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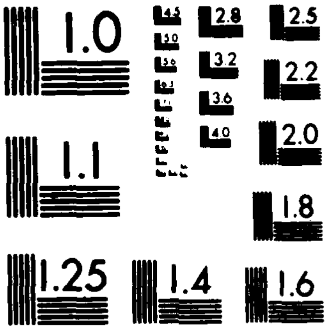

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ROBART II is a battery powered autonomous sentry robot being used by the Naval Ocean Systems Center in San Diego as a testbed in the research areas of environmental modeling and intelligent security assessment. An architecture of nine distributed microprocessors makes possible advanced control strategies and real-time data acquisition capability. Higher level functionality (map generation, path planning, position estimation, obstacle avoidance and statistical security assessment) is currently implemented by the Planner on an IBM-PC/AT computer, using a radio link for communication with the Scheduler. Numerous sensors are incorporated into the system to yield appropriate information for use in collision avoidance, navigational planning, environmental awareness, assessing terrain traversability, and performing security related functions.

Two separate drive motors provide for differential steering, allowing the robot to turn in place in order to maneuver in congested indoor environments. The entire unit is housed in a rugged plastic and fiberglass body, measuring 17 inches wide and 23 inches long at the base, and extending to a height of 50 inches. Special internal circuitry checkpoints are analyzed by self-diagnostic software, and operator assistance is requested if necessary through speech synthesis. [illegible]

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ROBART II
AN INTELLIGENT SECURITY ROBOT

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ROBART II is a battery powered autonomous sentry robot being used by the Naval Ocean Systems Center in San Diego as a testbed in the research areas of environmental modeling and intelligent security assessment. An architecture of nine distributed microprocessors makes possible advanced control strategies and real-time data acquisition capability. Higher level functionality (map generation, path planning, position estimation, obstacle avoidance and statistical security assessment) is currently implemented by the Planner ~~(Figure 1)~~ on

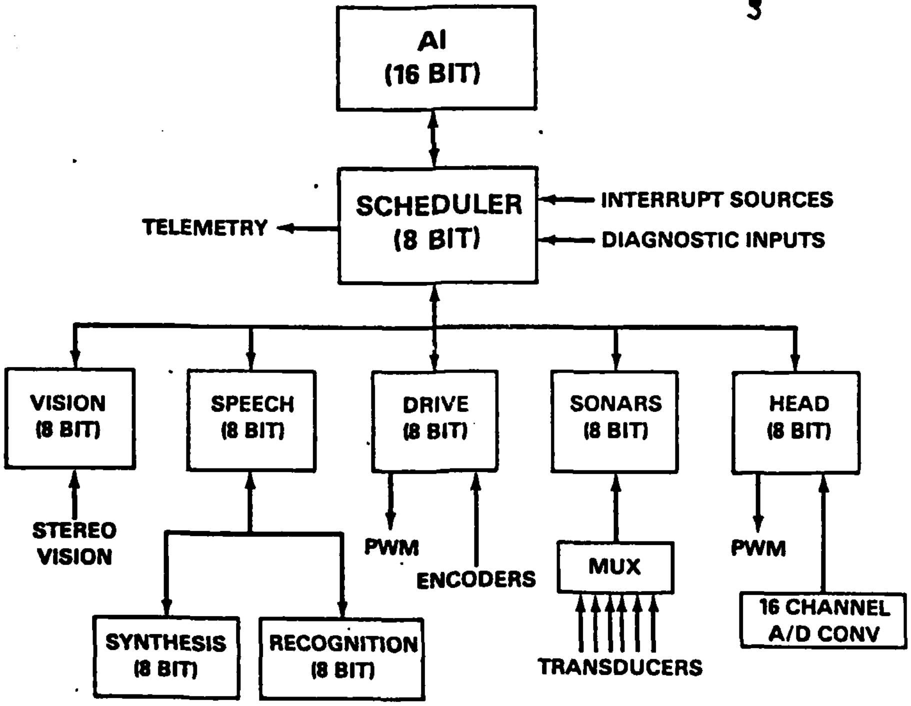

Figure 1. Distributed Computer Hierarchy for ROBART II.

an IBM-PC/AT computer, using a radio link for communication with the Scheduler. Numerous sensors are incorporated into the system to yield appropriate information for use in collision avoidance, navigational planning, environmental awareness, assessing terrain traversability, and performing security related functions.

Two separate drive motors provide for differential steering, allowing the robot to turn in place in order to maneuver in congested indoor environments. The entire unit is housed in a rugged plastic and fiberglass body, measuring 17 inches wide and 23 inches long at the base, and extending to a height of 50 inches. Special internal circuitry checkpoints are analyzed by self-diagnostic software, and operator assistance is requested if necessary through speech synthesis.

Ultrasonic Ranging

ROBART's original ultrasonic ranging capability was upgraded from the original six transducers [1] to a total of 36 discrete sensors to better support the research thrust of environmental modeling. For obstacle avoidance purposes, a fixed array of eleven transducers is installed on the front of the body trunk to provide distance information to objects in the path of the robot. The sequentially-fired array is controlled by a dedicated microprocessor, which performs all time-to-distance conversions and then passes the range information up the control hierarchy to the scheduling microprocessor. A ring of 24 additional ranging sensors (15 degrees apart) is mounted just below the robot's head, and used to gather range information for position estimation. A final ranging unit is located on the rotating head assembly, allowing for distance measurements to be made in various directions as required.

The physical configuration of the ranging sensors is based upon a heuristic developed during work with an earlier prototype [2], which simply observes: For purposes of modeling a robot's surrounding environment, the taller an observed object, the more permanent its position is likely to be. In other words, smaller objects are likely to be more transitory in nature than larger objects. For an indoor scenario, typical examples of such moving entities might include trashcans, boxes on the floor, or chairs. Less subject to motion, but still not rigidly constrained, would be desks and file cabinets. At the stationary end of the spectrum are structural walls, which extend from floor to ceiling.

It would be desirable, therefore, to use as navigational aids those entities in the environment which are less susceptible to relocation over the period of time the robot is operating in their vicinity. This suggests locating the associated navigational sensors as high as possible on the robot's structure. Conversely, transient objects not likely to be represented in the world model are best detected by sensors located near to the floor.

Short Range Proximity Sensing

A total of 35 dual-zone near-infrared proximity detectors are employed on the robot for collision avoidance. Pulsed output from two-high power LEDs operating at 880 nanometers is reflected from nearby objects, and sensed by a photodiode detector. An optical bandpass filter in conjunction with a differentiating network in the input circuitry effectively discriminates between valid returns and ambient noise. Two individually adjustable threshold detectors indicate when objects move to within 18 inches and 36 inches, respectively.

The proximity sensors are arranged in vertical columns on the body trunk and base of the robot, with the outputs within a given column logically ORed together to reduce processing overhead. This places a premium on angular as opposed to vertical resolution. (The robot is little concerned with how tall an obstruction is, but rather where it is in the X-Y plane.) Sensors are placed so as to provide a higher coverage density in the forward direction of travel, while still providing a full 360 degree protected envelope.

Advantages of this type of sensor over ultrasonic ranging for close proximity object detection are numerous. There is no appreciable time lag since the energy propagates at the speed of light, whereas it can take up to a full second to update a sequentially-fired ultrasonic array of only 12 sensors. In addition, the fact that the optical energy can be more easily focused to eliminate adjacent sensor interaction means that the sensors can all be fired simultaneously. Finally, the shorter wavelengths involved greatly reduce problems due to specular reflection, resulting in more effective detection of off-normal surfaces [1].

Long Range Proximity Sensing

A special programmable near-infrared proximity sensor was developed specifically for use on the prototype robot [3], to gather high resolution geometric information for use in navigational routines. The primary purpose of this head-mounted sensor is to provide precise angular location of prominent vertical edges, such as door openings. A Polaroid ultrasonic ranging sensor is used in conjunction with the system to provide range data (Figure 2).

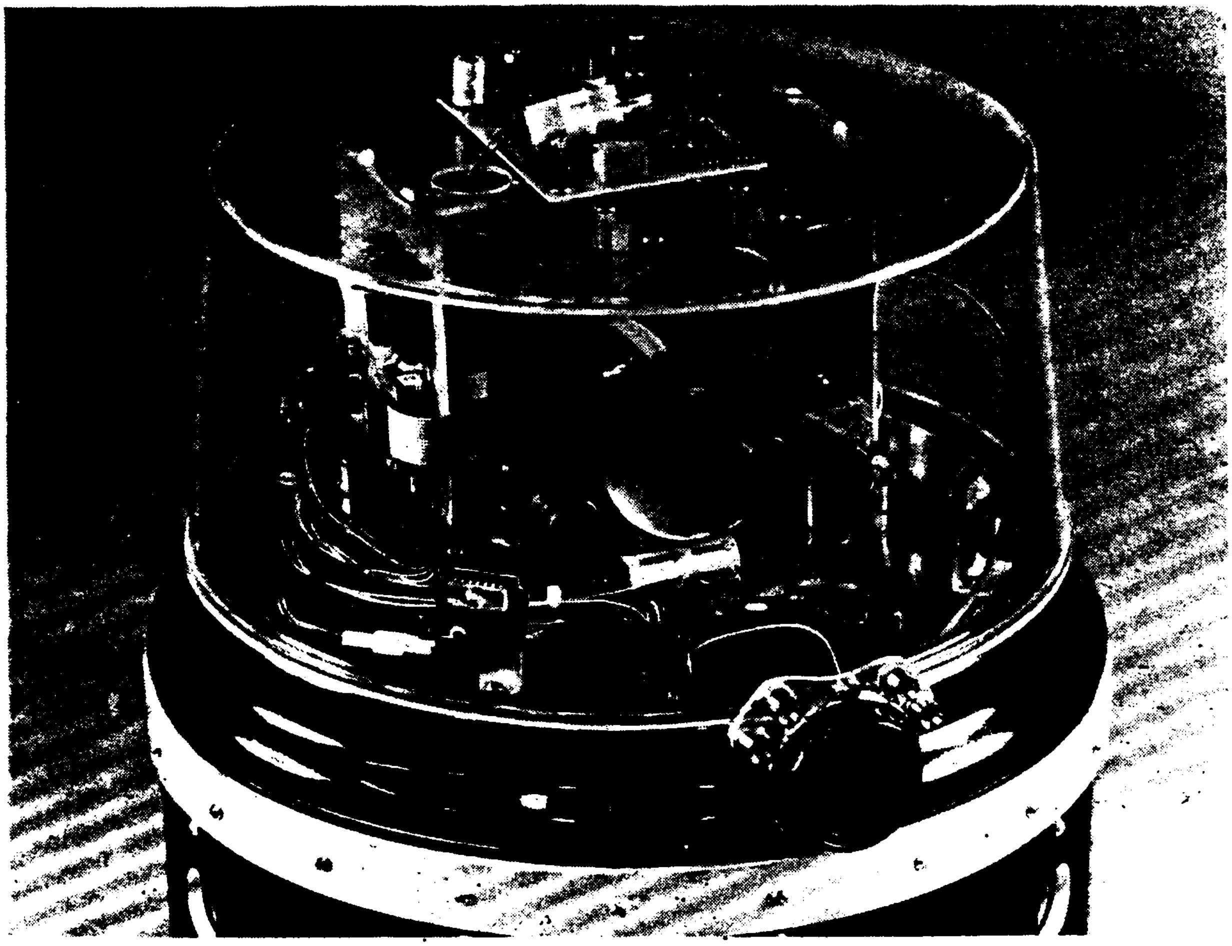

Figure 2. Programmable Proximity Sensor Used to Gather High Angular Resolution Data for Navigation.

An astable multivibrator produces a square wave train of short-duration pulses, driving high-power XC-880-A gallium aluminum arsenide LEDs, which emit energy in the near-infrared spectrum. The system utilizes an array of adjacent LEDs for increased range and sensitivity, with reflected energy focused on the lens of a TIL413 photodiode by a parabolic reflector. The output of this photodiode is passed through a L/C differentiator network, amplified, and then fed to four separate follow-on threshold detector stages. The receiver sensitivity is broken into four discrete levels by these individually adjustable threshold comparators. A strong return will cause all four channels to go low, whereas a weak return will cause only the most sensitive channel to indicate detection. No range information is made available, other than that which can be inferred from the strength of the returned energy.

Unfortunately, the varying reflectivities of different surfaces preclude signal strength from being a reliable indicator of distance. This turns out to be more a function of surface topography than of surface color; varying surface characteristics create uncertainties that thwart attempts to establish a practical correlation between signal strength and target distance.

Effective range is controlled by firing combinations of LEDs; thereby emitting regulated amounts of energy (i.e. the more LEDs illuminating the scene, the farther the detection range.) The number of LEDs in the array that are enabled at any given time is specified by a microprocessor, providing programmable control over the amount of transmitted energy (the total number of active emitters can be any value between one and four.) This in turn fixes the maximum range of the sensor. The robot "feels" around out to a distance of five or six feet, and notes those regions that are obstructed. Then the range of the sensor is extended a few more feet, and those areas that showed no reflected energy are probed again. This process is repeated at computer speed until the sensor has mapped the entire region in terms of range discontinuities as a function of bearing, out to its maximum possible range.

Experimental testing showed the system capable of seeing out to an average of six feet with one LED active, ten feet with two LEDs active, thirteen feet with three, and a maximum average range of fifteen feet attainable with all four.

Stereo Vision

A stereoscopic vision system provides for additional high resolution data acquisition, and is the robot's primary means of locating and tracking a homing beacon on the recharging station (Figure 3). The system does not represent a true three-dimensional capability, however, in that each of the cameras consists of a horizontally-oriented linear (as opposed to two-dimensional) CCD array.

The cameras in effect provide no vertical resolution, but furnish range and bearing information on interest points detected in the horizontal plane coincident with their respective optical axes, 44 inches above the floor. This is consistent, however, with the two-dimensional simplified world model employed by the robot, wherein objects are represented by their projection onto the X-Y plane, and height information is not taken into account.

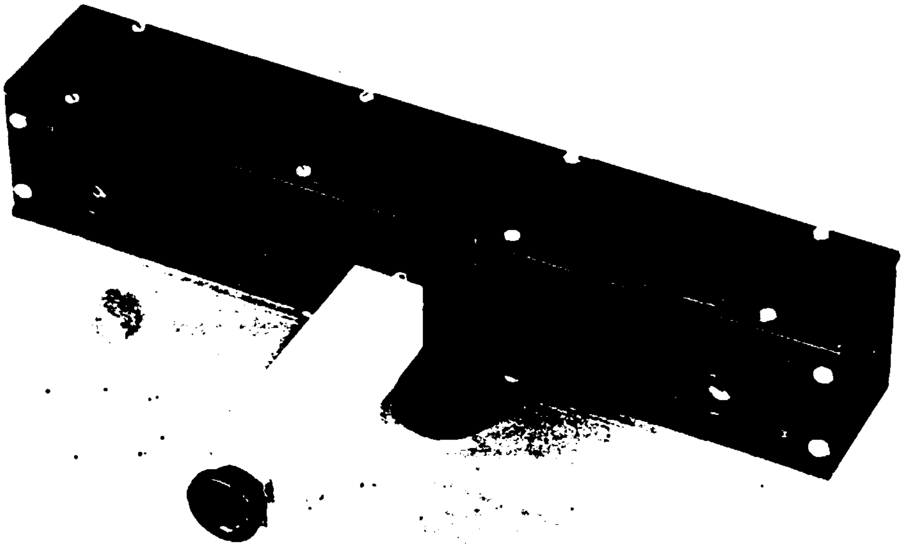

Figure 3. Active Stereoscopic Vision System

A structured light source is employed in conjunction with these stereo cameras for ranging purposes. A 6V incandescent lamp is pulsed at about a 10 Hz rate, and projects a sharply defined V-shaped pattern across the intersection of the camera plane with the target surface. This effectively eliminates the classical stereo correspondence problem, and greatly improves system performance when viewing scenes with limited contrast. The incandescent source was chosen over an active laser diode emitter because of simplicity, the response characteristics of the CCD arrays, and the limited range requirements for an indoor system. (Future plans call for replacing this system with a pair of two dimensional CCD cameras and an active laser source.)

Map Generation

Global path planning is carried out on a bounded internal floor map portraying the robot's workspace with six inch resolution. In a fashion largely derived from earlier work done by John Harrington of Sandia National Laboratories [4], range data from the ultrasonic sensors is used to build an initial map, a two dimensional array wherein each element is set to the number of valid sensor returns received for that area of the work space. At this point the raw map, essentially a gray scale plan view of the floor space, is thresholded for best approximation to the actual work space.

In order to model the robot as a moving point in the map space, objects in the floor map are next grown by an integral number of six inch units, greater than or equal to one-half the width of the robot plus a slight safety factor [5,6]. Final adjustments to either the plan view (depicted in blue) or its associated growth (depicted in red) can be manually entered through use of a special graphics editor as necessary to yield an accurate floor map. This yields the final floor map used by the global path planner: an array of six inch square grid units, each categorized by arbitrarily large array values as either object, growth, or free space.

Path Planner

Paths are generated by a two step process similar to that developed by Lee [7], and incorporated on the Sandia robot. Starting from the robot's current position in the floor map, each neighbor is searched for free space. If the adjacent area is not free, it is ignored; otherwise it's position in the X-Y array is marked with the value of a cost function which represents the distance from the starting location. The neighbor is then placed on a list of points to be subsequently searched. This process continues until either the goal position is found, or until the search list is empty, whereupon the algorithm has determined that no path exists.

Once a destination point is found, the planner will backtrack through the altered floor map by repeatedly choosing the neighbor with lowest cost value. If more than one neighbor exists with the lowest cost, the one which moves the robot in the same relative direction is chosen, thus putting a premium on moving in a straight line. As the path is generated, the planner saves each point at which a change of direction has occured. This direction inflection list completely specifies the global path as a list of straight line segments. The robot is capable of traversing each straight line segment of the path autonomously.

Position Estimation

Position estimation is performed at each direction inflection point to help correct cumulative dead reckoning errors [8]. The navigational ring of 24 ultrasonic sensors is used for this purpose. The ring is placed as high as possible from the ground in order to minimize distortion due to changing positions of transient objects in the work space. The robot generates a database of range returns, stored in polar coordinates, for each six inch square floor map unit marked as free. This in effect creates a unique signature of the workspace, as seen by the ring of sensors, for each X-Y position in the map.

At each inflection point in the path, the database is searched for a location with a signature which matches the current sensor range returns. (A sensor return matches a database value if it falls within a specified window of acceptance, approximately 1.5 times the map resolution.) Starting with the current dead-reckoned map position, the position estimator searches the database in an expanding fashion, looking for the entry (position) with the highest number of correlations matching the range values taken at the robot's present physical location. It also skews the current position sensor data one sensor position (i.e. +/-15 degrees) in each direction, in an attempt to correct for any error in current heading. If the highest number of correlations is not greater than a minimum threshold, then the estimator searches a new set of neighbors farther from the original dead-reckoned position. Initial results using this technique at Sandia [4] showed a sharp differential between the number of correspondences for a correct database match with respect to neighboring locations.

When a match is found with a high enough correspondence, the robot's position is known to within six inches (the database resolution). To improve the accuracy, the estimator will interpolate a new position within the map unit using the four sensor range returns pointing 0, 90, 180 and 270 degrees relative to the robot, as long as each of these readings match their corresponding database returns within the specified tolerance.

Collision Avoidance

Real-time obstacle avoidance is carried out continuously while the robot is in motion. A statistical approach is employed which takes advantage of the greater accuracy and reliability of ultrasonic sensors at close range. Transducers low to the ground are used in order to detect the changing positions of objects in the work space. As the robot moves along the global path, it maps those sensor returns which are less than a critical distance onto a separate, smaller localized floor map. (The critical distance chosen is approximately five feet, in order to maximize the accuracy of the range returns and filter out bad data resulting from specular reflection and beam divergence [1]).

The mapping of a return takes the form of increasing the intensity values in the collision avoidance map for the grid location corresponding to the detected object, as well as its nearest neighbors in the array. This technique, developed by Harrington [4], in effect performs low pass filtering of the data as the map is created. The 35 dual-zone near-infrared proximity detectors are used in conjunction with the lower array of ultrasonic ranging sensors to detect when an obstacle is blocking the robot's path, at which point forward travel stops. A new path is then generated from the localized collision avoidance map (as opposed to the absolute navigational map), using the next inflection point on the original path as the temporary goal.

Obstacle avoidance path planning also differs from global path planning in that the searching algorithm will decrement the localized floor map intensity values which do not represent free space. This tends to filter out erroneous sensor returns and sensor noise. It also means that the new path generated may not be obstacle free; there may be an obstacle in the path that is not represented in the global floor map. For this reason, the local path planner keeps track of the number of attempts to reach a global path inflection point. If this number reaches an unacceptably high value, the local path planner can yield control to other modules providing a more complex form of environmental mapping. If the execution of an obstacle avoidance maneuver is successful, the robot will then resume traversing the original global path.

Intelligent Security Assessment

ROBART has the ability to carry out a sophisticated security mission in both stand-alone autonomous mode, and in cooperation with radio-linked higher level assessment software. A wide range of multi-modal security sensors (passive infrared motion, optical motion, microwave motion, ultrasonic motion, vibration monitoring, discriminatory hearing, etc) gives the robot a robust view of the work space. The security software uses a temporally dependant statistical approach to sensor data fusion which computes a composite threat assessment. The cross-correlation of intrusion detection sensors, each operating on a different principle, allows the system to better differentiate between nuisance and actual alarms. An alarm threshold is dymanically computed, based on which intrusion sensor groups are currently active, ambient environmental conditions, time of day, and other relevant factors. If the composite threat exceeds this threshold, a true alarm condition exists. The robot is capable of carrying out a number of different response missions as deemed appropriate for the particular situation.

An advanced operator/user interface has been developed for the security assessment program, which runs on an IBM PC/AT. The operator display depicts environmental conditions, sensor availability and status, current threshold level, and threat assessment. The screen data is time stamped and overlayed on live video transmitted from a camera onboard the robot, and may be recorded by VCR for replaying at a later time.

The operator also has the choice of enabling data logging directly to the IBM hard disk of all information displayed. Significant data compression is achieved by saving only that data which represents a change in a previous sensor status. Log files may be replayed, after the fact, through the same operator interface. A full complement of file commands allow the user to step through or search for various sensor conditions. These statistical files are an important tool in analyzing sensor performance in intrusion detection; large amounts of data collected over an extended period of time will be analyzed to better characterize the individual intrusion detection sensors with regard to their performance under varying conditions. The resultant information will be used to develop a more intelligent algorithm for differentiating between actual and nuisance alarms.

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