SENSORS FOR MOBILE ROBOTS

THEORY AND APPLICATION

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A SECOND-GENERATION AUTONOMOUS SENTRY ROBOT

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The prototype robot, ROBART II, is a sophisticated multisensor platform employing a control hierarchy of nine microprocessors, and intended as a testbed for AI research in the fields of autonomous navigation and collision avoidance. ROBART II is a second-generation machine built to improve some of the capabilities of its predecessor ROBART I, a mobile autonomous sentry (see "A Computer Controlled Sentry Robot," *Robotics Age*, Mar/Apr '82).

Photo 1. This front view of the prototype robot ROBART II shows the five element ultrasonic sensor array. The upper body case is fabricated from a section of 12 in. plastic irrigation pipe and attaches to the base with four quick-release pins. The parabolic reflector for the long-range near-infrared proximity detector is visible under the plexiglass dome. The photo is courtesy of the Naval Surface Weapons Center.

This second prototype uses the same software development system as the original ROBART I and employs a single-board 6502-based microcomputer, designated as CPU #1, configured as the "Scheduler." Below this level in the hierarchy, however, is another layer of five 6502-based systems functioning as dedicated controllers. These microprocessors are assigned functions associated with speech, steering and drive, ultrasonic ranging, head motion, and vision. They are interfaced to the Scheduler through an 8-bit parallel bus and a multiplexed RS-232 serial port. A special in-circuit-emulator allows for these stand-alone controllers to be mapped into the address space of the Scheduler during software development and debugging, after which the resultant code is burned onto an EPROM and made resident on the individual boards themselves. This greatly simplifies the process of fine tuning software that interacts with programs running on a separate machine in the network, in that both machines can be brought up and made to run simultaneously in the development mode. Changes can be made as needed with no need to burn an EPROM until both sets of code have been perfected. At the very bottom layer in the hierarchy are two additional microprocessors, assigned respectively the responsibilities for speech synthesis and recognition.

Another very significant difference between the two prototypes is the addition of the "Planner" at the very top of the hierarchy in ROBART II. This 16-bit machine provides a home for the actual intelligence of the system. Research in this area is currently being conducted by Ms. Anita Flynn of the Artificial Intelligence Laboratory at MIT, using initially a radio link between the Scheduler on the robot and an IBM XT located some distance away. A single-board machine will eventually be installed on the robot to execute the code now being developed.

Only marginal performance was ever obtained from the single forward-looking ultrasonic ranging unit on ROBART I, and maximum range under optimum conditions was only about ten feet. In contrast, ROBART II has installed seven Polaroid ultrasonic ranging units, with five transducers mounted in a sequentially fired array centered on the forward axis. (See Photo 1.) This array configuration allows for beam splitting techniques to be employed to increase the horizontal resolution of the system, and to provide course and speed corrections for following a moving target while remaining a specified distance away. In this mode the robot's mean forward velocity is calculated as a function of distance to the target. A slight differential between left and right drive motor speeds is introduced as a function of how far off the array centerline the target appears. This results in the platform turning toward the target being followed, until the target is dead ahead, without the necessity of mechanically panning a single sensor back and forth to ascertain the target's relative position.

The remaining two ultrasonic sensors, mounted on the head, can rotate in turn up to 100 degrees either side of centerline. A dedicated 6502-based controller, CPU #3, performs all tasks associated with ultrasonic ranging. An 8-bit command from the Scheduler tells CPU #3 which sonars to fire; these units are sequentially enabled, and the time required for each to detect an echo is converted to distance and stored. Upon completion of the full sequence, CPU #3 requests permission to transmit the range information up the hierarchy and, when acknowledged, passes it to the Scheduler. The sequence is then repeated until altered upon command from the Scheduler. The incoming ranges are read in by an interrupt routine and stored in the Scheduler's Page Zero for use by any routines that need range information from any of the sensors. The sonar drivers themselves are interfaced to CPU #3 through a three-channel eight-input multiplexer. All time-to-distance conversions are done in software by CPU #3.

ROBART II also features a vastly improved mechanical design. The entire electronics package visible through the rear access doors is easily removed by loosening two retaining screws. All connections to the robot are made through numerous ribbon cables terminating in zero-insertion-force (ZIF) DIP sockets. The upper body separates from the fiberglass base unit for transportability and maintenance, and is held in place by four quick-release pins as shown in Figures 2 and 3.

The propulsion system uses two individually controlled drive wheels, one on either side of the base, with casters in front and rear for stability. This configuration allows the robot to spin in place about its vertical axis for markedly improved maneuverability. ROBART I employed a tricycle wheelbase with a steerable, driven front wheel which resulted in a much larger turn radius and poor maneuverability, but which offered better performance with regard to climbing over small obstructions. The small diameter casters on ROBART II are suitable only for indoor use, unable to surmount surface discontinuities greater than about one inch. The forward caster "floats" up and down attached to a spring-loaded shock absorber which keeps it in contact with the floor when traversing non-planar surfaces. Note that this is not a concern with a three-point platform.

The drive motors used on ROBART II are independently controlled through pulse width modulation (PWM), and synchronized by high-resolution optical encoders attached to the armature shafts. The optical encoders supply precise displacement and velocity information for use in dead reckoning during maneuvering. A dedicated 6502-based controller handles all drive and steering control functions as directed by the Scheduler. Pulse width modulation is implemented through special hardware resident on an interface card connected between CPU #4 and the power transistors controlling the motors.

SYSTEM ARCHITECTURE - ROBART II

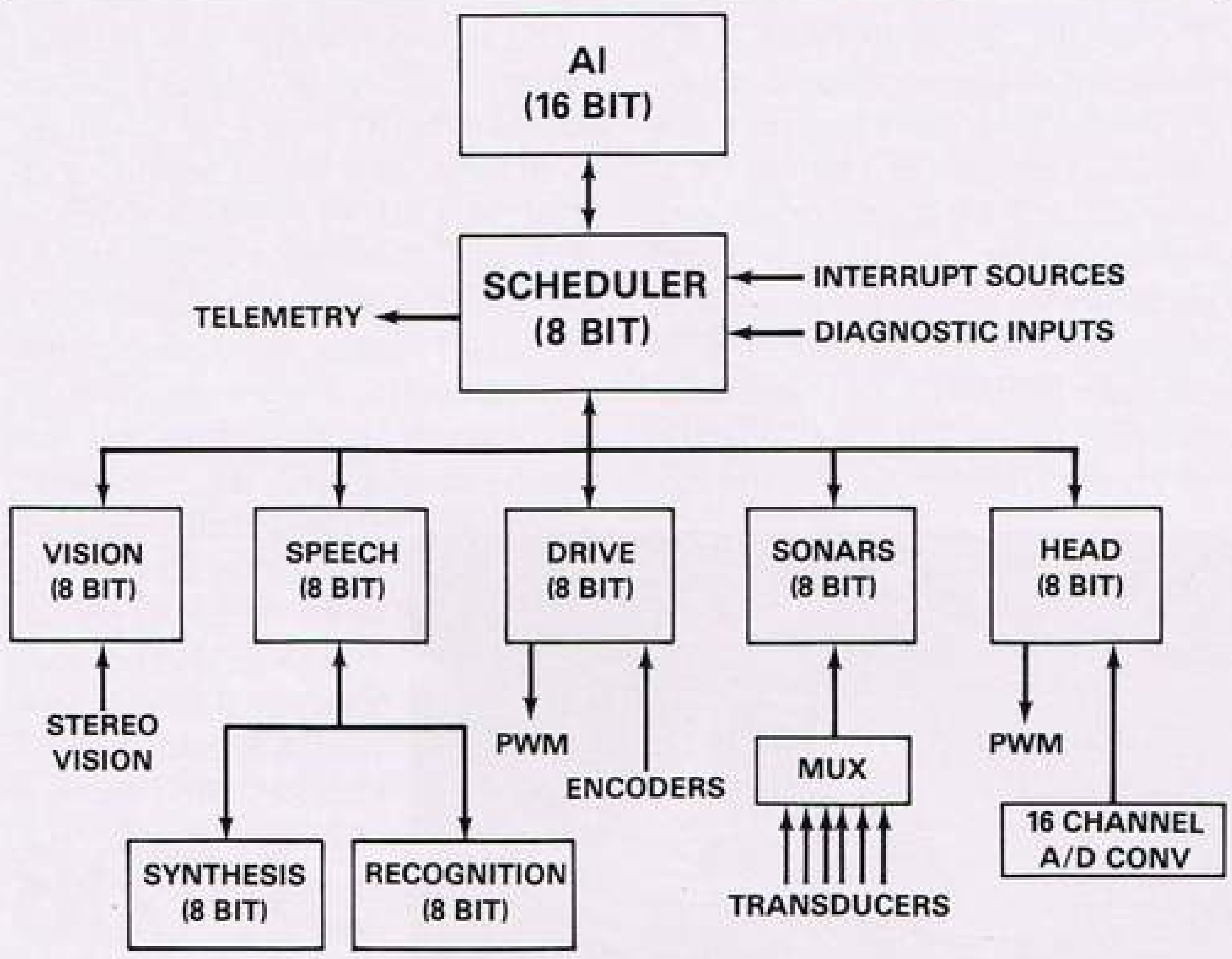

Figure 1. A network of nine microprocessors make up the control hierarchy for ROBART II, seven of which have been installed and tested to date. The dedicated 6502-based controllers at the intermediate level are all CMOS, with a current consumption of only 35 mA each.

For each motor there exists a directional control line and an on/off control line. The on/off control lines are connected to the outputs of the left and right pulse width modulators. The width of the pulses appearing on these outputs is set by the commands from CPU #4 to the PWM interface card, and determines the speeds of the respective motors. Conventional eight-inch wheelchair tires and motors provide a quiet, powerful propulsion system with minimal wheel slippage. Decoupling clutches on each wheel allow for "freewheeling" the robot around when the system is shut down.

A converging-type near-infrared proximity sensor is installed on each corner of the base of the unit, positioned so as to detect the presence of the floor. This precludes falls down stairways or other attempts to traverse unsuitable discontinuities that could entrap or even damage the unit. Any undesirable conditions detected by these sensors will cause the drive to be immediately disabled; the Scheduler is alerted as to which corner sensor detected the problem. The Scheduler then asks for help from the Planner and re-enables the drive if a high-confidence solution can be found. If not, speech synthesis is used to request human assistance. This same drive circuitry can be deactivated manually by an observer using a small hand-held transmitter similar to a garage door opener if so desired for safety or other reasons.

The only tactile sensors employed on ROBART II are the two circumferential bumpers around the base unit. Each consists of a free-floating plastic strip encased in a fixed housing, spring loaded so as to normally be in the extended position. A series of microswitches is arranged behind these strips in such a fashion that they are activated by any displacement of the strip. When the bumper comes in contact with another surface, the floating strip is locally depressed and in turn activates the appropriate microswitch to provide geometric resolution of the point of impact. Intelligent recovery is facilitated by the collision-avoidance software.

The most significant component of this continuous bumper design is the corner piece, designed with an angled cut at both ends so as to mate with the floating strips in the linear casings. When a corner comes in contact with another surface, it will press against a floating strip and cause it in turn to activate the microswitch nearest the corner. The angled construction also permits lateral motion of the strips within their casings when responding to oblique impacts, and is the key to the continuous yet collapsible floating design. The configuration doubles as a protective bumper for the surface of the robot base and any noncontact sensors mounted thereon.

The most useful navigational information available to ROBART I came from a long-range near-infrared proximity sensor mounted on the head with a maximum detection range of six to seven feet. A much improved version is employed on ROBART II, which provides for ranges up to 18 feet, variable threshold detection, and a programmable array of four high-power LED emitters. This sensor is used to complement the sonar range information from the head-mounted transducers when collecting data on the robot's surroundings.

Two other types of near-infrared detectors are used by ROBART II. Three medium-range multibeam proximity detectors (Banner CX1-6) are arranged in a forward-looking horizontal array for collision-avoidance purposes. These modulated-beam sensor units have adjustable maximum ranges, set for this application to about five feet. They provide extended protection capability in the direction of travel, and collectively can discern if an obstruction is directly ahead, or to the right or left of centerline. These sensors serve as complementary backup to the five-element sonar array.

The final type of near-infrared unit is a short-range proximity sensor employing a pulsed output from a pair of high-power LEDs. A differentiating receiver/amplifier drives a two-channel threshold detector, with adjustable thresholds set to indicate target detection at 30 in. on one channel, and 18 in. for the other channel. Thirty-five of these are planned for eventual installation on the robot, appropriately situated so as to provide a protective envelope totally surrounding the unit. Outputs will generate interrupts to alert the Scheduler that a collision is imminent; the robot's course will be altered accordingly.

Preliminary tests have been completed on a prototype of this sensor, and final design modifications are now being made prior to circuit board layout and construction.

Another dedicated controller in the hierarchy, CPU #5, is assigned all functions related to speech input and output. Below it in the hierarchy are CPU #7, a DT1050 speech synthesizer, and a soon-to-be-installed 6502-based speech-recognition unit which can recognize up to 256 words or phrases. Figure 2 shows the physical location of CPU #5 and the actual speech synthesizer, CPU #7.

A final 6502-based system is employed as a controller and signal processor for a stereoscopic vision system currently under development. To minimize processing requirements, this system employs two 256-element linear CCD arrays located in separate camera assemblies to be mounted on the head. Outputs from both cameras will be compared to ascertain distances to prominent vertical features using standard stereo ranging techniques. The excellent angular resolution afforded by an optical system of this type as well as the range information obtained will be used to augment data taken by the head-mounted sonar transducers for room mapping and collision-avoidance routines run by the Planner. In addition, the cameras will be used to locate and establish the range to a near-infrared beacon mounted on top of a stand-alone charging station which allows the robot to home in and make a connection for recharging its batteries.

ROBART II is equipped with a multitude of sensors for environmental awareness to support its role as an intelligent sentry robot. Special sensors monitor both system and room temperature, relative humidity, barometric pressure, ambient light and noise levels, toxic gas, smoke, and fire. In-

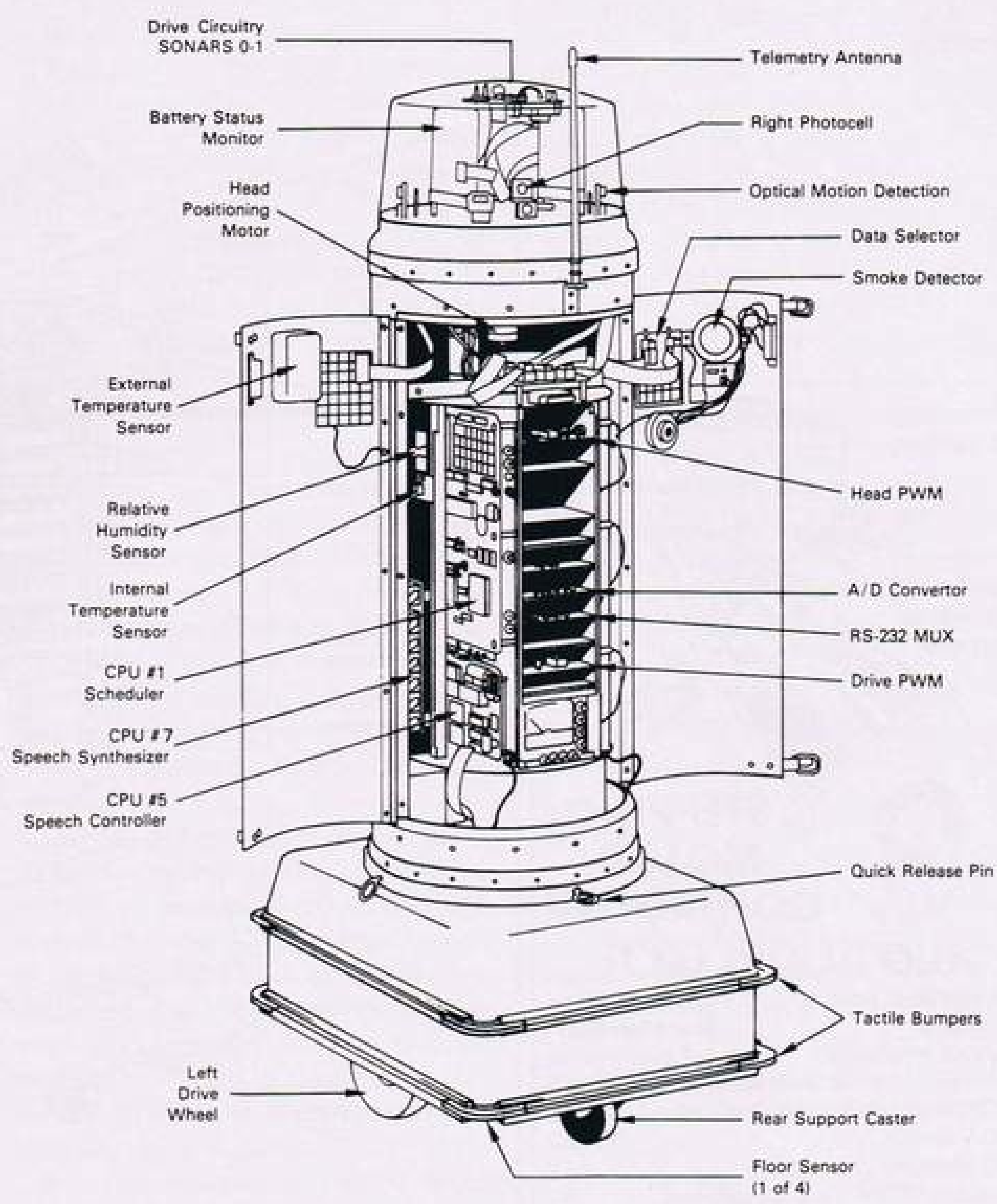

Figure 2. This left rear view depicts the location of numerous components. Near-infrared convergent-type floor sensors are located at each corner of the base shroud.

trusion detection is addressed through the use of five passive true-infrared body heat detectors, four passive optical motion detectors, ultrasonic motion detectors, vibration monitoring, and discriminatory hearing. Approximately 256 internal circuitry checkpoints on ROBART II constantly monitor circuit performance, system configuration, operator-controlled switch options, cable connections, and interface card integrity. Speech output is generated by the self diagnostics to advise of any difficulties.

While ROBART II is by no means complete at this point, most of the hardware has been installed and tested. A considerable amount of software has been written for the dedicated controllers in the lower level, and for the Scheduler. The communication protocols for information transfer up and down the hierarchy have been developed and implemented, and the entire system is currently operational and capable of limited autonomous behavior. With the addition of the stereo vision system and remaining near-infrared proximity detectors for collision avoidance, and the enhancement of the existing software packages for each of the dedicated controllers, ROBART II should prove to be an unequalled sensor testbed ideally suited for further research into the areas of collision avoidance, domain mapping, and autonomous navigation. The robot is quite often on loan to the Robotics Research and Development Lab at the Naval Surface Weapons Center in White Oaks, Maryland, where it is used for sensor evaluation and as a research tool by the Navy.

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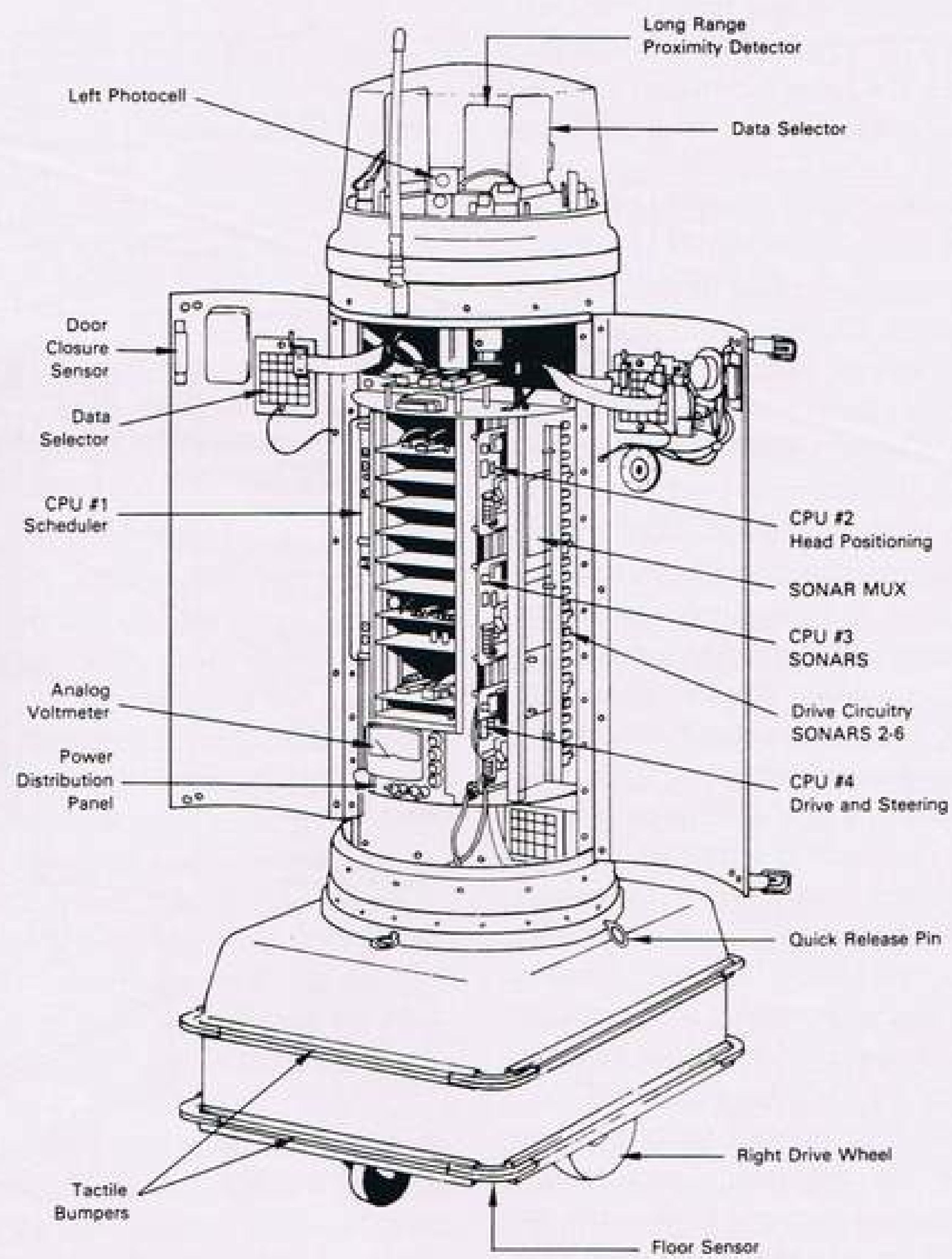

Figure 3. The right rear view shows the location of the SONAR multiplexer and individual driver cards. CPUs 2, 3, and 4 are single-board MMC-02 systems made by R.J. Brachman and Associates, each containing two 6522 Versatile Interface Adapters (VIAs) with 8 Kbytes of RAM/EPROM on board.