A SUPERVISED AUTONOMOUS SECURITY RESPONSE ROBOT

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ABSTRACT

Autonomous mobile robots typically require a preconceived and very detailed navigational model (map) of their intended operating environment, but most law enforcement and urban warfare response scenarios preclude the availability of such *a priori* information. ROBART III is an advanced demonstration platform for non-lethal robotic response measures, incorporating a supervised autonomous navigation system specifically configured to support minimally attended 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. The accuracy of the robot's real-time position estimation (and hence the model itself) is significantly enhanced by an innovative algorithm which exploits a heuristic that assumes the majority of man-made structures are characterized by parallel and orthogonal walls.

Intruder detection and assessment capabilities are supported by intelligent fusion of data collected by a multitude of various sensors. Initial detection is by a 360-degree array of eight passive-infrared motion detectors responding to the thermal energy gradient created by a moving human target, with partial validation from a Doppler microwave motion detector. The robot's head-mounted sensors (and non-lethal weapon system) are then panned to the center of any perceived disturbance for further assessment. Automatic tracking of any confirmed movement is accomplished through conventional image processing using a black-and-white video surveillance camera equipped with a near-infrared illuminator for low-light conditions.

The non-lethal response systems incorporated on ROBART III include a six-barreled pneumatically-powered Gatling gun capable of firing a variety of 3/16-inch-diameter projectiles, including simulated tranquilizer darts. A visible-red laser sight is provided to facilitate supervised operation as well as manual control of the weapon using remote video relayed to the operator from the robot's head-mounted camera. Three ear-piercing 103-decibel sirens can be activated to alert those nearby of imminent danger while simultaneously disorienting a confirmed intruder.

For increased effectiveness, a distributed master/slave sensor network can be instantiated by deploying a number of small slave robots that follow ROBART III into an unexplored structure in trailing convoy fashion. Slaves are deployed and recovered automatically, so the remote operator needs to provide supervisory control of only the master. The slave robots can perform a multitude of assigned functions, to include acting as a distributed video and motion sensor network, in addition to providing a seamless RF-relay capability throughout the building.

1. BACKGROUND

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 modeling approach is to employ a statistical certainty-grid representation (Moravec, 1985), 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). 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). Additional "special-case" values can be reserved in this fashion to encode other specific features or attributes in the model (i.e., doors, walls), as will be discussed later.

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 some *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 referencing criteria for outdoor applications, but is of no help indoors due to signal blockage by the building structure (Everett, 1995). Accordingly, traditional *autonomous navigation* techniques are of limited utility for scenarios 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.

Adding to the difficulties of indoor navigation is the problem of receiving reliable data, audio, and video communications as the robot explores deeper into an unknown structure. In cluttered environments, signal blockage and multipath reflections can quickly degrade performance to the point where communications can be lost altogether. As a consequence, it is quite easy for a teleoperated robot to get disoriented somewhere inside an unfamiliar building and be unable to move about in a meaningful fashion, or perhaps even exit back to the street. A seamless network of RF repeaters will be required in such cases to assure clear data and video connections, but these repeaters need to be strategically placed along the path of transit without increasing the burden on the operator controlling the robot.

For these reasons, many envisioned potential applications of robotic response vehicles in military scenarios remain impractical. Accordingly, this development effort specifically targets three critical

technological needs: 1) a simplistic graphical user interface for reflexive teleoperated control; 2) the ability to build an accurate world model on the fly to support autonomous operation; and, 3) robust data and video communications throughout the structure.

2. HUMAN-CENTERED MAPPING

Existing *autonomous 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 *reflexive teleoperated control* concepts (Laird, et al., 1990) 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 in familiar settings. 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.
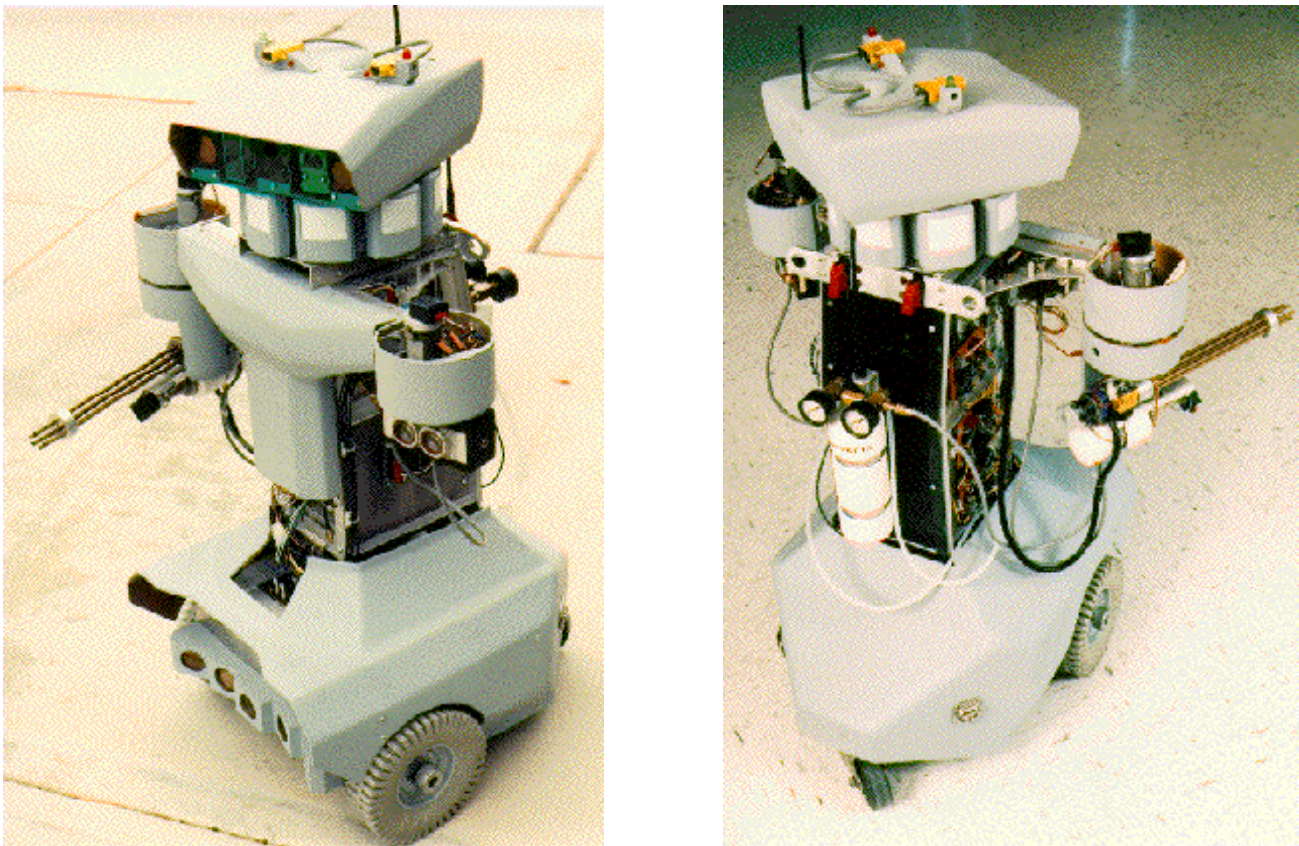

Figure 1. Front and rear views of ROBART III, an intelligent response robot capable of mapping unexplored structures.

ROBART III (Figure 1) specifically addresses this issue by integrating the applicable features of *reflexive teleoperated control* and *autonomous control* to produce a *supervised autonomous* system that

can quickly explore an unknown environment with minimal human oversight, generating a world model representation that supports increasing autonomy of operation.

2.1 Reflexive Teleoperated Control

Easing the driving burden on the operator was a major force behind the *reflexive-teleoperated control* scheme employed on a previous prototype, ROBART II (Laird, et al., 1990). The robot's numerous collision-avoidance sensors are called into play during manual operation to greatly minimize the possibility of operator error. The commanded speed and direction of the platform are 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 seeks to extend this concept of reflexive-teleoperation into the realm of sensor-assisted camera and weapons system control. A user-friendly graphical interface allows the operator to issue high-level commands to the robot, with low-level control details addressed in real-time by onboard intelligence (Ciccimaro, et al., 1998).

2.1.1 Reflexive Mobility Control

The operator can easily control platform motion by clicking on special behavioral icons depicted on the navigation display shown in Figure 2. 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. The platform's speed of advance is initially dictated by onboard intelligence as a function of perceived congestion, but can be adjusted to a certain extent by the operator using the arrow icons in the *Mobility Control* window shown in the lower right corner.

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. The head-mounted surveillance camera automatically pans to the correct position to allow the remote operator to monitor the doorway detection and penetration functions as they occur. For the example illustrated in Figure 2, the platform is following the left wall while 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).
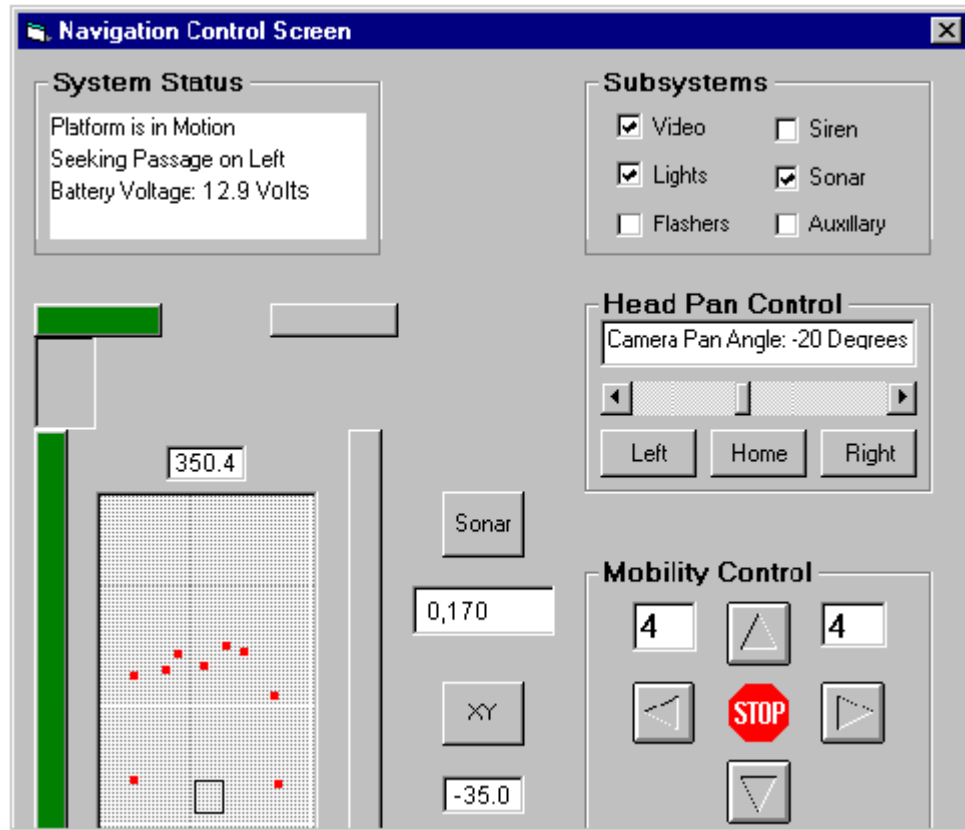
Figure 2. Highlighted icons to the left of the *Map Display Window* (lower left corner) indicate ROBART III is following the wall on its left, looking for an open doorway on the left.

2.1.2 Reflexive Non-Lethal Weapon Control

A key objective of this development effort is to extend the concept of *reflexive teleoperation* to include automated non-lethal weapon control in response to a perceived threat. 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. The intruder detection algorithm operates upon the output of a line-oriented Video Motion Detector (VMD) and a 360-degree array of passive-infrared sensors configured as a collar just below the head as shown in Figure 1. The intruder bearing in robot coordinates can be determined from the identity of the active passive-infrared array element, and used to pan the head-mounted surveillance camera to the center of any zone with suspected intruder activity. The VMD track output is then used to keep the intruder in the center of the visual field.

A combination of robot head and body movement are employed to keep the target centered if the head is about to reach its maximum pan limit (±100 degrees) relative to the robot. When a head pan angle of ±90 degrees is exceeded, the robot's body will automatically pivot in place towards the target, while the head smoothly moves at the same rotational speed in the opposite direction to keep the target in the center of the visual field. This coordinated action provides unlimited (i.e., > 360 degrees) pan coverage, and frees the operator from having to manipulate separate joysticks to manually achieve the same effect.

An automatic *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 turn to directly face the detected threat. The robot then becomes stationary while the gun begins to track the target using relative bearing information from the VMD and range information from the head-mounted ultrasonic sonar array. At this point, a non-lethal weapon response can be invoked if warranted. While ROBART III is responsible for automatic target tracking, the actual firing decision is made by the human operator upon seeing the weapon's laser spot lock on a validated target in the surveillance camera video.

The principle non-lethal response system currently incorporated on ROBART III is a six-barreled pneumatically-powered Gatling gun (see Figure 3) capable of firing a variety of 3/16-inch diameter projectiles (i.e., simulated tranquilizer darts or plastic bullets manufactured from Teflon or Delrin). 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. In addition to single-shot mode, all six barrels can be fired in rapid succession (i.e., approximately 1.5 seconds). The main air bottle is automatically recharged by a small 12-volt reciprocating compressor mounted in the robot's base (Ciccimaro, 1998).
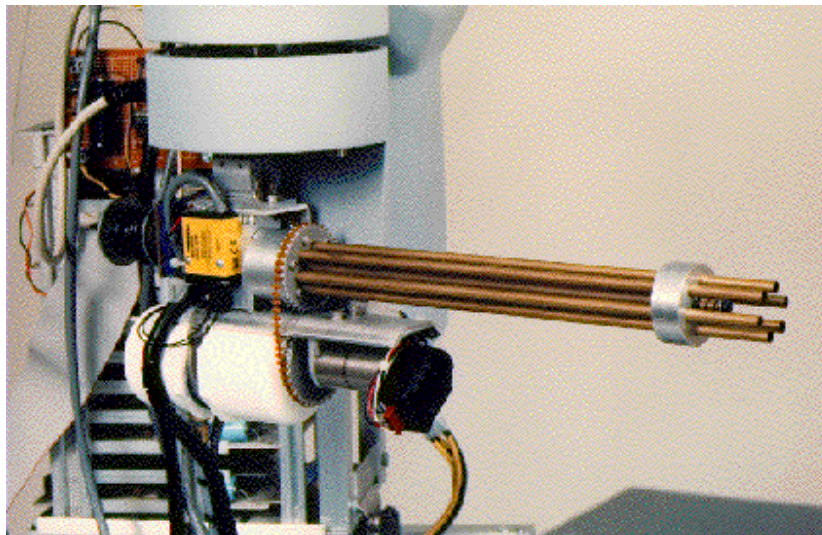

Figure 3. A six-barrel Gatling-style tranquilizer dart gun is employed on ROBART III to illustrate one of a multitude of automated non-lethal response options.

2.2 Autonomous Control

As previously stated, some type of world modeling scheme is required to evolve from *reflexive teleoperated control* to *supervised autonomous control*. The exploratory mapping of unknown structures into such a model benefits significantly when the interpretation of raw sensor data is augmented by simultaneous supervisory input from the human operator. The end result of such a "human-centered mapping" strategy 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 repeatedly referencing itself in the process to null out accumulated dead-reckoning errors.

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, as will be discussed in the next section. With just minimal human input, the robot doesn't just *think* it sees a wall, it *knows* it sees a wall. The operator, for example, upon first entering a building could instruct the robot using simple commands like: 1) "follow the wall on your left;" and, 2) "enter the next doorway on the left." Such high-level direction is provided by clicking on screen icons as depicted earlier in Figure 2. In addition to directing the robot's immediate behavior, however, these same commands can also provide valuable information to the world modeling algorithm, as explained below.

Prior to the start of building exploration, 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 side-looking sonar data can be positively identified from the outset as a wall-like structure, it can be unambiguously modeled right away as a *confirmed wall* without the need for statistical representation. This makes the resulting world model much less ambiguous in that key navigational features are expressly flagged as such, and the *find-path search* of the path planner can be optimized accordingly.

By way of further illustration, it's also quite probable that an open *doorway* will be detected during transit associated with the aforementioned example: (i.e., "enter the next doorway on your left"). 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, human observance, or in this case, both). Here the operator's "heads up" for the robot to expect a doorway, based on his or her assessment of the video telemetry, facilitates a high-confidence classification of the next perceived wall opening on the indicated side as a *doorway* feature. The resulting model representation of a *doorway* represents a portal of guaranteed passage, whereas a *confirmed wall* is always interpreted as a non-traversable boundary. Saving information describing the location and orientation of detected doorways is readily accomplished by assigning each of the two certainty-grid cells associated with the perceived locations of the door edges a unique "special-case" value that flags the feature later for the path planner.

Since *doorways* are openings in walls, additional valuable information can be inferred by assuming there must be an associated wall segment running along an imaginary line defined by the left and right sides of a door. Accordingly, the entire line of certainty-grid cells defined by the two specially marked door-edge cells in the model are encoded to represent the location of a *potential wall.* This particular inference (i.e., where there's a door, there must be a wall) is not all that significant in the foregoing example, since the door was discovered by following a known wall in the first place. But in the case where the operator invokes a *door-ahead* search (i.e., seek out a door opening directly ahead), the situation is essentially reversed, in that the exploring robot initially has no knowledge of the associated 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.

2.3 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. The problem, of course, is that no such advanced information on the absolute position and orientation of walls is available for previously unexplored environments.

The *Ortho-Mode* navigation scheme employed on ROBART III gets around this problem by exploiting the orthogonal nature of most building structures, where walls for the most part are either parallel or orthogonal. *Ortho-mode* uses the input from an inexpensive ($50) *Vector-2X* magnetoinductive compass (manufactured by Precision Navigation of Mountain View, CA) to address the issue of absolute wall orientation. The accuracy of the compass (optimistically advertised as ±2 degrees) need only be 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 using sonar data taken from the wall surface as the robot moves.

In the simplest type of *wall following*, the robot measures the range to the indicated side and reflexively drifts closer or further from the wall in order to maintain a pre-specified offset, reacting to each range value as soon as it arrives. A more elegant variation of this approach throws away any "noisy" range data that does not fall within an expected window of acceptance, smoothing the robot's trajectory accordingly. In an even better instantiation, the robot is told its starting location, lateral offset, and desired end point, but uses a number of sonar readings to obtain a line fit that approximates the wall orientation and displacement before reacting (Holland, et al., 1995). The robot then periodically corrects its heading and lateral position using the filtered data solution, with much better results.

This latter approach is employed in the *Ortho-Mode* scheme, only ROBART III is simply told to follow the wall to its left or right without any amplifying parameters (i.e., wall orientation and offset). The robot collects a number of side-sonar readings to obtain a least-squares line fit for the wall (Figure 4), which is used to maintain whatever stand-off distance was in effect at time of invocation. (Alternatively, the desired lateral offset can be predefined.)

The as yet unknown orientation of the wall is then derived from the magnetic compass heading once *wall-following* has stabilized, being automatically set to either 0, 90, 180 or 270 degrees (with respect to an arbitrary building North of 0 degrees). The choice is simply based on which of these four possibilities best matches the measured compass reading within a pre-specified window of acceptance. This reference value is stored in the model, and also used with subsequent line-fit solutions to precisely correct the robot's absolute heading register in the reference frame of the building.
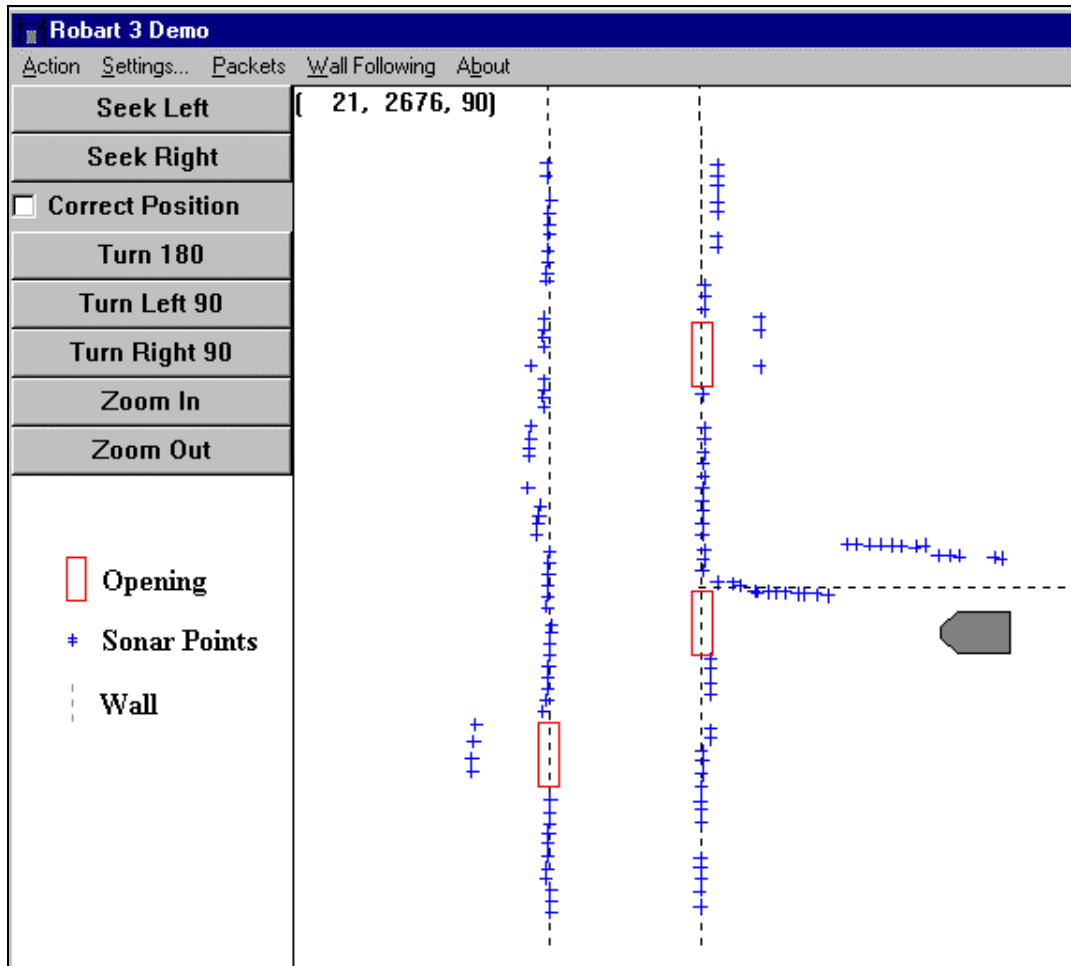
Figure 4. Plot of measured ultrasonic range data during mapping of a hallway and side passageway. The dotted lines show where the orientation of *Perceived Walls* have been "snapped" into precise alignment by the *Ortho-Mode* algorithm.

3. DISTRIBUTED MASTER / SLAVE NETWORK

To address the communication degradation problem, a master/slave network can be instituted in conjunction with building exploration by automatically deploying a number of slave robots to act as a distributed array of mobile repeaters. These slaves blindly follow ROBART III in trailing convoy fashion, being deployed and recovered automatically so the remote operator need only provide supervisory control of the master. The slave robots can perform a multitude of assigned functions, to include acting as a distributed video and motion sensor network and/or RF repeaters.

A fleet of ten Lynxmotion *Hexapod II* walking robots (six-legged, twelve-servo hexapods featuring two degrees-of-freedom per leg) are currently used to illustrate the feasibility of the master/slave network (Figure 5). This temporary demonstration platform was selected not on the basis of its future operational suitability, but because of its low-cost, ready availability, and limited payload potential, which forced designers to seek out new solutions in the form of small and lightweight componentry. For example, a combination of miniature ultrasonic and near-infrared ranging sensors are employed for collision avoidance. Short-range detection (4 to 31 inches) is handled by five Sharp *DP2D12* near-infrared triangulation ranging sensors: two side-looking units and a fan-shaped array of three covering the

forward sector. Long-range obstacle detection (1 to 10 feet) is accomplished with a forward-looking EDP *Mini-A Ultrasonic SonaSwitch*, a self-contained Polaroid-based sonar module with a 0- to 5-volt analog output.
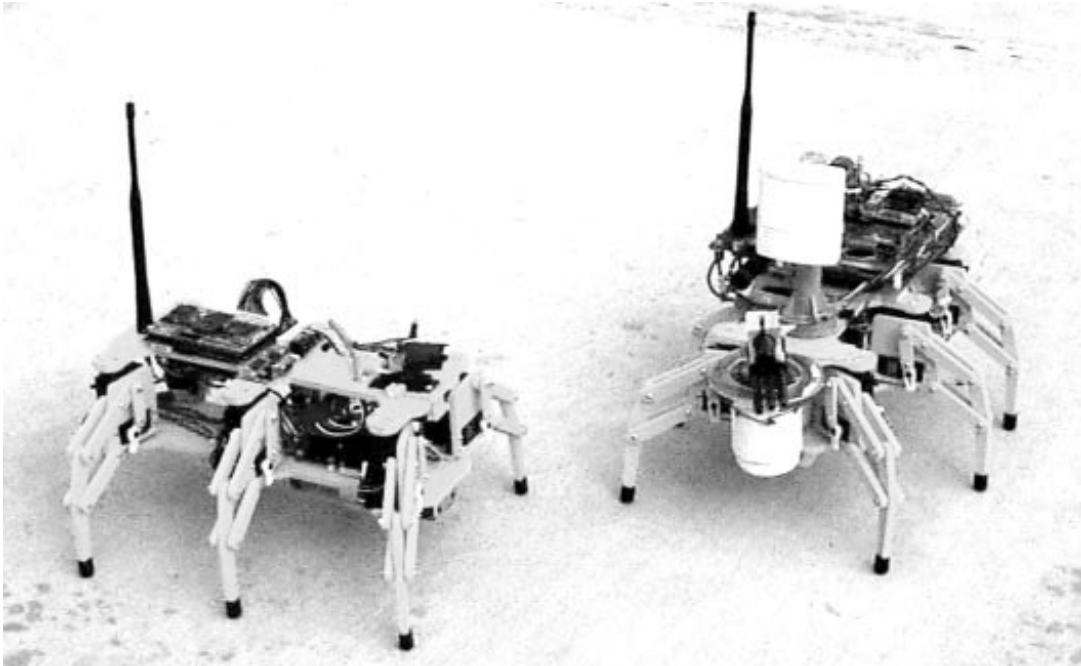

Figure 5. Two of eight slave robots in the early stages of development. The slave on the left is equipped with a near-infrared beacon-tracking sensor while the slave on the right is capable of intruder detection and response with a triple-barrel CO_2 BB cannon.

The small slave robots perform collision-avoidance, wall-following, and doorway-detection routines using algorithms similar to those running on ROBART III. For all other tasks, the slaves react in simplistic fashion to information that has been gathered and preprocessed by the master robot to minimize required complexity. For example, let's assume the master has just located an open passageway leading to an adjoining room while executing a wall-following command. A trailing slave, commanded to enter this doorway and take up station, breaks from the convoy and simply follows the known clear path along the indicated wall until the next opening is detected. The individual slaves can thus autonomously execute a small library of behavior primitives, but lacking a world model, have no absolute awareness of their own locations.

3.1 Slave Functions

ROBART III controls all management of the slaves and their various functions in transparent fashion, leaving the remote operator to concentrate on supervising just the master and not a collection of interacting robots. The slaves can perform a multitude of assigned functions, to include: 1) following in trail (convoying); 2) acting as distributed video and motion sensor network; and, 3) providing a seamless RF-relay capability (data, audio, and video) throughout the structure.

3.1.1 Convoying

An optical beacon-following scheme has been implemented as a simple way for multiple small robots to see and identify each other when convoying in single file. The master and slave robots are each outfitted with a rear-facing 180-degree array of 940-nanometer near-infrared emitters to serve as a homing beacon that can be detected out to a maximum range of about ten feet. Each slave is further equipped with a pair of Sharp *GP1U58X* near-infrared detector modules mounted side-by-side on top of a small pan unit at the front of the robot. The sensor field-of-view has been optically limited to about a 30-degree cone to control the overlap in coverage so the beacon must be directly centered before it becomes detectable by both channels.

The Sharp sensors have a built-in bandpass filter centered at 40 kiloHertz to minimize ambient interference from other near-infrared sources. Since the digital output stage of the module is AC coupled, the output pin goes low when a 40-kHz signal is detected, but returns to its normally high state in about 200 milliseconds. To work around this problem, the 40-kHz carrier frequency of the near-infrared beacon is modulated at 1 kHz. The "beacon-acquired" detector output subsequently becomes a steady 1-kHz square wave, which is converted to a binary status bit using a 1-kHz tone decoder.

A slave robot placed by the master in *Follow Mode* will scan back and forth in azimuth until one of the Sharp modules sees a valid beacon signal. The sensor pair is panned in the appropriate direction until both sensors can see the emitter. With the pan unit thus locked onto the master robot, the slave begins walking forward, turning in the process to align its body with the direction indicated by the beacon sensor. A *SonaSwitch* ranging module mounted on the pan unit directly above the Sharp sensors measures the longitudinal separation between the front of the slave and a cooperative acoustical reflector incorporated into the near-infrared beacon assembly. As the master moves forward, the slave will then tag along behind at a prespecified offset interval.

To retrieve the network of deployed slaves, the master retraces its path and individually directs them at the proper time to look for and follow the optical beacon. To preclude collisions as a recalled slave attempts to get back into a trailing position, the last robot (including the master) in the convoy must be uniquely identifiable. This is accomplished by changing the modulation frequency of the beacon emissions from the trailing robot to 2 kiloHertz using a digital potentiometer. The slave robots discriminate between the two possible modes by dynamically reconfiguring their tone detectors to identify which signal is being received.

3.1.2 Remote Intruder Detection and Response

In order to deter an intruder from playing "hide-and-seek" with the master, slave robots can be left behind at strategic vantage points (i.e., open doorways, hallway intersections) to watch its back, alerting the master (via the interconnecting RF link) to any perceived motion detected by their sensors. This remote intruder detection is accomplished primarily with passive-infrared motion sensors, augmented to some extent by the ultrasonic and near-infrared collision avoidance sensors. A miniature video camera mounted on the beacon-tracking pan unit supports remote video surveillance if desired by the operator. The master robot saves the deployed location and orientation of all slaves in the world model, and given the relative bearing (in slave coordinates) of the perceived disturbance, can easily plan a path back to the general location of the suspected intruder for further investigation.

The feasibility of a supervised (via remote video) non-lethal response from a slave robot has been illustrated using a triple-barrel BB cannon which can be fired on command by the operator (Figure 5). A 12-gram CO_2 cylinder is carried onboard as a lightweight compressed gas source. All three barrels fire at once, gravity fed from an integral 75-round magazine, and gun rotation is achieved using a pulse-proportional servo designed for radio-controlled toys.

3.1.3 Distributed Video

Availability of distributed video sensors throughout the structure can significantly contribute to the remote intruder detection and response function as discussed above. Another advantage is realized with respect to *reflexive teleoperation* of the master, as video relayed back to the remote operator from ROBART III's onboard surveillance camera can be somewhat limited in coverage. Even with the relatively wide 90-degree camera field-of-view, the lack of a tilt axis essentially precludes seeing the floor anywhere within five feet of the robot. This limitation can seriously impair the remote operator's situational awareness when maneuvering in tight quarters. An over-the-shoulder view from a trailing slave robot can provide a valuable perspective in such situations. Accordingly, the operator can switch views from the master's onboard camera to that of any individual slave, even while in motion, since the automatic collision avoidance afforded by reflexive teleoperation precludes the need to closely monitor video in the first place.

The slave robots on command can transmit video (one at a time) from their own onboard cameras over a separate low-power analog channel (Figure 6) to the master. The master specifies which (if any) slave has access to this channel, and that slave responds by turning on its onboard transmitter, a Micro Video *MV915VTx,* one of the smallest wireless video transmitters for the 900-MHz Industrial, Scientific and Medical (ISM) band. All other slaves respond by ensuring their transmitters are powered down. A two-channel video multiplexor onboard ROBART III is used to select which imagery is relayed to the remote operator over the high-power link (i.e., from the master's own head-mounted surveillance camera, or relayed video from the designated slave robot.)

A Trango *Eagle 1000* wireless video/audio system has recently been installed on the master for much improved signal quality and effective range back to the remote operator. (The previous ProVideo *WCS-50T* transmitter had a maximum indoor range of 150 feet, but with clear transmissions typically being received only as far as 50 feet.) The *Eagle 1000* provides exceptional line-of-sight transmission ranges of 3-4 miles outdoors, with indoor ranges averaging 300-1000 feet, and can also pass two binary alarm signals to its dedicated receiver on any of four user-selectable video channels.
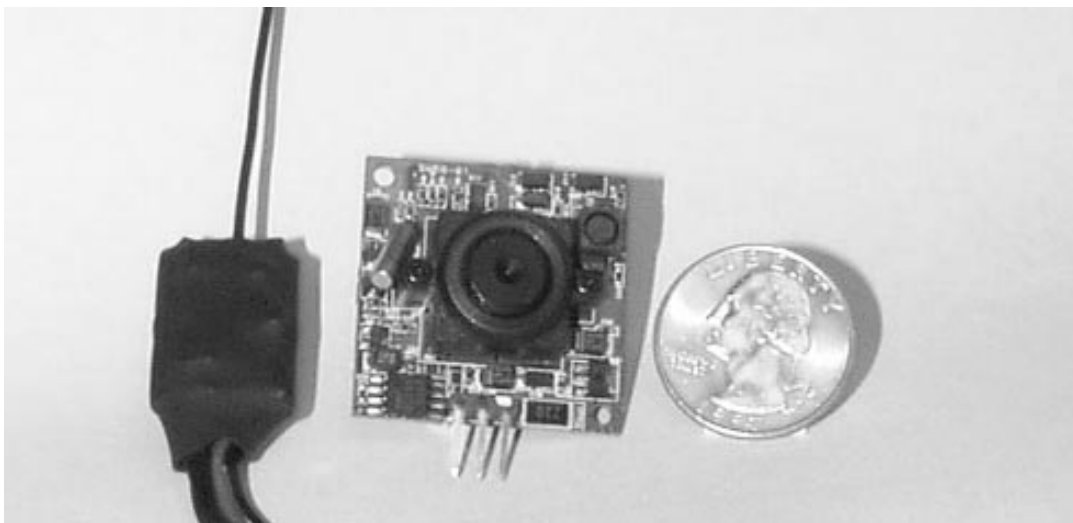
Figure 6. Micro Video *MV915VTx* wireless video transmitter (left) and *B/W MVC 058* pinhole camera (center) form the basis of the slave-to-robot analog video link.

3.1.4 Communications Relay

Non-line-of-sight communication between the master and slaves is currently implemented using a set of STI spread-spectrum RF modems, which can be configured for various forms of wireless network topologies such as point-to-point and broadcast mode. The master/slave data link is a hybrid of both, allowing the master to communicate with any of the slave robots, while the slaves can only communicate with the master and not with each other. As the exploring robot probes deeper into an unexplored building, video and data communication can become seriously degraded or lost altogether.

When this occurs, the master robot can dispatch an RF slave relay to restore a clear communications link between the operator and master. After a predetermined time with no incoming operator commands, the master will generate a communication timeout and automatically deploy a dedicated slave relay in an attempt to regain communications with the remote operator. A slave deployed as an RF relay is capable of communicating with both the master and remote operator, as is seen in the communication topology of Figure 7. The principle limitation of this current RF relay scheme, aside from the fact that much more elegant off-the-shelf modem technology has been recently introduced, is that it applies only to the data channel and does not address video or audio.

3.1.5 Expendable Point Man

Since the master response robot represents the one piece of equipment an assault team depends on most for remotely sweeping an unexplored structure for potential threats, a slave robot can be ordered to "take point" if hostile action is expected. This strategy would allow the inexpensive (i.e. expendable) slave robot to discover or wander into any danger and expose the threat, giving the master extra time to react and/or alert friendly forces. This function has not yet been implemented in the present system, as it requires some additional navigational capability (i.e., beyond beacon following) on the part of the slave.
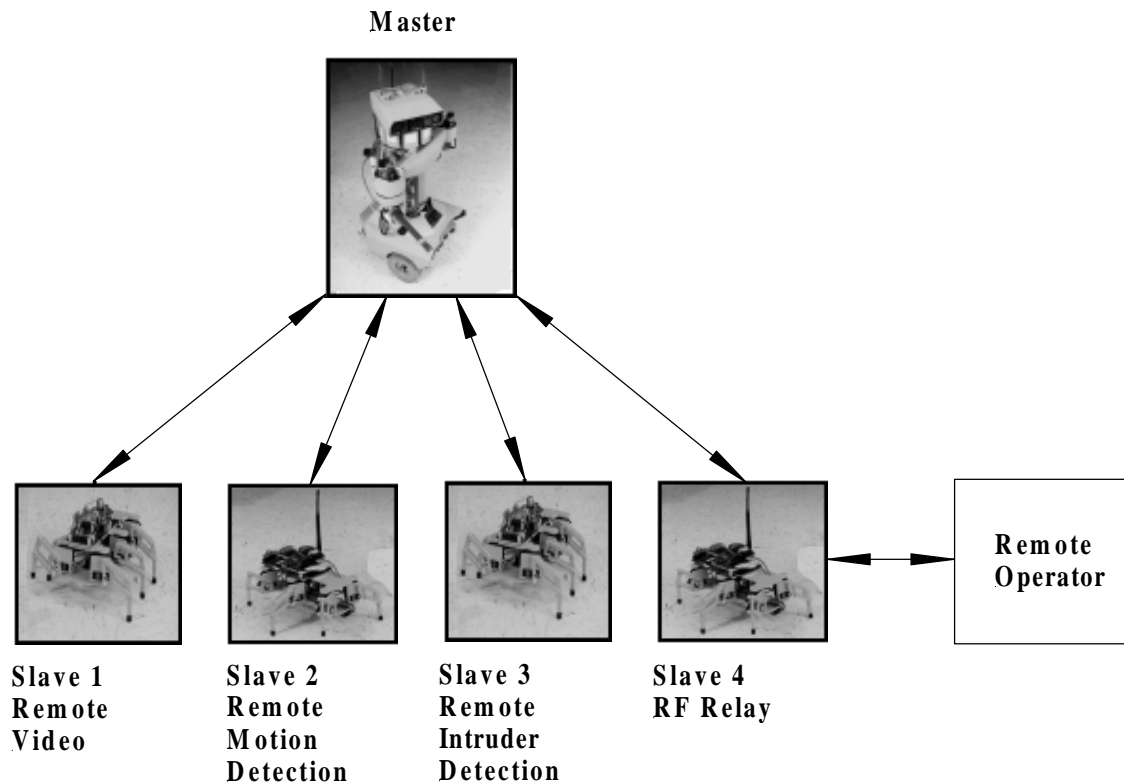
Master

Slave 1 | **Slave 2** | **Slave 3** | **Slave 4**
Remote | **Remote** | **Remote** | **RF Relay**
Video | **Motion** | **Intruder** |
 | **Detection** | **Detection** |

Remote Operator

Figure 7. Master / Slave data communication topology when direct communication between the master and remote operator is no longer possible

3.2 Digital Video Upgrade

Audio and composite video signals are currently relayed to the operator via a high-power analog video transmitter, but an experimental brassboard digital link has been developed to allow for eventual integration of RS-232 data, audio, and compressed video into a single format to reduce complexity, size, weight, and power consumption. Several issues were considered toward realization of an effective video stream channel:

- Loss of information content;
- Coding and decoding (CODEC) efficiency for compression of 2D image stream data;
- Minimization of radiation emissions for radio frequency links;
- Power consumption;
- Reliable communication strategy for a constellation of mobile robots.

The chosen solution as implemented (Figure 8) provides compression of the video stream, transmission of the compressed data over a band-limited serial RF channel, and decompression at the receiver.

Three image compression algorithms were considered: 1) discrete cosine transformation (DCT); 2) Moving Pictures Experts Group (MPEG); and, 3) a wavelet-based compression scheme (Grossman & Morlett, 1984). A survey of digital television industry standard practices and the status of the evolving IEEE-1394-compliant products was also conducted to ensure appropriate exploitation of commercial off-

the-shelf options. A conscious effort was made to implement successful algorithms in hardware where possible. To this end we selected the bi-orthogonal wavelet transform filter based on work by Grossman and Morlet (1984) and sub-band CODEC as implemented in the Analog Devices *ADV611* chip. Details about the hardware implementation of the CODEC can be found in Analog Devices literature (AD, 1998).
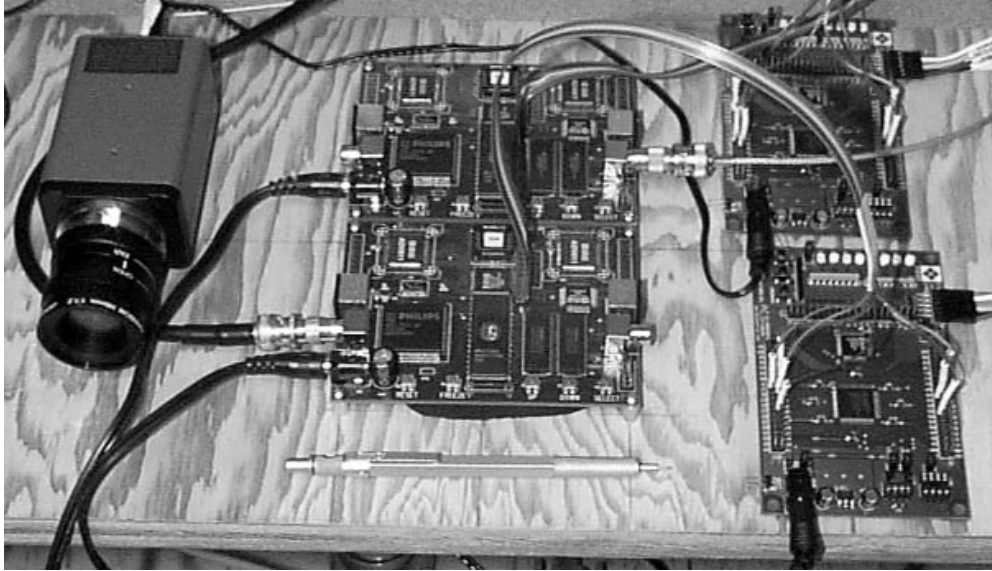

Figure 8. Experimental brassboard digital link which will allow for eventually integration of RS-232 data, audio, and compressed video into a single format.

Referring now to Figure 9, each video frame is digitized by a Philips *SAA7111A* chip, whereupon the digital image is transformed from video spatial data to spatial-frequency-filtered sub-bands. The result is then fed into a run-length encoder and Huffman encoder module. An Analog Devices *ADSP2185* digital signal processing (DSP) chip is utilized to output a synchronous bit stream to a communication device. The DSP chip also provides bin counting feedback to the CODEC module, so the degree of compression accommodates information quality at the synchronous data-rate bit clock. The system can process 30 frames per second, but is intentionally limited in this implementation to two frames per second in order to preserve information content in the image stream from general mission scenarios. The image stream as viewed at the receiver is relatively free of "blocky or blurred" artifacts at two frames per second, and is comfortably formatted to accommodate transfer over 115-kilobaud RF modems.
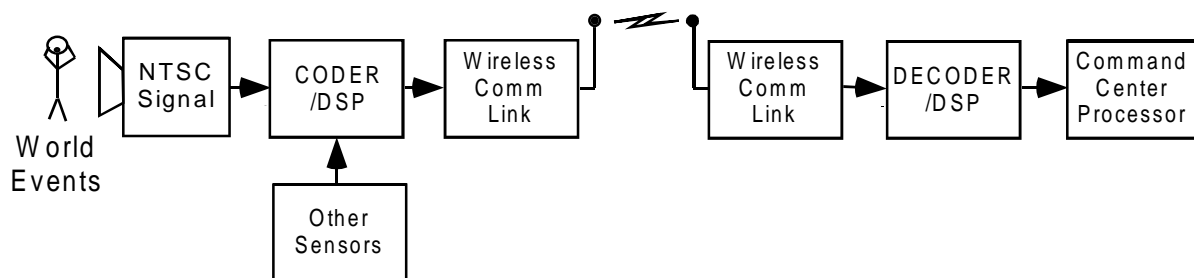

Figure 9. The video link is designed to provide a balance between keeping the operator informed and meeting physical bandwidth limitations.

In recognition of requirements for minimized RF emissions during some types of military surveillance missions, and complexities associated with individually relaying multiple signals (i.e., audio, video,

data), several data streams now share a single bandwidth-limited communications channel. A universal asynchronous receiver/transmitter (UART) was implemented in a pair of field-programmable-gate-arrays (FPGAs) to preserve the flexibility to later integrate other types of information content into the serial bit stream. Future instantiations of this video pipe design will include realization of a formatter placed within the FPGA. The formatter will provide capability to integrate other useful measurements such as temperature, pressure, global positioning system data, spectrometer data, and other physical data from sensors into the data stream.

4. CONCLUSION

This paper provides a status update on the implementation of a prototype tactical/security response robot capable of exploration in unknown structures. A *human-centered mapping* strategy 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. A distributed surveillance and communication network can be transparently deployed in the form of multiple autonomous slave robots for increased effectiveness while exploring deep into unknown structures.

Future efforts will focus on a number of potential upgrades to the current "feasibility-demonstration" prototype:

- Implement a *reflexive teleoperated pursuit mode* that slaves platform steering to the weapon pan axis, allowing the robot to automatically "move to where the gun is pointing;"
- Implement a small inexpensive laser rangefinder in place of the outdated Hamamatsu triangulation ranging sensor for detecting open doorways;
- Move the world modeling software to a single-board Pentium-based processor onboard the master robot;
- Substitute a digital frame grabber for the line grabber currently running the video motion detection algorithms;
- Develop a more robust (i.e., faster, bigger payload capacity) wheeled version of the slave robots to replace the mobility-limited hexapods;
- Incorporate an optimized integrated data/video link to reduce complexity and facilitate full relay capabilities for data, audio, and compressed video.

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