TELEROBOTICS FOR HIGHWAY MAINTENANCE & CONSTRUCTION*

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ABSTRACT:

The maintenance and construction activities of the California Department of Transportation (Caltrans) have been thoroughly studied, and a summary of such activities are tabulated and presented in this report. In addition, a brief overview of the Telerobotics concept is presented. The possibilities of applying Telerobotics to highway maintenance and construction tasks have been explored. In particular cases, proper recommendations are made. Finally, as a part of this study, a new class of robot manipulators, termed as the "Dual-Arm Cam-Lock Manipulator" were designed on a mobile platform for possible applications in bridge inspection and maintenance.

I. WHAT IS TELEROBOTICS?

Like computers, aircraft, and automobiles, tele-robotics (or tele-manipulation) is a technology with multi-purpose mission and extensive reliance on human control. The prefix "Tele" means "remote" or "at a distance", and *Telerobotics* is the technology that couples the human operator's visual, tactile, and other sensory perception functions with those of a remote manipulator. It consists of relaying sensory information from the manipulator environment to the human operator [1].

An effective telerobotics system must provide the human operator with the feeling of being present at the remote site by allowing him/her to see and feel the objects being manipulated. This is generally done using appropriate sensors at the remote site, and human interfaces or display systems at the operator site to help him/her perceive the sensory information. This information generally enhances the operator's motion control function, making him/her capable of coping with unforeseen changes in the state of the work area. It further elevates the manipulation capabilities of the telerobotics system. Figures 1-3 display conceptual diagrams of various telerobotics and telemanipulation systems.

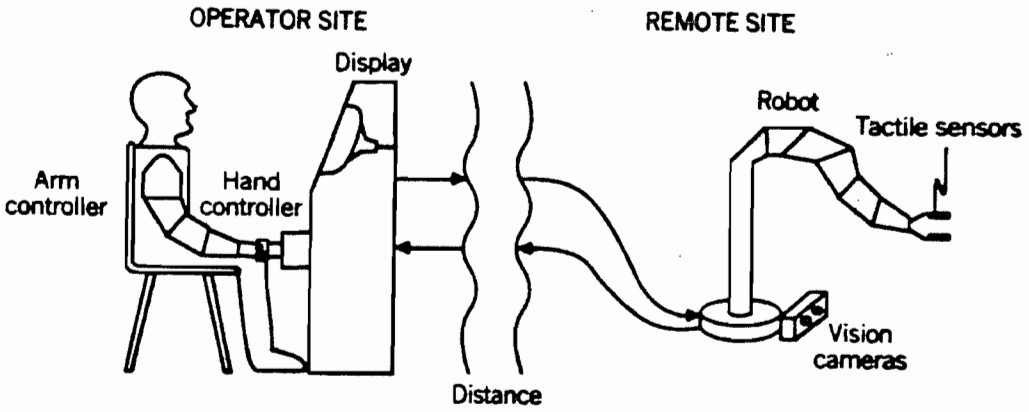
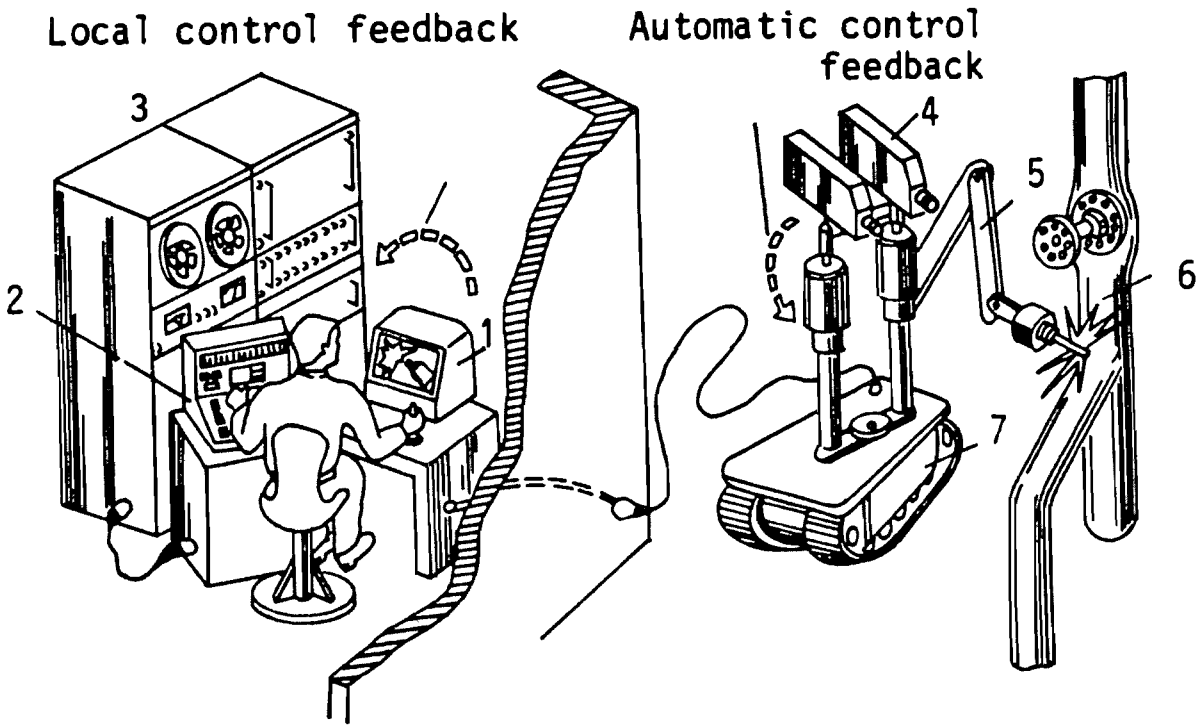


Figure 1. The operator commands the robot using teleoperation. Feedback from visual and tactile sensors to the operator provides telepresence [1].



1) Display
2) Control Panel
3) Control Computer
4) Sensors
5) Manipulators
6) Working Object
7) On Board Computer

Figure 2. A Typical Telerobotics System. Functional Scheme of the Interactive Control Systems of Robots(supervisory and dialogue combined) : These are intelligent robots which do not simply receive human commands (supervisory only), but themselves participate actively in scene recognition and decision making. They are applied in underwater pilotless devices, in explosive environments, in mines without human worker, in nuclear power plants, etc.

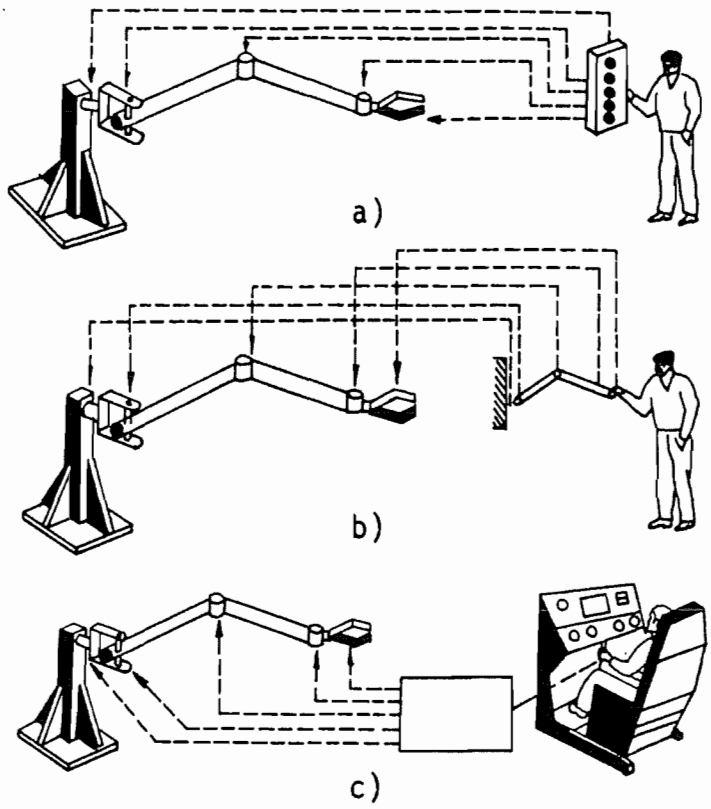


Figure 3. Various Types of Remotely Controlled Manipulators:

(a) *Direct Control Manipulators* : The human operator remotely switches on the actuator of each manipulator joint by pressing the corresponding button.

(b) *Master-Slave Manipulators* : The manipulator is remotely controlled by the human operator from a distant safe position by means of a master device, which is kinematically similar to the manipulator itself.

(c) *Semi-Automatic Manipulators* : Remotely controlled by a multi-functional joy-stick (with arbitrary kinematics to suit small movements of the hand) on the command panel of the operator.

The topic of telemanipulation may require further clarification due to the fact that teleoperated devices and/or systems are often referred to as "robots" in the general public press. We believe that the proper use of the word telemanipulation implies the presence of a human being in the control loop. This concept permits the operator to enhance control of the device by first processing commands through a computer. When the computer attains the capability of at least limited autonomous control, then the device becomes something beyond normal telemanipulation and will be referred to as *Telerobot*. Telemanipulator, and Telerobot are used primarily because necessary tasks have to be performed under conditions or in environments that are too dangerous, unhealthy, or unpleasant for human operators. Therefore, such tasks may be performed manually and remotely from a safe place by means of a suitable teleoperator system/controller, while all the skills of the human operator are still used.

The typical telerobotics/telemanipulator application may be classified by a number of dominant characteristics [2]:

* The tasks are unstructured and not very repetitive.

* There is little or no control of the details of the tasks and their location.

* The telemanipulator has to be brought to the task site, rather than the workpiece being brought to the robot site.

* In a large fraction of the cases, the tasks are not only unstructured but little prior knowledge exists as to the tasks to be performed.

Generally, when first planning a remotely operated system involving a telemanipulator or telerobot, the most important issue concerns the method of bringing the telemanipulator/telerobot and the task objects into a common working area. Clearly, for unstructured heavy tasks distributed in a facility consisting of many rooms or in a large outdoor area, mobile telemanipulators/telerobots must be considered.

Telerobotics maintains considerable advantages over its simpler predecessor, including: 1) all non-contact motions can be performed in a programmed mode, and 2) the incorporation of real-time coordinate transformations allows one to make teleoperator control more effective for most control modes. Two examples of telerobotics applications are shown in Figures 4 and 5. Figure 4 displays the schematic diagram of a Personal Occupied Woven Envelope Robot, and Figure 5 displays the schematic of an Astrobot with

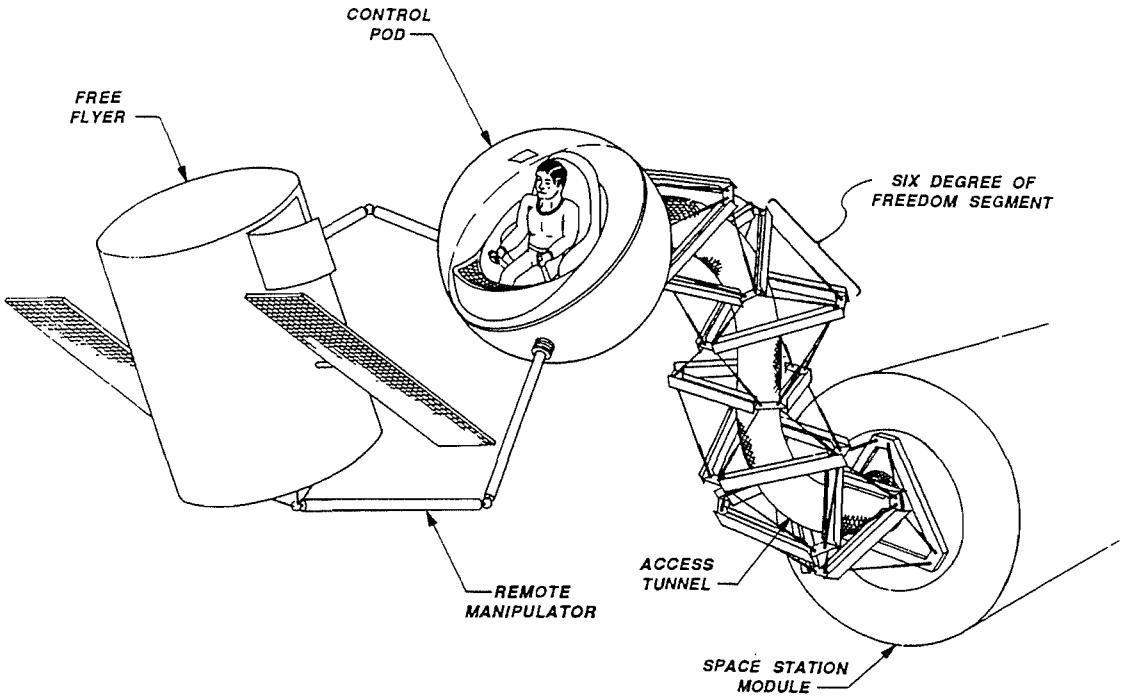


Figure 4. Personal Occupied Woven Envelope Robot (POWER), consisting of a huge, flexible, hollow manipulator arm comprised of numerous 6-DOF electrically actuated segments. The operator rides in the control cabin located at the free end of the arm [3].

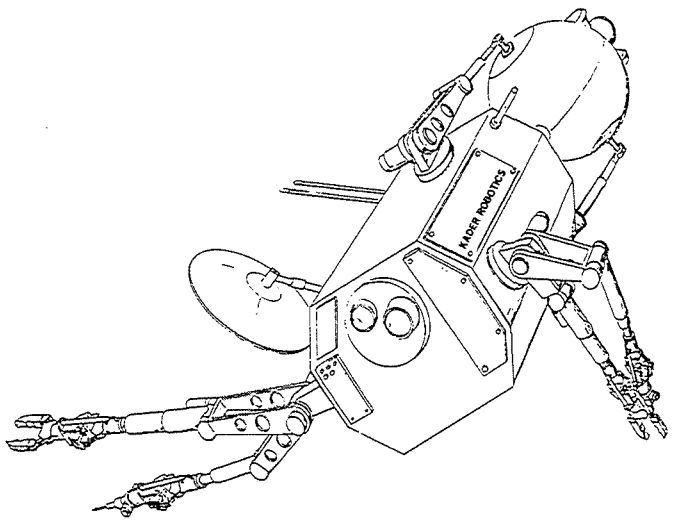


Figure 5. Kader Astrobot with propulsion unit. This state-of-the-art telerobot concept seeks to minimize human extravehicular activity by employing remote manipulators of high dexterity [3].

propulsion unit. The majority of telerobotics research is found in space and undersea applications. In space telerobotics the main goal is to develop an earth-based human control of remote space tasks such as satellite repair and retrieval. Similarly, underwater applications of telerobotics provide an opportunity for deep-sea exploration, sunken ship retrieval, and oil line repair and construction. Telerobotics is also applied in the nuclear industry, typically for nuclear waste cleanup and removal, and handling of radioactive materials within huge glove boxes. Each of these applications of telerobotics have two important factors in common: the task environment is either unsuitable or extremely dangerous to human being, and the tasks are generally unstructured. Many highway maintenance and construction tasks are also both dangerous and unstructured. According to these criteria, it seems likely that highway maintenance and construction tasks may also be well-suited for application of telerobotics. Examples of such applications are briefly discussed in the next section.

Telerobotic systems generally rely on an accurate picture of the task site (remote environment) in order to allow the operator to make informed control decisions. Figures 6 and 7 illustrate the concept of transferring information between the operator and the task site. Figure 8 shows the general control schemes of an automatic robotics system. These complex automatic systems are used in production plants in groups, replacing human involvement in production processes.

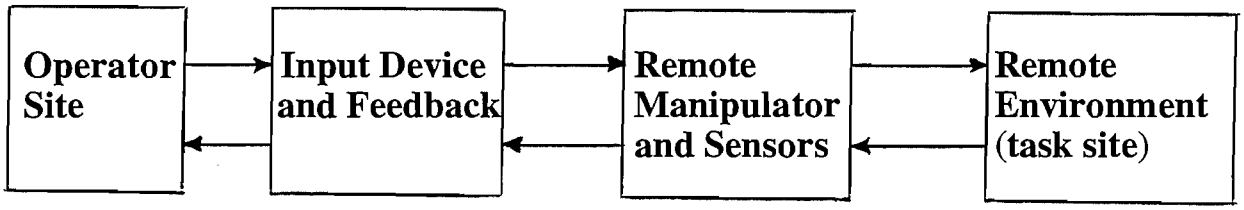


Figure 6. Basic telerobotics system control structure.

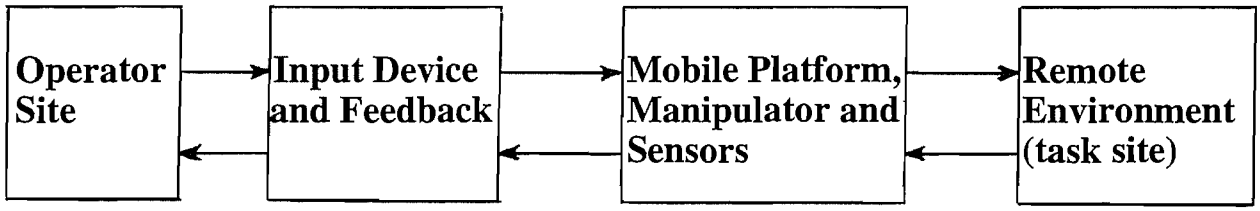
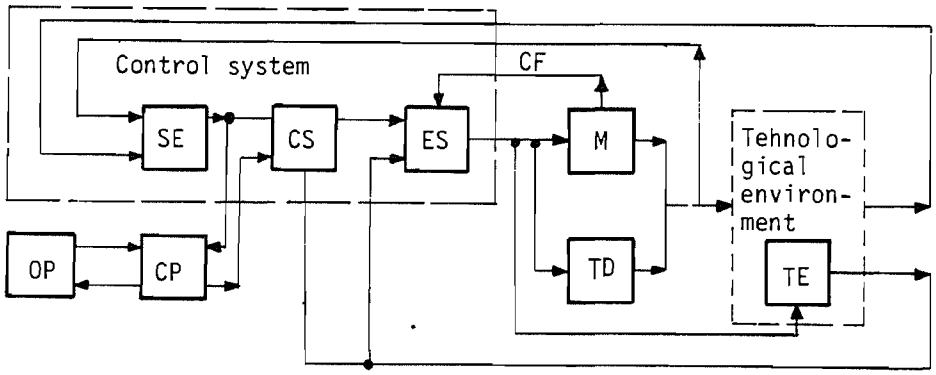


Figure 7. Mobile telerobotics system control structure.



SE - Sensor Element, **OP** - Operator, **CP** - Control Panel, **CS** - Computer System, **ES** - Executive System, **M** - Manipulator, **TD** - Transfer Device, **CF** - Control Feedback.

Figure 8. General Scheme of Automatic Robotics System; Information, Manipulation, and Control.

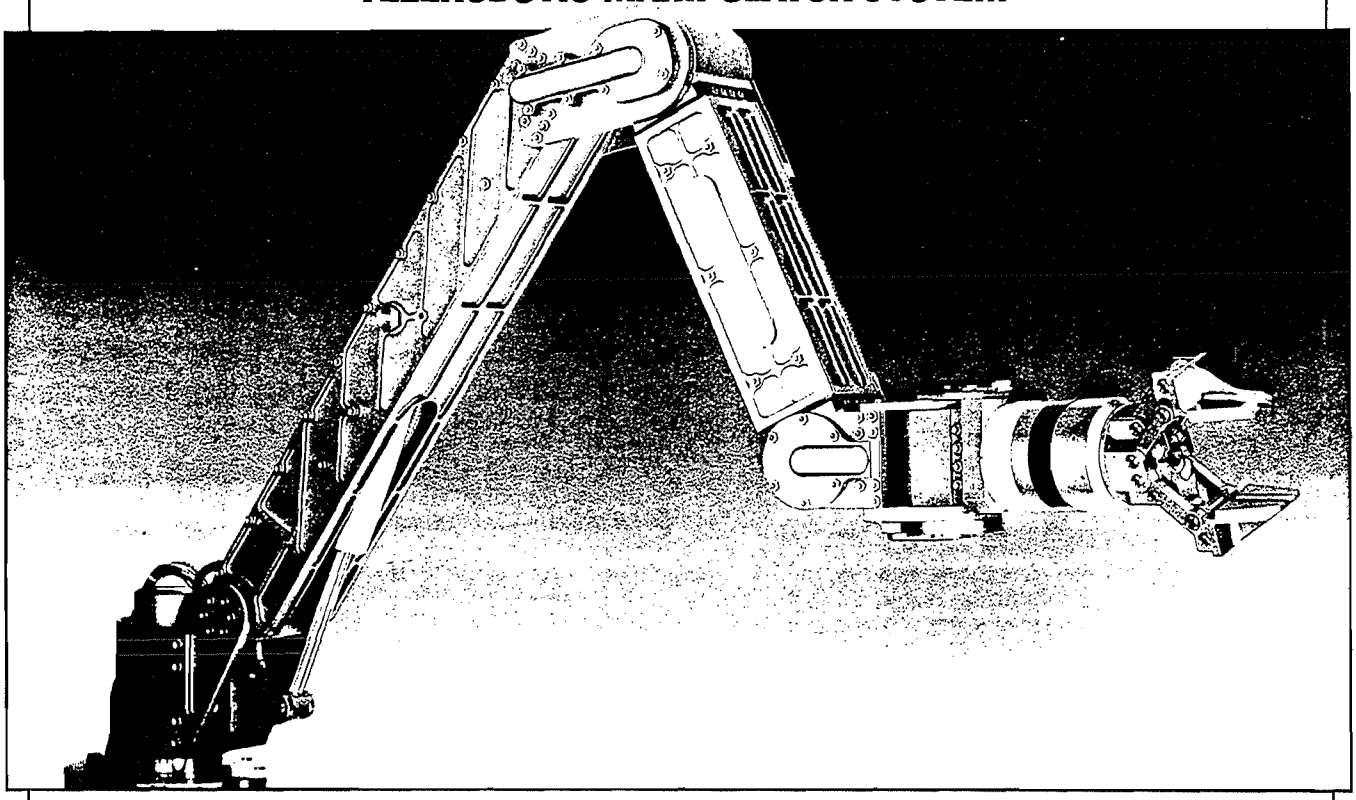
Commercially Available Telerobotics Systems.

It would be very desirable to locate various off-the-shelf telerobotics systems and simply mount them to Caltrans trucks for particular applications. However, such systems must satisfy the general as well as specific requirements of the highway maintenance and construction technology. Therefore, in order to design and/or select a commercially available telerobotics system, one must first identify the requirements and limitations of each task that is to be automated. As mentioned earlier, in this report, we plan to identify these tasks in the context of Caltrans maintenance and construction activities. Comprehensive evaluation of these tasks for telerobotics application is left for the future studies, and shall be done on an individual basis.

In the following pages, general information concerning a number of commercially available telerobotics systems is provided for review.

TITAN II

TELEROBOTIC MANIPULATOR SYSTEM



To meet the increasing demands of remote manipulation in hostile environments, Schilling Development, Inc. has developed a second-generation TITAN II — a dexterous, servo-hydraulic telerobotic manipulator with six degrees of freedom. Schilling's seven-year experience in producing equipment for extreme environments has driven the design refinements available in the TITAN II, such as high-resolution bilateral force feedback, advanced telerobotic control, and end effector interchange. Offered in a number of configurations, the TITAN II addresses applications in radioactive, deep-ocean, toxic-chemical and high-voltage environments.

The variety of remote work tasks requires the telemanipulator to be highly reliable, field maintainable, and adaptable. The TITAN II provides a turn-key solution for manipulative tasks in a wide range of hostile environments. The standard configuration features titanium construction, high payload, wide range of motion, intuitive control, and smooth, fluid operation.

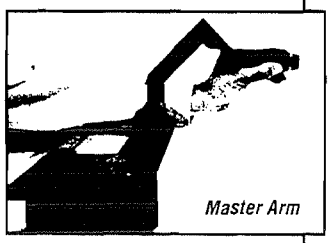
To aid the operator in performing tasks that might otherwise be impossible or impractical, the TITAN II is available with options such as force feedback, advanced telerobotic control, and tool interchange. Force feedback combines visual feedback with direct experience of motion and forces acting on the slave arm by reflecting the forces to an electrically actuated master arm. The Advanced Telerobotic Controller (ATC) offers true robot control of the slave arm. The ATC incorporates a modular control architecture to accommodate a number of input devices, graphical interface, real-time sensor inputs, and data transmission types. Instantaneous transition from teleoperated control to robot control and complex trajectory generation greatly enhance capability and productivity. Tool interchange allows a practical means of deploying various tools at the remote worksite.

For radioactive environments, Schilling has designed a hardened version of the TITAN II to tolerate an accumulated exposure of 10^7 RAD with no loss in performance.

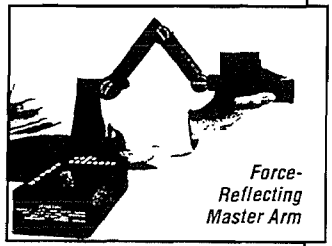
Cartesian Controller*

FEATURES:

- *High dexterity*
- *Heavy lift*
- *Titanium construction*
- *Comfortable and intuitive control*
- *Compatible with multiple fluid types*
- *Optional force feedback, advanced telerobotic control, tool interchange, and radiation hardening*



Master Arm



Force-Reflecting Master Arm

SCHILLING

GENERAL DESCRIPTION

Modes of Operation

Master/Slave Position Controlled ..... standard
Cartesian/Tool Frame Control ..... optional
Force Control ..... optional
Bilateral Force Feedback ..... optional

Input Devices

Passive Master Arm ..... standard
Cartesian Controller ..... optional
Force-Reflecting Master Arm ..... optional
Graphical Interface and Trajectory Generation .. optional

Degrees of Freedom

Six Plus Grip ..... standard
Tool Interchange ..... optional

Power System

Hydraulic ..... Multiple fluid compatible

STANDARD DIMENSIONS AND SPECIFICATIONS

Maximum Reach ..... 76.3 in.
Lift Capacity (maximum) ..... 1200 lb
Lift Capacity (full extension) ..... 240 lb
Wrist Torque ..... 75 ft-lb (peak)
Jaw Capacity ..... 4.0 in.
Weight ..... 175 lb

RANGE OF MOTION

	Hardware Range
Waist Yaw	270°
Shoulder Pitch	120°
Elbow Pitch	270°
Wrist Pitch	180°
Wrist Yaw	180°
Wrist Rotate	
Slaved	270°
Continuous	0-55 rpm

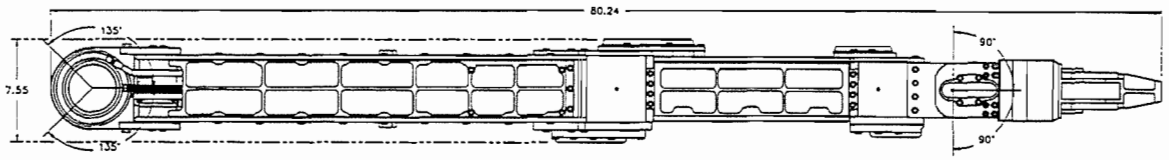
HYDRAULIC REQUIREMENTS

Fluid Type ..... Hydraulic Oil
Optional Fluid ..... Consult Factory
Flow ..... 1.5 to 5 gpm
Pressure ..... 3000 psi nominal

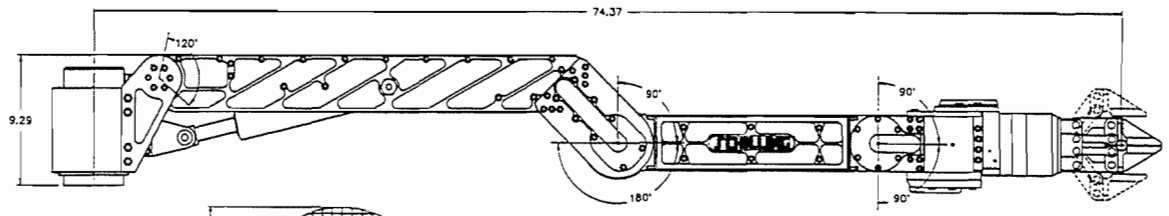
ELECTRICAL AND TELEMETRY REQUIREMENTS

Consult Factory

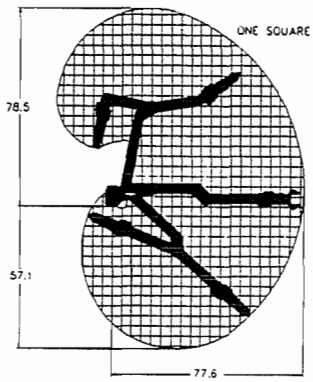
Plan View

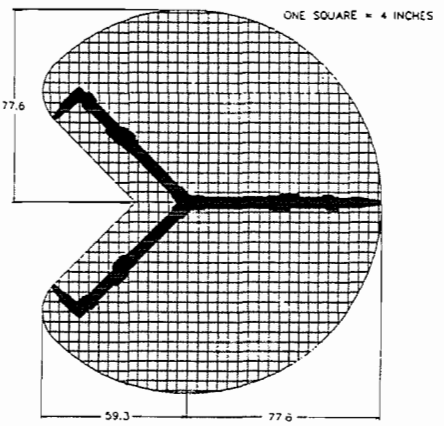


Elevation



Elevation





Plan View

SCHILLING DEVELOPMENT

1632 DA VINCI COURT, DAVIS, CA 95616
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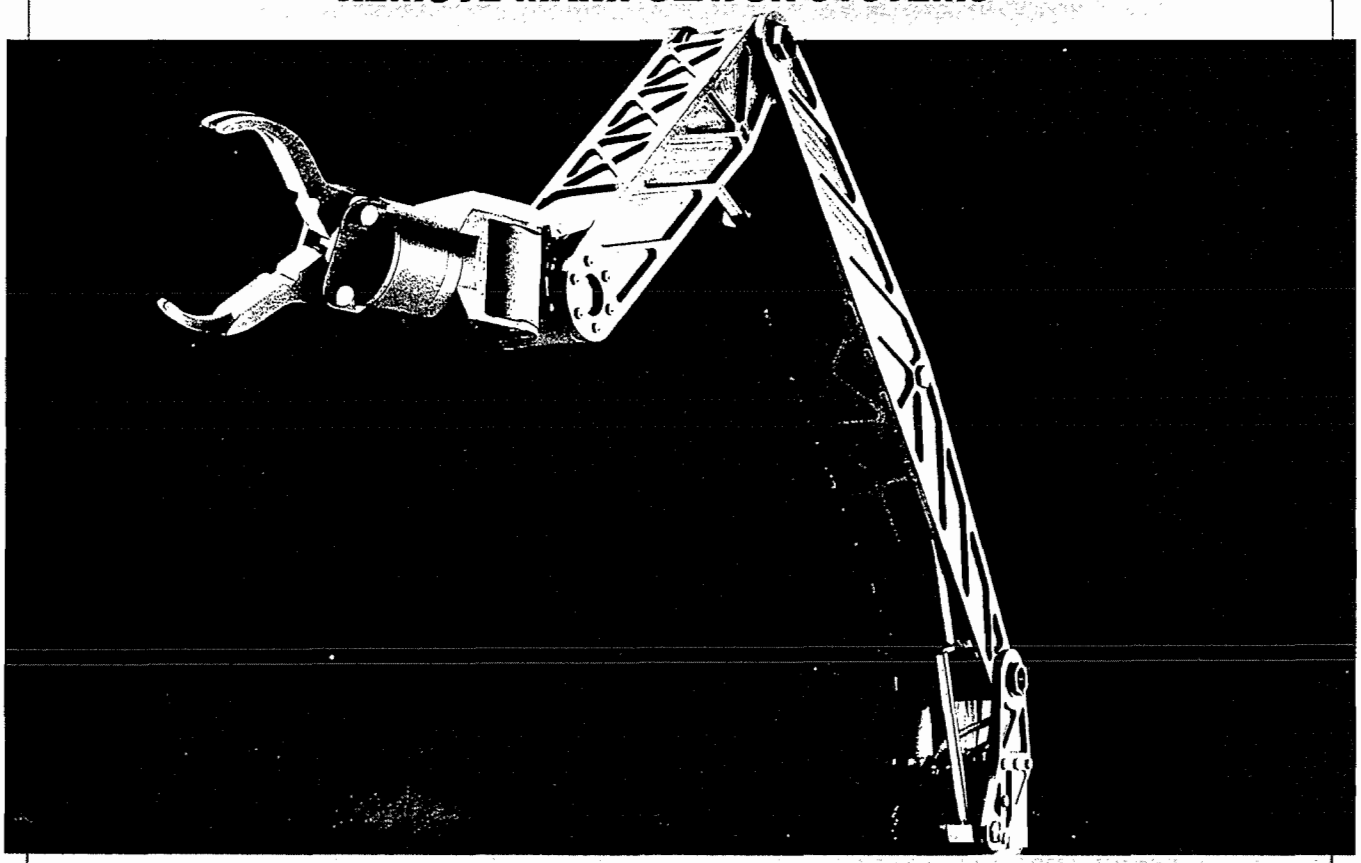
*Dimension 6 force/torque control ball, reproduced with permission of CIS Graphics, Inc.

TITAN 7F and GAMMA 7F

REMOTE MANIPULATOR SYSTEMS



Schilling Development, Inc. meets user requirements for seven-function remote manipulators with two highly dexterous and powerful servo-hydraulic, Master/Slave systems - The TITAN 7F and GAMMA 7F. Each are constructed primarily of 6-4 titanium and employ advanced electronic and mechanical design for use whenever manipulative tasks must be performed in locations or environments where man cannot safely or practically venture. Applications range from undersea to radioactive environments.

The TITAN 7F has acquired an impeccable reputation since its introduction in 1987 and is seeing service for a variety of commercial, scientific and military users. Typical tasks range from undersea salvage, maintenance and construction to ordnance handling and toxic cleanup.

Building upon the TITAN 7F's established record of reliability and performance, the GAMMA 7F provides for operation in radioactive environments. Through careful selection of radiation resistant materials, the GAMMA 7F is designed to tolerate an accumulated exposure of 10^7 RAD gamma radiation. Now a standard, commercially proven product is available that eliminates costly development, rework costs and reliability concerns associated with custom designed equipment.

The TITAN 7F and GAMMA 7F are controlled by compact master arms that provide for comfortable and intuitive manipulator control. Advanced hydraulic and control system technology combine smooth and fluid operation with an extremely tight control loop giving the manipulators human-like speed and accuracy.

FEATURES:

- *Available for undersea and terrestrial applications.*
- *Microprocessor, servo controlled.*
- *Dexterous and powerful.*
- *250 lb. payload at full arm extension.*
- *Radiation hardened to 10^7R.*
- *Oil hydraulic and silicon base fluid compatible.*
- *Titanium construction.*
- *Portable master controllers that are simple to learn, easy and comfortable to operate and require little space.*
- *Compact and powerful three-axis wrist assembly.*

SCHILLING

GENERAL DESCRIPTION

Mode of Operation ..... Spatially Correspondent
Input Device ..... Compact Master Control Arm
Number of Functions ..... Seven
Power System ..... (TITAN 7F) Oil Hydraulic
(GAMMA 7F) Multi Fluid Compatible

DIMENSIONS AND SPECIFICATIONS

SLAVE ARM

- Maximum Reach ..... 78 inches
- Lift capacity at Full Extension ..... 250 lbs.
- Jaw Capacity ..... 4.0 inches (standard)
- Jaw Closure Force ..... 350 lbs. max.
- Weight in Air ..... 147.0 lbs.
- Weight in Water ..... 113.0 lbs.

MASTER CONSOLETTE

- Height ..... 10.0 inches
- Width ..... 6.0 inches
- Length ..... 19.0 inches
- Weight ..... 10.0 lbs.

SLAVE CONTROLLER ASSEMBLY

- Height ..... 4.0 inches
- Width ..... 7.5 inches
- Length ..... 16.0 inches
- Weight in Air ..... 27.0 lbs.
- Weight in Water ..... 14.5 lbs.

PERFORMANCE

	Hardware Range	Max. Slew Rate
Waist Yaw	270°	90°/sec.
Shoulder Pitch	90°	90°/sec.
Elbow Pitch	120°	90°/sec.
Wrist Pitch	180°	400°/sec.
Wrist Yaw	180°	400°/sec.
Wrist Rotate		
Slaved	270°	
Continuous	0 to 55 rpm	
Wrist Torque	70 ft. lbs. (peak)	

HYDRAULIC REQUIREMENTS

3000 psi - 3.0 gpm nominal

ELECTRICAL REQUIREMENTS

25 watts nominal powered by 120/240 VAC or 20-30 VDC

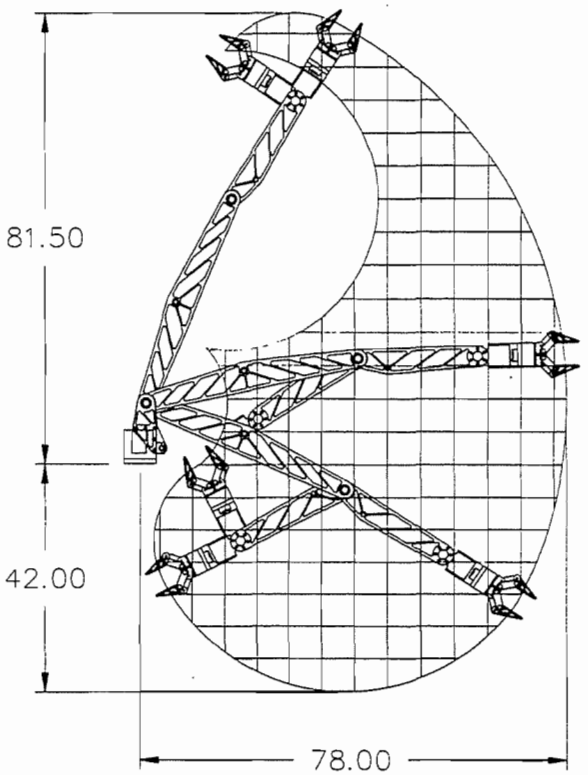
TELEMETRY REQUIREMENTS

RS-422 type media - Single twisted wire pair;
RG-108 or equivalent

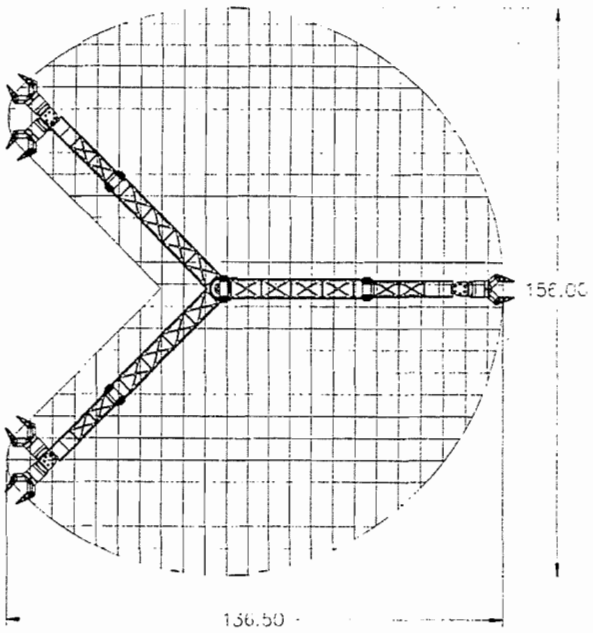
OPTIONS

Contact Schilling Development, Inc. for details.
Available in single and dual manipulator configurations.

Side Elevation View



Plan View



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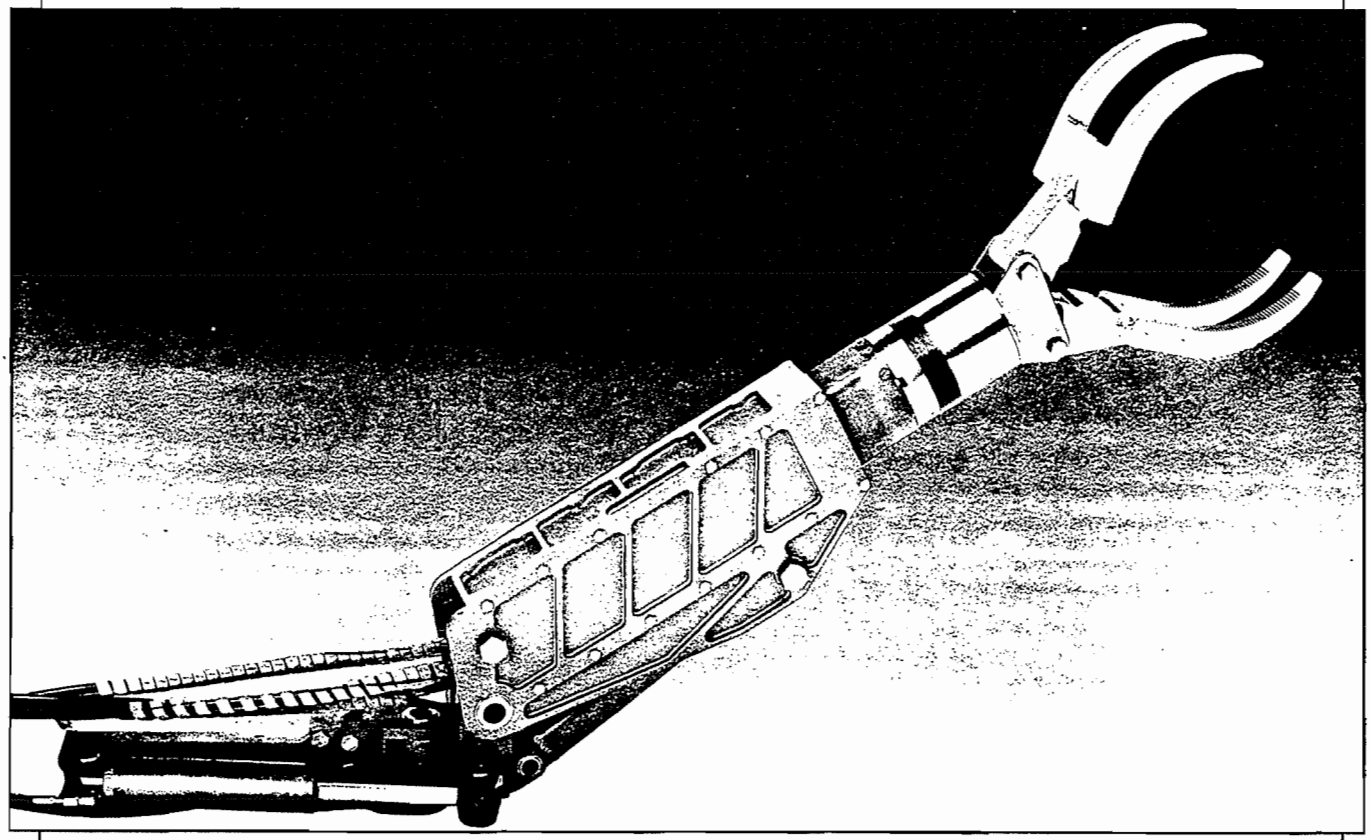
Description and specifications are subject to change without notice. Contact Schilling Development for latest information.

RIGMATE

REMOTE MANIPULATOR SYSTEM



The Schilling Development RigMate manipulator system is a five-function, rate-controlled, heavy-lift grabber designed for use with a wide range of remotely operated undersea vehicles. This system delivers the power, performance, flexibility, and reliability required in the uncompromising undersea environment.

Power

The RigMate offers a higher power-to-weight ratio than any other manipulator in its class. Weighing just 80 lb in seawater, the RigMate can lift 595 lb when retracted and 400 lb at its full 48-inch extension. The wrist, which provides continuous 360° rotation, is driven by a high-torque, low-speed, gerotor hydraulic motor that produces 150 ft-lb of torque.

Performance

The RigMate's five functions include base yaw, shoulder pitch, boom extend/retract, wrist rotate, and grip. The base yaw and shoulder pitch each provide 105° of motion, while the boom function extends the gripper by 12 inches.

The RigMate can be configured for right-hand or left-hand installations, and can be stowed vertically or horizontally.

Reliability

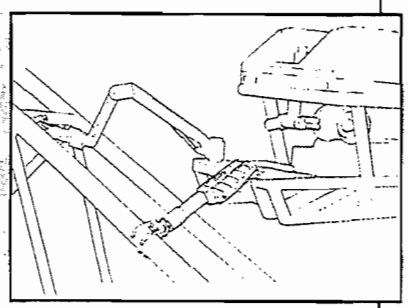
The newly designed linear actuators in the base yaw, shoulder pitch, and boom extend/retract functions have been life tested under full load for over 250,000 cycles with no signs of wear. The actuators use the latest cap seal technology to minimize leakage, providing long life and low maintenance. Actuator shafts and fittings are protected by the arm structure.

The boom extension function features a polyurethane debris scraper to prevent sand and silt from entering the bearing area. Composite bearings that slide on portions of the boom are also protected from damage. The boom extension actuator is located coaxially in the boom center for protection and to eliminate jamming.

All rotary joint bearings are a composite of Nomex™, epoxy, and Teflon™, and are self lubricating and free flooding to sea water.

FEATURES:

- *High reliability*
- *Easy maintenance*
- *595-lb lift capacity*
- *150-ft-lb, high-torque wrist*
- *360° continuous wrist rotation*
- *12-inch extension*
- *Vertical or horizontal stowage*
- *Right-hand or left-hand mounting*



SCHILLING

GENERAL DESCRIPTION

Number of Functions ..... Five rate-controlled
Grip Force ..... 550 lb (249 kg)
Jaw Capacity ..... 12.0 in. (305 mm)
Overall Length
Retracted ..... 36 in. (.91 m)
Extended ..... 48 in. (1.2 m)

Weight (with stainless steel gripper)
In Air ..... 100 lb (45 kg)
In Water ..... 80 lb (36 kg)

Lift Capacity @ 3000 psi
Retracted ..... 595 lb (270 kg)
Extended ..... 400 lb (181 kg)

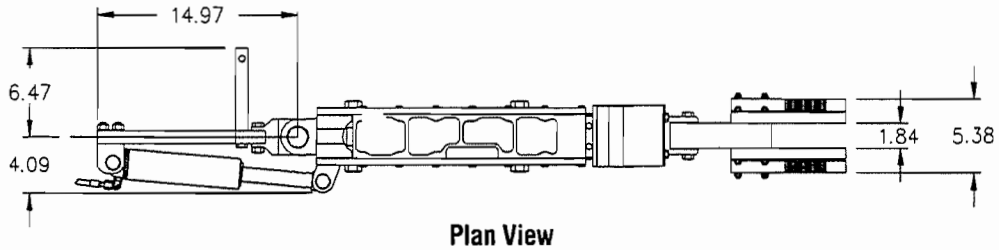
Performance

Base Yaw ..... 105° (+90°/-15°)
Shoulder Pitch ..... 105° (+75°/-30°)
Boom Extend and Retract ..... 12 in.(305 mm)
Wrist Rotate ..... 360° continuous
Wrist Torque ..... 150 ft-lb (203 Nm)

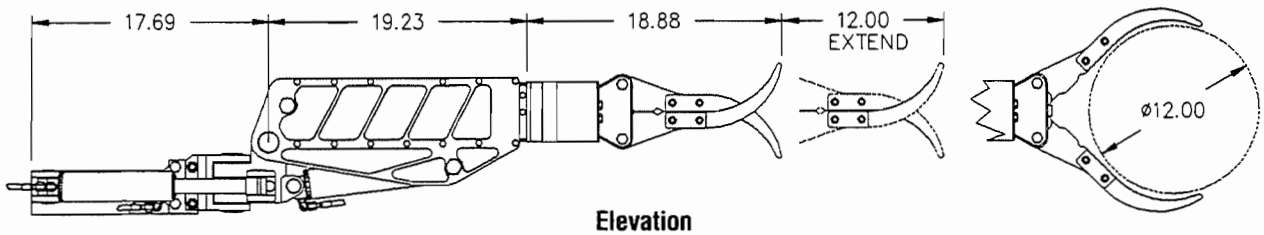
Hydraulic Requirements

Operating Pressure ..... 3000 psi (207 bar)

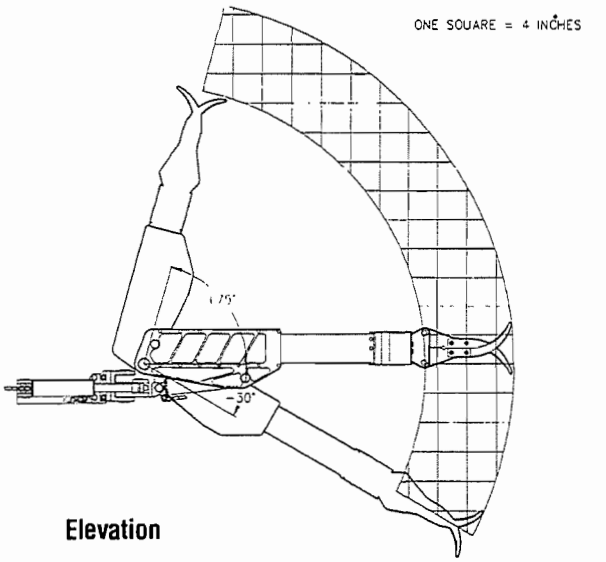
Description and specifications are subject to change without notice.
Contact Schilling Development for latest information.



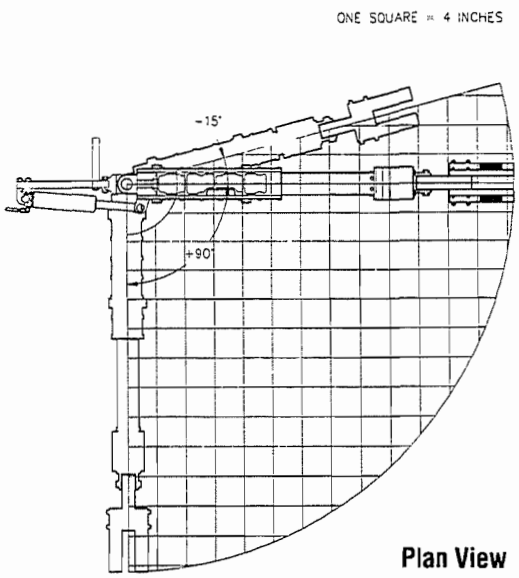
Plan View



Elevation



Elevation



Plan View

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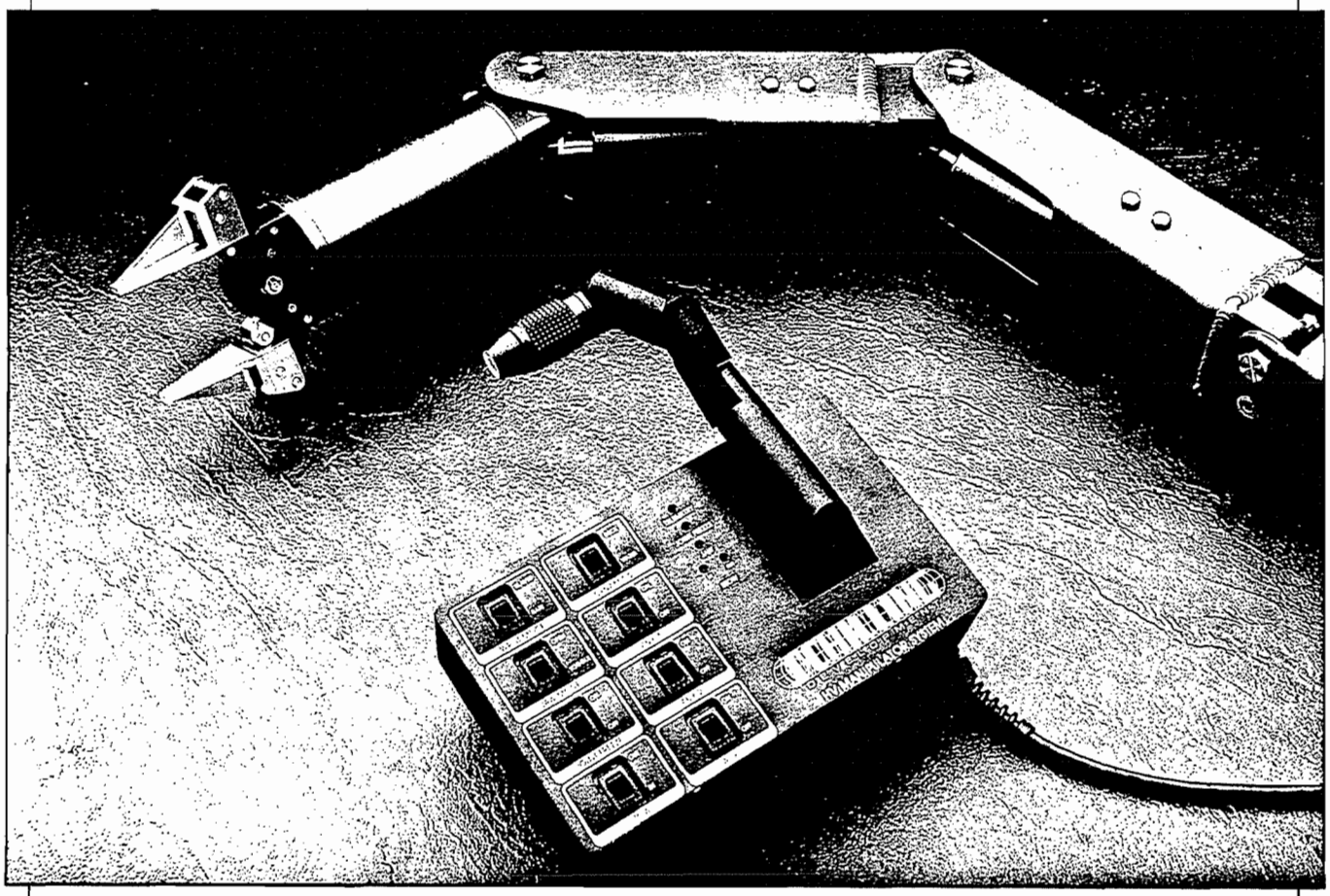
HV and GAMMA SERIES

REMOTE MANIPULATOR SYSTEMS



For customers who require five-function and six-function remote manipulator systems, Schilling Development, Inc. provides the HV series and GAMMA series of products. These servo-hydraulic, microprocessor-controlled remote manipulator systems are rugged and reliable. They are designed to perform manipulative tasks in places that are unsafe for human workers, such as undersea and radioactive environments.

In the HV series, the five-function HV5F and six-function HV6F have performed reliably for commercial, scientific, and military customers since their introduction in 1986. Typical tasks range from undersea salvage, maintenance, and construction to ordnance handling and toxic cleanup.

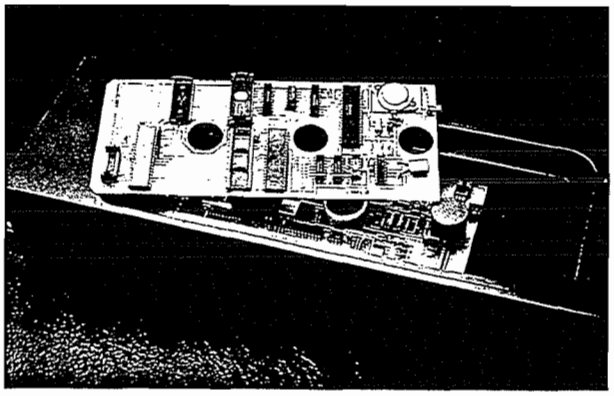
In the GAMMA series, the five-function GAMMA 5F and six-function GAMMA 6F are radiation hardened for operation in radioactive environments. Each system will tolerate an accumulated exposure of 10^7 RAD gamma with no performance loss. This high level of protection exceeds the radiation tolerance requirements of most applications in radioactive environments.

The HV and GAMMA series systems are controlled by compact master arms that are small kinematic replicas of the slave arms. The master arm fits easily in the operator's hand. It is controlled by movements of the wrist and fingers, allowing comfortable and intuitive control.

Overall system design combines advanced hydraulic system technology with a fast, tight control loop to produce slave arm movements with human-like speed and accuracy.

FEATURES:

- *Available for undersea and terrestrial applications*
- *Microprocessor and servo control*
- *Rugged and reliable*
- *60-lb payload at full arm extension*
- *Radiation hardened to 10^7 R*
- *Compatible with hydraulic oil and water/glycol*
- *Portable master controllers that are small, compact, simple to learn, and easy and comfortable to operate*



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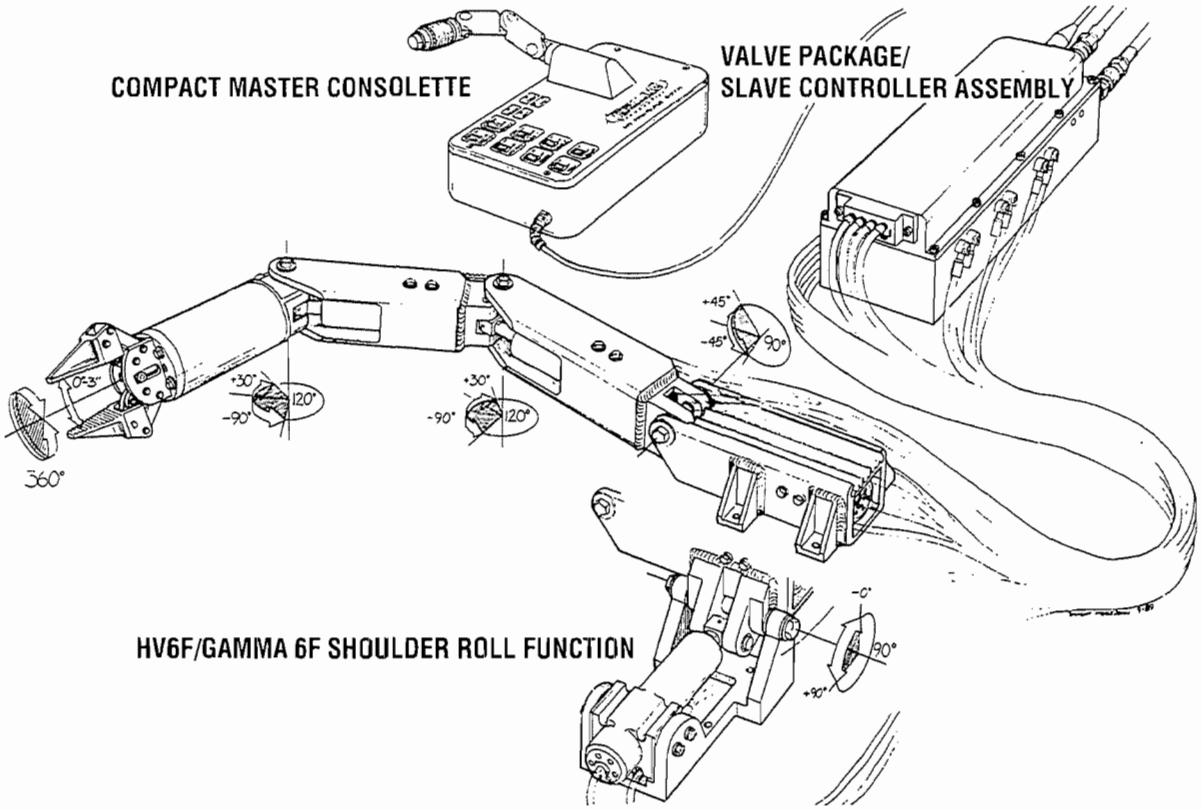


HV AND GAMMA SERIES OVERVIEW

GENERAL DESCRIPTION

Mode of Operation ..... Spatially Correspondent
Input Device ..... Compact Master Control Arm
Number of Functions ..... (HV5F and GAMMA 5F) Five
(HV6F and GAMMA 6F) Six
Power System ..... (HV Series) Oil Hydraulic
(GAMMA Series) Multi Fluid Compatible

DIMENSIONS AND SPECIFICATIONS

SLAVE ARM

Maximum Reach ..... 36 inches
Lift capacity at Full Extension ..... 60 lbs.
Jaw Capacity ..... 3.0 inches (standard)
Jaw Closure Force ..... 200 lbs. max.
Weight in Air ..... (HV5F and GAMMA 5F) 36.0 lbs.
(HV6F and GAMMA 6F) 44.0 lbs.
Weight in Water ..... (HV5F and GAMMA 5F) 18.0 lbs.
(HV6F and GAMMA 6F) 22.0 lbs.

MASTER CONSOLETTE

Height ..... 4.5 inches
Width ..... 6.0 inches
Length ..... 10.0 inches
Weight ..... 8.0 lbs.

VALVE PACKAGE/SLAVE CONTROLLER ASSEMBLY

Height ..... 6.0 inches
Width ..... 7.25 inches
Length ..... 17.0 inches
Weight in Air ..... 36.0 lbs.
Weight in Water ..... 24.0 lbs.

PERFORMANCE

	Range	Max. Slew Rate
Shoulder Roll (HV6F/GAMMA 6F Only)	90°	300°/sec.
Shoulder Pitch	90°	300°/sec.
Elbow Yaw	120°	400°/sec.
Wrist Yaw	120°	600°/sec.

Wrist Rotate:
Slaved ..... 270°
Continuous ..... 0 to 90 rpm
Wrist Torque ..... 20 ft. lbs.

HYDRAULIC REQUIREMENTS

1.25 gpm @ 2000 psi (HV5F and GAMMA 5F)
1.50 gpm @ 2000 psi (HV6F and GAMMA 6F)

ELECTRICAL REQUIREMENTS

25 watts nominal powered by 120/240 VAC or 20-30 VDC

TELEMETRY REQUIREMENTS

RS-422 type media - Single twisted wire pair;
RG-108 or equivalent

OPTIONS

Contact Schilling Development, Inc. for details.
Available in single and dual manipulator configurations.

SCHILLING DEVELOPMENT
1632 DA VINCI COURT, DAVIS, CA 95616
(916) 753-6718 • FAX (916) 753-8092

II. CALTRANS MAINTENANCE & CONSTRUCTION ACTIVITIES

In this section we study part of the maintenance and construction activities of the California Department of Transportation as they relate to the applications of telerobotics as well as the future goals of the AHMCT center.

Highway Maintenance is the preservation, upkeep, and restoration of the roadway, facilities, and structures, including toll bridges and appurtenant facilities as nearly as possible in the condition for which they have been designed, constructed and improved. Maintenance also includes the operation of highway facilities and services to provide safe and satisfactory highway transportation.

Legal definition of Maintenance for Streets & Highways includes:

- The preservation and keeping of rights of way, and each type of roadway, structure, planting, illumination equipment and other facilities, in the safe and usable condition to which it has been improved or constructed, but does not include reconstruction or other improvements.

- Operation of special safety conveniences and devices, and illuminating equipment.

- The special or emergency maintenance or repair required by accidents, by storms or other weather conditions, slides, settlements, or other unusual or unexpected damage to a roadway, structure, or facility.

Types of Maintenance Operations:

1. Stationary Operations: Work activities in which workers on foot or equipment occupy any part of paved shoulder or the traveled way at one location for more than twenty minutes.

2. Short-Term Operations: Work activities, such as pavement patching, pavement marker replacement, etc., which can be performed during light traffic volumes, without interfering with traffic or placing the employee in jeopardy.

3. Moving Operations: Work activities, such as striping, sweeping, etc., which move along the travel-way, usually slower than the prevailing speed of traffic.

Type of Tasks and Operations Normally Performed by the California Department of Transportation.

1. **Highway Landscape:** Performance of landscape maintenance operations on highways.

2. **Tree Maintenance:** Care and pruning of roadside trees and shrubbery.

3. **Highway Bridge Inspection and Maintenance:** Crack identification, repair, replacement, or painting of bridge structures.

4. **Highway Electrical Maintenance:** Maintenance of all traffic signals, highway lighting and other electrical devices.

5. **Maintaining Damages:** maintaining damages due to motor vehicle accidents on highways, i.e. damage to road blocks, signs, lights, etc.

6. **Traffic Guidance on Streets & Highways:** Involves all work necessary to replace and maintain distinctive roadway markings on the traveled way such as: re-striping existing stripes and replacement of pavement markers; assembly, installation, replacement, and cleaning of traffic signs on state highways; etc.

7. **Storm Maintenance:** Involves routine patrol activities, maintenance, and repair of both minor and major damage caused by storm.

8. **Assistance in Fighting Fires:** Detection and control of fires which may start within right-of-way, in order to aid in suppression of forest fires in the National Forests.

9. **Maintenance of State Park Roads and Parking Areas:** Includes cleaning and preserving the rest areas, and repairing possible minor and/or major damages.

10. **Maintenance and the Environment:** Minimize environmental degradation while performing maintenance duties.

11. **Snow Removal and Ice Control:** Cleaning highways from snow and ice for the safety and convenience of the traveling public.

12. Spills of Substances on Highways: Removing hazardous/non-hazardous spills on highway rights-of-way, picking up litter and debris, sweeping roads and highways.

13. Maintaining Flexible and Rigid Pavements: Involves repairs and maintenance of asphalt concrete surfaced pavements and portland cement concrete pavements. Include repair of cracks and joints, pot holes and local depressions, paved shoulder defects, and other surface deterioration.

14. Stenciling Operations, Striping, and Photogrametry: Includes painting signs and marks on state roads and highways for guidance, safety, etc.

15. Maintaining Clean Air/Water: Avoid chemical contamination, i.e. use of salts such as sodium chloride or calcium chloride for ice and snow control on pavement should not affect water streams/lakes.

16. Cleaning, Repair and Reconstruction of Highways and/or Bridges: This type of operations generally takes place immediately after major road destruction due to the earthquake, flooding, etc.

<<< Highway Landscaping and Tree Maintenance >>>

Treatment, maintenance, and replacement of all vegetative materials planted within the State Highway Rights-of-Way are part of CalTrans responsibilities. This task includes watering, fertilizing, plant replacement, weed control by hand and mechanical means, tree trimming and/or removal, chipping, and miscellaneous work such as pest control and inhibitor spray.

Table 1. Principal Tasks in Landscaping are Defined and Classified.

TASK	HOW ?	WHY ?
Weed Control *; includes hand pulling, hoeing, using whip or weed eater, mowing of all turf areas and weeds, fertilizing turf areas.	Usually with chemicals, or biological, or manual, or power assisted equipment.	For appearance, preservation of the facility, health, and aesthetic reasons.
Pruning, Removing, Replacing *; includes growth control of shrubs, trees, and ground cover. Fertilizing shrubs, trees, and ground cover. Cleaning and removal of downed vegetation in landscaped areas.	Usually with chemicals, or manual, or power assisted equipment.	For safety, preservation of the facility, improving visibility, appearance, health, and aesthetic reasons due to accident, vandalism, disease, die out, or other plant damage.
Irrigation *; includes watering plants, repairing irrigation systems, monitoring and programming automatic irrigation system to insure system functionality.	Usually with manual, or power assisted equipment.	For preservation of the facility, and keeping the plants healthy.
Miscellaneous work such as pest control and inhibitor spray.	As applicable.	As applicable.

* These tasks are usually responsive, or assigned frequently. Telerobotics may be applied to automate many of these tasks.

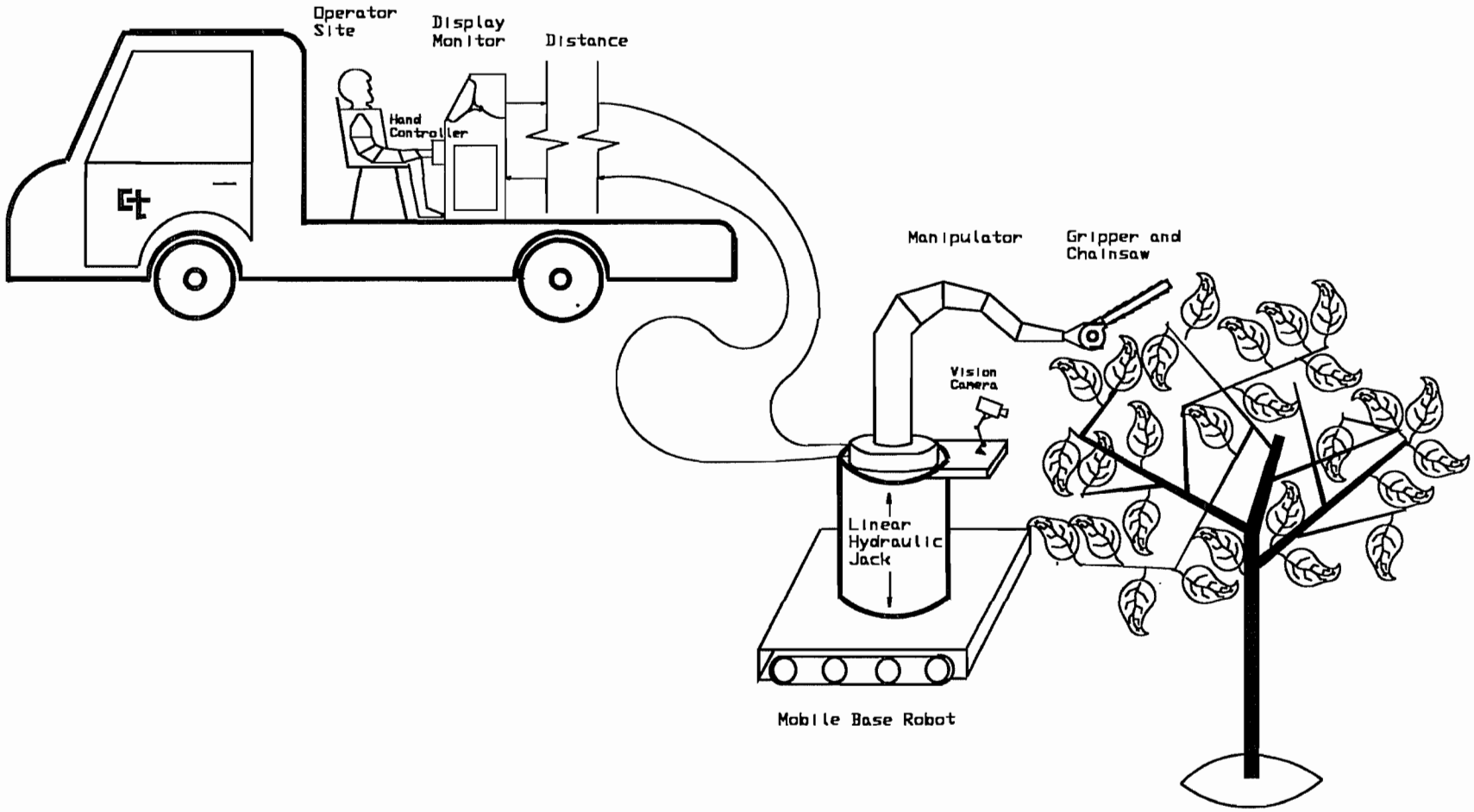


Figure 9. Telerobotics Application in Pruning Trees and Shrubs.

<<< Highway Bridge Inspection and Maintenance >>>

Maintenance and work performed on all structures which provide for passage of highway traffic over, through, or under obstacles such as bridges, tunnels, ferries or docks are also part of Caltrans responsibilities. This work includes bridge/tunnel inspection and repair, painting, and cleaning.

Inspection Tips and Details: In performing structure inspection, other than brief daily or weekly checks, the following points should be carefully observed:

1. Condition of approaches (paving, shoulder, slopes, and drainage).
2. Condition of deck wearing surface.
3. Condition of deck . Note excessive wear or vibration.
4. Condition of curbs and railing (chips, and cracks).
5. Condition of paint on railings.
6. Cracked or broken stringers.
7. Looseness or undue vibration of steel or timber truss members.
8. Crushed bearings or decayed timbers.
9. Broken chord member, sheared splices.
10. Condition of expansion bearings and deck expansion joints.
11. Condition of piles, piers, or abutments.
12. Accumulation of dirt and debris on decking, in drainage openings, etc.
13. Erosion or scour.
14. Fire hazards.
15. Spalled concrete.
16. Badly bent or broken steel or timber members.
17. Condition of stream channels.
18. Looseness, pounding or breaking of welds in steel grid decking.
19. Machinery bearings (lubrication, looseness, unusual noise, etc.).
20. Electrical contacts (corrosion, arcing, etc.).
21. Power for machinery (blown fuses or open circuit breakers, worn or broken power lines, excessive heating, etc.).

Minor Defects: Those which can be corrected with little or no risk of structure collapse or rendering of damage to adjacent or related members while making repairs or replacements. Examples include:

1. Damaged or misplaced clearance markers.
2. Damaged or missing advisory and warning signs (Speed and/or Weight Limit, Vertical Clearance, Narrow Bridge, One Lane Bridge, etc.)
3. Scaled or deteriorated paint on timber railings and curbs.

4. Damaged or deteriorated railing and curbs.
5. Uneven or cracked approach and deck surfacing.
6. Broken or loose timber decking.
7. Broken timber stringers.
8. Ineffective supplemental bents.
9. Accumulated drift adjacent to bents and piers.
10. Minor erosions.
11. Accumulated dirt or debris on decks, adjacent to bearings, and on chords of trusses.
12. Plugged drains.
13. Settlement or roughness of approaches.
14. Fire hazards.
15. Faulty electrical contacts.

Major Defects: Those defects involving individual members which effect structural stability of an entire span, thus requiring underpinning of the span or supplementing of the member before removal. Examples are as follows:

1. Bent or damaged steel beams, girders or truss members.
2. Cracked or spalled concrete members, other than curb and railing.
3. Crushed or decayed timber stringers, caps, posts or piles.
4. Broken or weakened chord members of failed truss joints.
5. Unusual looseness or vibration of truss members.
6. Loosened or decayed timber deck over an extended area.
7. Defective bearings on substructure or in deck at expansion joints.
8. settled bents or piers.
9. Major erosion or scour.
10. Lack of paint on steel members, other than curb and railing.
11. Extensive fire damages.
12. Poor alignment or balance of movable bridge spans.
13. Excessive noise or vibration from operating machinery.
14. Lack of lubricant in machinery bearings.
15. loose bolts.

Table 2. Principal Tasks in Highway Bridge Maintenance are Defined and Classified. These tasks are usually responsive, or assigned frequently.

TASK/PROBLEMS	HOW ?	WHY ?
Substructure; includes repair of abutments, backwalls,piers, wingwalls, columns, footings, struts, caps, buffers, protective coatings to concrete surfaces.	Usually manual, or power assisted equipment.	Usually for safety, and/or preservation of the facility.
Superstructure-Steel; repair or realign structural steel members, replace or tighten bolts or rivets, lubricating hinge pins & bearings, replace suspender rope shields, etc.	Usually electrical, or mechanical, or manual, or power assisted equipment.	Usually for safety, or preservation of facility, or traffic service.
Superstructure-Concrete; maintain and repair concrete members such as: decks, girders, etc., and applying protective coatings.	Usually manual, or power assisted equipment.	Usually for safety, and/or preservation of the facility.
Expansion Joints*; cleaning joints by any method;repairing spalls at joints, joint headers, expansion dams, grates, and shields; sealing joints.	Usually replacement, or manual, or power assisted equipment.	Usually for safety, and/or preservation of the facility.
Railings*;maintaining, repair, cleaning, and painting of all types and parts of bridge rails.	Usually manual, or power assisted equipment.	Usually for safety, and/or preservation of the facility.
Drainage Systems*; cleaning, maintenance, and repair of all parts of deck drainage system.	Usually manual, or power assisted equipment.	Usually for safety, and/or preservation of the facility.
Painting*; all rigging, surface preparation, painting of bridge structures, and all paint related activities.	Usually manual, or power assisted equipment.	For Appearance and preservation of the facility.
Miscellaneous; all legitimate work such as removal of debris, repair of ladders, walkways, etc.	As applicable.	As applicable.

* Telerobotics may be applied to automate many of these tasks.

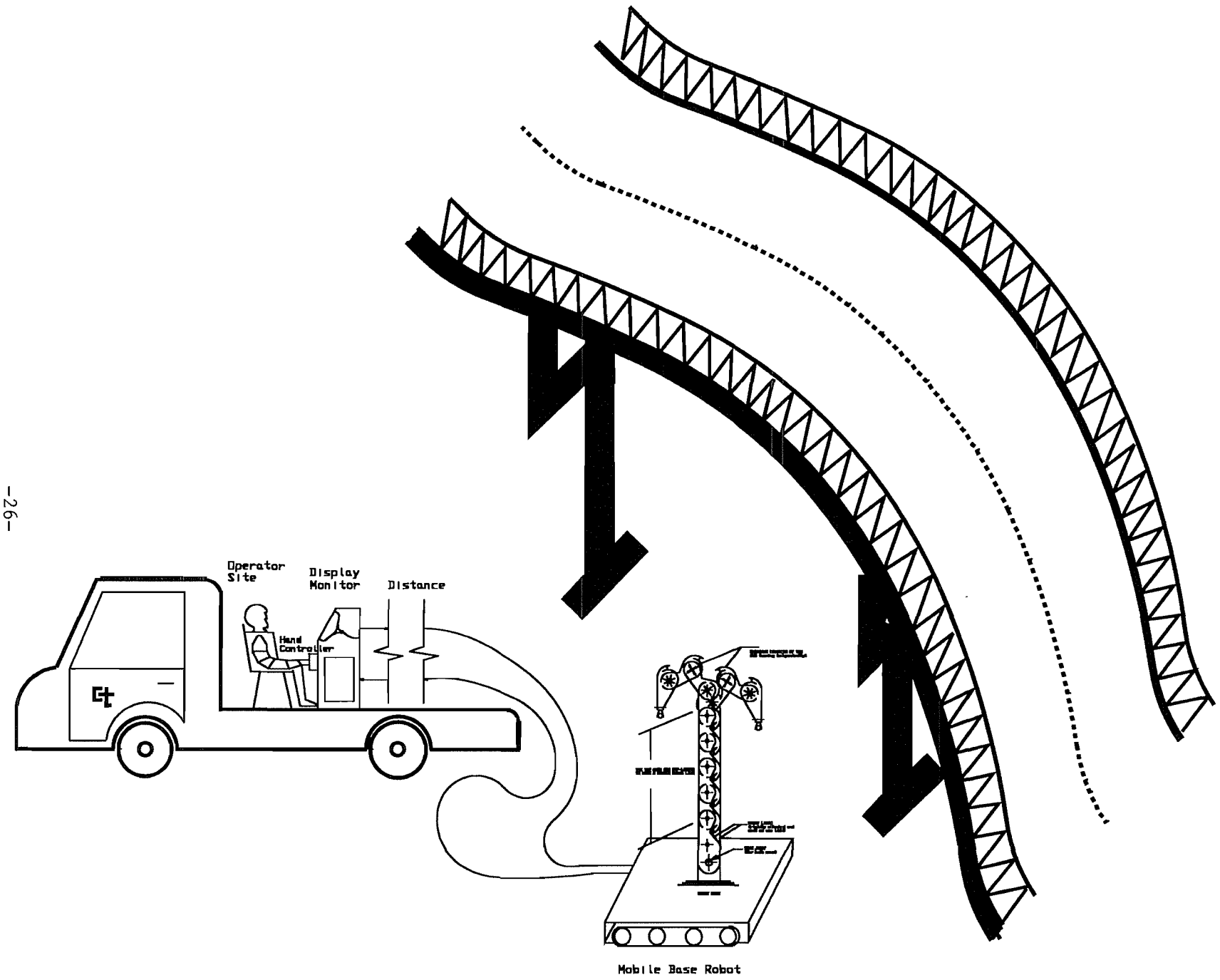


Figure 10. Telerobotics Application in Bridge Inspection and Maintenance [8-9].

<<< Highway Electrical Inspection and Maintenance >>>

This work includes inspection and maintenance performed on highway electrical facilities used for control of traffic signal systems, highway and sign lighting systems, toll bridge electrical systems, and all other related systems.

Table 3. Problems and Tasks Associated with Highway Electrical Maintenance (usually responsive, or assigned frequently) are Presented.

TASK/PROBLEM	HOW ?	WHY ?	TELEROBOTICS
Highway Lighting; any maintenance or repair on H.L.Systems	Troubleshoot and repair, changing lamps, etc.	Usually safety and appearance.	For changing lamps and light bulbs.
Sign Lighting; any maintenance or repair on S.L. Systems.	Troubleshoot and repair, changing lamps, etc.	Usually safety and appearance.	For changing lamps and light bulbs.
Toll Bridge Electrical Repair; work on toll collection equipment, toll bridge call boxes. Including night lighting patrols.	By toll collection equipment , or toll bridge call boxes.	Usually safety.	Maybe.
Traffic Signals; any repair to restore traffic signals to full service.	Usually knockdown replacement, re-lamp, troubleshoot & repair.	Usually safety.	For changing lamps or bulbs, and knockdown replacement.
Flashing Beacons; any repair to restore flashing beacons to full/temporary service.	Usually knockdown replacement, re-lamp, troubleshoot & repair.	Usually safety.	For changing lamps or bulbs, and knockdown replacement.
Ramp Meters; any repair to restore ramp metering to full or temporary service.	Usually knockdown replacement, re-lamp, troubleshoot & repair.	Usually safety.	For changing lamps or bulbs, and knockdown replacement.
Traffic Surveillance Equipment; repairs to restore equipment to full service. Including changeable message signs, and closed circuit televisions.	Usually bench work, or troubleshoot/repair.	Usually safety.	Maybe.
Traffic Counters & Speed Monitoring Equipment; any repair to restore these equipment to full or temporary service.	Usually bench work, or troubleshoot/repair.	Usually safety.	Maybe.
Miscellaneous; all other electrical maintenance.	Re-lamp, knockdown replacement, bench work, troubleshoot.	Usually safety and appearance.	Maybe.

<<< Traffic Guidance on Streets and Highways >>>

This category involves all work necessary to replace and maintain distinctive roadway markings such as: layout; re-striping existing stripes, and replacement of pavement markers; assembly, installation, replacement, and cleaning of traffic signs on state highways; repair and maintenance of energy dissipaters such as sand filled attenuators, water type bumpers, or truck escape ramps, etc.

Table 4. Principal Tasks in Highways and Streets Guidance.

TASKS	HOW ?	WHY ?	TELEROBOTICS ?
Pavement Striping; repair, replacement, or cleaning of painted or plastic lane lines, edge lines, or center lines.	Usually replacement.	Usually safety, or traffic service.	Applicable.
Pavement Markings; Spraying legends, crosswalks, gore points (paint/plastic).	Usually replacement.	Usually safety, or traffic service.	Applicable.
Raised Pavement Markers; Placement of reflecting or none-reflecting markers.	Usually replacement, or manual.	Usually safety, or traffic service.	Applicable.
Signs; repair / replace damaged, or missing signs. Tighten bolts, and clean dirty signs.	Usually replacement, or manual, or power assisted equipment.	Usually safety, or traffic service.	Applicable.
Roadside Markers; clean/repair/replacing roadside markers like postmile, culvert, and object markers.	Usually replacement.	Usually safety, or traffic service.	Applicable.
Guardrail; raising or replacing of guardrail sections, painting and cleaning of rails.	Usually replacement, or manual, or power assisted equipment.	Usually safety, or traffic service.	Applicable for cleaning and painting.
Median Barrier; repair or replacement of damaged metal beam/cable/ concrete barriers.	Usually replacement, or manual, or power assisted equipment.	Usually safety, or preservation of facility.	Maybe.
Vehicle Energy Attenuators; repair attenuator, or replace fill material.	Usually replacement.	Usually safety, or preservation of facility.	Maybe.
Miscellaneous; all other work in this category like traffic control devices, etc.	As applicable.	As applicable.	Maybe.

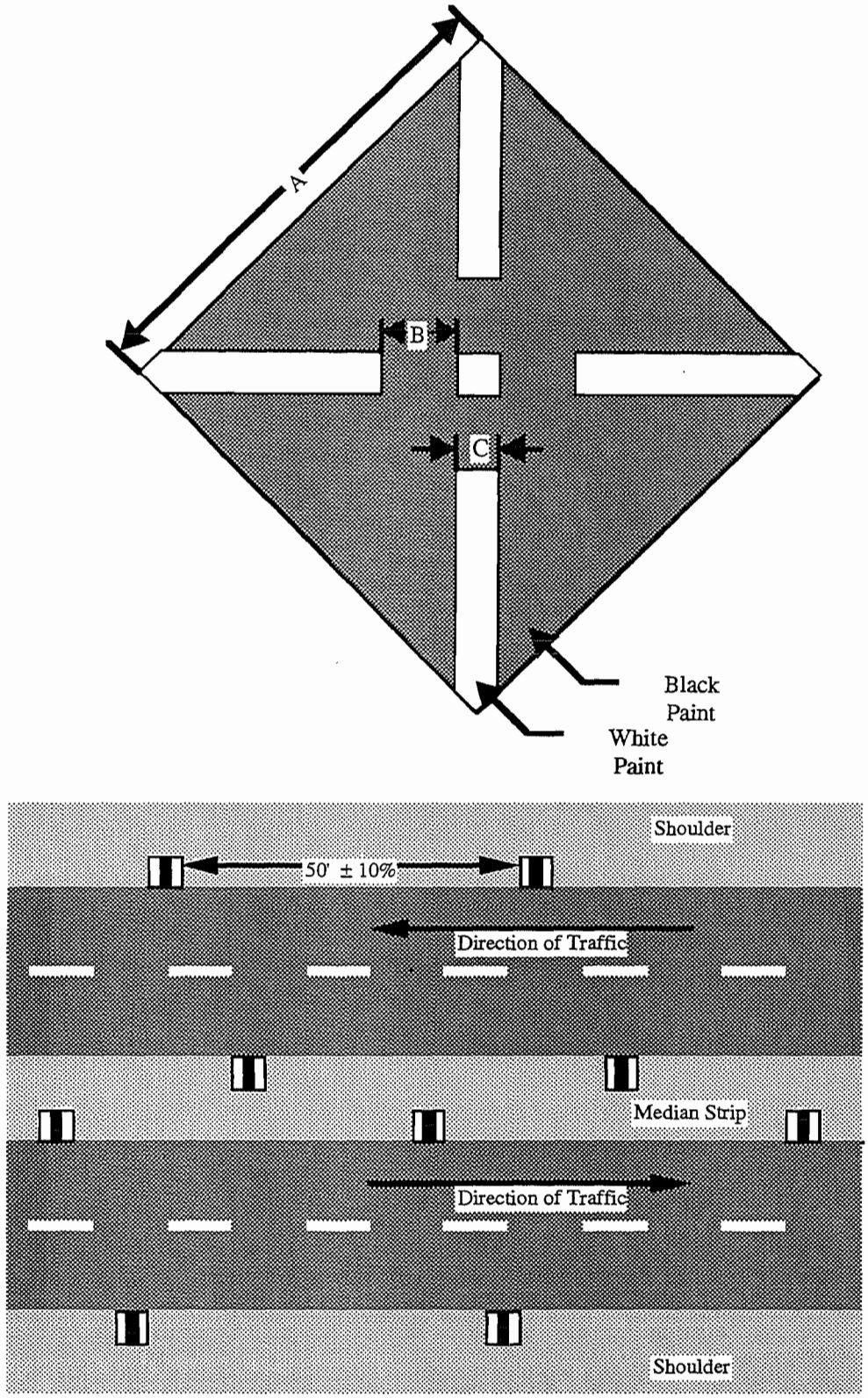


Figure 11. Photogrammetric Pavement Signs and Markers on Highways.

<<< Storm Maintenance >>>

This group of tasks includes routine patrol activities, maintenance, and repair of both minor and major damages caused by storm. It also covers the damage to highway facilities by other extraordinary events such as earthquakes, slides, tidal waves, etc. These tasks are usually responsive. Any site requiring an effort in excess of 150 hours at a spot location is considered as major damage.

Table 5. Principal Tasks in Storm Maintenance.

TASK	HOW ?	WHY ?	TELEROBOTICS ?
Sand/Rock Patrol and Removal; check for fallen rocks or drifted sand, and blade or remove them.	Usually power assisted equipment.	Usually safety, or preservation of facility.	Applicable in some situations.
Storm Patrol; patrolling during/after storms to check the function of drainage facilities, and cleaning debris from drains.	Usually power assisted equipment.	Usually safety, or preservation of facility.	Applicable in some situations.
Minor Slides Damage; cleaning up any small slide, or downed vegetation.	Usually power assisted equipment.	Usually safety, or preservation of facility.	Applicable.
Major Damage, Immediate Actions; emergency re-opening of closed roadway facilities.	Usually power assisted equipment.	Usually safety, or traffic service.	Applicable in some situations.
Major Damage Public Protection; placement & removal of warning devices, flag persons, lookouts.	Usually manual.	Usually safety.	Applicable.
Major Damage, Permanent or Long-Term Repairs; long-term repairs pending future restoration or reconstruction.	Usually power assisted equipment.	Usually traffic service, or preservation of facility.	Maybe.
Miscellaneous; repairing any other damages due to storm.	As applicable.	As applicable.	As applicable.

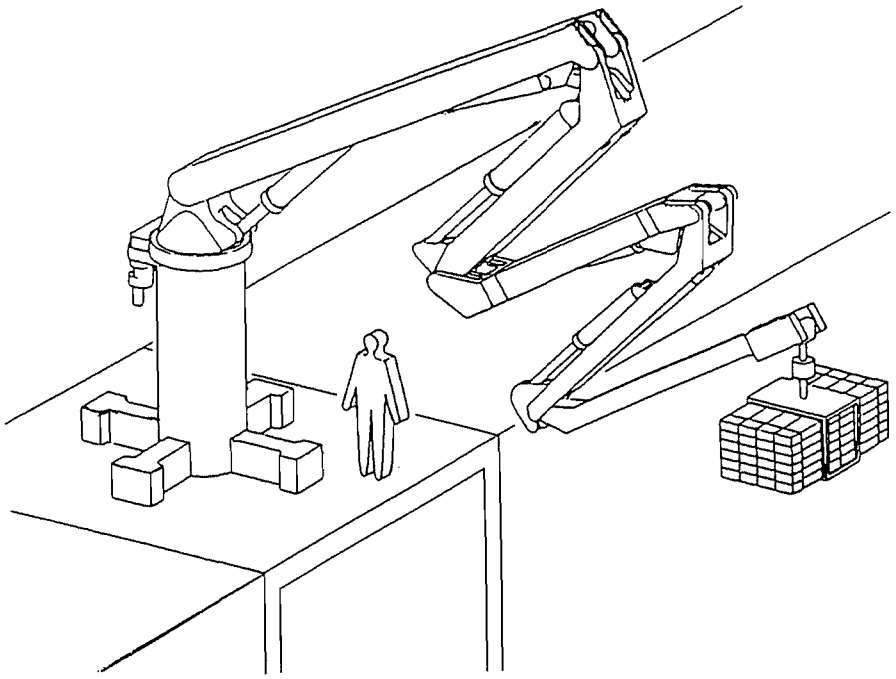


Figure 12. Mobile Telerobotics Systems as Flexible Cranes in Construction Industry, and in Storm/Earthquake Clean-up Picking Large Objects.

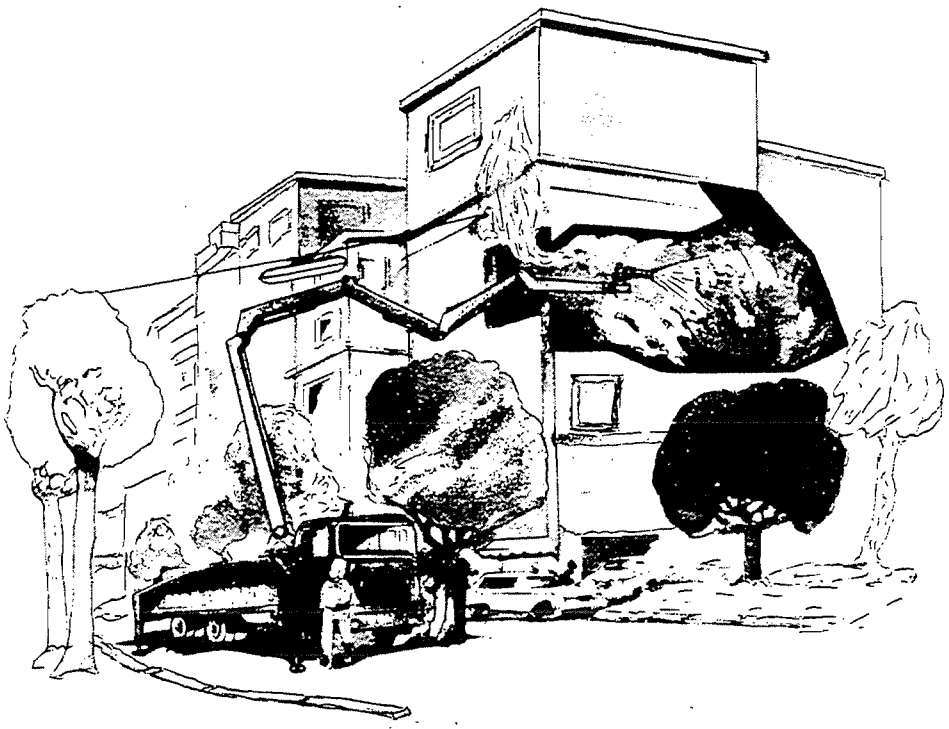


Figure 13. Mobile Telerobotics Systems Assisting in Fire Fighting.

<<< Snow and Ice Control / Removal >>>

This category includes all work in connection with snow removal, drift prevention, installation and maintenance of snow fences, snow-pole installation and removal, and skid chain fabrication and repair. Maintenance and control of chain control locations and appurtenant signs and gates, and mechanical spreading of abrasives and the use of both solid and liquid deicing agents are also included. These tasks are usually responsive, or assigned frequently.

Table 6. Principal Tasks in Snow and Ice Removal.

TASK	HOW ?	WHY ?	TELEROBOTICS ?
Remove Snow From Traveled Way; snow removal from traveled way, shoulders, rests, vista points, and other facilities.	Usually power assisted equipment.	Usually safety, or traffic service.	Maybe in some situations.
Cover Snow & Ice on Pavement; applying abrasives(i.e. salt), and spreading sand & cinders to pavements to improve traction.	Usually power assisted equipment.	Usually safety, or traffic service.	N/A.
Maintain Snow Poles, Signs and Appliances; Installation & removal of all special hardware such as poles, signs, chains, fences, etc.	Usually manual.	Usually safety, or traffic service, or preservation of facility.	Applicable in some situations.
Miscellaneous; any other legitimate work in this category.	As applicable.	As applicable.	As applicable.

<<< Maintaining Public Facilities >>>

This category consists of a wide variety of custodial maintenance in connection with rest-rooms, fountains, picnic areas at roadside rests, and other public facilities. Maintenance of roadway surfacing, signs, pavement markings, buildings, and electrical installations are also included in this category. These tasks are usually responsive or assigned frequently.

Table 7. Principal Tasks in Maintaining Public Facilities.

TASK	HOW ?	WHY ?	TELEROBOTICS ?
Roadside Rests; cleaning floors, walls, toilets, picnic tables, mirrors; mowing lawns, emptying trash, picking up litter, etc.	Usually chemical, or manual, or power assisted equipment.	Usually preservation of facility, or traffic service.	Applicable in some situations.
Vista Points and Park & Ride Lots; maintenance of facilities to insure cleanliness such as sweeping, weed control, maintaining plants, empty trash.	Usually chemical, or manual, or power assisted equipment.	Usually preservation of facility, or traffic service.	Applicable in some situations.
Weigh Stations and Weigh in Motion; regular maintenance and repair of weigh stations such as changing burned out lights, repairing fences, painting buildings, or patching pavements.	Usually manual, or power assisted equipment.	Usually preservation of facility, or traffic service.	Applicable in some situations.
Miscellaneous; all other legitimate work in this category.	As applicable.	As applicable.	As applicable.

<<< Containment and Removal of Substance Spills & Litter on Highway >>>

Caltrans is responsible for maintaining a safe and usable highway system. The department must attempt to contain spilled material, ascertain whether it is hazardous, and remove it. This area includes all work concerning roadbed and roadside clean-up operations to ensure that the highway presents a safe, neat, clean, and attractive appearance. Principal tasks in handling a spill are:

1. **Containment**
2. **Identification**
3. **Clean-Up**

The order of containment and identification may be reversed if the spill is not spreading rapidly, and identification may be done without delay. However, if an unidentified spill is expanding and threatening adjacent sensitive areas, containment must begin immediately if it can be done without exposure to

Table 8. Principal Tasks in Handling a Spill.

TASK	CONDITION OF SUBSTANCE	AGENCY
Containment	----------	* Qualified Spiller * CalTrans * Clean-Up Specialists
Identification	- Documented	* CalTrans * Qualified Spiller
	- Requires Chemical Analysis	* Clean-Up Specialists * Qualified Spiller
Clean-Up	- Unidentified, presumed Hazardous	* Qualified Spiller * CalTrans * Clean-Up Specialists
	- Identified, Hazardous	* Qualified Spiller * CalTrans * Clean-Up Specialists
	- Hazardous, but Routinely Handled by Caltrans	* Qualified Spiller * CalTrans
	- Non-hazardous	* CalTrans * Spiller

personnel. Conventional methods include interception with dikes or ditches at sufficient distance to avoid contact with the material.

Table 9. Principal Tasks in Highway Spills Clean-up. These tasks are usually responsive, and/or assigned frequently.

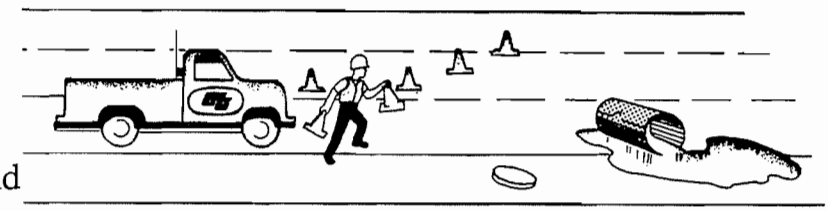
TASKS	HOW ?	WHY ?	TELEROBOTICS ?
Debris Pickup; removing of debris / carcasses from on or near traveled way.	Usually manual, or by power assisted equipment.	Usually safety.	Applicable.
Freeway Patrol; patrolling of the traveled way for litter or debris.	Usually manual, or by power assisted equipment.	Usually safety.	N/A
Sweeping; sweeping litter and debris in curbed and/or diked areas.	Usually manual, or by power assisted equipment.	Usually traffic service, or appearance.	Maybe.
Litter Pickup; picking up litter or debris within the right of way.	Usually manual, or by power assisted equipment.	Usually traffic service, or appearance.	Applicable.
Spills; handling of spilled materials on and off the traveled way or unpaved shoulder.	Usually chemical, or manual, or by power assisted equipment.	Usually safety, or traffic service.	For identification and clean-up of toxic/non-toxic materials.
Graffiti; control of Graffiti and/or painting of signs on & off the traveled way.	Usually chemical, or manual, or by power assisted equipment.	Usually safety, or traffic service.	Applicable.
Miscellaneous; all other legitimate work in this category.	As applicable.	As applicable.	As applicable.

As a Caltrans maintenance employee, if you find spilled chemicals and don't know what to do???

- Stay Clear,

- Protect Traffic,

- Do not leave the site, and



- Call for the Experts and/or Telerobotic Vehicles to assist you in:

  * Containment,

  * Identification, and

  * Clean-Up.

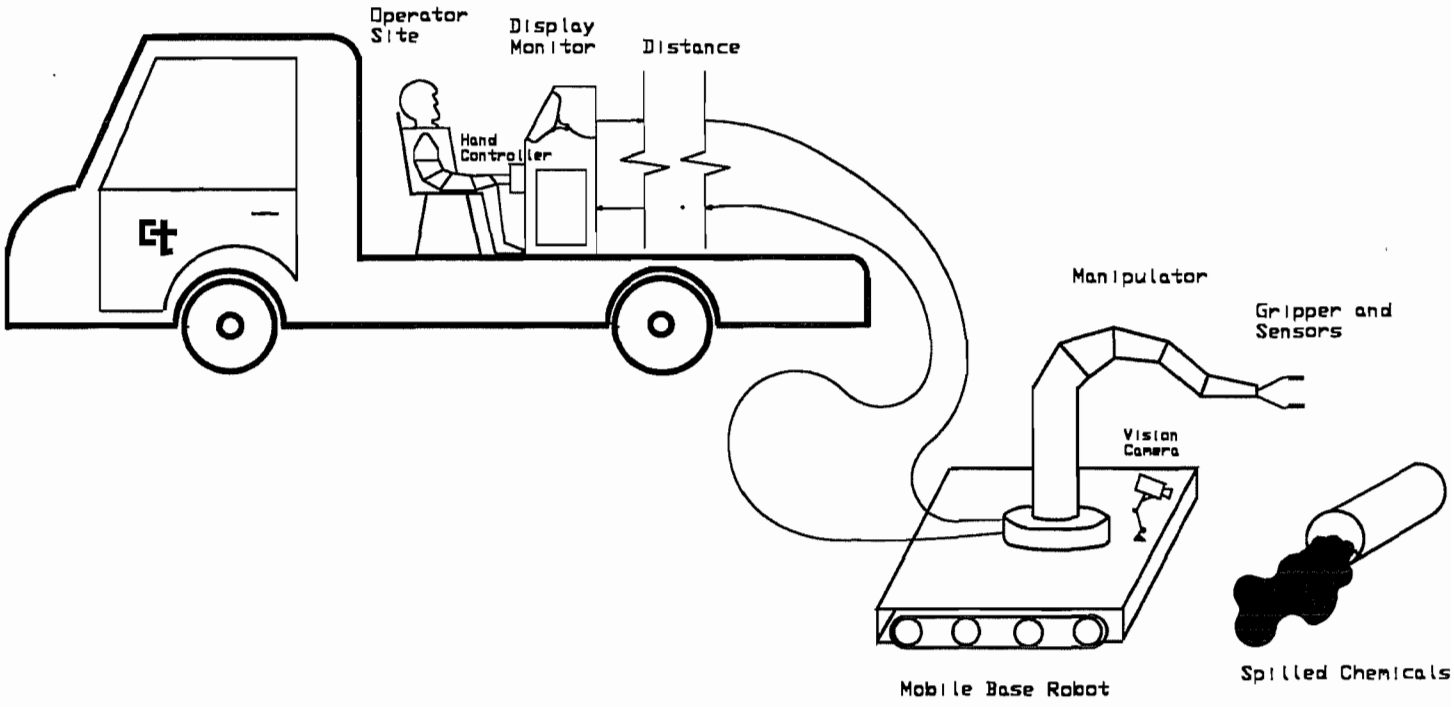


Figure 14. The operator commands the mobile robot using teleoperation. Feedback from visual and tactile sensors to the operator provides telepresence.

<<< Maintaining Flexible and Rigid Pavements >>>

Maintenance and repair of surface, base, and paved or asphaltic concrete shoulders are generally performed under this category. All highways with asphaltic concrete surfacing are considered as flexible pavement, and those with cement concrete pavement are considered as rigid. This category generally covers tasks such as crack/joint repair, pot holes/local depressions repair, paved shoulder repair, etc. These tasks are usually responsive or planned condition.

Table 10. Principal Tasks in Maintaining Flexible and Rigid Pavements.

TASK	HOW ?	WHY ?	TELEROBOTICS ?
Crack/Joint Repair; filling Transverse / Longitudinal cracks or joints.	Usually manual. An automatic system is also developed by the AHMCT center.	Usually preservation.	Applicable.
Poor Ride Quality; pavement defect is causing the traveling public an irritating ride. Includes dips, abrupt settlements.	Usually overlay, or grind, or replacement.	Usually traffic service.	Maybe applicable.
Structural Pavement Failure; pavement failure that requires repair and an overlay or seal. Incudes block / alligator cracking or base repair, etc.	Usually seal, overlay, grind, or replacement.	Usually preservation.	Maybe applicable.
Pot holes / Local Depressions; all work for repairing them.	Usually manual.	Usually preservation, or traffic service.	Maybe applicable.
Preventive Maint.; work that delays deterioration of the pavement.	Usually seal.	Usually preservation.	Maybe applicable.
Paved Shoulder Repair; all other shoulder repairs, including surface defects and joint displacements (up/down).	Usually seal, overlay, or grind.	Usually preservation.	Maybe applicable.
Bridge Approach / Departure; repair of structural failure and/or riding quality of bridge approach or departure slab.	Usually replacement, overlay, or power assisted equipment.	Usually preservation, or traffic service.	Maybe applicable.

<<< Maintaining Tubes and Tunnels >>>

Tunnel or tube maintenance includes washing, cleaning, tile repair, and the maintenance of electro-mechanical equipment such as: ventilating system, fire alarm system, carbon-monoxide analyzer system, electrical and lighting system, etc. Tunnel structural repairs are also performed under this category.

The above services and repairs are usually performed by electrical, mechanical, manual, and/or power-assisted equipment. They are performed usually for the reasons of safety, preservation of the facility, and traffic service. Telerobotics may very well have an application in this category.

Figure 15. A TUNNEL. This term is used in the name of a passageway which carries state highway traffic underground such as through a hill or mountain.

Figure 16. A TUBE. This term is used in the name of a passageway which carries state highway traffic below or under a body of water.

III. CONCLUSIONS

The maintenance and construction activities of the California Department of Transportation have been studied. In addition, possibilities of applying telerobotics technology to highway maintenance and construction were explored. An assessment of the Caltrans Highway Maintenance Manuals indicates that telerobotics could be applied to automate the following operations: crack sealing, highway signs and guide marker washing, containment and removal of hazardous materials, trimming roadside trees and shrubs, storm/earthquake clean-up, highway pavement markings, traffic signals and highway lighting systems maintenance, bridge inspection and maintenance, tunnels and tubes maintenance, and fire fighting.

In developing a telerobotics maintenance system to automate the above tasks, one must consider the following parameters: environmental conditions, payload, workspace, accuracy, structural stiffness/strength, degrees of freedom, highway mobility, and definitely the economic issues.

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