jamb at this point, it is possible for the robot to drift slightly to the right and collide with the door frame.

Here is where things can become a little tricky. One of the many shortcomings of a monostatic (single transducer) ultrasonic ranging system is the inherent minimum effective operating range (typically nine inches in the case of the Polaroid system, four inches for the higher-frequency PCUC units) due to transducer ring-down. This minimum range *dead zone* causes the robot to become effectively sonar-blind to the door jambs (which close to within the nine-inch minimum range) at the worst possible time.

Accordingly, close-range collision avoidance is addressed by the Sharp GP2D12 near-infrared triangulation sensors. These compact (only 1.77 x .55 x .60 inches) inexpensive devices, with an effective range of four to thirty inches, are ideal for close-in obstacle avoidance and can be mounted almost anywhere due to their small size. The Sharp sensors support an optimized algorithm similar to the sonar collision-avoidance algorithm to finish guiding the robot through the door opening. For purposes of redundancy, the Banner SM912D near-infrared proximity sensor double checks for potential collisions, since it is not as affected by noise, poor directionality, crosstalk, and specular reflections as the sonar transducers.

## 3. WORLD MODELING

Existing mobile robots typically require a preconceived and very detailed map (world model) of their intended operating environment for path planning and collision avoidance algorithms in support of their autonomous navigation needs, but most law enforcement and urban warfare scenarios preclude the availability of such *a priori* information. While teleoperated control concepts support limited remote operation of *tactical mobile robots* in unexplored urban environments, there is the additional burden of keeping track of the robot's position and orientation. This seemingly trivial task can quickly become very tedious if not impossible due to the limited information readily gleaned from an onboard video camera by even a highly skilled operator. The situation is further complicated by potential video signal degradation, poor lighting, little or no scene contrast, and the fact that the user probably has no previous experience in recognizing landmark features within the field of view.

As a consequence, it is quite easy to get lost somewhere inside an unfamiliar building and be unable to move about in a meaningful fashion, or perhaps even exit back to the street. ROBART III specifically addresses this critical technological need by integrating the applicable features of reflexive teleoperated control and autonomous control to produce a *supervised autonomous* system that can quickly explore an unknown operating area with minimal required human oversight, generating in the process a world model representation that supports increasing autonomy of operation.

A very simplistic supervisory interface is employed, wherein the operator can easily control platform motion by clicking on special behavioral icons depicted on the navigation display shown in Figure 5. For example, selecting a *wall-following* icon to either side of the robot's own icon would cause the platform to enter wall-following mode, maintaining its current lateral offset from the indicated wall using side-looking sonar. The *wall-following* icons are implemented under Windows 95 as long vertical command buttons situated on either side of the map window in the lower left corner of the screen.

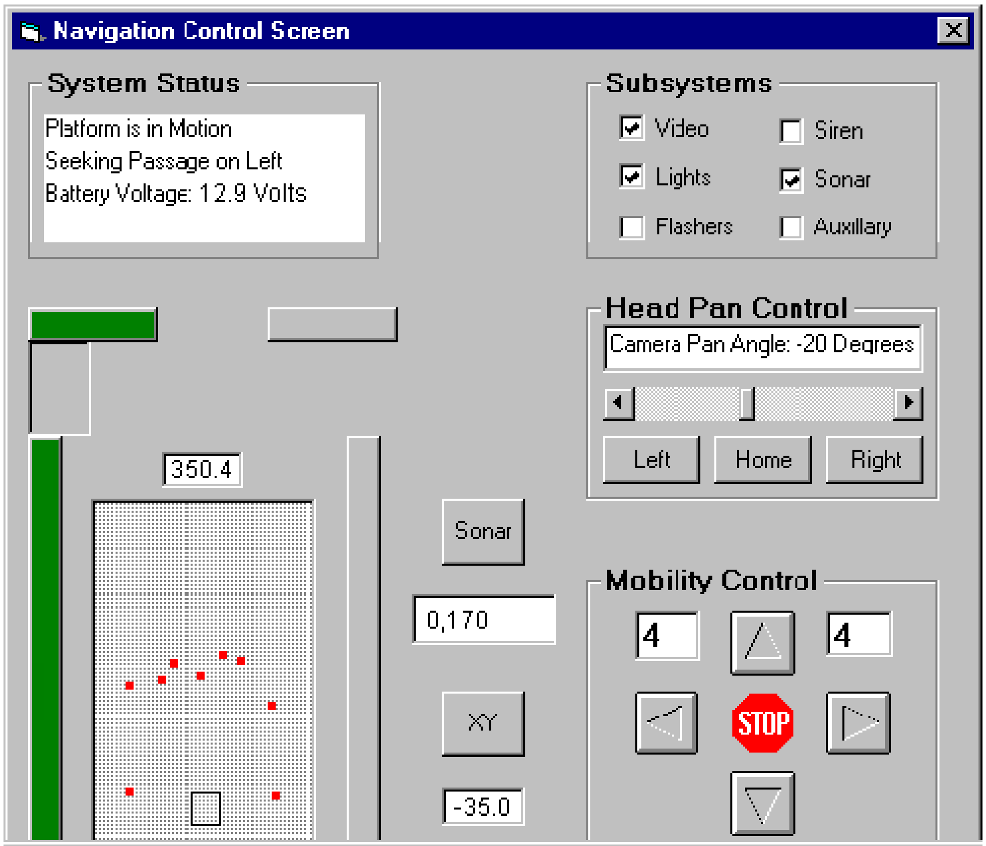


**Figure 5**. On the Navigation Control Screen for ROBART III, the nine dots displayed in front of the rectangular robot icon at the bottom of the map indicate the measured range to perceived objects in the intended path.

Two additional wall segment icons are seen above the map in the form of short-length horizontal command buttons. The open spaces between these graphical depictions of wall structures represent three potential *doorways*: one directly ahead of the robot and one on either side. By clicking in one of these *doorway icons*, the robot is instructed to seek out and enter the next encountered location of that type of door along its current path. For the example illustrated above, the platform is looking for a door off to the left, as indicated by the highlight box shown in the selected *doorway icon* and the associated text displayed in the *System Status* window above the map.

### 3.1 Human-centered mapping

The exploration and mapping of unknown structures benefits significantly when the interpretation of raw sensor data is augmented by simultaneous supervisory input from the human operator. The end result of such an approach is a much faster and more accurate generation of object representations (relative to conventional sensor-only configurations), particularly valuable when there is no *a priori* information available to the system. In a nutshell, the robot can enter and explore an unknown space, building a valid model representation on the fly, while dynamically rereferencing itself in the process to null out accumulated dead-reckoning errors. In support of this objective, ROBART III has been mechanically and electronically equipped specifically to support supervised autonomous operation in previously unexplored interior structures. A "human-centered mapping" strategy has been developed to ensure valid first-time interpretation of navigational landmarks as the robot builds its world model (currently on an external RF-linked desktop PC).

For example, a mathematical line-fit analysis is typically used to detect the presence of a suitable wall-like structure that can be used as a navigational reference. With just minimal operator input, the robot doesn't just think it sees a wall, it knows it sees a wall. Under this scheme the operator, upon first entering a building, would guide the robot by instructing it using commands like: 1) "follow the wall on your left" or 2) "enter the next doorway on the right." Such high-level direction is provided by clicking on screen icons as previously described. The end result of such an approach is a much faster and more accurate generation of object representations (relative to conventional sensor-only data collections), particularly valuable when there is no *a priori* information available to the system.

In other words, in addition to directing the robot's immediate behavior, these same commands also provide valuable information to the world modeling algorithm. Upon entering a previously unexplored building, the world model is initialized as a two-dimensional dynamic array with all cells initially marked as *unknown*. (An *unknown* cell is treated as potentially traversable, but more likely to be occupied than confirmed *free space*.) If some specific subset of the current sonar data can be positively identified from the outset as a wall-like structure, it can be unambiguously modeled as a *confirmed wall* without the need for statistical representation. This makes the resulting world representation much less ambiguous and therefore less subject to error. The path planner knows without a doubt that there is no possible route crossing line segment AB in the map representation, having just executed a wall-following maneuver along its real-world parallel.

Unless, of course, an open *doorway* was detected during the aforementioned transit. A *doorway* represents another distinctive feature of the real world that can be exploited in the generation of the model, provided there is some suitable means of positively identifying such (i.e., by robot sensors or human observance). The only difference is that *doorways* represent portals of guaranteed passage, whereas *confirmed walls* are interpreted as non-traversable boundaries. The detection of open doorways is already supported by onboard optical and sonar sensors employed in conjunction with the automated doorway detection and traversal routines previously discussed. Saving information describing the location and orientation of detected doorways is readily accomplished by assigning the two certainty-grid cells associated with the perceived locations of the door edges a unique value that flags the feature later for the path planner.

Another example of clear space where unobstructed travel is guaranteed is seen in the representation of the robot's current position, where obviously there are no objects. So as the robot moves forward in an exploratory fashion, it basically generates a *trail* that can be recorded in the model as traversable, simply by changing the model representation for those cells actually traversed, from *unknown* to *clear space*. This feature initially provides a convenient mechanism wherein the path planner can "remember" how to retrace a path (for example, to exit the building). More importantly, it ultimately will yield a set of known interconnecting path segments (*trails*) in more complicated floorplans that can support optimal planning. For example, after circumnavigating the interior of the building, there may very well be a much shorter path to the point of original entry than afforded by retracing the original exploratory route.

Since *doorways* are openings in walls, additional valuable information can be inferred by assuming there is likely to be an associated wall segment running along an imaginary line defined by the left and right sides of a door. Accordingly, the line of certainty-grid cells defined by the two specially marked door-edge cells in the model are suitably encoded to represent the location of a *potential wall.* Such *potential wall* representations extend to the map boundaries in the direction of unexplored (*unknown*) territory, but would terminate upon intersection with any previously identified features such as *trails, confirmed walls,* and *doorways*. From the path-planner's perspective, the cost of crossing this *potential wall* representation is higher than the cost of traversing *unknown* floor space, but less than the cost of traversing a *confirmed wall*. A traversal through the associated *doorway* of course has zero cost.

## 3.2 Wall following

As previously mentioned, two self-contained Electro Corporation piezoelectric PCUC-series ultrasonic sensors operating at 215 KHz are used to generate range data for the wall-following algorithm. These sonar sensors operate at a much higher frequency then the 49.4 KHz Polaroid sensors, so there are no problems associated with crosstalk during simultaneous operation. These side-looking sonar range readings are used to obtain the robot's lateral offset and heading with respect to the wall. To avoid oscillatory and unstable motion during wall following, large variances in sonar data are filtered, enabling the robot to move about in the unexplored building structure with a more steady motion. By collecting range data along with lateral displacement, the *Method of Least Squares* can be used to calculate the slope of the line representing the robot's path of travel. Using the form of the least-squares straight line:

$$y = mx + b \tag{1}$$

yields the sum of squares:

$$M = \sum_{i=0}^{n} (mx_i + b - y_i)^2 \tag{2}$$

where *M* is a function of *m* and *x*. A necessary condition for *M* to be minimum is:

$$\begin{aligned} \frac{\partial M}{\partial b} &= 2\sum_{i=0}^{n} (mx_i + b - y_i) = 0 \\ \frac{\partial M}{\partial m} &= 2\sum_{i=0}^{n} (mx_i + b - y_i)x_i = 0 \end{aligned} \tag{3}$$

which reduces to:

$$\begin{aligned} \sum_{i=0}^{n} b + \sum_{i=0}^{n} mx_i &= \sum_{i=0}^{n} y_i \\ \sum_{i=0}^{n} bx_i + \sum_{i=0}^{n} mx_i^2 &= \sum_{i=0}^{n} x_i y_i \end{aligned} \tag{4}$$

now:

$$\sum_{i=0}^{n} b = nb\,,$$

and we can factor out *m* and *b* in the other terms and solving for the slope and intercept results in the following:

$$\begin{aligned} b &= \frac{\sum_{i=0}^{n} y_i - m\sum_{i=0}^{n} x_i}{n} \\ m &= \frac{n\sum_{i=0}^{n} x_i y_i - \sum_{i=0}^{n} x_i \sum_{i=0}^{n} y_i}{n\sum_{i=0}^{n} x_i^2 - \sum_{i=0}^{n} x_i \sum_{i=0}^{n} x_i} \end{aligned} \tag{5}$$

where:

*m* = slope
*b* = intercept
*n* = number of samples taken (five in this case)

The robot's heading with respect to the wall can be calculated by taking the $\tan^{-1}$ of the slope *m*.

During wall following, a minimum clearance of six inches is allowed between the robot shoulder pods and the wall. If the robot drifts within this range, measures are taken to avoid colliding with the wall and damaging either the weapon system mounted on the right arm or the range finder mounted on the left arm.

## 3.3 Orthogonal navigation

The Achilles Heel of any world modeling scheme, however, is accurate positional referencing in real-time by the moving platform. Since all sensor data is taken relative to the robot's location and orientation, the accuracy (and usefulness) of the model quickly degrades as the robot becomes disoriented. While wall following is a very powerful tool in and of itself for determining the relative offset and heading of the robot, conventional schemes normally assume some *a priori* information about the wall in the first place to facilitate its utility as a navigational reference. In short, a relative fix with respect to an unknown entity does not yield an unambiguous absolute solution, for obvious reasons.

ROBART III uses a new and innovative world modeling technique that requires no such *a priori* information. This navigation scheme, called *"ortho-mode"*, exploits the orthogonal nature of most building structures where walls are parallel and connecting hallways and doors are orthogonal. *Ortho-mode* also uses the input from a magnetic compass to address the issue of absolute wall orientation. The accuracy of the compass need be only good enough to resolve the ambiguity of which of four possible wall orientations the robot has encountered. This information is stored in the model in conjunction with the wall representation (i.e., wall segment running north-south, or wall segment running east-west), in arbitrary building coordinates. The precise heading of the vehicle (in building coordinates) is then mathematically derived, as previously discussed, using sonar data taken from the wall surface as the robot moves.

In *simplistic wall following*, a robot reads the range to one side or the other (usually with a sonar sensor) and will drive closer or further from the wall in order to maintain a pre-specified distance. Each sonar value is treated separately from all the others. In *wall referencing* the robot is told its starting and ending location as well as how far the wall is to the left or right. In this case, the robot uses a number of sonar readings to obtain a line fit that approximates the heading and distance of the wall. The robot will then correct its lateral position from the wall as well as its heading. In *orthogonal wall following*, the robot is told that there is a wall to the left or right and that its heading is 0, 90, 180 or 270 degrees with respect to a building North of zero degrees. The robot uses a number of sonar readings to obtain a least-squares line fit for the wall, which is then used to both maintain some distance from the wall as well as to correct the robot's heading.

*Ortho-mode* helps significantly in the accurate generation of a world model. As the robot follows a wall building its map, the robot will not follow the wall perfectly. The robot will tend to drift left or right as corrections are made in its path, even taking measures to avoid obstacles in the robot's path. Generating a map from just sonar data will create walls and hallways with a very irregular appearance which may or may not resemble the wall the robot is following. *Ortho-mode* corrects this problem by taking the irregular wall sonar data and performing a least-squares line fit on the wall readings to generate a straight line. This method of mapping assumes that all walls are straight and that the robot is not moving in a straight line in the unexplored structure. Interconnecting hallways are easily generated assuming the orthogonal nature of man-made structures.

## 4. THREAT DETECTION AND RESPONSE

Extremely robust intruder detection and assessment capabilities with minimal nuisance alarms are achieved through intelligent fusion of a multitude of inputs from various onboard motion sensors.

### 4.1 Motion Tracking

When first entering a room, ROBART III will enter *Motion Tracking Mode* to search for intruders. In this mode, the intruder detection algorithm operates upon the output from the Video Motion Detection (VMD) system and a 360-degree array of passive-infrared (PIR) sensors configured as a collar just below the head as shown in Figure 2. The VMD hardware consists of a video camera, a video line digitizer, and a dedicated microprocessor. By comparing the observed intensity changes for three preselected (but reconfigurable) scan lines, it can detect motion and then output the centroid of any such motion in a pixel value which represents the perceived intruder bearing in camera coordinates.

The PIR array consists of eight passive-infrared motion detectors symmetrically oriented 45 degrees apart to define eight discrete sectors. Based on the known orientation of the PIR array, the intruder bearing in robot coordinates can be determined from the identity of the active array element. Beam splitting techniques can also be applied to this binary (on/off) sensor output data to further improve angular resolution. The PIR data is used to pan the head-mounted surveillance camera to the center of any zone with suspected intruder activity, whereupon the VMD output is then used to track and keep the intruder in the center of the visual field. The VMD data has more priority than the PIR data in the tracking decision, but the PIR data will be used when the VMD data is not available (i.e., intruder is out of the camera field of view) or is shown to be erroneous.

Both visual and PIR tracking involve a combination of robot head and body movement to keep the target in the visual field. During visual tracking, the head moves to the center of any alarmed zone until it reaches its maximum pan limit (±90 degrees) relative to the robot. When this pan limit is encountered, the robot's body will pivot in place towards the target while the head smoothly moves at the same speed in the opposite direction to keep the target in the center of the visual field. This coordinated action provides the robot with unlimited (i.e., > 360 degrees) pan coverage.

## 4.2 Weapon tracking

The *Gun Track Mode* can be activated by the host while ROBART III is in *Motion Tracking Mode*, causing the robot to re-center its head and face toward the current detected threat. The robot then becomes stationary and the gun will automatically track the target using the relative bearing information from the VMD and range information from the head-mounted and concave ultrasonic sonar arrays. The gun tracking algorithm currently relies on the bearing from the camera to the target, getting range data from the corresponding sonar transducer. To reduce the target ambiguity associated with the sonar readings, ROBART III continuously updates a range template to establish the position of a moving target in terms of sonar range and bearing. The angle from the gun to the target can be determined by the following relationship:

$$\overline{GT} = \overline{CT} + \overline{CG} \tag{6}$$

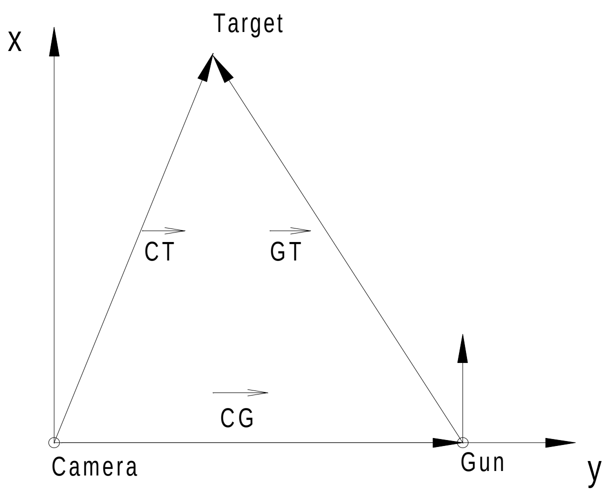


**Figure 7.** Gun tracking vectors

where $\overline{CT}$ = Vector from camera to target
$\overline{CG}$ = Vector from camera to gun
$\overline{GT}$ = Vector from gun to target

Note: In this calculation, we neglect the small offset distance between the sonar to the camera, and assume the range from the sonar to the target is the same as the range from the camera to the target.

At this point, a non-lethal weapon response can be invoked. The operator can dictate what type of weapon control to use before entering gun track mode: manual or automatic. In manual control, the firing decision is made by the operator. A visible-red laser sight facilitates manual operation of the weapon using video relayed to the operator from the head-mounted surveillance camera. The operator then can decide to fire the gun when seeing the weapon lock on the target via the video monitor. An intruder will not feel safe even in total darkness, since the camera can see clearly in no/low light conditions with the use on an active near-infrared illuminator. In automatic mode, ROBART III is responsible for making the firing decision locally, firing the gun after it has locked onto the same target for a pre-determined time and only after intruder confirmation based on cross-correlation with other sensors.

# 5. NON-LETHAL RESPONSE

## 5.1 Pneumatically-powered Gatling gun

The principle non-lethal response system currently incorporated on ROBART III is a six-barreled pneumatically-powered Gatling gun (see Figure 8) capable of firing a variety of 3/16-inch diameter projectiles. Munitions include simulated tranquilizer darts constructed from sharpened 20-gauge spring steel, plastic bullets manufactured from Teflon or Delrin, and 3/16 steel ball bearings.

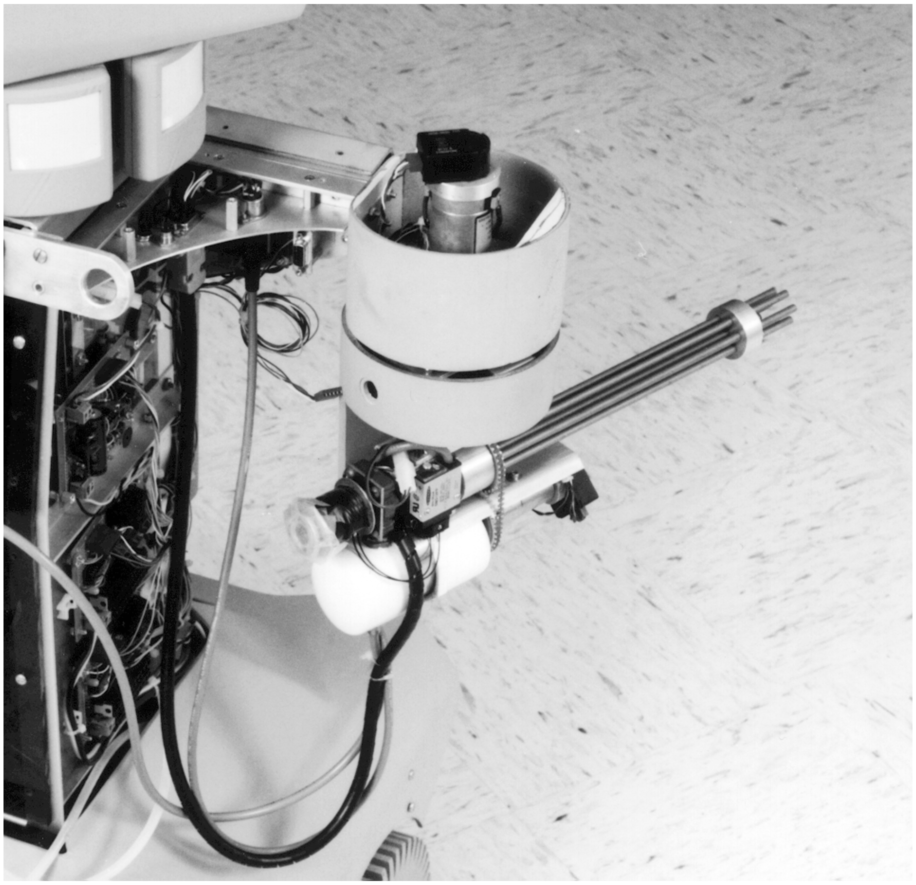

**Figure 8.** ROBART III's six barrel Gatling-gun shown on the left shoulder pod. The spinning-barrel mechanism also imparts a rather intimidating psychological message during system initialization

Projectiles are expelled at a high velocity from 12-inch barrels by a release of compressed air from a pressurized accumulator at the rear of the gun assembly. To minimize air loss, the solenoid-operated valve linking the gun accumulator to the active (top) barrel is opened under computer control for precisely that amount of time required to expel the projectile. The valve assembly is a modified dishwasher fill valve, bored out for minimal flow restriction and rewound for 12-volt DC operation. The gun accumulator is maintained at a constant pressure of 120 psi by a second solenoid valve connected to a 150-psi air bottle externally mounted on the rear body trunk. In addition to single-shot mode, all six darts can be fired in rapid succession (i.e., approximately 1.5 seconds) under highly repeatable launch conditions to ensure accurate performance. The main air bottle is automatically recharged by a small 12-volt reciprocating compressor mounted in the robot's base.[2]

A rotating-barrel arrangement (powered by a miniature PortEscap gearhead motor with an armature-driven phase-quadrature optical shaft encoder) is incorporated to allow for multiple firings (six) with minimal mechanical complexity. (The spinning-barrel mechanism also imparts a rather intimidating message during system initialization.) A Banner SM312FP proximity sensor is fiber-optically coupled to look down the bore of the bottom barrel to determine the presence or absence of a projectile. Before the weapon is loaded, the gun encoder is initialized by slowly rotating the barrel assembly under computer control until a reflection/no-reflection transition is sensed, indicating the presence of an empty barrel. Once this referencing operation is complete, the computer can precisely align each barrel with the valve orifice by indexing a predetermined number of encoder counts in the clockwise direction. The system can also track how many rounds have subsequently been loaded and/or fired using the same sensor.

Azimuthal and elevation information from the motion detector is available to the right-shoulder pan-and-tilt controller for purposes of automated weapon positioning. To facilitate aiming the weapon in manual operation, a 5-milliwatt 670-nanometer (visible-red) laser is bore-sighted to the dart gun barrel. Watching video relayed from the head-mounted surveillance camera, the remote human operator simply aims the gun with a joystick until the laser spot is on the desired target.

## 5.2 Other non-lethal devices

An optional BB-firing auto cannon is under development to provide a higher rate of sustained automatic fire for intruder deterrent. High-powered strobe lights and three ear-piercing 103-decibel sirens can be activated to temporarily confuse and disorient a confirmed intruder while simultaneously alerting friendly forces nearby.

# 6. SUMMARY

This paper covers the implementation of a prototype tactical/security response robot capable of exploration in unknown structures. The system is able to confront intruders with a laser-sighted tranquilizer dart gun, and automatically track a moving target with the use of various sensors. A *Human-centered mapping* scheme ensures accurate first-time interpretation of navigational landmarks as the robot builds its world model, while *orthogonal navigation* exploits the fact that the majority of man-made structures are characterized by parallel and orthogonal walls.

# 7. REFERENCES


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