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Telerobotics: Research Needs for Evolving Space Stations

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1. Introduction

The definition of telerobotics (TR) has not yet stabilized nor made the standard English language dictionary. I tend to use telerobotics as meaning remote control of robots by a human operator using supervisory and some direct control. Thus, this is an important area for the NASA evolving space station. By robot, I mean a manipulator/mobility device with visual or other senses. I do not name manipulators, as in many industrial automation set-ups, robots even if they can be flexibly programmed: rather calling these programmable manipulators. Our own laboratory at the University of California, Berkeley, has been involved in problems in display of information to the human operator, in problems of control of remote manipulators by the human operator, and in communication delays and band-width limitations as influencing both control and the display. A number of recent reviews have appeared with discussions of the history of telerobotics beginning with nuclear plants and underseas oil rigs.

2. Three Simultaneous Research Directions

I believe that we should engage in triplicate or three way planning. It is important to carry out our research to accomplish tasks (i), with man alone, if possible, such as in EVA (extra-vehicular activities), (ii) with autonomous robots (AR), and (iii) with telerobotics. By comparing and contrasting the research necessary to carry out these three approaches, we may clarify our present problems.

There are problems using man alone. The space environment is hazardous. It is very expensive to have a man in space; NASA must have quite adequate cost figures obtained from the demonstration projects that have already been accomplished with the shuttle program. We may also need a higher quality of performance than man alone can provide in terms of strength, resistance to fatigue, vigilance, and in meeting special problems. For example, if the space suit is not of constant volume under flexible changes of the limbs, then a great deal of strength is used up just in maintaining posture.

Problems with autonomous robots lie in our not having mastered the technology to build them and have them perform satisfactorily. They are not yet available! Indeed, designs are not yet fixed and it is not certain how feasible they will be, especially in terms of robustness and reliability.

Therefore, we can see that telerobotics is a viable leading edge technology. However, all three directions should be intensively pursued in research and development, especially for the next stages of the evolving space station planning.

FIGURE 1: TRIPLICATE PLANNING

PROBLEMS WITH MAN ALONE

- HAZARDOUS ENVIRONMENT: (SPACE SIMILAR TO NUCLEAR PLANTS, UNDERSEAS)
- EXPENSIVE (I.E. EVA IN SPACE)
- NEED INCREASED QUALITY IN
  - STRENGTH
  - FATIGUE RESISTANCE
  - VIGILANCE
  - PERFORMANCE

PROBLEMS WITH AUTONOMOUS ROBOTS

- NOT YET AVAILABLE
- DESIGN NOT FIXED
- FEASIBILITY NOT CERTAIN
- RELIABILITY NOT TESTED

THEREFORE: TR IS A VIABLE LEADING EDGE TECHNOLOGY

ALL THREE DIRECTIONS SHOULD BE SUPPORTED FOR EVOLVING SPACE STATION PLANNING, RESEARCH, AND DEVELOPMENT.

3. Space Station Tasks

One of the major roles that NASA can play is to hypothesize tasks for the evolving space station. In this way research regarding the design of telerobots to accomplish these tasks can be guided. For a list of seven groups of tasks see Figure 2.

As I will consider later, it is important to distinguish between those tasks unique to the NASA/evolving Space Station and those with "industrial drivers" that will accomplish development of new technologies in hopefully a superior fashion and thus enable conservation of limited NASA resources.

FIGURE 2:

NASA SHOULD HYPOTHESIZE <u>TASKS</u> FOR EVOLVING SPACE STATION

<u>HOUSEKEEPING</u>

LIFE SUPPORT SYSTEMS
INVENTORY CONTROL, ACCESS AND STORAGE
RECORD KEEPING
GARBAGE DISPOSAL

<u>PROTECTION</u>

FROM SPACE GARBAGE
FROM METEORITES
FROM TRAFFIC FLOW

<u>MAINTENANCE</u>

SATELLITE
VEHICLES
SPACE STATION ITSELF

<u>CONSTRUCTION</u>

ADDITIONAL SPACE STATION STRUCTURES

<u>MANUFACTURING</u>

CRYSTAL GROWTH, BIOPHARMACEUTICALS

<u>MOBILITY</u>

AUTOMATIC PILOTING
NAVIGATION
PATH PLANNING

<u>SCIENTIFIC</u>

LANDSAT TYPE IMAGE PROCESSING FOR AGRICULTURE
METEOROLOGY
ASTRONOMY
HUMAN FACTORS RESEARCH
SCIENTIFIC RECORD KEEPING

4. <u>Problems in Telerobotics</u>

This next section of my talk, reviews of problems in telerobotics, will be abbreviated. The review is divided into problems in telerobotics concerning displays, vision and other senses (Figure 3) and problems in telerobotics dealing with control and communication (Figure 4).

In each section, I start with basic properties of the human operator and end up with planned capabilities of autonomous robots. In between, I try to cover what knowledge exists now in our field of telerobotics. (See also companion paper by Stark et al in this volume.)

FIGURE 3: <u>DISPLAY PROBLEMS FOR THE HUMAN OPERATOR</u>

HUMAN VISION LLV, MLV, HLV

DISPLAY GRAPHICS (RASTER/VECTOR)

ON-THE-SCREEN ENHANCEMENTS
ON-THE-SCENE ENHANCEMENTS
OTHER SENSES DISPLAYED;
INPUTS TO OTHER SENSES

PERSPECTIVE AND STEREO DISPLAYS

TASK PERFORMANCE CRITERIA

HELMET M[illegible]

[illegible]NCE: SPACE CONSTANCY

HUMAN OPERATOR (H.O.) PERFORMANCE

FATIGUE, EFFORT, VIGILANCE

ROBOTIC VISION*

LLV - CHIPS
MLV - BLOCKWORLD AND HIDDEN LINES
HLV - ICM, AI

*Note: LLV is lower level vision, MLV, middle level vision, HLV higher level vision, including ICM, image compression by modeling and AI, artificial intelligence.

FIGURE 4: <u>CONTROL AND COMMUNICATION PROBLEMS FOR THE HUMAN OPERATOR</u>

BASIC PROPERTIES OF H.O., ESPECIALLY FOR EVA TASK PERFORMANCE

NERVE, MUSCLE, AG/AT MODEL+
SAMPLED-DATA (SD) AND ADAPTIVE CONTROL
PREDICTION, PREVIEW, OPTIMAL CONTROL--KALMAN FILTER

H.O. CONTROL OF VEHICLES, MANUAL CONTROL

H.O. CONTROL OF TR

H.O. SPECIAL CONTROL:

PREVIEW, DELAY, BILATERAL, HOMEOMORPHIC CONTROL

LOCOMOTION (HUMAN, ROBOTIC):

NAVIGATION--PATHWAYS
POTENTIAL FIELD ALGORITHMS

HLC (HIGH LEVEL CONTROL):

SUPERVISORY CONTROL
MULTIPERSON COOPERATIVE CONTROL; RCCL; FUZZY SETS

AUTONOMOUS ROBOTIC (AR) CONTROL

SENSORY FEEDBACK, ADAPTIVE CONTROL, AI

+Note: AG/AT is an agonist/antagonist muscle pair, reciprocally innervated for fast movements and co-contracted for posture and impedance control.

5. Industrial Drivers For Certain Necessary Space Station Technologies.

This next section deals with the future, and especially with "industrial drivers" other than NASA for new technologies which may be required in the evolving Space Station. In Figure 5 I list nine components of a telerobotics system that certainly seem to be driven by important industrial hardware requirements, research and development. Therefore, it seems reasonable for NASA to sit back and wait for and evaluate these developments, saving its resources for those necessary technologies that will not be so driven.

FIGURE 5: DRIVERS OTHER THAN NASA FOR NINE NEEDED TECHNOLOGIES

ROBOTIC MANIPULATOR AND CONTROL SCHEME

- JOYSTICK - AIRCRAFT
- AR MANUFACTURING INDUSTRY, NUCLEAR INDUSTRY, MINING INDUSTRY, SENSORS: FORCE AND TOUCH; COMPLIANT CONTROL

ROV AND MOBILITY

- MILITARY, TANKS AND OTHER VEHICLE PLANS?
- UNDERSEA ROV - OIL AND COMMUNICATIONS INDUSTRY
- LOCOMOTION - UNIVERSITY RESEARCH
- SHIPPING INDUSTRY: SHIPS AT SEA (AR, TR, MAN)

TV CAMERA

- ENTERTAINMENT INDUSTRY - COMMERCIAL DEVICE
- SECURITY INDUSTRY
- NEED MOUNTS, CONTROLS AND MOTORS FOR PAN, TILT AND FOR STEREO VG

GRAPHICS

- ENTERTAINMENT INDUSTRY IS A BETTER DRIVER THAN COMPANIES BUILDING FLIGHT SIMULATORS;
- HMD AS AN EXAMPLE.
- EM SENSORS RESEARCH/HEAD-EYE MOUSE

ICM

- LANDSAT
- SECURITY
- MEDICAL INDUSTRY - CT AND MRI
- INDUSTRIAL PRODUCTION LINES
- TD - IMAGE UNDERSTANDING

COMPUTER

- COMPUTER INDUSTRY
- (HDW) AND (SFW)
- COMPUTER SCIENCE RESEARCH BASE IS NOW VERY BROAD

COMMUNICATION

- COMMUNICATION INDUSTRY IS HUGE
- SHIPS AT SEA
- BW COMPRESSION
- REMOTE OIL RIGS
- ARCTIC STATIONS

PLANS AND PROTOCOLS TO COMBAT H.O. FATIGUE AND TO PROMOTE H.O. VIGILANCE

- OFFICE AUTOMATION FORCES
- AIR TRAFFIC CONTROL NEEDS
- SECURITY INDUSTRY

COOPERATIVE CONTROL

- MILITARY - SUBMARINE CONTROL
- HELICOPTER FLIGHT CONTROL
- AIR TRAFFIC CONTROLLERS
- NUCLEAR INDUSTRY
- CHEMICAL PLANT INDUSTRY

Looking at these figures gives us some concept of how industrial development may provide various types of technologies for the evolving Space Station; indeed, NASA may be able to pick and choose from off-the-shelf items! For example, the most powerful computers on the last space shuttles were the hand-held portable, computers that the astronauts brought aboard which contained much greater capability than the on-board computers; those had been frozen in their design ten years ago in the planning stages for the space shuttle.

6. Necessary Telerobotics Technologies to be Sparked by NASA

However, there are several areas in telerobotics that may likely not be driven independently of NASA, or where NASA may have an important role to play. Indeed, the Congress has specifically mandated that 10% of the Space Station budget should be used for Automation and Robotics development, and that this in some sense should spearhead industrial robotics in the United States (Figure 5).

FIGURE 6: AREAS SPARKED BY NASA NOT INDUSTRIALLY DRIVEN

VISUAL ENHANCEMENTS FOR GRAPHIC DISPLAY

TELEPRESENCE WITH STEREO HELMET MOUNTED DISPLAY (HMD)

MULTISENSORY INPUT PORTS:

- WORRY ABOUT H.O. OVERLOAD CONDITION (ESPECIALLY WITH COOPERATIVE CONTROL AND COMMUNICATION)

HIGHER LEVEL ROBOTIC VISION:

- EXAMPLE--IMAGE COMPRESSION BY MODELING (ICM) (TO REQUIRE LESS INFORMATION FLOW AND FASTER UPDATE)

SPECIAL CONTROL MODES FOR H.O.

- HOMEOMORPHIC CONTROL
- BILATERAL CONTROL
- TIME DELAY AND PREVIEW CONTROL FOR TIME DELAY
- COMPLIANT CONTROL

HIGHER LEVEL CONTROL LANGUAGES

- (SUCH AS RCCL; FUZZY CONTROL; PATH PLANNING BY POTENTIAL FIELD CONSTRUCTION)

REMOTE OPERATING VEHICLES (ROV) SPECIAL CONTROL PROBLEMS:

- NAVIGATION, ORIENTATION, OBSTACLE AVOIDANCE FOR ROV

COOPERATIVE CONTROL:

- COOPERATION AMONGST HUMANS, TELEROBOTS, AND AUTONOMOUS ROBOTS

COMPLIANT, FLEXIBLE, HOMEOMORPHIC MANIPULATORS

- GRASP VERSUS TOOL USING

HOMEOMORPHIC DUAL MODE CONTROL

IMPEDANCE CONTROL

7. University NASA Research

I now would like to make a plea that NASA should expand and stimulate telerobotics research conducted within the university environment. Of course, as a professor I may have a bias in this direction and I am willing to listen to contrary arguments! In addition to the benefits of the research accomplished by universities, NASA also gets the education and training of new engineering manpower specifically directed towards telerobotics, and focused on the evolving Space Station.

What kind of university and educational research should be funded in general by NASA. I believe there are two levels of cost (with however three directions) into which these educational research labs should be classified.

(i) First are Simulation Telerobotics Laboratories. Here we need graphics computers, perhaps joysticks, perhaps higher level supervisory control languages, cameras, image compression techniques and communication schemes. I would guess that our country needs at least thirty such systems for education and training. These systems should be very inexpensive, approximately $50,000 each. They need not even be paid for by NASA, since universities can provide such research simulation laboratories out of their educational budgets or from small individual research grants. Our Telerobotics Unit at Berkeley has been thus funded. A good deal of exploratory research can be carried out inexpensively in this manner.

(ii) Second, we need Telerobotic Laboratories with physical manipulators present as important research components. In this way, experiments with various robotic manipulators, especially those with special control characteristics such as flexibility, homeomorphic form, new developments in graspers, and variable impedance control modes, other than are found in standard industrial manipulators, would be possible. I guess that there are about five such laboratories in some stage of development at major universities in the country. I would further estimate that these laboratories could each use an initial development budget of $300,000 to enable them to purchase necessary hardware in addition to software as existent in the Simulated Telerobotics Laboratories.

Another set of costly laboratories would be Telerobotics Laboratories with remote operatoring vehicles (ROV). Here again, we need about five laboratories at universities with first class engineering schools. Again, I estimate about $300,000 each for the initial hardware support of these ROV labs. They could then study transfer vehicles, local Space Station vehicles, Moon/Mars Rovers, and even compare MMU vs. telerobotic controlled vehicles.

The university laboratories would contrast with and serve a different function than ongoing aerospace industrial laboratories, and NASA and other government laboratories. These latter assemble hardware for demonstration and feasibility studies. Then unfortunately they are somehow unable to carry out careful human factors research dealing with the changing design of such pieces of equipment. In the university setting, this apparatus could be taken apart, changed, revitalized, modified and the flexibility would inform our current capability. I would like to contrast the Gossamer Condor and Gossamer Albatross with the NASA program. It was clear that if McCready was ever to be successful, he had to build an experimental plane which was expected to break down each experimental day. But the plane could be repaired in a few minutes! This "laboratory bench" concept is so different from twenty-year-ahead-planning currently controlling our space program that has been effectively eliminated at NASA. I think it is important to reintroduce rough-and-ready field laboratories back into the space program.

8. NASA Prizes

Another role that NASA might play is to offer demonstration contracts or, even better, prizes for accomplishment of specific tasks. Again I turn to the Kremer Prize: here a private individual donated prize money to be awarded to the first to build a man-powered aircraft conforming to certain carefully laid out specifications.

Communication channels for controlling remote vehicles and remote manipulators are already set up. Thus we could have prize contestants demonstrating at differing locations on earth at one "g"; next demonstrations using elements capable of operating in space, or even more stringently, of having that minimum mass capable of being lifted into space; and then we might have true shuttle and space station demonstrations.

9. Intellectual problems in TR for the Space Station

Finally, I would like to leave you with the thought that the list of to-be-sparked-by-NASA problems in Figure 5 contains many important intellectual problems facing the area of telerobotics. Although these areas are being approached in our research community at the present time, it may not be possible to forsee what novel kinds of challenges will face the evolving Space Station in twenty years. Even though I may not predict accurately, I certainly hope I am there in person to watch telerobotics playing a major role in operating the Space Station. Acknowledgement: Support from JPL (956873), Dr. Bejczy; NASA-Ames (NCC-85), Dr. Ellis; and discussion with colleagues Drs. W. S. Kim, F. Tendick and B. Hannaford.