Collaborative Control:
A Robot-Centric Model for Vehicle Teleoperation

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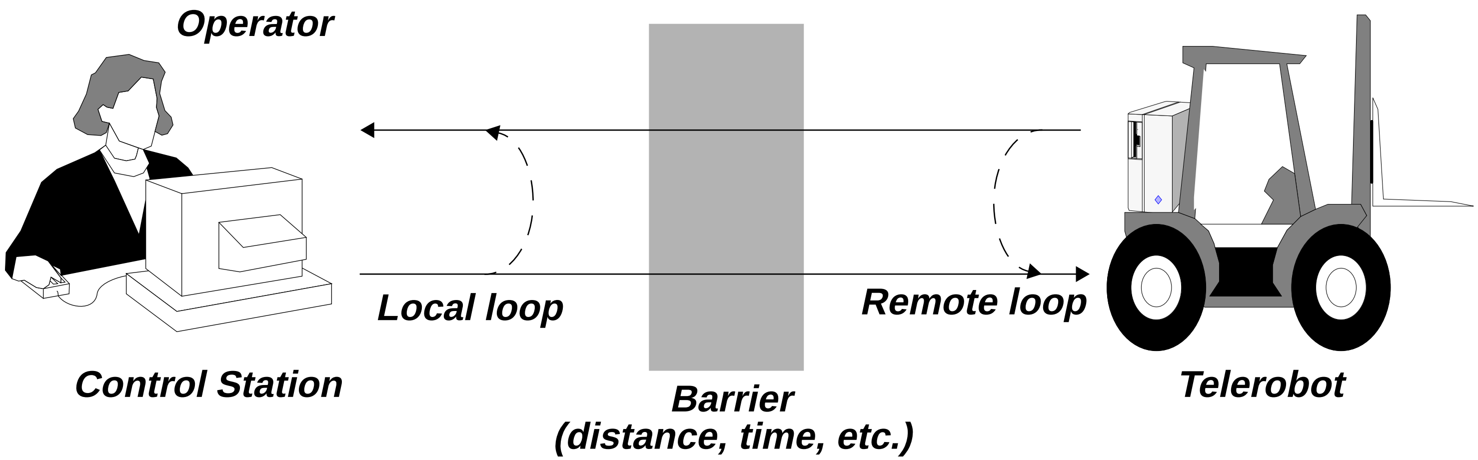
Vehicle Teleoperation



- **Remotely controlling a vehicle**
  - ground, underwater, free-flying, etc.
- **Operator at a control station**
  - input devices (mouse, hand-controllers)
  - feedback displays (video, graphics, numerical)
- **Telerobot**
  - sensors, actuators, and often some level of autonomy

Vehicle Teleoperation

A spectrum of control modes . . .

- **Direct teleoperation**
  - actuators are "directly" controlled by the operator at all times
  - if the operator stops, control stops (but vehicle might not . . .)
  - traditionally used for underwater ROV's and UGV's
- **Supervisory control**
  - specify "symbolic", "high-level" goals for autonomous execution
  - analogy to human group interaction (supervisor to subordinate)
  - requires some level of robot autonomy

System Design Issues

- **Control station**
  - video displays (image frequency, resolution, color, display device)
  - GUI's (maps, 2D/3D graphics, audio)
  - control devices (hand-controllers, mouse, speech recognition)
- **Communication link**
  - bandwidth (sensor data, video, commands)
  - latency (processing, transmission, etc.)
- **Telerobot**
  - autonomy & intelligence
  - perception, cognition, actuation, etc.
- **Operator**
  - experience, skill, knowledge, training
  - sensorimotor constraints (bandwidth, reaction times, etc.)
- **Rate controlled with "inside-out" camera video**

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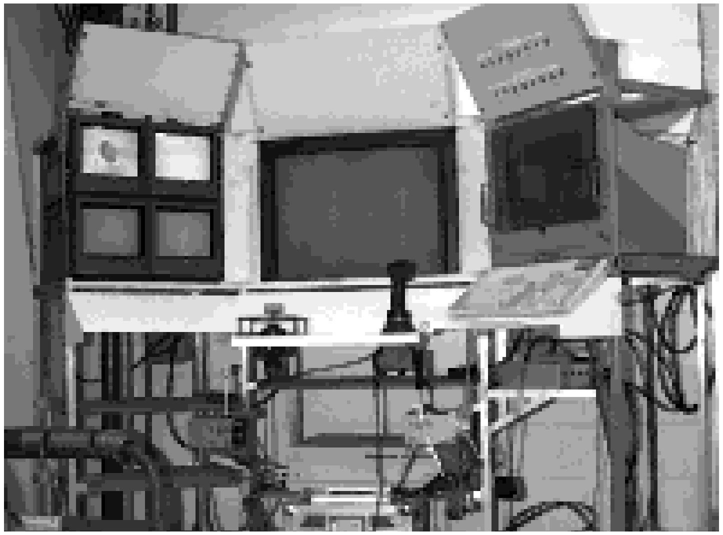
Vehicle Teleoperation Systems

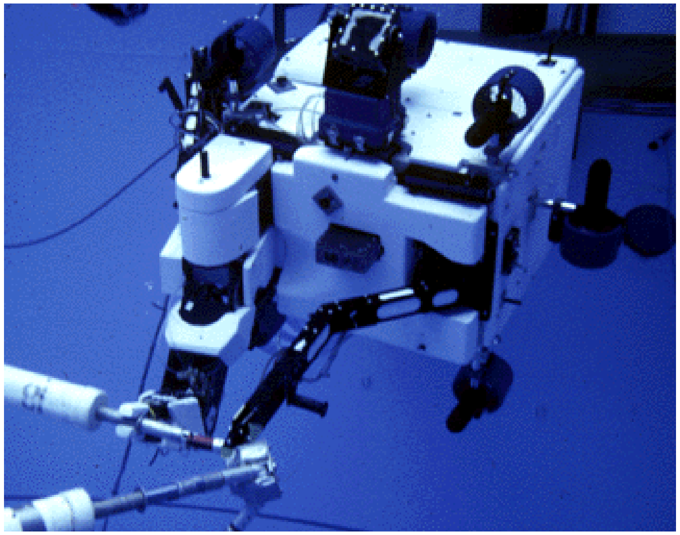
- Sandia National Laboratory (1984-88)
- underwater ROV's
- free-flying space robots (MIT/U-Md Space Systems Lab, 1980-98)
- ROBOCON (CMU, 1997)

• **Position controlled with multi-modal, supervisory control interfaces**

- Ames Marsokhod and "VEVI" (NASA ARC, 1992-96)
- Dante II and "UI2D" (CMU, 1994)
- Navlab II and "STRIPE" (CMU, 1995-1997)
- Nomad and the "Virtual Dashboard" (CMU and NASA ARC, 1997)
- Sojourner and the "Rover Control Workstation" (NASA JPL, 1997)

Vehicle Teleoperation Systems





RECS (MIT / U-Md. Space Systems Lab, 1989-93)

- **Rate-controlled teleoperation of underwater free-flying robots (BAT, MPOD, SCAMP)**
- **Multiple video displays, hand controllers, GUI's**

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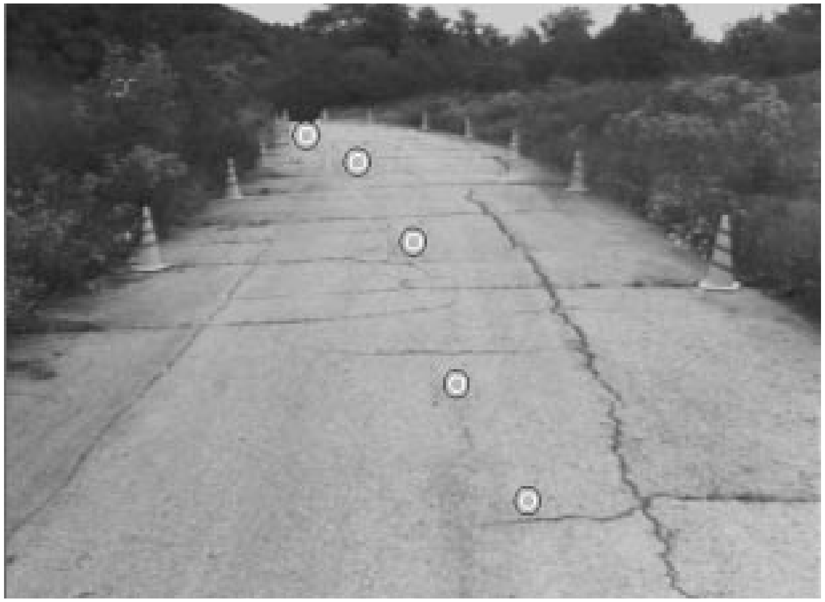
Vehicle Teleoperation Systems



STRIPE (CMU, 1995)

- **Supervisory (position) control of Navlab II**
  - Operator selects waypoints in an image (sent from the vehicle)
  - Waypoints are sent to vehicle controller for execution
- **Can work with low-bandwidth, high delay**

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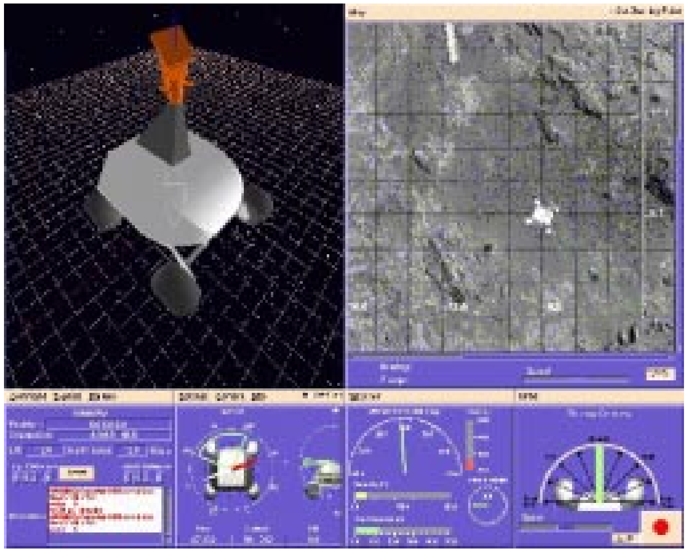
Vehicle Teleoperation Systems



Nomad / Virtual Dashboard (CMU / NASA ARC, 1997)

- **Rate control driving with optional safeguarding**
  - Operator selects turn radius and speed
  - Multiple feedback displays (vehicle attitude, position, status)

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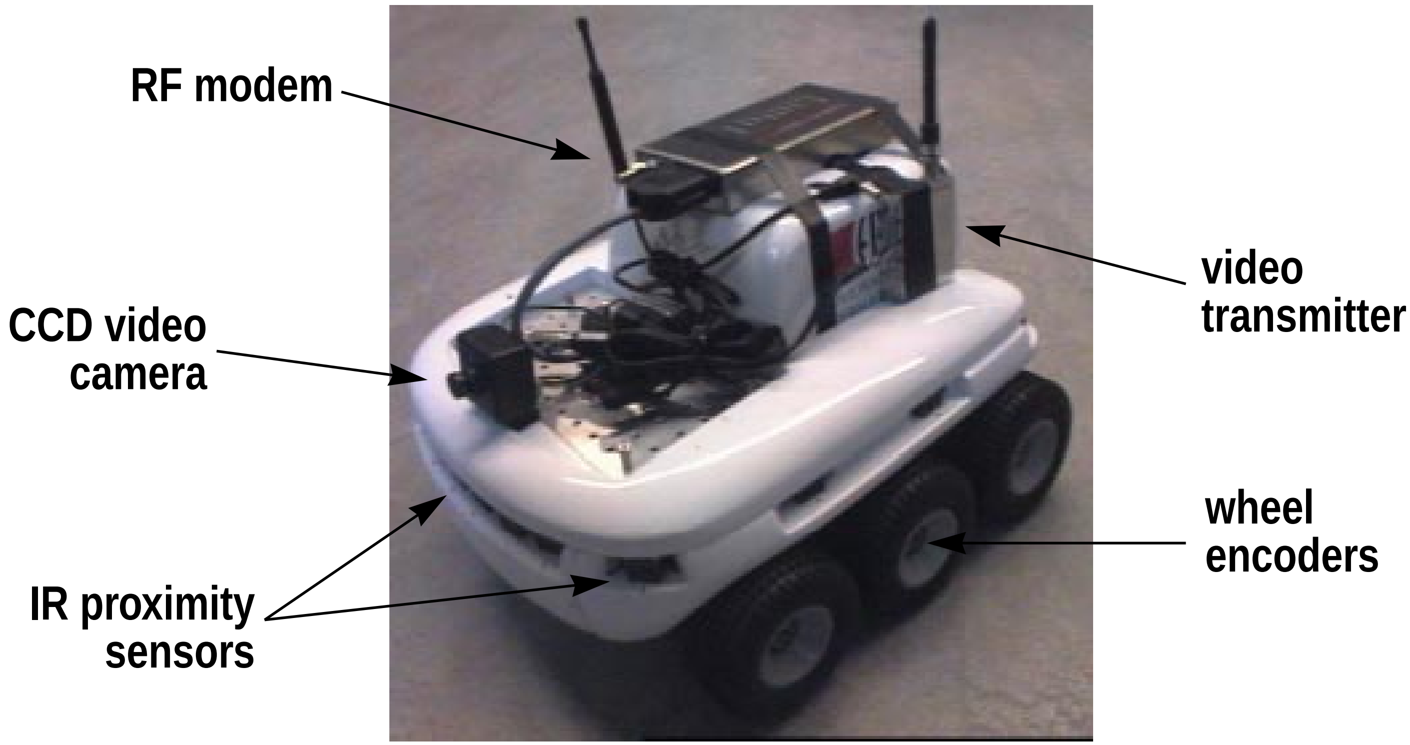
Previous Work

Safeguarded Remote Driving

- **Vehicle teleoperation in unknown, unstructured environments (reconnaissance, surveillance, ...)**
- **Multimode control**
  - direct actuator (motor) control
  - rate control (heading, translation)
  - safeguarded position control
- **System**
  - Koala mobile robot
  - Saphira robot control architecture
  - wireless communication links
  - X/Motif GUI (SGI based)

Koala Mobile Robot



- 6-wheeled, skid-steered vehicle (K-Team)
- 32x32x20 cm, NiCd powered, Motorola 68331

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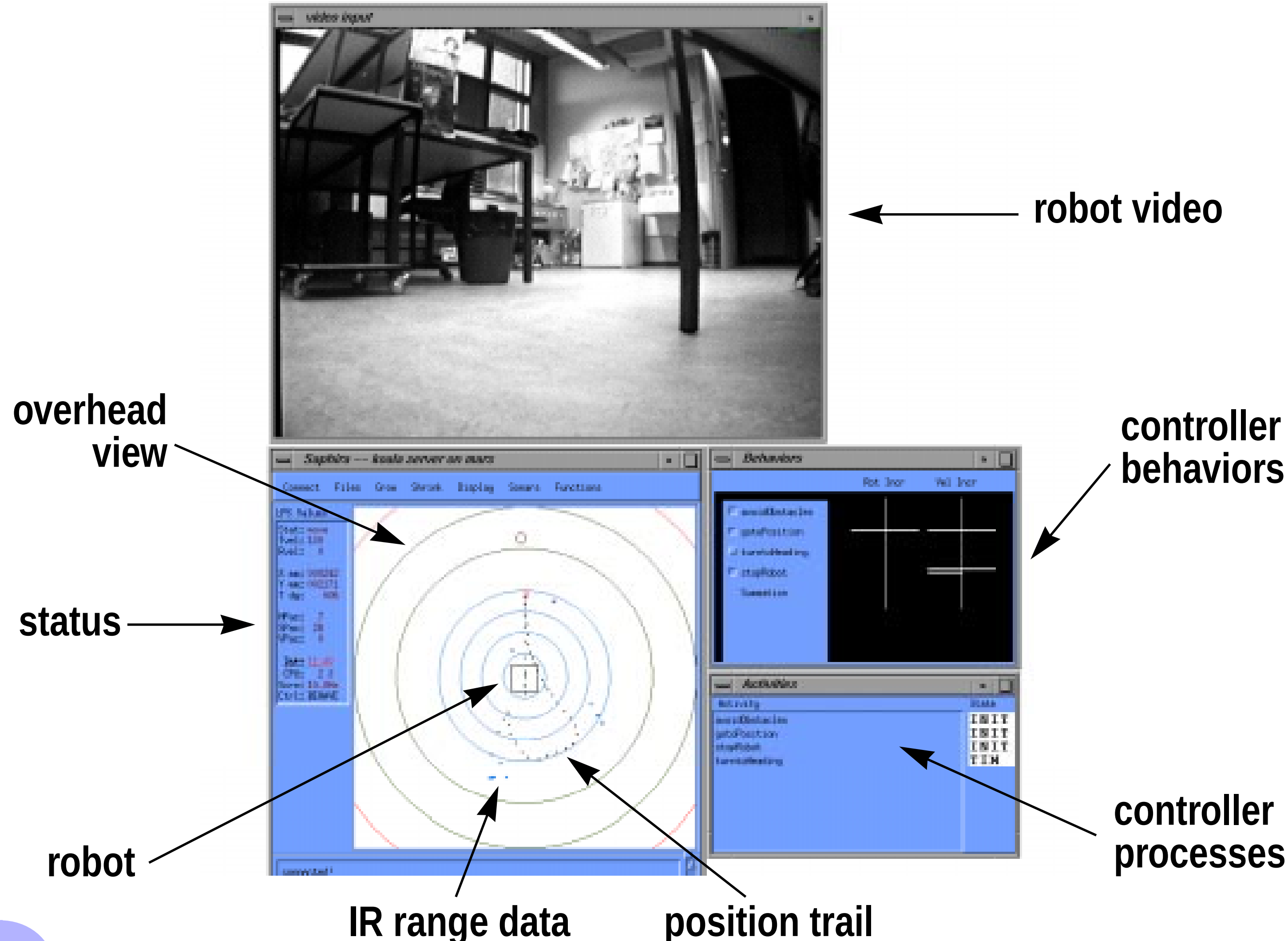
Remote Driving Interface



VIDEO

“Safeguarded Remote Driving”

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Experiences

- **Inadequate sensing for safeguarded teleoperation (limited range IR's, lack of tilt)**
- **Variety of operator errors**
  - imprecise control (tracking error, oversteering)
  - failure to detect obstacles
  - vehicle rollover & pitchover
  - judgement errors
  - loss of situational awareness

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Vehicle Teleoperation Problems

- **Operator**
  - loss of spatial awareness: disorientation, loss of context
  - cognitive errors: “mental model” vs. what’s really out there
  - perceptual errors: distance judgement, display interpretation
  - poor performance: imprecise control, obstacle detection
  - other: simulator sickness, fatigue
- **Communications**
  - reduced efficiency & performance: latency, bandwidth, reliability
- **System**
  - inflexibility: static data & control flow, task specific automation
  - lack of robustness: operator variation, human resources, etc.

→ *These problems are due to the traditional teleoperation model: “human as controller”*

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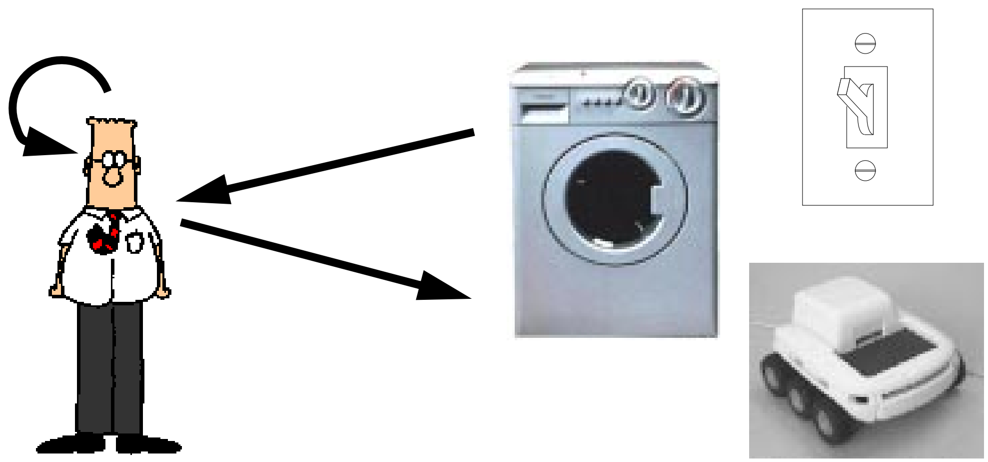
"Human as Controller"

- **Throughout the history of telerobotics, systems have been *human-centric***
  - designed and operated with a human point of view
  - natural consequence: telerobotics evolved directly from other human controlled systems
- **Dominant paradigm: "human as controller"**
  - human receives information, processes it, and select an action
  - action serves as control input to the system



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“Human as Controller” Problems

- **Performance limited by human resources and capabilities**
  - operator handicap: limited skill, knowledge, attention
  - sensorimotor limits: reaction time, decision making, fatigue
  - errors: cognitive, perceptual, motor skills
- **Efficiency bounded by quality of human-machine connection**
  - operator interface: display quality, modeling, control inputs
  - communication link: noise, power, delay
- **Robustness reduced by imbalaced roles (human as supervisor, robot as subordinate)**
  - human “in-the-loop” cannot perform other tasks
  - robot may have to wait for human directives

A Novel Approach

- **We want to teleoperate vehicles**
  - in difficult environments (planetary surfaces, active battlefields)
  - in spite of poor communications (low bandwidth, high delay)
  - with high performance regardless of operator capabilities

THESIS STATEMENT:

Teleoperated systems can be significantly improved by modeling the human as ***collaborator*** *rather than* ***controller***

- **A new teleoperation model: *collaborative control***

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Collaborative Control

- **A "robot-centric" model**
  - human is treated as an imprecise, limited source of planning and information (just like sensors, maps, and other noisy modules)
  - robot works more like a "peer" and makes requests of the human (note: it still follows higher-level strategy set by the human)
  - use collaboration to perform tasks and to achieve goals
- **Human and robot engage in *dialogue***
  - to exchange ideas and resolve differences
  - to allow the robot more execution freedom (robot decides when to follow, modify, or ignore human advice)
  - to negotiate who has "control" (i.e., who is "in charge")
- **Analogy to human collaborators**
  - work jointly towards a common goal
  - each collaborator has self-initiative and contributes as best she can
  - allow negotiation and discussion to occur

Related Research

Supervisory Control

- Human specifies “high-level” goals which are achieved autonomously by the robot
- Must divide problems into achievable sub-goals
- Classic reference:
  - Ferrell, W., and Sheridan, T., “Supervisory Control of Remote Manipulation”, IEEE Spectrum, Vol. 4, No. 10, 1967

Multi-operator teleoperation

- Operators share, trade and negotiate control
- Multiple operators and/or multiple robots
- Example (“virtual tools”)
  - Cannon, D., and Thomas, G., “Virtual Tools for Supervisory and Collaborative Control of Robots”, Presence, Vol. 6, No. 1, 1997.

Related Research

Cooperative teleoperation ("teleassistance")

- **supply aid (support) to the operator in the same manner an expert would render assistance**
- **Example (knowledge-based operator assistant)**
  - Murphy, R., and Rogers, E., "Cooperative Assistance for Remote Robot Supervision", Presence, Vol. 5, No. 2, 1996.

Human-Robot Architectures

- **Directly address mixing humans and robots**
- **Can incorporate humans as system module**
  - DAMN, TCA
- **May use prioritized control**
  - layered hierarchy: NASREM
  - safeguarded teleoperation: Ratler & Nomad

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Research Issues

Human Computer (Robot) Interaction

- **“non-traditional” roles of operator and robot**
  - robot seeks dialogue, not just direction
  - human may make requests but the robot may not follow
- **difficulties for the robot**
  - human is not omniscient (but we knew that...)
  - needs to recognize when human is unavailable or unhelpful
- **toughest research question**

At what level does the robot need to model the human?

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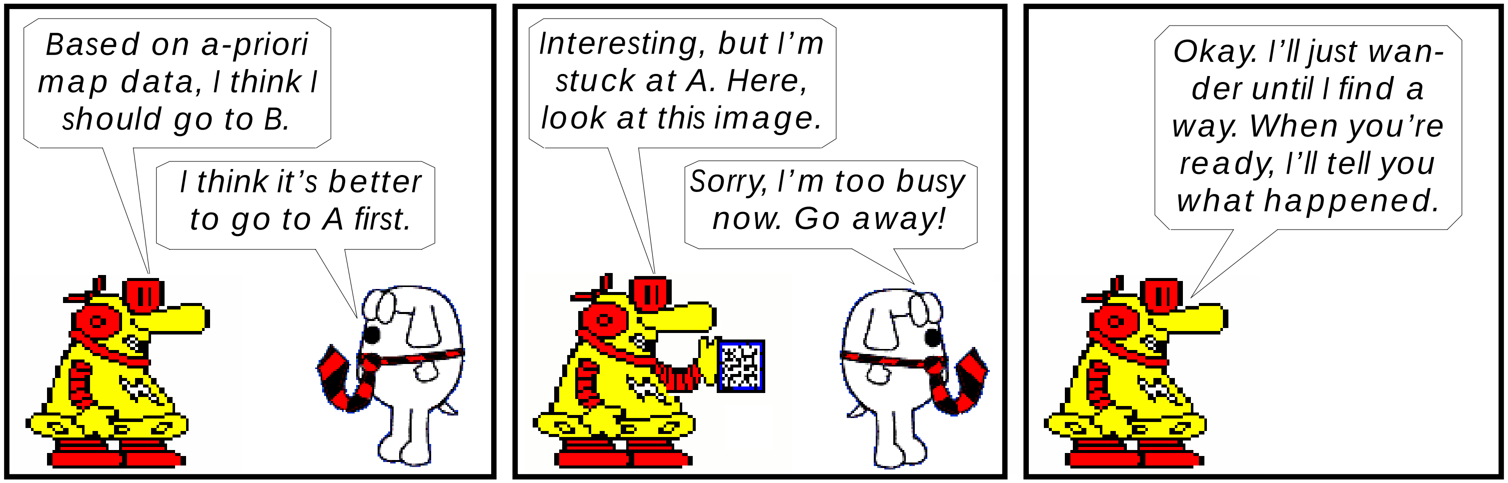
Research Issues

Dialogue



- **good dialogue is 2-way and interactive**
- **must support info exchange, negotiation, etc.**
- **toughest research question**

How does the robot format its queries & interpret the responses?

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Research Issues

User Interface Design

- **Traditional teleoperation: UI serves the user**
  - displays provide information for decision making
  - mode changes are user triggered
  - “user centered design”
- **Collaborative control**
  - need to support the robot’s needs
  - have to consider “peer” interactions
- **toughest research question**

How should the interface operate? Shared/traded with the robot?

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Research Issues

System Design

- **Impact of dialogue and peer interaction**
  - control: sharing, trading, negotiation
  - mechanism for deciding who is “right”
- **Information handling**
  - sensor data for human and robot perception
  - abstract data for decision making
  - coherent format for dialogue
- **Invalid advice**
  - how to cope with out-dated or irrelevant advice
- **toughest research question**

How does the system decide what action to take?

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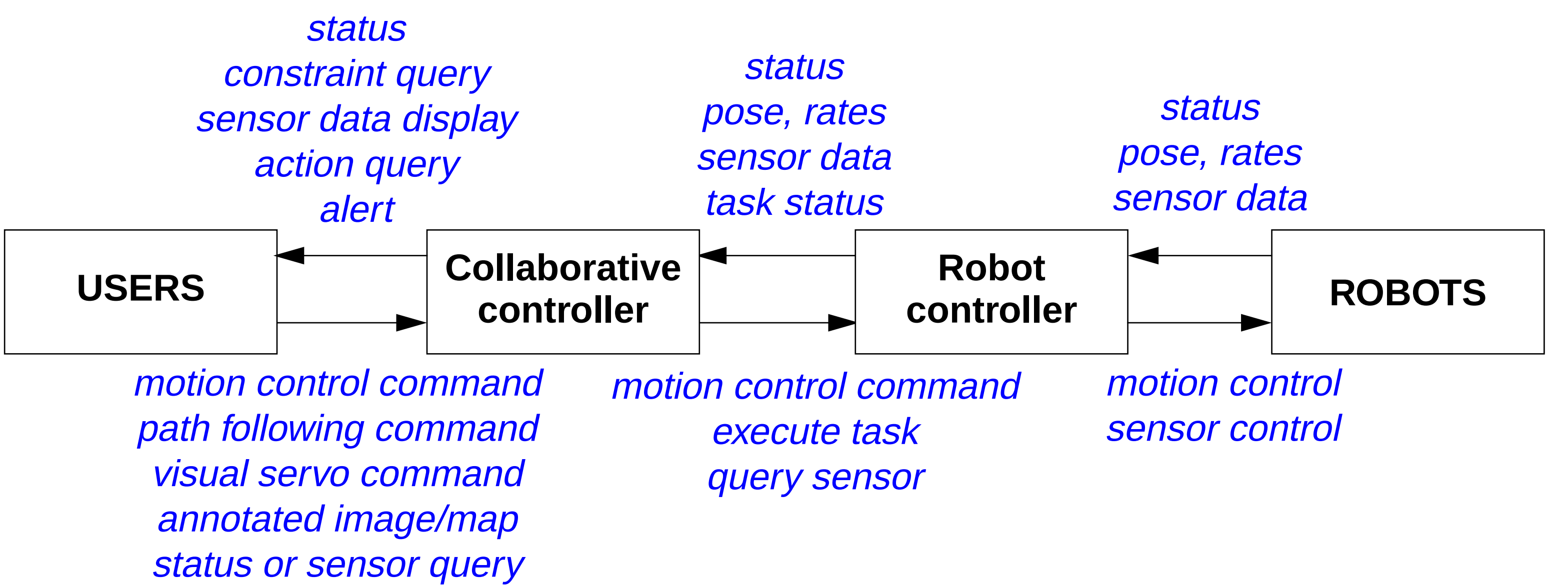
Thesis Work

Dialogue

- **Limit scope: do not address broad research topics (e.g., use of natural language)**
- **Focus: vehicle mobility (remote driving)**



Thesis Work

Dialogue

- **Research questions**
  - how does the robot decide when to say something?
  - how does the robot decide what/which is the right question to ask?
  - how does the robot interpret a response (or lack of response)?
  - how does the robot communicate and negotiate with the human?
- **Scenario**
  - robot is stuck & must decide how to get "unstuck" (i.e., what to do)
- **Possible queries**
  - "I think I'm in a cul-de-sac. Look at this map (track of robot's prior movements). Do you concur?" (*asking confirmation*)
  - "Look at this image and tell me where to go." (*seeking direction*)
  - "Unless you say otherwise, I am going to start randomly wandering in 10 seconds." (*stating a position)*

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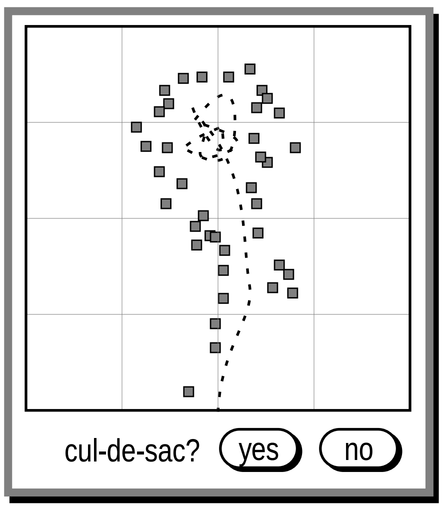
Thesis Work

Dialogue

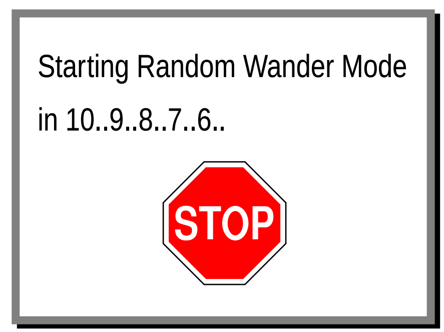
- **Impact on user interface design**
  - What interaction style(s) and technique(s) are appropriate?
  - modal dialog box? pop-up window? level of context/detail?

"I think I'm in a cul-de-sac. Look at this map. Do you concur?"



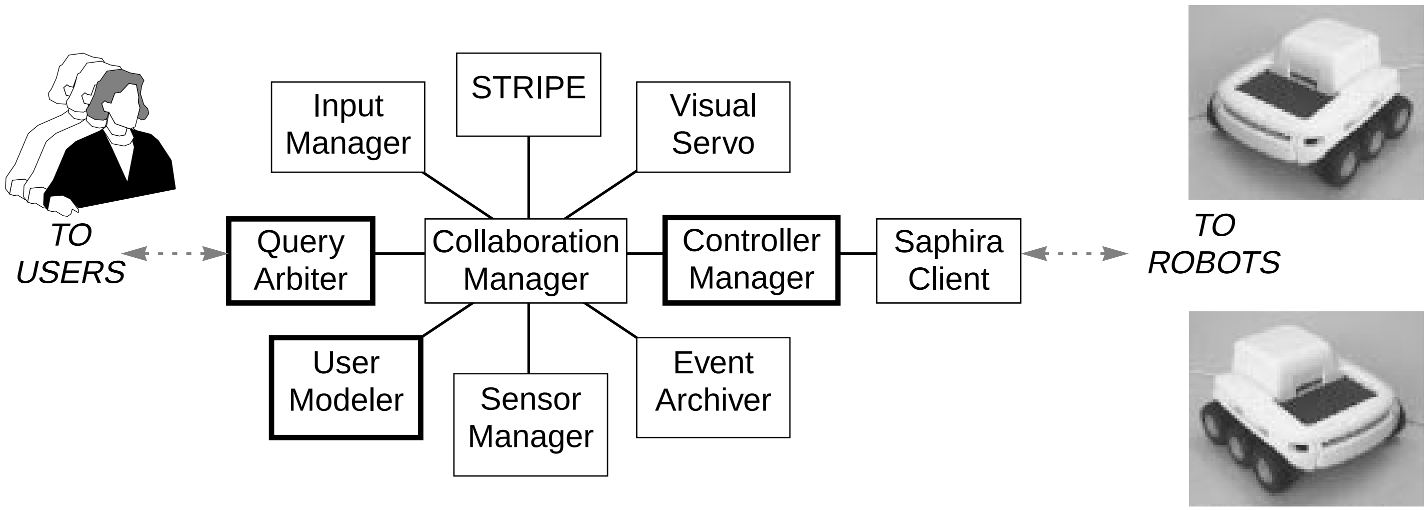
"Look at this image and tell me where to go."

"Unless you say otherwise, I am going to start randomly wandering in 10 seconds."



Thesis Work

Collaborative Controller



- **Mediates between human and robot**
- **Supports dialogue, control, robot needs**
- **Hardest components to build**
  - Controller manager: decides who is "in charge", what action to take
  - Query arbiter: decide which query to ask the human and when
  - User modeler: estimate user capability and availability

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Thesis Work

User Interface

- **If collaborative control works, it should be possible to optimize use of human resources**
- **Thus, I plan to build a "non-intrusive" user interface for remote driving**
  - non-intrusive = does not excessively consume resources such as attention, cognition, motor skils, etc.
- **Design criteria**
  - high usability (usable by mom, unbreakable by a baby)
  - low cognitive workload ("tell-at-a-glance")
  - touch screen based (rapid, non-intrusive input)
  - support different types of mobile robots (Koala, Pandora, etc.)

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Thesis Work

Experiments

- **validate and assess collaborative control**
- **field tests and human performance study of a remote driving task (single operator)**
- **experimental variables**
  - independent: comm link, user resources, user, etc.
  - dependent: performance, usability, workload, etc.
- **potential test scenario**
  - drive course from A to B while distracted (e.g., playing DOOM)
- **error analysis**
  - identify and classify error sources
  - sensor noise, system variables

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Schedule

Spring 1998	robot hardware and control improvements collaborative controller development
Summer 1998	user interface development validation experiments
Fall 1998	complete software development implement system at CMU (e.g., Pandora)
Spring 1999	remote driving experiments data collection and analysis
Summer 1999	thesis writing and defense

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Conclusion

- **I believe that collaborative control can . . .**
  - solve many of the conventional teleoperation problems
  - compensate for inadequacies in autonomy, in human capabilities, and in communications
  - enable a human and robot to work as *partners*
- **In my thesis, I expect to demonstrate**
  - a new model for vehicle teleoperation (collaborative control) which is significantly better than existing methods
  - the importance of dialogue for improving teleoperation performance and productivity
  - a teleoperation system which is robust, easy to use, and performs well in dynamic, uncertain, and hazardous environments

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