

Teleoperation and autonomy

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Slide material contributions from Robin Murphy, Jussi Suomela

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How is a robot controlled?

1. By the human operator
2. Mixed human and robot
3. By the robot itself

Levels of autonomy!

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Levels of autonomy

1a. Remote control

- Visual contact / no sensor feedback



1b. Tele-operation – OCU provides sensor data

- Simple t-o: control of individual joints, motors etc.
- User space t-o: motion primitives e.g. internal closed loop velocity control of vehicle
- Safety-guarded t-o: e.g. emergency stop

2. Semi-autonomous (supervisory) control

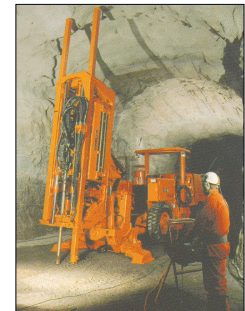
- Shared control
- Traded control

3. Autonomous robots – not here yet

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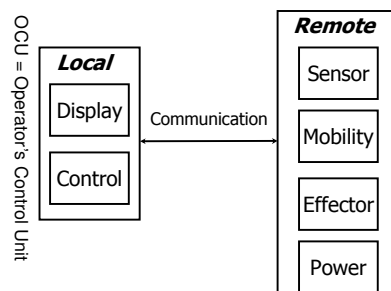
Remote control

- Not only toys
- The operator has most of the time straight visual contact to the controlled target
- Control commands are sent electrically by wire or radio



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Components of a Teleoperated system



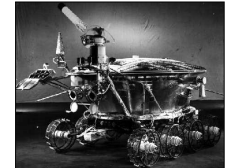
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Teleoperation Applications

Space

- Perfect for teleoperation: safety and costs
- Problems with very long delay

Lunokhod 1 (Луноход) "moon walker"
First t-o vehicle on the Moon 1970



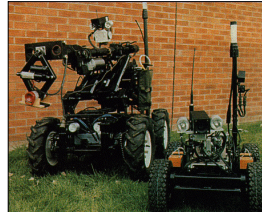
Sojourner, first t-o vehicle on another planet. Landed on Mars 1997



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Teleoperation Applications

- Military
 - underwater
 - ground
 - air
 - semiautonomous / internal closed loop control
- Anti terrorist
 - typically internal closed loop control



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Teleoperation Applications

Medical

- Endoscopic surgery
 - Surgery through small incisions or natural body openings
 - minimal damage, smaller risks
- Telesurgery
 - Surgeons can work over distances



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Teleoperation Applications

Mining

- Unsafe areas
- Cheaper operation



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Teleoperation Applications

USAR robots

(WTC Scenario by Hunt)

"Remote" robot



"Local" operator



"Local" feedback



All images from <http://www.usarcenter.com> and adapted to depict USAR robots chosen for pedagogical purposes. Two different robotic systems are shown.

Problems with Tele-operation



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Problems with Tele-operation (Murphy after 9/11)

- Lighting conditions
 - High variation in ambient light makes computer vision tasks difficult
- No "tactile" feedback
 - Couldn't really tell when the robot was stuck or when it was free
 - Robot didn't have proprioception (internal sensing)
 - Operator didn't have an external view of the robot itself
- Communications
 - High dropout rate after about 10 feet away!



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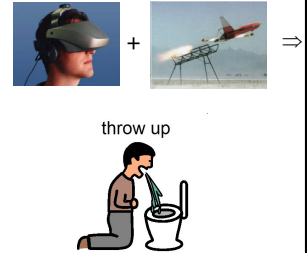
Simulator Sickness

- Common in Teleoperation
- Similar to motion sickness, but can occur without any actual motion of the operator
- Symptoms: apathy, general discomfort, headache, stomach awareness, nausea...

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Simulator Sickness

- Caused by *cue conflict*
- In cue conflict different nerves get different information from the environment
- Typically conflict between visual and vestibular inputs
- Especially when HMD is used and the time lags in vision and control



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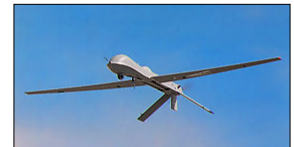
Delays

- Acceptable control loop times
 - Nyquist sampling theorem: measuring frequency $> 2 \times$ system frequency
 - In practise (mobile machines):
 - $< 0.1s$: perfect
 - $< 0.5s$: ok
- Delays depend on
 - Transmission speed (max. 300 000km/s)
 - System delays
- Long delays cause *Cognitive fatigue*

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Not really unmanned...

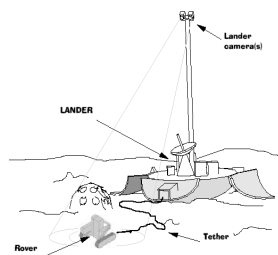
- 4 people to control it (52-56 weeks of training)
- one for flying
 - two for instruments
 - one for landing/takeoff
 - plus maintenance, sensor processing and routing



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Long delay teleoperation

- Earth-Moon-Earth: 2 seconds
- Earth-Mars-Earth: 37 seconds
- No possibilities for external closed loop control with a moving robot
- Instead: "move and wait" teleoperation



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Tele-operation

- + Doesn't depend on machine intelligence
- + Doesn't depend on a present operator
- Depend on good communication
- Hard for the operator \Rightarrow
 - Cognitive fatigue
 - Simulator sickness
 - Many operators required

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Tele-systems Best Suited for Tasks:

- that are unstructured and not repetitive
- that require dexterous manipulation, especially hand-eye coordination, but not continuously
- that require object recognition or situational awareness
- that don't need display technology that exceeds bandwidth and time delays limitations of the communication link
- where the availability of trained personnel is not an issue

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Ways to improve Tele-operation

- Improve the HRI \Rightarrow less demanding for operator: TELE-PRESENCE
- Make the robot more intelligent \Rightarrow less demanding for operator and communication system: SEMI-AUTONOMY

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Tele-presence (remote presence)

"Virtual reality"

Provide sensory feedback such that the operators feels they are "present" in robot's environment

- Ideally all human senses transmitted
 - Vision, hearing and touch
 - Smell and taste
 - Balance, motion
- Demands higher bandwidth
- Less problems with Cognitive fatigue and Simulator sickness

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Vision

- Humans get 90% of their perception through vision
- "To see is to believe"
- Eyes are very complex opto-mechanical systems
 - FoV is (H)180 deg x (V)120 deg
 - Focused area only few degrees
 - Movements over whole area
- Extremely difficult system to be imitated

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Interface with Vision

- Head tracking
- HMD \Rightarrow relatively good feeling of presence



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Hearing

- Human range 16 – 20000Hz
- Important in telepresence
- Noise can be filtered out

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Touch & Force

- Tactile information ("touch")
 - mechanoreceptors – activated by pressure on the tissues
- Kinesthetic information ("force")
 - sense of position and motion of limbs and associated forces conveyed by receptors in the skin around the joints, tendons, and muscles, together with neural signals

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Interface with Haptic feedback

- tactile sensing of the robot manipulator is fed back to the fingers of the operator



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Interface with kinesthetic (force) feedback

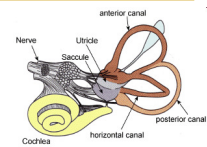
- Force is fed back to the operator
- Generates a real response in gripping and manipulation tasks
- Also in virtual environments



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Vestibular sensors

- Located inside the inner ear
- Responds to
 - Angular acceleration (and thus rotation)
 - Spatial orientation
 - Linear acceleration in the horizontal and vertical plane, i.e. to gravity
- ⇒ pose and movements of the head are detected



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Vestibular feedback

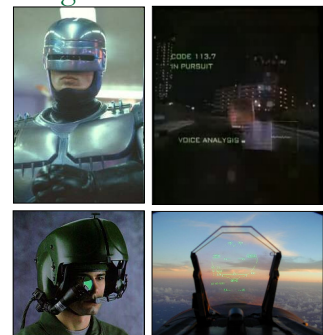
- Usually not needed in teleoperation
- Expensive to implement
- Usually in simulators to create presence
- If vision and vestibular sensors mismatch => simulator sickness



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Better than the real thing: Augmented reality

- Real information (usually image data) is mixed with additional virtual information
- Numerical information, real-time models, etc.



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Tele-presence applications

- ❖ Lawn mower
- ❖ Tele conferences
- ❖ "Taking care of" elderly
- ❖ Baby sitters
- ❖ Home robots
- ❖ Security
- ❖ Garden clubs

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Ways to improve Teleoperation

- Improve the HRI => less demanding for operator : TELE-PRESENCE
- Make the robot more intelligent => less demanding for operator and communication system : SEMI-AUTONOMY

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Semi-autonomus control

- General idea:
 - Teleoperation for hard tasks
 - Autonomy for simple tasks
- Reduces cognitive fatigue/simulator sickness
- Demands lower bandwidth
- Less sensitivity to delays

Two major types:

- Shared control
- Traded control

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Shared control

The human operator

- Delegates a task
- Monitors the process
- Interrupts for hard sub-tasks, and if anything goes wrong

Two parallel control loops (the human and the robot control different aspects of the problem):

1. Autonomous (high intensity)
2. Teleoperated (low intensity)

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Shared control

Example (space robotics)
Task: *Release the bolts on shield H34.*

- Autonomous motion to shield H34.
- The human monitors and may interrupt if the situation becomes unsafe.
- The human releases the bolts by tele-operation

Note: Constant monitoring needed



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Traded control

- The human operator
 - Initiates action
 - Neither monitors nor interrupts
- If the operating conditions go outside the abilities of the robot, control is transferred to the human
- When the human takes over, she has to quickly acquire *situational awareness*
- When the robot takes over, it has to quickly acquire *situational awareness*

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Situational awareness

Most often refers to the operator's perception of the world

Important for

- pure teleoperation
- operator take over in semi autonomous systems:
Low awareness \Rightarrow longer take-over time

Three levels of situation awareness (Endsley 2000):

1. there is perception of the relevant status information
2. there is comprehension of the status information
3. there is prediction, i.e. the ability to use this comprehension to consider future situations

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Situational awareness

Experiences of robotic rescue researchers at the WorldTrade Center (Casper 2002):

- 54% of the time spent was reported to have been wasted trying to determine the state of the robot
- The operator gets confused by the egocentric camera view regarding Attitude (roll, pitch)

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Traded control - Sojourner



The first Mars rover, launched in December 1996. Landed on the surface of Mars on July 5, 1997.

11.5 kg

630 x 480 mm

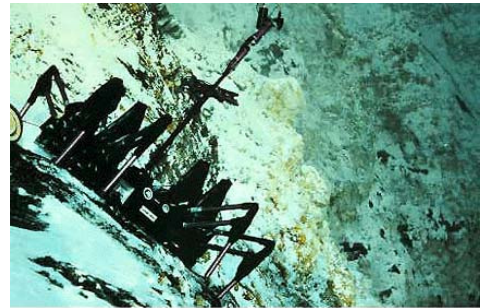
Worked by Teleoperation and semi-autonomous control

Example: "DRIVE TOWARD THAT STONE"

Sojourner avoids obstacles on the way

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Dante I



Dante I on the rim of Erebus.

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Dante II



Mt. Spurr, Alaska.

Photo by Bill Ingalls/NASA

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Dante II



Dante II was airlifted to the Mt. Spurr exploration site because of the weather and rough terrain. Even though it was summer in Alaska, snow-melt land-based vehicles could not be used to transport Dante II to the rim of the volcanic crater.

Photo by Bill Ingalls/NASA

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Interface design



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Interfaces

- Between the operator and robot/vehicle
- Strong connections with HMI and HCI, but additional problems
- As usual:
The user interface is absolutely critical
 - make up 60% of commercial code



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Interface layout

depends on

- The level of autonomy
- The level of sensing/perception



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Levels of autonomy (again)

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Interface - Remote control

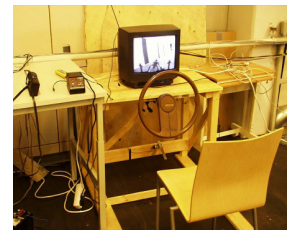
- No sensor feedback
- Low bandwidth



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Interface –Simple Tele operation

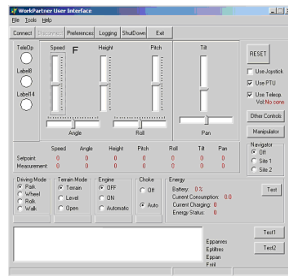
- "Direct" tele-operation
- Same view as onboard
- External closed loop control of motor speeds, height, ...
- Operator controls with hand controllers (like onboard)
- Realtime operator decision making is necessary
- High bandwidth, low delay communication



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Interface – User-space Tele operation

- Multimodal/multisensor
- Integrated display with combined sensor information
- Internal control-loops for speed, height, ...
- (Autonomous safety functions)



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Interface – Semi-autonomous Control

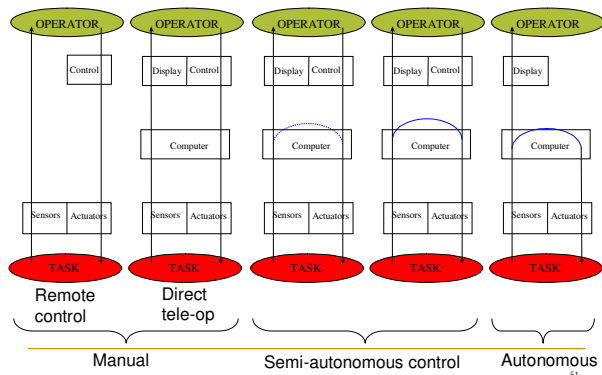
Support for

- high-level commands
 - Move to ...
 - Grip
 - Look for ...
- monitoring of success/errors
- Interruption of tasks



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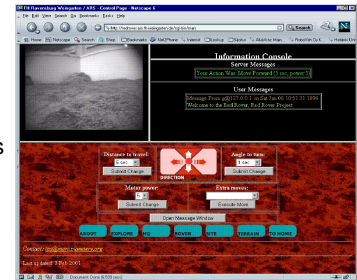
Control methods (Sheridan 2003)



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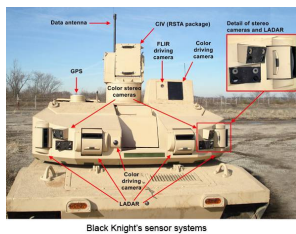
Novel interfaces

- "novel" is relative
- gestures
- gazes
- brainwaves
- muscle movements
- WEB interfaces
 - multimodal
 - supervisory



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The Black Knight



Black Knight's sensor systems

http://www.youtube.com/watch?v=hRDs__6dFsE&feature=related

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The Black Knight's OCU

- Objects that are detected are overlaid on the driving map enabling drivers to maneuver around them
- Can plan paths to be manually driven by its operator
- *Guarded teleoperation:* The vehicle stops when it detects lethal obstacles in its path.



Black Knight's Robotic Operator Control Station (ROCS) displays images from the vehicle's driving cameras and includes a game controller-style hand controller and a touch screen interface for maps and vehicle systems.

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The Remote Robotic Reconnaissance Vehicle (R3V)

- Enhanced situational awareness using fused sensors



The robotic vehicle with a FLIR (forward looking infrared) and a low-light camera



Operator Control Unit (OCU), for control and display

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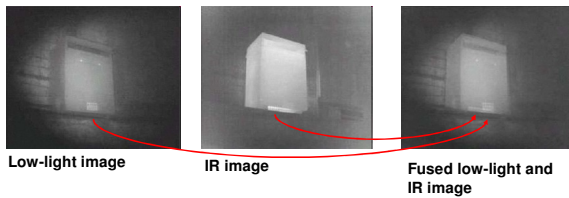
OCU – Operators Control Unit



- Vehicle status and remote video via a 1024x768 LCD display
- Vehicle control: Speed, Steering
- Camera control: zoom camera, fader controls and camera tilting, manual iris, focus and gain control.

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Fusion of IR and camera



Low-light image

IR image

Fused low-light and IR image

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Assessing the usability of a HRI

- Effectiveness:** the percentage of a task that the user is able to complete
- Efficiency:** depends on the time needed to complete a given task
- User satisfaction:** subjective

The three measures are weighted:

- Life critical applications:** more weight to the effectiveness
- Time critical applications:** more weight to efficiency
- Entertainment:** more weight to user satisfaction

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Camera display modes

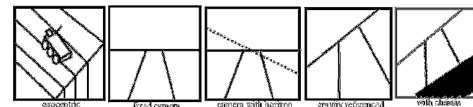
Three basic ways to monitor a robot's location, orientation and the world around it

- Egocentric:** Inside-out perspective; "Through the windshield"
- Exocentric:** Outside-in perspective; Radio-controlled planes.
- Mixed perspective:** Inside-out perspective but includes information about orientation, e.g. artificial horizon displays

(Wang, Levis, Hughes 2004)

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Camera display modes

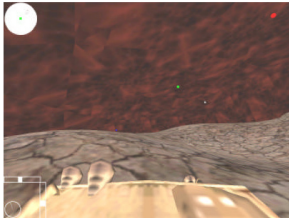


Problems:

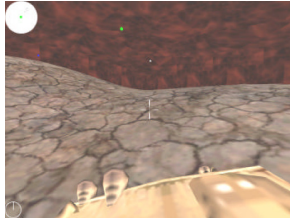
- Exocentric views hard to achieve
- A fixed camera on the vehicle may give an illusion of flatness
- The angle of the horizon line gets confused with the roll of the vehicle; the "graveyard spiral" (Roscoe 1999)
- Gravity referenced display with the tilted vehicle's chassis improves situational awareness

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Gravity referenced display



Fixed Camera
(note the roll display in lower left corner)

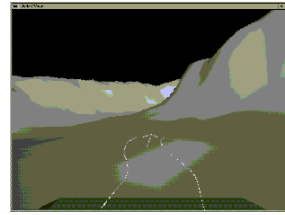


Gravity Referenced Display
(note the indication of roll provided by the tilt of the robot's body)

Pictures: Jijun Wang

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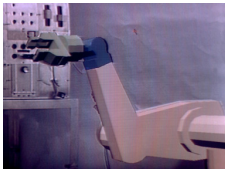
Predictive Displays



- Predicts 5 seconds ahead by simulation based on user actions and vehicle velocity
- Superimposed information on the display:
 - The length of the lines: Indirect velocity information
 - An arrow describing the vehicle's predicted position and heading
- A representation of the vehicle body

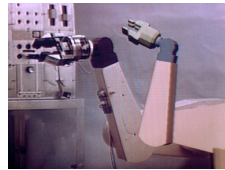
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Predictive Displays



(Kim and Bejczy, 1993)

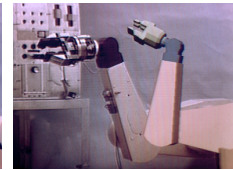
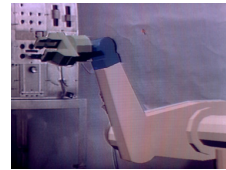
The operator can manipulate a computer graphics simulation of the slave robot.



This simulated robot can be superimposed over the video returning from the remote site

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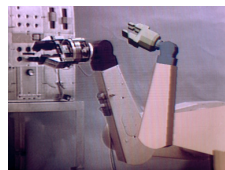
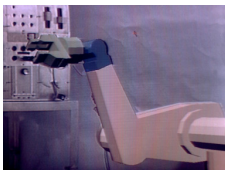
Predictive Displays



"Time Clutch" : a foot pedal which, when pressed allows the simulated robot to move without the physical robot moving. The operator's inputs are held in

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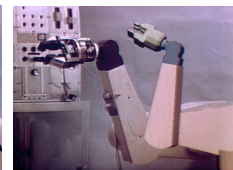
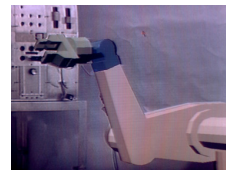
Predictive Displays



"Position clutch" : disengages the operator's commands entirely from the physical robot so that the operator can fine-tune positioning in the simulator.

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Predictive Displays



"Time brake" : emptying out the command memory until the simulated robot "comes back" to the current physical robot state

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References

S. Lichiardopol, A Survey on Teleoperation, Technische Universiteit Eindhoven, 2007

M. Endsley, 'Theoretical Underpinning of Situation Awareness: Critical Review (2000)' in Mica R. Endsley and Daniel J. Garland (Eds.) *Situation Awareness Analysis and Measurement*. Lawrence Erlbaum Associates, Mahwah, New Jersey, pp. 3-32, 2000.

Jijun Wang, Michael Lewis, Stephen Hughes, Gravity-Referenced Attitude Display for Teleoperation of Mobile Robots, In PROCEEDINGS of the HUMAN FACTORS AND ERGONOMICS SOCIETY 48th ANNUAL MEETING 2004.