TCRP
REPORT 86

TRANSIT
COOPERATIVE
RESEARCH
PROGRAM

Public Transportation Security
Volume 3

Robotic Devices: A Guide for the Transit Environment

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TRANSIT COOPERATIVE RESEARCH PROGRAM

TCRP REPORT 86

Public Transportation Security:

Volume 3

Robotic Devices: A Guide for the Transit Environment

DAVID M. ROSE
Science Applications International Corporation
San Diego, CA

SUBJECT AREAS
Public Transit • Planning and Administration

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TRANSPORTATION RESEARCH BOARD
WASHINGTON, D.C.
2003
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TRANSIT COOPERATIVE RESEARCH PROGRAM

The nation's growth and the need to meet mobility, environmental, and energy objectives place demands on public transit systems. Current systems, some of which are old and in need of upgrading, must expand service area, increase service frequency, and improve efficiency to serve these demands. Research is necessary to solve operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the transit industry. The Transit Cooperative Research Program (TCRP) serves as one of the principal means by which the transit industry can develop innovative near-term solutions to meet demands placed on it.

The need for TCRP was originally identified in *TRB Special Report 213—Research for Public Transit: New Directions*, published in 1987 and based on a study sponsored by the Urban Mass Transportation Administration—now the Federal Transit Administration (FTA). A report by the American Public Transportation Association (APTA), *Transportation 2000*, also recognized the need for local, problem-solving research. TCRP, modeled after the longstanding and successful National Cooperative Highway Research Program, undertakes research and other technical activities in response to the needs of transit service providers. The scope of TCRP includes a variety of transit research fields including planning, service configuration, equipment, facilities, operations, human resources, maintenance, policy, and administrative practices.

TCRP was established under FTA sponsorship in July 1992. Proposed by the U.S. Department of Transportation, TCRP was authorized as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). On May 13, 1992, a memorandum agreement outlining TCRP operating procedures was executed by the three cooperating organizations: FTA, The National Academies, acting through the Transportation Research Board (TRB); and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA. TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Committee.

Research problem statements for TCRP are solicited periodically but may be submitted to TRB by anyone at any time. It is the responsibility of the TOPS Committee to formulate the research program by identifying the highest priority projects. As part of the evaluation, the TOPS Committee defines funding levels and expected products.

Once selected, each project is assigned to an expert panel, appointed by the Transportation Research Board. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, TCRP project panels serve voluntarily without compensation.

Because research cannot have the desired impact if products fail to reach the intended audience, special emphasis is placed on disseminating TCRP results to the intended end users of the research: transit agencies, service providers, and suppliers. TRB provides a series of research reports, syntheses of transit practice, and other supporting material developed by TCRP research. APTA will arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by urban and rural transit industry practitioners.

The TCRP provides a forum where transit agencies can cooperatively address common operational problems. The TCRP results support and complement other ongoing transit research and training programs.

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NOTICE

The project that is the subject of this report was a part of the Transit Cooperative Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the project concerned is appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical advisory panel selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and while they have been accepted as appropriate by the technical panel, they are not necessarily those of the Transportation Research Board, the National Research Council, the Transit Development Corporation, or the Federal Transit Administration of the U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical panel according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

To save time and money in disseminating the research findings, the report is essentially the original text as submitted by the research agency. This report has not been edited by TRB.

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FOREWORD

By S. A. Parker
Staff Officer
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This third volume of *TCRP Report 86: Public Transportation Security* will be of interest to transit general managers, police, and security personnel as well as operations, communications, technology, training, and human resources staffs. Federal, state, and local law enforcement will also find the report useful. The objective of this report is to provide a guide to robotic devices for use in public transportation environments. The section on environments identifies the expected conditions a device must operate in and navigate through and develops a prototypical requirements specification. A second section serves as a primer on the features available for robotic devices and provides a market survey of readily available systems that are appropriate for some identified environments. The third section demonstrates how to perform a selection analysis by matching a requirements specification against the market. This volume was prepared by Science Applications International Corporation, under TCRP Project J-10B(3).

Emergencies arising from terrorist threats highlight the need for transportation managers to minimize the vulnerability of passengers, employees, and physical assets through incident prevention, preparedness, response, and recovery. Managers are seeking to reduce the chances that transportation vehicles and facilities will be targets or instruments of terrorist attacks and to be prepared to respond to and recover from such possibilities. By being prepared to respond to terrorism, each public transportation agency is simultaneously prepared to respond to natural disasters such as hurricanes, floods, and wildfires, as well as human-caused events such as hazardous materials spills and other incidents. In the last week of October 2001, the TCRP budgeted $2 million for security-related research in fiscal year 2002.

This is the third volume of *TCRP Report 86: Public Transportation Security*, a series in which relevant information is assembled into single, concise volumes, each pertaining to a specific security problem and closely related issues. These volumes focus on the concerns that transit agencies are addressing when developing programs in response to the terrorist attacks of September 11, 2001, and the anthrax attacks that followed. Future volumes of the report will be issued as they are completed.

To develop this volume in a comprehensive manner and to ensure inclusion of significant knowledge, available information was assembled from numerous sources, including a number of public transportation agencies. A topic panel of experts in the subject area was established to guide the researchers in organizing and evaluating the collected data and to review the final document.

This volume was prepared to meet an urgent need for information in this area. It records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. Work in this area is proceeding swiftly, and readers are encouraged to be on the lookout for the most up-to-date information.

Volumes issued under *TCRP Report 86: Public Transportation Security* may be found on the TRB website at http://www4.trb.org/trb/crp.nsf/All+Projects/TCRP+J-10.

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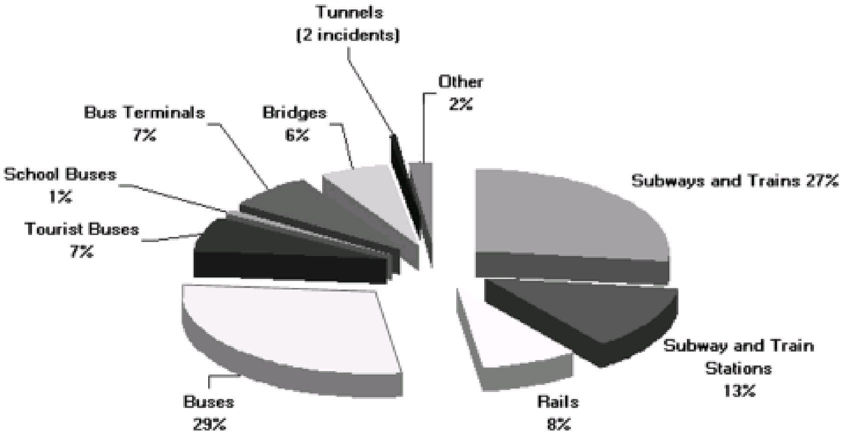
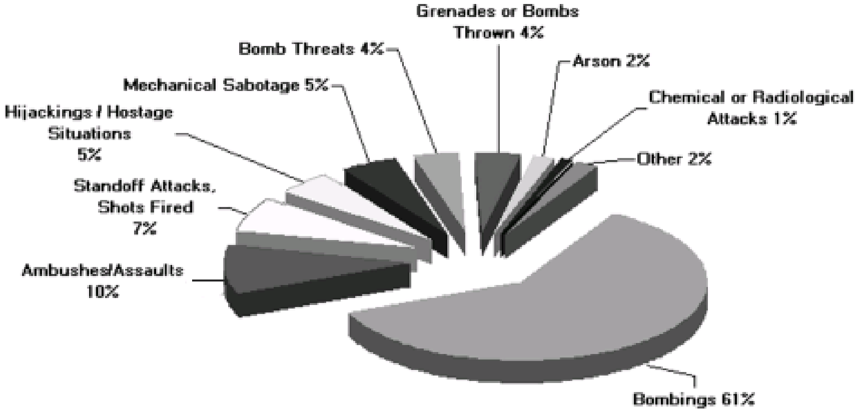
INTRODUCTION

The need for unmanned tele-operated robotic vehicles has risen to public awareness with the successful use of such devices in the search and rescue effort following the September 11, 2001, disaster. Although robots have long been used in search efforts and homeland security missions such as explosive ordnance detection and disposal, perpetrator location and observation, and similar military applications, their major strength of interrogating areas impenetrable by humans while keeping their human operators out of harm's way is now being realized. Robot systems include a wide variety of remotely controlled vehicles equipped with cameras, sensors, and other navigational instruments to provide feedback to the user at a control station. Payloads can include additional sensors such as X-ray cameras; nuclear, biological, and chemical hazard detectors; bomb disarming devices; weaponry; and a variety of other deployable systems such as medical supplies.

The objective of this report is to aid in the appropriate selection of a device for various transit scenarios.



Targets of Attacks on Public Surface Transportation Systems (1920–1997)



Used Against Surface Transportation Systems (1920–1997)

By permission of the International Institute for Surface Transportation Policy Studies

OVERVIEW

This document is organized into three sections that describe the process of selecting a robotic device for general and specific applications in the transit environment. The first section, “Environments,” identifies the expected conditions in which a device must operate and through which it must navigate. The second section, “Available Robotic Systems,” explains the features available for robot devices and provides a market survey of readily available systems that are appropriate for at least some transit applications. Finally, the section called “Selection Analysis” identifies the limitations in meeting the requirement specifications for transit applications. This section also reviews operator demands, training, and maintenance.

This illustration is based on a review of several transit environments. When selecting a robotic device for transit applications, end users should strive to ensure that the physical and operational capabilities of the device meet the demands of the targeted transit environments.

ENVIRONMENTS

In this section, the transit environments in which a robotic device must be able to function are listed and illustrated. These environments are discussed in the subsections titled “Structures,” “Vehicles,” “Roadways and Terrain,” “Weather Conditions,” “Optical Navigation Environments,” “Radio Environments,” “Hazardous Environments,” and “Other Requirements.” Both normal conditions and hazardous situations are examined. At the end of the “Environments” section, a compilation of robotic device performance requirements is assigned values, and constraining specifications are tabulated. This requirements specification defines the goals for a robotic device in a generic transit application.

Structures

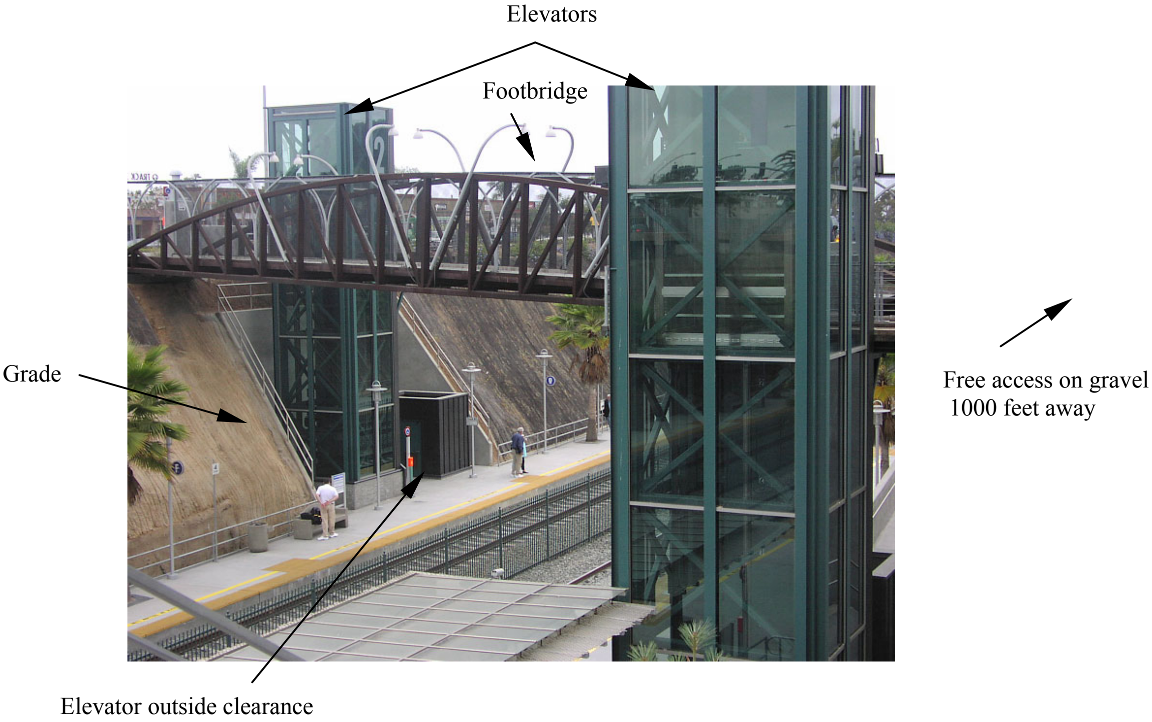
For the purpose of this report, structures are defined as buildings that are boarding/alighting points, equipment or vehicle storage garages, or permanent structures that in other ways provide a service to the transit system. This section does not include tunnels or bridges; these will be discussed later.

Train and bus stations are structures of primary interest. They range in complexity of design and layout from small, one-room Quonsets to substantial buildings. Two environmental conditions will be considered here and throughout this report: standard obstacles under normal operating circumstances and random obstacles in disaster situations. Under normal conditions, the size of a robotic device should allow it to negotiate seating benches, fare collection equipment, ticketing counters, restrooms, offices, and so forth. Stairs and stairwell landing areas will define the robotic device climbing and turning requirements. The reach of the articulating arm that might carry a gripper, camera, or other sensor should be sufficient to access any elevated surfaces and recesses. In a disaster such as a building collapse, debris, rubble, and fallen structures will determine the robot height dimension and climbing requirement. Exemplary environments will be examined and a compilation of robotic device requirements relating to mobility and service capabilities in structures will be presented.

Washington DC Union Station
Photo by Mark M. Piotrowski, courtesy of Washington, D.C. Chapter NRHS

Commuter train station, track level

In general, for normal operating conditions, large and small stations and terminals present identical obstacles. Although a terrorist attack is more likely to occur at a large busy terminal, smaller stations tend to have slightly smaller spaces and therefore are more demanding environments for robot use. Thus, for this report, local commuter stations were studied because they represent worst-case examples. Smaller stations are also more numerous and may provide more opportunities for the investigation of false alarms than larger stations. Two stations were analyzed, a commuter train station and a bus station in southern California. The train station waiting room presented no remarkable challenges to a robotic device as it was built for handicapped access. Handicapped access provides more than adequate mobility and reach clearances for almost all robot devices in the small-to-medium class. Access to the train, however, requires the use of a footbridge and an elevator. In the event of a disaster (assuming that conventional access would not be functional), access to the train would require a descent down a 60% grade or approximately a 1,000-foot drive on gravel. Further, in the event of structure collapse, in this station or in larger stations, access would be restricted in height to ground-based supporting structures such as counters or platforms. Although the bus station access was not as challenging, the structure makes identical demands on robotic devices.



Commuter train station, street level - footbridge connecting north- and south-bound boarding/alighting platforms

Other structures, such as storage and repair buildings, were also examined. Lack of handicapped access meant that for a robotic device to function in these structures, it would need to have stair-climbing capability. In general, a robotic device would not have size restrictions in order to function in these structures.

Courtesy of Center for Robot-Assisted Search and Rescue

Structure disasters produce several types of environments for robots, as seen in their use at the World Trade Center. These include small passageways (typically in the ducting between floors), highly variable passageways caused by random building members and material distributions, and impenetrable areas or tall drop-offs. Investigating these different environments requires an arsenal of specialized robotic devices. However, it is highly impractical for any one agency to own this number of devices. More typically, a single bomb of relatively low energy will demolish a portion of a building (as seen in some terrorism acts in the Middle East). This kind of destruction produces a more negotiable environment, consisting of passageways created by structure collapse onto desks, seats, and so forth, and produces 2- to 10-inch diameter rubble and steps.

Vehicles

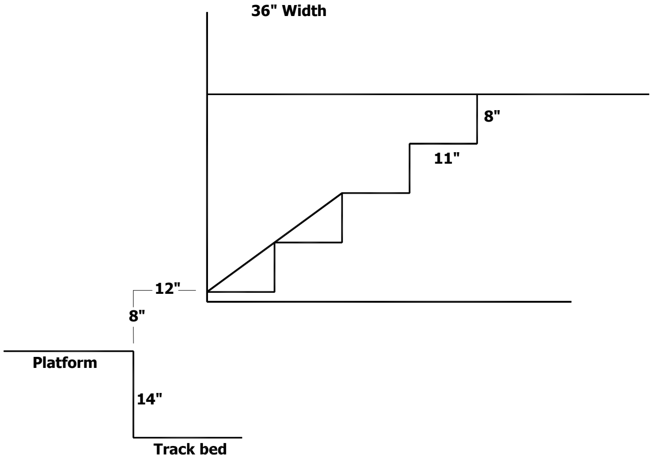
Vehicle Access/Egress

Vehicle entrance and egress present the most challenging mobility constraints on a robotic device. Although handicapped access allows good mobility to seating and restrooms, such access is not afforded to locations that are apt to have suspicious packages, perpetrator hiding places, or injured passengers. Further, the handicapped assist equipment may not be available in the event of a disaster or even a minor power outage.

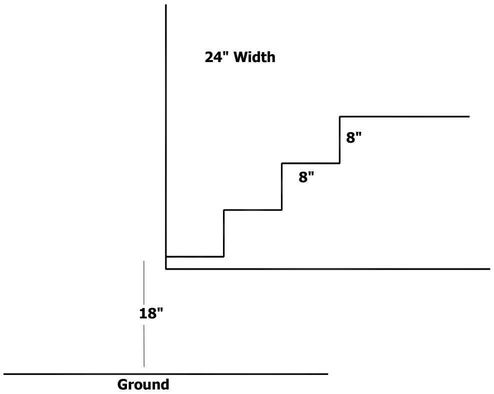
By permission of Amtrak Cascades

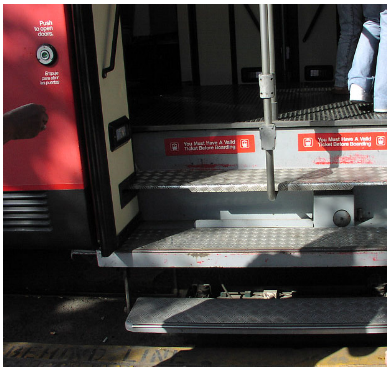
An analysis was performed on several vehicles, including commuter trains of pre- and post-1980s vintage, an intercity bus, and a trolley. Shown on the following page are the critical constraining dimensions of these vehicles for establishing robot requirements. Shown on the next page are data on vehicle parameters that will dictate the robotic device's physical dimensions, stair-climbing ability, and power requirements. In "Vehicle Pathways, Overheads, and Transitions," data on vehicle parameters that will dictate the device's turning radius, manipulator arm reach and dexterity requirements are provided. In the section, "Vehicle Special Obstacles," data on vehicle parameters such as extreme stair pitch and passageways of unusually small width are provided. In "Vehicle Special Obstacles," the vehicle parameters created by disaster situations are also discussed.

Train pre-1980s

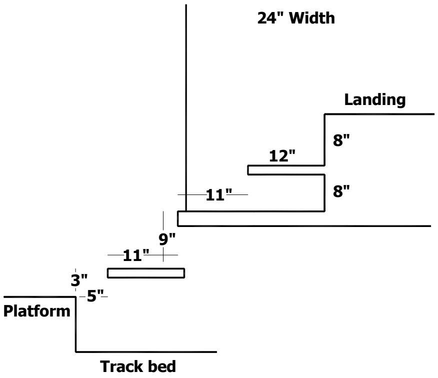


Intercity Bus





Commuter Trolley



Vehicle Pathways, Overheads, and Transitions

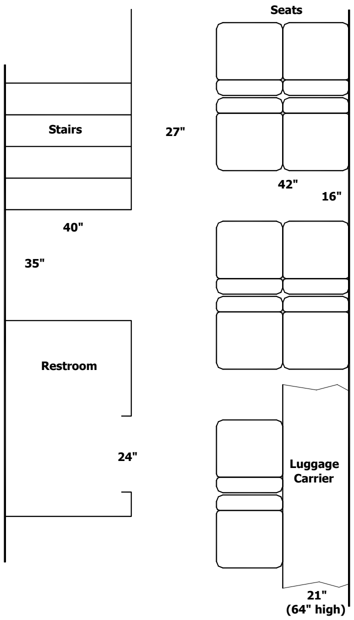
Shown below are corridors, seating, and overhead baggage compartments for typical transit vehicles. The arrangement and dimensions of these items are the primary factors in determining the requirements for a robot arm—typically a device that has multiple links and joints, provides an extension for reaching, and terminates in a claw-like gripper. Looking into an overhead carrier and removing a package or deploying an X-ray camera to examine a package under a seat are just two examples of the demands on the arm and gripper. Shown below are examples of the kind of detailed drawings of vehicle floor plans that would be needed to determine robotic device requirements.


Train post-1980s

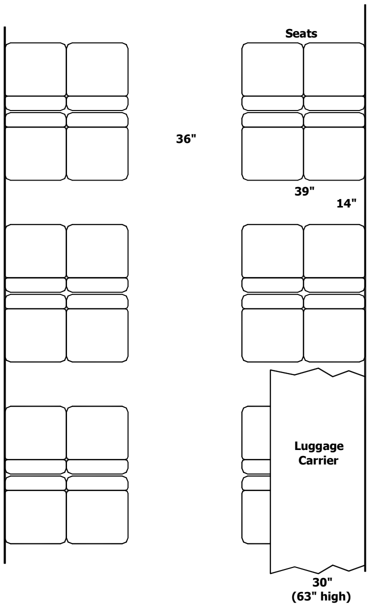

Train pre-1980s


Intercity Bus


Commuter Trolley



Train post-1980s



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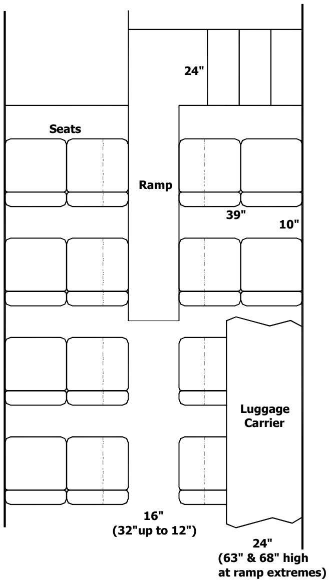
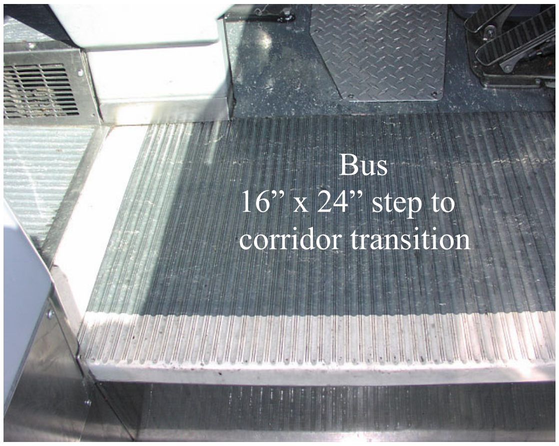


Bus



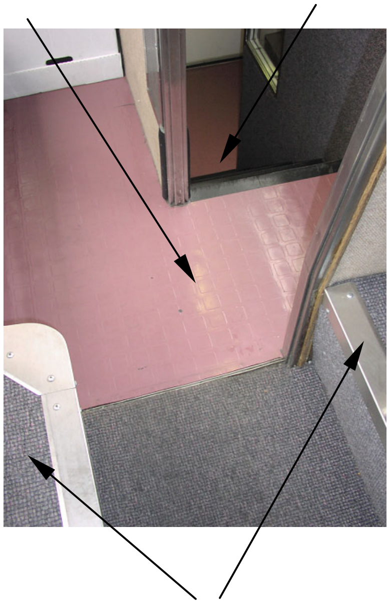
Compared with trains, buses have few unique mobility obstacles. With some exceptions, public transit buses are designed primarily for seated transport and do not have features such as diners, sleepers, or unique function areas. Because of this and the shorter commutes than trains, buses have comparatively smaller mobility areas and present the more stringent access requirements. On buses, the height of the first step, steepness of steps, transition from steps to corridor, and width of corridor all make access more difficult for a robotic device.

Vehicle Special Obstacles

Rail cars comprise a wide variety of designs for functions ranging from dining to sleeping. Although no special function cars were studied for this report, a commuter train provided many obstacles that would challenge a robotic device. Shown below are features of a dining area on an upper deck. These features include a steep and narrow stair climb, an extremely small turning landing, and a dining floor raised above a very narrow corridor. Also shown is a stairway transition to upper-level seating, which has a severe stair incline and a small transition landing.

Stair-to-corridor transition
landing 24” x 40”

Narrow stairs
20” wide, 50% pitch



Raised eating deck
20” wide x 13” high corridor

Stairs
36” wide, 50% pitch

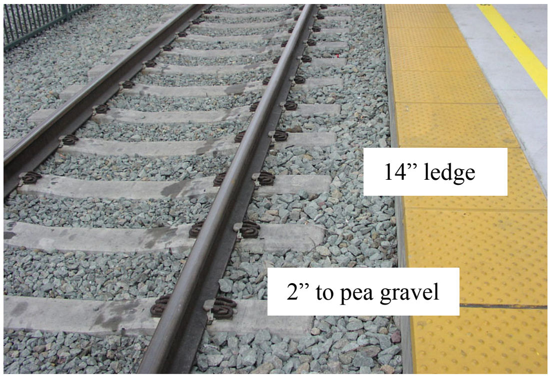
Stair-to-corridor transition
landing 36” x 36”

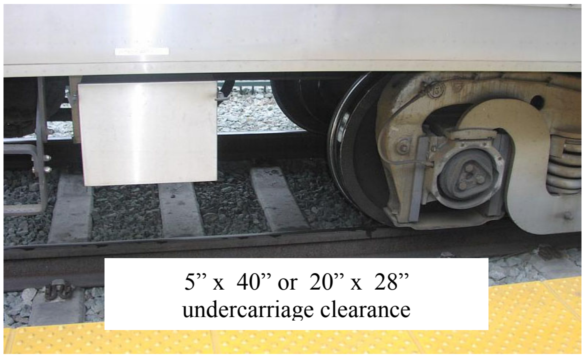
Personal items within vehicles can be as much of an obstacle for a robotic device as vehicle structure. Obstacles such as randomly placed luggage can present a formidable mobility impasse for a robotic device, even if it is not operating in a disaster situation. Such obstacles have a wide variety of shapes and sizes; no a priori standard can be used. Stair-climb and debris-diameter parameters should be used to estimate a robotic device's ability to negotiate random items. The effects of a disaster—debris, wreckage, and angle of floor and walls—also cannot be predicted, and any attempt at a specification must be tempered with a classification of the severity of the situation. Robots are primarily used in a disaster for search and observation in impenetrable locations. In the worst-case scenario, the vehicle height will be reduced to the height of other supporting structures such as seat bases, tables, and so forth. In such cases, attempts at conventional access are typically abandoned, and the robotic device is deployed through a window. In hazardous situations, the device is sometimes thrown through the window. Therefore, a critical requirement for the device, in addition to climbing and debris-traversing ability, is small physical size. Requirement specifications for incline climb, debris diameter, and physical size will all need to be considered in selecting a robotic device; however, it is important to remember that deployment of robotic devices in a disaster situation is a best-effort basis.

By permission of North Bank Fred

Roadways and Terrain

Roadways and terrain consist of paved streets and highways, railroad and subway tracks, bridges and tunnels, and all surrounding areas that a robotic device must traverse to access the vehicle thoroughfare. A robotic device can negotiate paved roads in good condition quite easily. Railroad tracks in open country are similarly unchallenging in the area along the track. Crossing the rail, however, will be difficult for a robotic device. Climbing the rail will be a challenge, and if the surrounding terrain is gravel or loose dirt, this will be a challenge too. To function in these conditions, a robotic device will have to meet certain wheel or continuous-tread requirements. Common rail sizes range from 132 to 136 lbs/yard, depending on whether they are 7 1/2- or 8-inches high. Gravel, dirt, sand, grass, and low brush get trapped in robotic device wheel and tread mechanisms; this requires that the device undercarriage and drive system design include either guards or a compliant drive train.





Unusual terrain features such as potholes and lowered track beds require that a device be able to straddle holes and drive off ledges. With vehicles on roadways or tracks, a clearance dimension also becomes critical. Shown above is a typical reduced-access railway situation in which the reduced access is caused by the vehicle. It will be difficult to find a robotic device that can negotiate high dividers, median barriers, and other extremely impenetrable roadway obstacles. The device will have to navigate around them.

Disaster situations on roadways include bridge collapses, smoke- or chemical-agent-filled tunnels or subways, weather- or bomb-damaged roads, and so forth. Unlike buildings, where floor-based fixtures might support a collapse and allow some vertical clearance, the extreme mass of roadway structures will overload such supports. In roadway collapses, the vehicles themselves are the supports that determine the clearances, and, as seen in the earthquake-damaged Cypress Street section of I-880 (Oakland, CA) shown below, will be reduced to an impenetrable height. No set standard can be suggested for such occurrences. The robotic device with the smallest physical dimensions that performs to all other requirements will fare best in a disaster.


By permission of ABS Consulting

Damaged Cypress Street section of I-880

Weather Conditions

Weather conditions can challenge robotic device functioning ability. For the device to be mobile in snow and water and operable and storable in certain temperature ranges, certain requirements have to be met in the traction and motor power of the device's drive system; the robustness of electronic, electrical, and mechanical components with respect to temperature; and water-sealing capabilities. Military requirements are used in the sample requirements specification.

By permission of Larry McNaughton

Optical Navigation Environments

Optical navigation refers to the robotic device operator's ability to operate the device remotely without seeing it or the terrain directly, relying only on the optical system on the robot. Optical navigation environments include lighting conditions, visibility (e.g., smoke or fog), and optical properties of targets (e.g., infrared, diffuse, or transparent). The demands of these environments must be met not only by a device's lighting and camera system, but also by other features. These include the use of multiple views, adequate picture quality in video presented to the operator, and the capability of commanding the optical system to simulate the operator actually being at the robot's location with the ability to look around. This feature is called "situational awareness" and is the single most important feature for ease and safety in controlling the robotic device. Some minimum robotic device requirements for transit environments include path flood lighting, end-effector lighting, and a steerable spotlight. Camera requirements include a forward-looking path camera, an overhead-steerable camera, and an arm-mounted camera for monitoring the end effector or viewing areas only accessible by the extended arm. The device's video presentation must allow the operator to view all the images with minimal confusion. The ability to zoom in/out is also a requirement for at least one camera. The system should also have auto focus, auto iris (mechanical or electronic), and image stabilization. For disasters with a smoke-filled environment, an infrared lighting and camera system is required.

Radio Environments

How well a robotic device can be operated remotely depends on the radio environment in which it is used. Interfering radio transmission from other sources is of little concern for the use of robotic devices in transit environments. However, closed metal structures, such as bus and train bodies, impair radio transmission and will limit the range of tele-operation. A radio link range for open terrain is determined by accessibility to the target and a safe operating distance in hazardous situations. An alternative to a poor radio link is an optical-fiber tether from the operator station to the robotic device. Two considerations—vehicle or structure length and a safe operating distance—will dictate how long the tether will have to be. Tethered operation of robotic devices is generally less desirable because cable kinking during deployment can lead to potential entanglements and possible fiber breakage.

Hazardous Environments

Hazardous environments typically include nuclear, biological, or chemical (NBC) threats. These hazards present several electrical and mechanical challenges for the robotic device. The main concern is whether it will able to operate in the presence of high radiation and corrosive chemicals. Nuclear radiation primarily affects the electronics of the device, including the video system. Biological hazards do not affect the device, but require it to be decontaminated, usually with a bleach solution. Chemical hazards, such as an acid spill, present the threat of corrosion. Robotic devices used in these kinds of hazardous environments need to meet requirement specifications for liquid-sealing ability and corrosion resistance of materials.

Other Requirements

The critical performance requirements for robotic device use in various parts of the transit environment have been reviewed above. There are, however, other requirements that must be met for robotic devices to operate successfully in the transit environment. These requirements are the following:

- Weight—The human carrying weight of the entire robotic system and individual components.
- Endurance—The length of the mission, usually a function of battery life.
- Speed—Robotic device ground speed, which determines time to target.
- Audio—The ability to listen and talk via the robotic device.
- Load—Amount of payload weight the robotic device and manipulator arm can carry.
- Set-up and turnaround times—Time to prepare to deploy and to refurbish for another mission.
- Reliability—Mean time between failure (MTBF) for mission hours.
- Maintainability—Mean time to repair (MTTR) and availability of spare parts and support.
- Usability—Ease of use, intuitive operation, and training.
- Industry compatibility—Conformance to industry standards, off-the-shelf components, common communication protocols, and ability to link to industry sensors and payloads.
- Survivability—Robustness of the design for shock, vibration, impact, and watertight seals.
- Cost—Within the typical budget of a law enforcement or civic agency.

Requirements Specification

As seen in the section “Environments,” transit vehicles, structures, operating arena, and other related environmental conditions dictate requirement specifications for robotic devices used in transit applications. Table 1 presents a compilation of the requirements discussed in “Environments” with specifications determined by worst-case environmental demands. The source of the specification is given, and the objective of the requirement is listed for reference. This compilation, appropriately tailored, can serve as a requirements specification for a robotic device. Some requirements are not specific to the transit environment, so military standards or typical industrial-product specifications have been used to complete the specification. Two of these specifications are the Naval Sea System Command (NAVSEA) “Man Transportable Robotic System” (MTRS) solicitation and the National Institute of Justice (NIJ) “Bomb Disposal/Law Enforcement Robot Design Guidelines.”

TRANSIT ENVIRONMENT ROBOT SYSTEM REQUIREMENTS

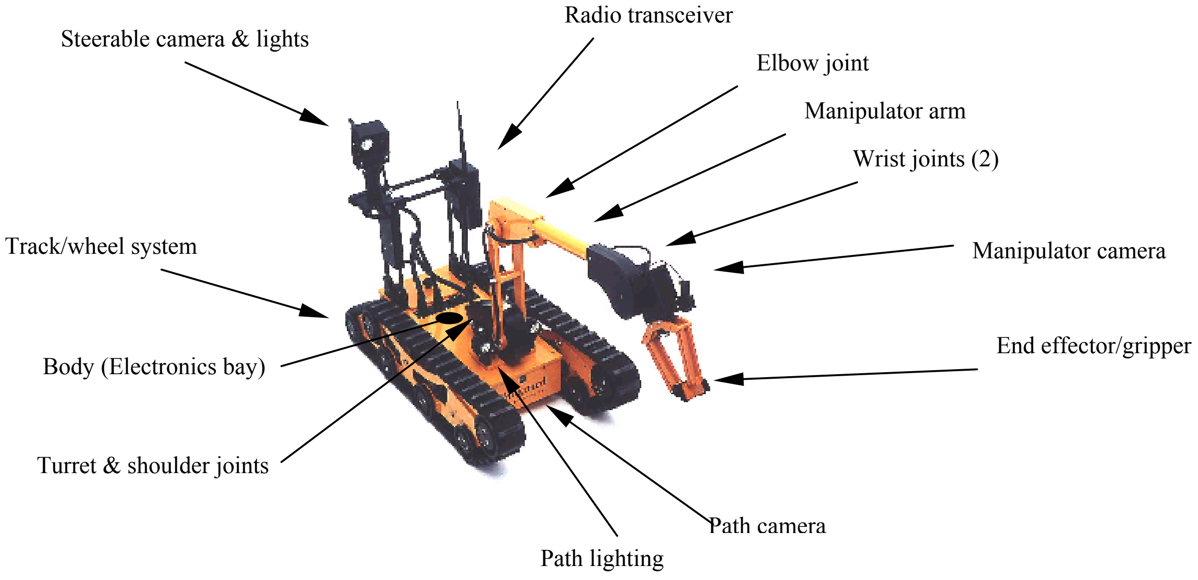
Table 1

REQUIREMENT	SPECIFICATION	OBJECTIVE	SOURCE
Size Length Width Height	Limited by Turn Circle, below 16 in. max. 12 in. max.	Stair to corridor transition Corridor width Under seat, disaster debris	Train corridor transition Bus corridor Bus seats
Weight	150 lbs max.	Carried by two people	Typ. human factors spec.
Speed	2 mph min.	On scene in 15 min	Typical access distance
Stair Climb Solid Gap	8 in. x 8 in. 12 in. x 8 in.	Building, vehicle stairway Curb to vehicle empty span	Bus & train steps Train step
Inscribed Turn Circle Severe Typical	16 in. 36 in	Stair to corridor transition	Bus entrance Train upper deck
Slope Climb Traverse	60 deg. 45 deg.	Embankments	Train Station
Snow	4 in. deep min.	Roadside terrain	MTRS spec.
Hurtle	8 in.	Railroad track	Typical track
Curb	14 in.	Railroad platform curb	Train station
Rubble, Debris	4 in. diameter min.	Concrete building collapse	MTRS spec.
Loose Sand	2 in. deep min.	Roadside terrain	MTRS spec.
Gravel	2 in. diameter min.	Railroad track	Train station
High Grass, Brush	6 in. high min.	Roadside terrain	MTRS spec.
Shallow Water & Rain	2 in. deep min.	Pooled rain	MTRS spec.
Range Wireless Wired	½ mi min. ⅛ mi min.	Safe access Inside car, safe access	Train station Vehicle & safety
Endurance	½ mi driving, 1hr mission, ½ mi driving	Drive to/from mission, all functions for 1 hr	MTRS spec. & NIJ guidelines
Payload Weight	50 lbs min.	X-ray sensor payload	Typical sensor
Manipulator Reach Load Grip Dexterity	68 in. from ground 15 lbs 4 in. diameter min. 5 degrees of freedom	Luggage carrier X-ray source Retrieve pipe bomb Reach into overhead	Bus NIJ guidelines MTRS spec. Bus
Set-up Time Deploy Refresh	10 min, no tools 2 min no tools	Quick response time Quick battery change time	MTRS spec. MTRS spec.
Video Cameras Zoom Infrared	Path, steerable, arm 20X Optional	Full situational awareness Detailed viewing Night/smoke vision	Typical & hazardous rail environments
Lights	Path, steerable, arm, infrared	Same as video	Same as video
Audio	Two way, recordable	Survivor location Perpetrator statements	MTRS spec. & NIJ guidelines
Power	Rechargeable battery, 110VAC	Common battery charger	MTRS spec.
Data & Power Jacks	RS232, USB, 12VDC	Sensor & payload data	MTRS spec.
Usability	8 hrs training	Minimize training/practice	NIJ guidelines
Survivability	10 ft drop & tumble on dirt	Dropped, thrown, fall, etc.	Rough deployment
Reliability	100 mission hrs MTBF	Maximize up time	Typ. product standard
Maintenance	30 min MTTR	Minimize maintenance	Typ. product standard

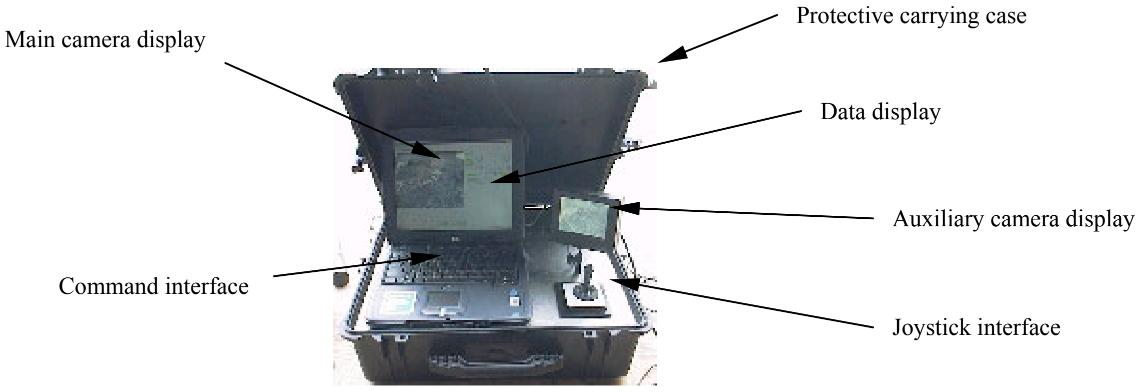
AVAILABLE ROBOTIC SYSTEMS

Introduction to Robotic Systems

A robotic system consists of a vehicle to carry a payload and an operator control station (OCS) for tele-operation. The vehicle is designed for specific mobility needs such as high-speed travel, traversing rough terrain, and/or maneuvering in small spaces. The payloads are typically a manipulator or an end effector on an arm, sensors, and actuators. Payloads could include an X-ray camera, chemical-agent detector, drug-detection devices, bomb-disarming systems, and so forth. The OCS displays feedback from the vehicle, typically video, and provides controls to operate the vehicle.



Robot Vehicle



Operator Control Station

By permission of EOD Performance

Robot Vehicle Features

Robot vehicle features include the subsystems that enable the robot to perform missions as a tele-operated vehicle. These include the subsystems that provide mobility and remote-object manipulation. They also include the subsystems that provide operator feedback for controlling the vehicle remotely.

Mobility System

The mobility system consists of tread tracks or wheels powered by drive motors. Some vehicles have track extensions that add additional tread length to either lift the vehicle for additional arm height or aid in stair or obstacle climbing. The track length and the slope of the leading pulley arrangement determine the pitch of stairs that the vehicle can climb. However, vehicles with longer track length are less able to turn in tight quarters. Vehicles are capable of turning about their center (zero-radius turn) by driving the tracks in opposite directions.

By permission of iRobot

Wheels can be added for faster speeds on smooth or paved roads. Typically, wheels are manually bolted onto a hub of the track system, raising the treads from contacting the ground. Ideally, the track extensions or wheels should be remotely deployable.

Manipulator Arm

By permission of EOD Performance

The manipulator arm is for moving payloads. An end effector, typically a gripper, is used in applications such as placing sensors or retrieving items and for dexterous movements such as opening a door, using a tool, and positioning equipment. A further use is to extend the visual range of the vehicle by mounting a camera on the end of the manipulator. This might be done, for example, to look into overhead luggage compartments. The manipulator should have at least 5 degrees of freedom, meaning the end effector can be moved in any of the three coordinate directions and rotate around both a vertical axis and a horizontal axis. This is accomplished by motorized joints in the manipulator-arm links including a "turret," “shoulder,” “elbow,” “wrist twist,” and “wrist rotation.” The gripper should be able to squeeze between the “fingers” and grasp a cylindrical object such as a pipe bomb.

Vehicle Control Systems

Robotic device control electronics can be a proprietary processor, a standard microprocessor, or a standard personal computer (PC) processor. Among these processors there are differences in cost, weight, flexibility, and expandability. The proprietary processor is the least expensive, the lightest, the least flexible, and the least expandable of the processors, and the PC processor is the most expensive, heaviest, most flexible, and most expandable of the processors. Flexibility and expandability are desirable for future enhancements, features, and options. This makes the PC processor a good choice if the cost and weight of the overall robotic device meets necessary requirements. Further, the PC processor uses a more common programming language than the others, making it more universally serviceable on an engineering level if custom functionality is desired.

The communication link is a major subsystem in vehicle control. Several schemes are used. Video data use relatively high bandwidth (5 MHz) for frame rates sufficient to prevent jerky motion, whereas commands and audio and sensor data require less bandwidth (20 KHz). One of two popular techniques is to use two transceivers, one high-frequency channel for the large video bandwidth, typically 2.4 GHz, and the other a low-frequency channel, 900 MHz for example, for the relatively low data rate of the commands. FM transceivers are common, and video data are susceptible to signal loss that causes pauses or jumping of the picture. The second technique uses a single transceiver with a wireless Ethernet 802.11 protocol. This technique is a digital transmission method, and loss of signal is not as noticeable. This transmission uses spread spectrum modulation, in which the video is carried on the main frequency, and the other data use a sideband. This technology is more adapted to a PC controller and is not as widely deployed as the other types of controllers.

In addition to radio frequency links, cable tethers are used. Two types are available, optical-fiber and wire cable. Optical fiber is generally smaller and more lightweight than wire, and it has higher bandwidth to support longer transmission distances.

The fire control system, although a minor feature for most missions, is noteworthy because of the safety concern. For firing bomb disruptors, the fire control circuit should be failsafe with the use of at least two actuations from the control station and at least two mechanical switches that cannot fail at the same time in the fire position.

Robotic systems must operate in environments with extreme temperatures. Further, the vehicle itself produces heat from the controller and drive motors. The vehicle's electronics bay should be equipped with a temperature control system that usually cools the device, but can also heat it.

Video, Lighting, and Audio Systems


By permission of Mesa Association.

At a minimum, the vehicle needs a forward-looking camera for the operator to see the path. Generally, robotic devices have a number of cameras to provide good situational awareness and other specific cameras to provide detailed viewing. Typically, there is a steerable color camera or a 360-degree panoramic camera. Additionally, a manipulator-arm mounted camera provides "snooping" capability or can be used to aim disruptors. One or more of these cameras should have zoom capability, typically 10X or greater optical and 100X or greater digital. However, digital zoom capability sacrifices resolution and is not recommended at extremely high powers. All cameras should have auto focus and either mechanical or electronic auto iris capability. The typical resolution of these cameras is 320 x 240 at 15 frames per second (FPS). Lighting is generally provided for each camera. Lighting should be dimmable from full brightness to off. High-intensity white light-emitting diodes (LEDs) are used for weight and energy savings. Infrared lighting and cameras are occasionally used. Vehicle audio capability usually includes a microphone and speaker. Audio compression is employed to reduce signal transmission bandwidth and provides a sound quality similar to portable telephones.

Modularity and Compatibility

For serviceability as well as transportability, the ability to remove the tread track assemblies and the manipulator-arm assembly from the body (usually the electronics bay) is desirable. These should be self-contained assemblies attached with a few captured fasteners and cables with electrical connectors that plug into a bulkhead on the body. The electronics in the body bay should ideally contain plug-in circuit boards similar to a PC. Fastener-mounted circuit boards with cable connectors are an alternative. Other electronics, such as power supplies, motor controllers, and so forth, should also be easily removable. The electronics should be designed so that the field-replaceable units are at a subassembly level no lower than a circuit board or off-the-shelf item and a level no higher than a removable electronics rack in the robot body. The vehicle battery should be changeable in a few minutes without the use of tools. Multiple batteries should be used if necessary to keep the weight of each battery pack under a few pounds. A vehicle carrying case should be a standard accessory.

Compatibility has several elements. Modular features on robotic devices should be interchangeable among vehicles. Also, the components should be readily available from several sources whenever possible. Batteries, PC components, cameras, lights, and so forth should be designed to use consumer products when practical. Finally, a vehicle should be controllable from any control station with the proper radio frequency set-up. Controllers and vehicles should have a selection of broadcast channels that allow fleet control without interference. A software protocol standard has been set forth for military robotic devices with the objective of enabling any manufacturer's controller to command any other manufacturer's vehicle. This is the Joint Architecture for Unmanned Ground Systems (JAUGS). This protocol is being required in military contracts, but is in its infancy; no commercial cross-manufacturer control has yet been demonstrated.

Sensor, Actuator, and Other Auxiliary Devices

Payloads such as sensors and actuators typically have electrical data outputs or actuation command inputs that must be communicated to or from the OCS. These signals must therefore interface with the robotic vehicle. Standard communication protocols and hardware are primarily used, and, therefore, the robotic vehicle should have one or more RS232 (a wiring protocol), Universal Serial Bus (USB), or Ethernet ports. It should have power jacks, typically 12 VDC, for external devices, as well as a battery-charger jack. There should also be quick-connect firing circuit terminals such as "radio speaker jacks" capable of handling 2 amps of current.

Operator Control Station Features

The OCS features include the subsystems that provide the ability to control the vehicle and payloads to perform the mission. Direct controllers include the subsystems that provide the man-machine interfaces for remotely controlling the robotic device and getting feedback.

Mobility Control

There are several techniques for controlling robotic motion. Two of the more popular techniques are "direct" control and "proportional" control. Direct control provides "go" and "stop" commands, and the robot moves at a given speed. These controllers usually provide the ability to select from three speeds, for example, slow, fast, and very fast. Reverse is also provided. The go, stop, and speed commands on the simplest controllers are issued with single keystrokes or buttons. Turning commands are likewise initiated with keystrokes: a single stroke is a little turn and several strokes are a sharper turn. Proportional controls have continuously variable speed and steering adjustments in which the motion is *proportional* to the movement of the interface device, typically a joystick or PC mouse. If the interface device is moved a little forward, the vehicle moves slowly forward. If the interface device is moved a great deal to the left, the vehicle moves at a fast speed in a sharp left turn. This user interface is well known from video games. A proportional control system is more intuitive and requires less effort and concentration to use, but is typically more expensive.

Manipulator Control

The manipulator is typically commanded using a direct control system at a fixed speed. The interface device can be keystrokes, buttons, or a joystick. Here, the interface type makes little difference because the commands are discrete motions such as arm left/right, arm up/down, arm in/out, gripper open/closed, and so forth. Most of the links and joints in the manipulator provide circular motions so that arm commands are not strictly up/down or in/out. An up command, for example, is actually a shoulder-joint command that is a rotary motion. The arm also moves a little in or out as well. Therefore, when navigating to a precise target, like a key in a lock, a difficult iteration of commands is necessary. In more elaborate controllers, this is alleviated by the controller calculating the combination of motions required to move the gripper in a straight line. With a system like this, the user can command linear motion. A further refinement is the ability to use a coordinate system. The operator could define a zero X, Y, Z location and then command the gripper to go to a measured location using keyboard-entered coordinates.

Video, Lighting, Audio, and Navigation Control

The control of functions in the video and lighting systems is basic, particularly controlling the lighting and the direction of the steerable camera(s), often referred to as the "pan/tilt" camera(s). These systems' display of information is of greater importance because they are the eyes and ears of the operator. As mentioned earlier, there are typically three cameras with corresponding lighting. The operator display console should display images in such a way that the operator is aware of all the data without being overwhelmed. The best display technique is a thumbnail image from all cameras and a large main display of one image. The operator should be able to select a desired image from the thumbnails and display it by pushing a button or selector switch. Camera iris control should be automatic, with an operator switch and/or knob for manual operation.

Camera auto-focus control is internal to the camera and generally not accessible by the operator. The video display should be daylight readable with backlighting for night viewing.

Two-way audio should have a toggle switch (stays on or stays off) for listening and a momentary switch (must be held on) for talking. For both audio and video, the controller should have output jacks for recording on external devices.

Navigation systems that provide the operator with robot location and heading are used on the more advanced systems. These tools include electronic compasses, global positioning systems (GPSs), range-finders, and so forth.

Other Features

Disruptor fire control should be controlled with two cover-protected switches. One switch arms the circuit, and the other switch fires the device. For added safety, there may also be a software command; however, the arm and fire controls should be mechanical switches.

The OCS should be battery powered with a jack to recharge the battery or power the controller. There is often a jack for an external high-powered antenna. The OCS enclosure should be a lightweight portable unit that is watertight for use in rain or decontamination. A backpack should be an optional accessory.

Available Systems

Numerous commercial off-the-shelf (COTS) robots are available in a range of sizes and abilities. Vehicles range from units small enough to be thrown, which are used strictly for surveillance, to large all-terrain vehicles (ATVs) for carrying or towing huge payloads. This report illustrates a selection process for small to mid-sized robot systems only. This is based on a cursory examination of the transit requirements of the previous section. These robot systems will meet most of the terrain and obstacle requirements, specifically size and weight requirements for the defined environment, as well as man transportability requirements. Also, these robot systems are priced within the budget of an organization equivalent to a local government agency. Further, this report focuses on selecting a single multipurpose system meeting the most number of requirements, rather than selecting a family of robot systems spanning all requirements, because owning a family of robotic devices is not within the budget of most transit organizations. Therefore, a list of small to mid-sized candidates is compiled in Table 2, and their fit to transit requirements is discussed in the section on selection analysis.

CANDIDATE ROBOT CRITICAL FEATURE TABLE

Table 2

Manufacturer	Name of Robot	Country of Origin	Vehicle Weight OCS (lb)	Length (inch)	Width (inch)	Height (inch)	Drive & Speed (mph)	Control Link* & Range (miles)	Arm Lift Extended (lbs)	Arm Lift Retracted (lbs)	Reach Horiz. Vert. (inch)	Stair Climb	Max Grade (deg)	Cost ($K)
AB Precision (Poole) Ltd.	Cyclops L.E.	UK	59.5	34.5	15.6	8.25	Track 1	Cable 1.1		11		Y		85
	Cyclops Mk4C	UK	88.2	34.2	19.3	8.25	Track 3.4	RF 8.5 FO		11		Y		120
	Lynx	UK	39.7	25.5	17.75	17.75	Wheel 1.2	Cable .28				N		25
	Groundhog	UK					Wheel	RF				N		58
	Bison	UK					Wheel	RF				N		88
Angelus Research	Intruder	USA	42	22	17	10	Rollers 1	RF .6	No Arm	No Arm	No Arm	N	6-8	10
	ART	USA	40	22	13	7	Track 1	RF .9	No Arm	No Arm	No Arm	N	6-8	
Cybernetix (Giat)	TSR 202	FR	594	47.25	26.4	39	Track 2.5	RF 2.2 Cable 1.3	26.5	154	93.6	Y	40	150
	Track Castor Wheel	FR	92.6 61.7	31.4 26.8	15.7 15.7	15.7 16.9	Track 1.5 Wheel 1.5	RF 2.2 Cable 1	11	22	43	Y N	30	
	Track RM 35 Wheel	FR	165	33.1	23.3	19.7	Track 1.7 Wheel 1.7	RF 2.2 Cable 1.3	11	31	57	N	30	
EOD Performance	Vanguard	CAN	95	36	17	16	Track .75 Wheel	RF Cable .75	20	40	38 52	Y	38	25
Engineering Tech. Inc.	RATLER	USA	33	22	19.6	12	Wheel 2.3	RF 5.2	No Arm	No Arm	No Arm	N		
Foster-Miller	Talon	USA	85	34	22.5	11	Track 4	RF 1 FO	30	40	53	Y	45	60
	Solem	USA	48	20	14.75	8	Track 1	RF 1	No Arm	No Arm	23	Y	45	41
	Ferret	USA	480	57.5	26.5	57.5	Track 1.5	RF .4 Cable						
HDE MFG	MURV-100	USA	49.6	23.8	17	4.5	Wheel .8	RF 5 FO	20	35	60	N		25
HighCOM Security	MR-5	CAN	550	50	26.7	31.5	Track 7.3 Wheel 7.3	RF Cable .1	44	130	67 95	Y		
Inuktun	MicroVGTV	USA		12.5	6.5	2.5	Track .2	Cable .02	No Arm	No Arm	No Arm	N		15
	MDV	USA	90.4	23.6	14.2	16.6	Track .4	Cable .56	No Arm	No Arm	No Arm	N		40
iRobot	Icecap	USA	52	24	20	6.5	Track 4.9	RF .4 FO 1.3	TBD	TBD	78	Y	60	85

(Table 2 continued)

Manufacturer	Name of Robot	Country of Origin	Weight Vehicle OCS (lb)	Length (inch)	Width (inch)	Height (inch)	Drive & Speed (mph)	Control Link* & Range (miles)	Arm Lift Extended (lbs)	Arm Lift Retracted (lbs)	Reach Horiz. Vert. (inch)	Stair Climb	Max Grade (deg)	Cost ($K)
Kentree	Brat	IRE	125 Track 121 Wheel	35.4	20	20.9	Track 1.5 Wheel 4	RF 1.7 Cable	13.2	18	47	Y	42 wheel 45 track	62
	Hobo	IRE	502	57.8	27.6	34.7	Wheel 2.5	Cable 1.4	66.1	165	59	Y	42	120
	Rascal	IRE	72.8	31	16.2	13.6	Wheel 1.6	RF 1.7 Cable	No Arm	No Arm	No Arm	N	35	48
	Imp	IRE	165.3	31.4	16.6		Track .45	RF 1.7 Cable	11	22		Y	45	62-70
Mesa Associates	MATILDA	USA	98	26	20	12	Track 2.1	RF 1.4	25	25	42	Y	45	66
OAO Robotics (Lockheed-Martin)	MPR 150	USA	218.3	38	23.5	31	Track 1.5	User Spec. 9		60		Y		90
	Recorm	USA	99.2	37	24	25	Wheel 3	User Spec. 9						150
Pedsco	RMI 10	CAN	141.1	32.3	21.6	19.7	Wheel 2.5	RF 1.7 Cable	75	75	77 118	N	45	50
	RMI 9	CAN	264.6	41.3	24.4	26.8	Wheel 2.5	RF 1.7 Cable	180	180	140 144	Y	45	60
Remotec (Northrop Grumman)	Andros F5A	USA	550	35.3	27.6	41	Track 2.0	RF 4.3 Cable	60	100	64 92	Y	45	75.5
	Andros F6A	USA	350	49	17.5	44	Track 3.5	RF 1.7	25	60	48 84	Y	45	63.4
	Andros Mini	USA	190	42	24	37	Track 1.1	RF 1.1 FO	15	40	45 87	Y	45	60
	Wolverine	USA	597.4	57.2	27.6	39.4	Track 2.0	RF 4.3	60	100	64 100	Y	45	66.4
Ricardo	Brawn	UK	440.9	24.4	29.5	33.8	Track	RF FO	50.7	51				
ROV Tech.	SCARAB IIA	USA	125	35	14	10	Track .57	Cable .22				Y		87
Terra A.C.	Predator	USA	520	39.6	29	25	Wheel	RF 1.6 Cable		40				
	Merlin	USA	60	30	17.3	15.6	Track	RF .5 Cable		20				25
	Scorpion	USA	55	30	16.2	9	Track	RF .5 Cable	NA	NA				15

* Control link is the link between the operator control station and the robot vehicle. “RF” is radio frequency, “FO” is a fiber-optic cable, and "Cable” is a wire cable. The RF distances are line-of-sight.

SELECTION ANALYSIS

Selection Rationale

Many comparative studies on robot systems have been performed in the past. Some have examined highly specialized robots such as tele-operated road construction equipment and small stealth fleet robots for gathering large-area intelligence. Competitions among research and academia robots such as RoboRescueCup have provided another arena for comparison. For the most part, however, homeland security studies have had similar requirements to this study and resulted in similar selections. To provide objective evaluations of performance, a standardized testing course is used such as that built by the National Institute of Standards and Technology (NIST). A standardized testing course could include overturned furniture, collapsed floors, broken pipe, and mannequin victims. Agencies such as the Center for Robot-Assisted Search and Rescue (CRASAR) at the University of South Florida, using such test courses, have selected a group of robot systems that have demonstrated their performance at the World Trade Center rescue effort and other emergency robotic mobilizations. Other programs, such as the military competition, MTRS, presently in progress, have attracted these same candidates. These programs and selecting agencies have fairly consistently chosen a small group of robot systems for search and rescue, explosive ordnance device (EOD) detection and disposal, and perpetrator location and stabilization.

Robotic device requirements for transit applications are very similar to requirements for military and EOD applications except that the application environment is more specific. Although transit vehicles have a myriad of configurations, the main difference in requirement specifications for robotic devices in the transit environment is stair-climbing ability in tight quarters. Available candidates can be sorted by comparing the transit environment requirements specification, Table 1, with the available robotic systems, Table 2. Some robot systems met most of the requirements but have one severe shortcoming: typically a delicate (non-robust) design (which compromises survivability), the lack of a manipulator arm, or a lack of articulation (degrees of freedom) in the manipulator arm. Width, turning radius, and weight were other severe shortcomings for a generic solution.

It should be emphasized that this illustration of initial robot identification is based on manufacturers' marketing literature and that the selection analysis is a best-fit effort rather than a one-for-one comparison of requirements and specifications. In any robotic device selection process, demonstrations of candidate systems should be performed before final selection and purchase.

Robot systems not chosen as good all-in-one solutions should be considered if the need arises for specialized missions utilizing their abilities or if a specific requirement not met by the systems is of greater importance to the end user than recognized here.

As with any major purchase of a product produced by several manufacturers, a comparison demonstration should be performed as a final evaluation. The available systems have unique strengths and weaknesses, and these need to be weighed by an end user in an actual environment.

Operator Demands, Training, and Maintenance

Demands on the operator of a robotic device start with deployment. Robot systems for consideration should be man transportable, meaning they weigh from 50 to 100 lbs, and, the entire system, including OCS and accessories, can be carried by two people. Deployment can be as demanding as throwing the robot vehicle through a window or backpacking it to a remote area. Operational demands, on the other hand, are not as physical as deployment demands. However, operational demands require mental concentration, good manual dexterity, the ability to multitask, and the ability to process input from a number of sources. As an example, an operator might have to precisely guide the manipulator to place a sensor next to a suspect package in tight quarters, monitor two other cameras for encroaching fire or perpetrators, and listen for sounds of survivors. In addition to the abilities listed above, operating the vehicle and manipulator to a fine degree of control takes practice. Operators should be selected who not only possess the skills required for the mission, but who are also proficient at similar hand-eye coordination tasks such as operating radio-controlled model cars or planes. Training will then be mostly a matter of learning the robot system features; just a few hours will be needed to become familiar with the feel of the controls. Manufacturers provide training courses for learning the system features and capabilities. A typical two-day course costs about $3,000 per person. The curriculum includes the following:

- OCS set-up, operator controls, display screen functions, and radio link theory;
- Vehicle set-up, major components and modules installation, fiber-optic use, camera use, auxiliary systems use, manipulator and gripper capabilities, and battery charging and care; and
- Practical training in packing and setting up, basic operation, practice missions, and trouble-shooting, and providing a question and answer session.

Usually training is held at the manufacturer's location in classes for multiple purchasers. Training can be arranged at the users' location if tuition for many students is purchased or if the trainer's transportation and accommodation expenses are paid.

Maintenance contracts are also available for extending the typical 90-day warranty. These contracts vary with manufacturer size. Smaller manufacturers require the device to be sent to their factory; larger manufacturers have 24-hour turn-around field service. The yearly price is typically 5% to 10% of the sales price. Maintenance training is available from larger manufacturers and is about the same cost as user training.

EOD and NBC accessories such as X-ray equipment, chemical agent detectors, nuclear sensors, and so forth should be considered along with the purchase of a robotic system. These can sometimes be purchased or recommended through the robot manufacturer or found on the Internet. An independent purchase should be coordinated with the robot system manufacturer for mechanical and electrical compatibility.

GLOSSARY

ATV – all-terrain vehicle
COTS – commercial off-the-shelf
CRASAR – Center for Robotic-Assisted Search and Rescue
Degrees of freedom – linear and rotational directions in which a mechanism can move
Digital zoom – enlargement of a digital picture by enlarging the picture elements in the display
Disruptor – pneumatic or hydraulic cannon for destroying an ordnance detonating system
End effector – mechanism on the end of a manipulator arm, specialized for performing tasks such as gripping or connecting to a piece of equipment
EOD – explosive ordnance device
Ethernet – communication protocol for computing devices
FPS – frames per second
GPS – global positioning system
GHz – gigahertz
Infrared – wavelength of light below visibility level, usually associated with heat
JAUGS – Joint Architecture for Unmanned Ground Systems
KHz – kilohertz (one thousand cycles per second)
LED – light-emitting diode
Manipulator arm – multijointed mechanism for moving an end effector or payload
MHz – megahertz (one million cycles per second)
MTBF – mean time between failure
MTRS – Man Transportable Robotic System (a NAVSEA program)
MTTR – mean time to repair
NAVSEA – Naval Sea Systems Command
NBC – nuclear, biological, chemical
NIJ – National Institute of Justice
NIST – National Institute of Standards and Technology
OCS – operator control station
Optical fiber – a glass or plastic fiber for communicating using light pulses
Optical zoom – enlargement of a digital image by optically magnifying the image presented to the digitizer
PC – personal computer
Radio link – a communication means between two pieces of equipment over a transmitter/receiver
RS232 – wiring protocol for electronics communication
Tele-operated – equipment operated from a distance
TSWG – Technical Support Working Group
USB – Universal Serial Bus
VDC – Volts Direct Current

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   www.abprecision.co.uk/eod/remote%20vehicles/remote%20vehicles.html
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   JAUGS
   www.jauswg.org

   NAVSEA MTRS
   www.ih.navy.mil/contracts/ MTRS%20Questions%20and%20Answers.pdf

   NIJ Final Report on Law Enforcement Robot Technology Assessment
   www.nlectc.org/jpsg/robotassessment/robotassessment.html (assessment)
   www.ojp.usdoj.gov/nij/sciencetech/slides/ImprovedBombRobotProject.pdf (results)

   NIST Performance Metrics for Autonomous Mobile Robots
   www.isd.mel.nist.gov/projects/USAR/

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation