Motion Control Issues for a Tactical Response Robot

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ROBART III is an advanced demonstration platform for non-lethal tactical response that extends the concepts of reflexive teleoperation into the realm of coordinated camera and weapons control. The robot's ultrasonic and optical collision-avoidance sensors facilitate operation in unstructured and unexplored buildings with minimal operator oversight, allowing its deployment in law enforcement and urban warfare scenarios.

The basic goal of a robotic system is to perform some useful function in place of its human counterpart. Benefits typically associated with the installation of fixed-placed industrial robots are improved effectiveness, higher quality, reduction in manpower, improved reliability, and cost savings. Additional drivers include the ability to perform tasks humans cannot do, and the removal of humans from dangerous or life-threatening scenarios [1]. The latter category has historically been very appealing with regard to a number of military and law enforcement applications involving mobile robots, and noteworthy advances in the supporting technologies are beginning to produce favorable results [2,3].

More important, the nature of warfighting has progressively shifted away from rural and more toward urban battlefields, where human losses are projected to be staggering, and robotic alternatives show considerable promise [4]. The combined effects of this powerful "technology push" and simultaneous "applications pull" have stimulated a groundswell of renewed interest in tactical mobile robotics within the U.S. Department of Defense that seems unprecedented in terms of its magnitude and fervor.

The type of high-level control strategy used on such a mobile platform runs the full spectrum defined by *teleoperated* at the low end and *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

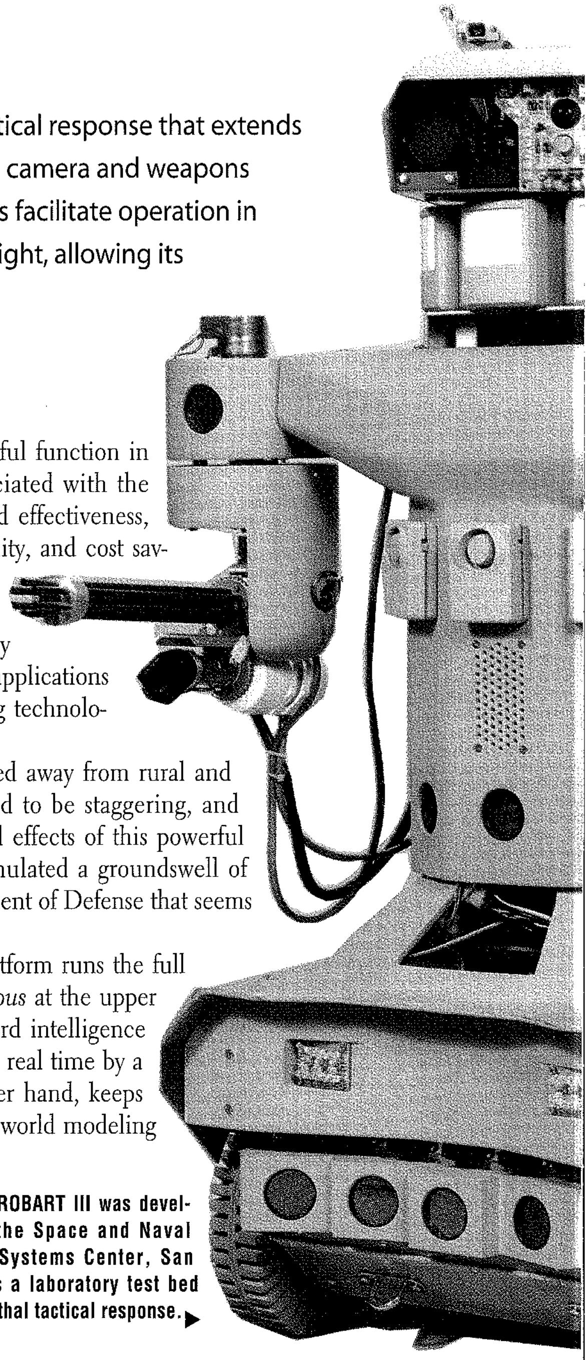
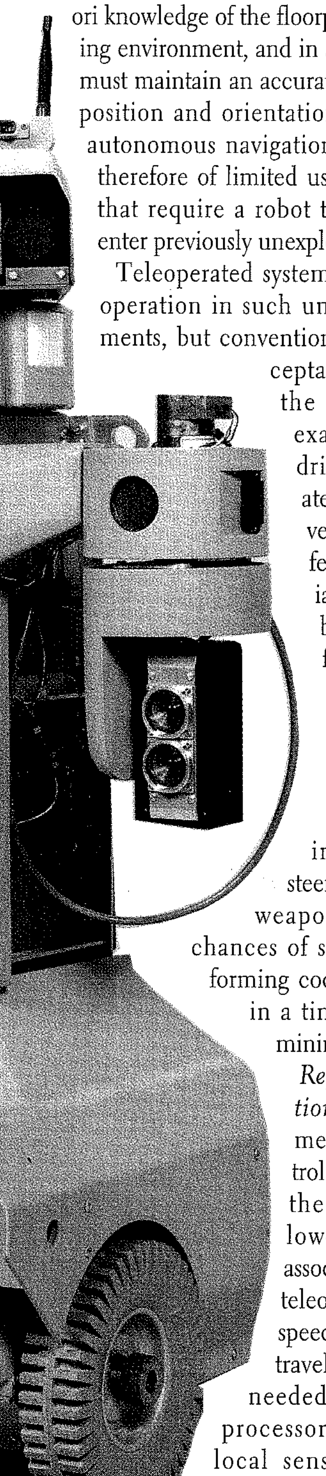


Photo 1. ROBART III was developed at the Space and Naval Warfare Systems Center, San Diego, as a laboratory test bed for non-lethal tactical response.

scheme to represent the location of perceived objects in its surroundings.

The existence of an absolute world model permits automatic path planning and subsequent route revisions in the event a new obstacle is encountered. Unfortunately, however, 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. Conventional autonomous navigation techniques are therefore of limited use in applications that require a robot to spontaneously enter previously unexplored structures.



Teleoperated systems 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. If a remote operator has to master simultaneous inputs for drive, steering, camera, and weapons control, the chances of successfully performing coordinated actions in a timely fashion are minimal.

Reflexive teleoperation combines elements of both control strategies to free the operator from low-level concerns associated with direct teleoperation: vehicle speed and direction of travel are modified as needed by an onboard processor in response to local sensor inputs, but under the high-level supervisory control of the remote operator [1]. This computer-aided driving approach helps minimize the possibility of collisions in cluttered surroundings, while significantly reducing the stress and fatigue associated with conventional remote operation of a mobile system. More advanced schemes implement intelligent behaviors such as wall following and doorway penetration, in addition to the basic reflexive avoidance maneuvers.

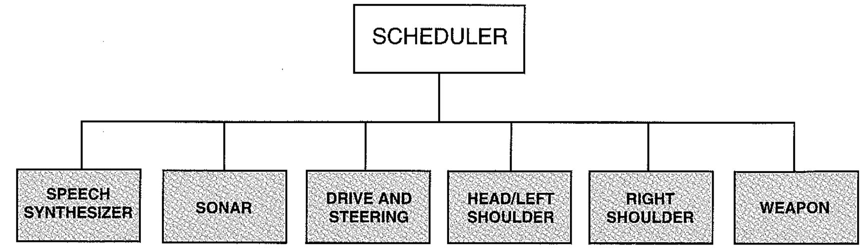


Figure 1. The onboard computer architecture is configured as a simple master/slave hierarchy connected by a multidrop RS-232 network.

ROBART III (see Photo 1, page 109) is an advanced demonstration platform for nonlethal tactical response that extends the concepts of reflexive teleoperation into the realm of coordinated camera and weapons control. A rich mix of ultrasonic and optical collision-avoidance sensors facilitates operation in unstructured and unexplored buildings with minimal operator oversight. The objective is to provide sensor-aided motion control of mobility, camera, and weapon functions to ease the driving burden of a remote operator in law enforcement and urban warfare scenarios.

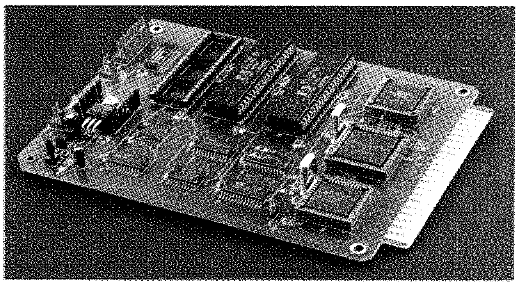
System Overview

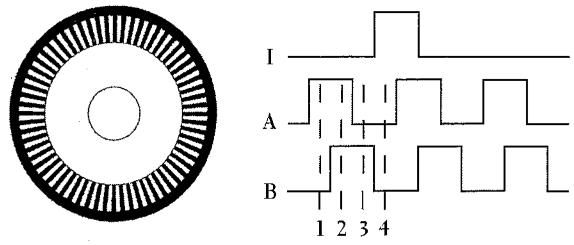
The onboard computer architecture for ROBART III (see Figure 1) is arranged as a simple master/slave hierarchy connected by a multi-drop RS-232 network. The Scheduler computer serves as the master, parsing high-level commands received from the remote host processor, then routing them to the appropriate destination. The Scheduler also requests information from the individual slaves, and orchestrates various behavior routines that require coordinated actions from multiple subsystems. A simple example would be altering the platform's heading via the Drive and Steering computer, based on a perceived obstacle reported by the Sonar computer, but still in accordance with a high-level goal specified by the remote host.

The Head/Left Shoulder computer controls the pan action of the head-mounted surveillance camera and other sensors mounted behind the faceplate, as well as the pan axis of a triangulation-ranging sensor mounted on the left shoulder pod. Neither the head nor the left shoulder has a tilt axis. The Right Shoulder computer controls the pan-and-tilt actions of the nonlethal response weapon. Due to a two-axis I/O limitation of the current hardware, a Weapon computer is currently required to control the rotating motion of the Gatling-style weapon. Photo 2 shows a new three-axis microcontroller designed to alleviate this shortcoming, with the added advantage of having two additional RS-232 serial ports.

Ultrasonic and optical proximity and ranging sensors are strategically located to provide full collision-avoidance coverage in support of the advanced teleoperation features desired. A 16-channel sonar multiplexer based on the bidirectional LH1500 solid-state relay is used to sequentially select individual transducers for connection to a single Polaroid 783821 ranging module. Fourteen Polaroid electrostatic transducers have been installed to date: two head-mounted sensors; a five-element forward-looking array on the front panel of the mobility base; one forward- and one rear-

Photo 2. An in-house designed 68HC11 microcontroller incorporates up to three Hewlett-Packard HCTL-1100 PID controllers. Two are shown here.





STATE	CH A	CH B
S_1	HIGH	LOW
S_2	HIGH	HIGH
S_3	LOW	HIGH
S_4	LOW	LOW

Figure 2. The observed phase relationship between the Channels A and B pulse trains can be used to determine the direction of rotation with a phase-quadrature encoder, while unique output states S1–S4 allow for up to a fourfold increase in resolution [5].

facing sensor on each shoulder pod (four total); and three more on the front body trunk. 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 than the 49.4 kHz Polaroid sensors used for collision avoidance, eliminating problems associated with crosstalk from simultaneous operation.)

Twelve Sharp GP2D12 near-infrared (NIR) triangulation-ranging sensors located in the shoulder pods and base are used for high-resolution environmental awareness in proximity to the robot (i.e., <30 in.). Two Banner SM312D NIR proximity sensors are located on the top of the head for collision avoidance. A longer range SM912D unit is located behind the face plate, intended primarily to assist in locating potential doorway openings. A Hamamatsu H1783 Auto-Focus Module NIR range finder mounted on the left shoulder pod is then scanned back and forth at a 1 Hz rate to precisely determine the location of the left and right door edges.

For purposes of continued discussion, the motion-control issues for ROBART III can be divided into three general categories: mobility control, camera control, and nonlethal weapon control. Furthermore, given the telereflexive control strategy used, each category can be further subdivided into low-level control-loop details, and high-level sensor-assisted operator control.

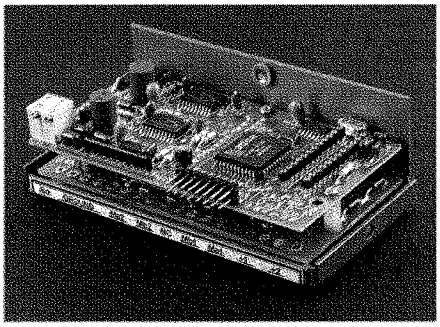


Photo 3. Shown with the cover removed, the VANTEC CDRF-23 is a dual-axis H-bridge capable of handling continuous motor currents up to 30 A per axis.

Mobility Control

As a laboratory prototype, ROBART III is intended only for indoor operation on relatively smooth planar floor surfaces. (Other government-funded programs are addressing the complex mobility issues for tactical applications.) Differential steering is used with a single passive caster in the rear of the platform directly behind the battery compartment. The left and right drive wheels are 8-in. wheelchair snow tires driven by a pair of 12 V A-Bec electric wheelchair motors. A 500-count BEI MX152 incremental optical encoder (see Figure 2) is attached to each of the motor armature shafts for precise velocity control and dead-reckoning displacement information. System power is supplied by an 80 amp-hr, 12 V gel-cell battery that provides roughly 6–8 hr of continuous operation between charges.

The encoder outputs for the drive motors are passed to a pair of Hewlett-Packard HCTL-1100 general-purpose motion control ICs mounted on a daughterboard that plugs into the Drive and Steering computer. The HCTL-1100 serves as a dedicated proportional-integral-differential (PID) controller, freeing its host processor of all low-level time-intensive tasks associated with decoding the phase-quadrature encoder pulses, calculating and maintaining motor velocity, and keeping track of absolute displacement [6]. The Drive and Steering computer, meanwhile, is tasked with passing the desired velocity commands to the left and right PID controllers, and dynamically calculating the dead-reckoning solutions for vehicle displacement (X,Y) and heading (θ) from the HCTL-1100's three-byte encoder displacement registers.

The eight-bit parallel outputs of the PID controllers are provided to a VANTEC CDRF-23 dual-axis power amplifier (see Photo 3). The amplifier, specifically designed for the motion control needs of a battery-operated differentially steered platform, incorporates paralleled MOSFETs in the H-bridge circuit to minimize the ON-resistance (and hence the power loss across the FET junctions). This concern is especially critical for high-current 12 V systems. For example, an ON-resistance of just 0.3 Ω will result in a drop of 3 V on both the high and low sides of the bridge for a motor current of 10 A. Ignoring line and connector losses, this leaves only 6 V left across the motor windings.

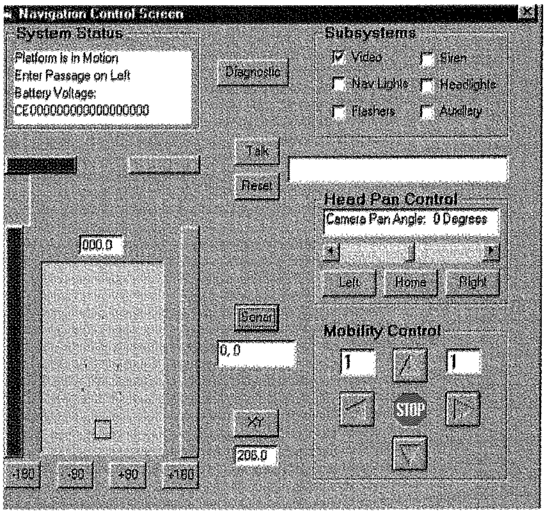


Photo 4. The high-level driving icons surrounding the Map Window (lower left corner) can be seen on the Navigation Control Screen. The robot has been instructed to enter the next door encountered on the left.

A very simple graphical user interface (GUI) has been implemented under Visual Basic to support the development and diagnostic needs of this technology-based effort (see Photo 4). The Mobility Control Window (lower right corner) provides a convenient way for the operator to set the desired speed, and, if necessary, manually change the platform's heading. Each time the operator clicks on the forward arrow button, for example, the platform's velocity is increased ▶

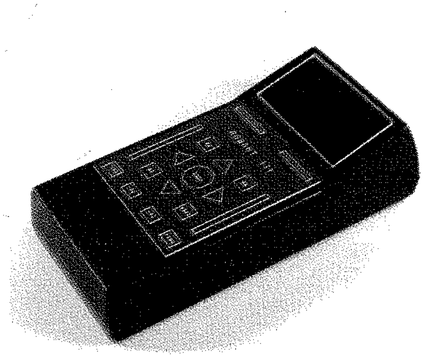


Photo 5. The stand-alone control pendant mimics the primary drive icons shown in Photo 4, and uses a small vibrator to provide tactile velocity feedback to the operator.

one increment. Clicking on either the right- or left-turn arrows imposes a differential turn on the forward velocity, speeding up one wheel and slowing down the other. The more times a turn arrow is clicked, the bigger the differential and hence the faster the rate of turn. If the forward (or reverse) speed is zero (i.e., platform stopped), clicking a turn button causes the robot to pivot in place.

Once the platform is set in motion, the operator can easily direct its subsequent actions by clicking on special behavioral icons on the navigation display. For example, selecting a wall-following icon causes 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 as long vertical command buttons on either side of the Map Window in the lower left corner. The five dots in front of the rectangular robot icon at the bottom of the map indicate the measured range to perceived objects in the path.

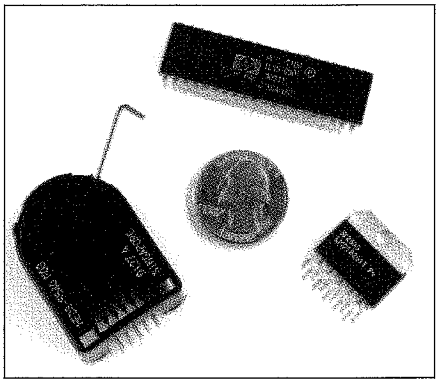


Photo 6. The major components for a low-current digital control system are (clockwise left to right): a Hewlett-Packard HEDS-5540 incremental optical encoder, a Hewlett-Packard HCTL-1100 PID controller chip, and a National Semiconductor LMD18201 H-bridge power amplifier [5].

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. Clicking on one of these doorway icons instructs the robot to seek out and enter the next encountered location of that type of door along its current path. For the example shown in Photo 4, the platform is looking for a door off to the left, as indicated by the highlighted box in the selected doorway icon; the associated text is displayed in the System Status Window above the map.

The primary mobility controls shown in Photo 4 are mimicked on a stand-alone handheld pendant (see Photo 5) by means of an array of capacitive touch-sensor icons based on the Quantum Research QProx E6S2 matrix decoder. A high-resolution 2.5 in. color LCD monitor provides video output, in addition to selected status information overlaid at the top of the screen. A miniature motor-driven eccentric of the type commonly found in vibrating pagers is mounted inside the enclosure to provide tactile motion feedback to the operator [7]. The speed of this motor, and hence the vibration of the case, is varied in direct proportion to the velocity of the remote platform.

Camera Control

The camera pan axis is powered by a 12 V Pittman GM9000-series gear motor with an integral phase-quadrature optical encoder. The much lower operating current (typically ≤1 A) allows the use of National Semiconductor's LMD18200 H-bridge shown in Photo 6. Computer-aided camera pan is provided to support the three system functionalities of platform mobility, intruder assessment, and weapon tracking. For mobility, the camera pan commands are embedded within the "seek-door" behaviors. If the robot is instructed to enter the next door on the right, for example, the camera immediately turns 45° right of center to acknowledge the behavior request and provide a better view of the doorway detection process. As soon as the door is detected and the penetration behavior invoked, the camera pans to compensate for the platform's rate of turn in order to keep the door opening in the center of its field of view.

The intruder detection and assessment algorithms operate on the output from the video motion detection (VMD) system and a 360° array of passive infrared (PIR) sensors configured as a collar just below the head. The PIR data are used to pan the surveillance camera to the center of any zone with suspected intruder activity. The VMD output is then used to track and keep the intruder in the center of the visual field, using a combination of robot head and body movement.

Whenever the head reaches its maximum pan limit (±100°) relative to the robot, the mobility base will pivot in place toward the target. The head meanwhile moves at the same speed in the opposite direction to keep

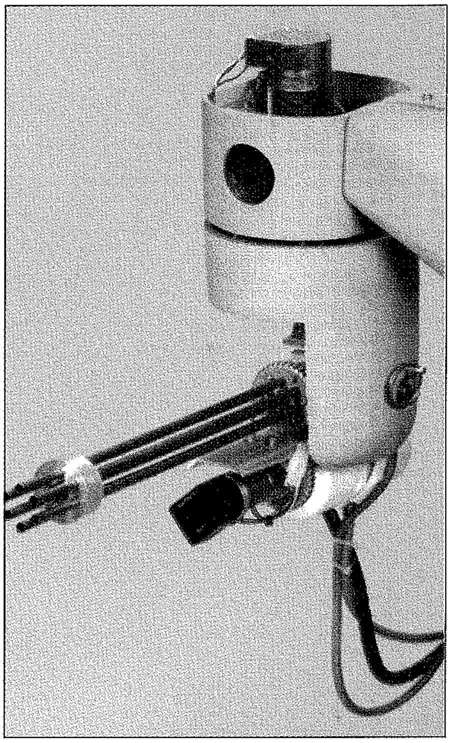


Photo 7. A six-barrel pneumatic tranquilizer gun is used to demonstrate computer-assisted control of a non-lethal weapon.

the primary target in the center of the visual field. This coordinated action provides the robot with unlimited (i.e., continuous) 360° pan coverage.

Non-Lethal Weapon Control

The principal non-lethal response system incorporated on ROBART III is a six-barreled pneumatically powered Gatling gun (see Photo 7) capable of firing simulated tranquilizer darts or plastic bullets. Projectiles are expelled at a high velocity from 12-in. barrels by a release of compressed air from a pressurized accumulator at the rear of the gun assembly. The main air bottle is automatically recharged by a small 12 V reciprocating compressor mounted in the robot's base. Pan-and-tilt-axis PID control is implemented using the same components shown in Photo 6.

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 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. With the same sensor, the system can also track the number of rounds subsequently loaded and/or fired.

The operator specifies the type of control strategy, manual or automatic, to use when entering weapon-tracking mode. In manual mode, the firing decision is made by the operator. A 5 mW 670 nm visible-red laser sight facilitates manual training of the weapon using video from the head-mounted surveillance camera. The surveillance camera pan can be slaved to the weapon pan axis so that the camera automatically looks wherever the operator points the weapon. The mobility base can also be slaved, causing the robot to turn and face the direction the weapon is aimed. If a forward drive speed is entered at this point, the operator merely has to keep the weapon trained on the intruder, and the robot will automatically give chase.

In automatic mode, ROBART III is responsible for making the firing decision, contingent on a confirmed target solution stabilized for a predetermined time interval, and pre-authorization from the operator. Azimuth and elevation information from the VMD is available to the right-shoulder pan-and-tilt controller for automated weapon positioning. When weapon-tracking is activated in automatic mode, the robot centers its head and turns to face toward the current threat. The mobility base then becomes stationary while the weapon begins tracking the target.

Summary

ROBART III, an advanced demonstration platform for non-lethal tactical response, extends the concepts of reflexive teleoperation into the realm of coordinated camera and weapons control. The robot's ultrasonic and optical collision-avoidance sensors facilitate operation in unstructured and unexplored buildings with minimal operator oversight. Sensor-aided motion control of mobility, camera, and weapon functions serves to ease the driving burden of a remote operator in law enforcement and urban warfare scenarios.

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