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TELEROBOTICS IN REHABILITATION: BARRIERS TO A VIRTUAL EXISTENCE

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p- 10

The Need for Telerobotics in Rehabilitation

There are over 67,500 quadriplegics in the United States today, with an estimated 2,400 to 4,000 new injuries occurring each year (Stover et al., 1986). These injuries occur most frequently among young males between the ages of 16 and 30. Due to advances in medical treatment (antibiotics and skin care), these individuals now have a relatively normal life expectancy. They are alive, but dramatically cut off from most aspects of a normal existence. They live, virtually, through the actions of others. Perhaps, life would be more fulfilling if they were also offered the opportunity to directly control their environment through telerobotic tools for independent living. Virtual telerobotic environments for the rest of us could bring reality to these individuals.

It is estimated that caring for a quadriplegic, including standard medical treatment, equipment maintenance and attendant care, costs about $47,000 (1980 dollars) per year. This translates to approximately 1.9 million dollars over forty years (Kalsbeek et al., 1980). The net direct cost to the Department of Veterans Affairs will be approximately $5 billion for its current population of service connected quadriplegics. On the promising side, Young et al (1982) estimated that every dollar spent for rehabilitation research and development returns $11 in cost benefits to society. In the case of quadriplegia, the cost of attendant care (nominally $25/hr to the insurer and increasing) can be reduced by providing personal telerobots (nominally $5/hr and decreasing). Hammel et al. (1989) demonstrated that telerobots can satisfy the vocational manipulation needs of personal computer users for periods of over four hours at a time without attendant intervention. Employment makes it possible to recover some or all of the indirect cost of severe disability.

Barriers to Telerobotics Technology in Rehabilitation and Health Care

If the direct cost of severe disability is so high, and telerobotics technology is available to help reduce costs, then what have been the barriers to its widespread acceptance and deployment? Clinical experience with telerobots suggests that there are several key barriers:

Social Barriers: As a society, we place little emphasis on restoration of function for persons with disability, we prefer to “take care of them”. Because the economics of cost and benefit are not coupled, we fail to see the opportunity. However, even if we began deployment today, our society has educated too few persons to support the advanced assistive devices (i.e., we have enough researchers to create independent living tools, but too few development and service persons to support clinical and domestic usage). These are the dominant factors impeding wider adoption of advanced technical aids for persons with disability.

Institutional Barriers: Government programs are scattered and disjoint. There is no systematic vision and considerable inter-agency protectionism. Perhaps most significantly, the "conflict of interest" witch hunt in government makes it virtually impossible to transfer laboratory results to the commercial sector in a timely and cost-effective manner. For its part, the commercial sector does not take the investment risk to develop these devices because it is not clear that third party reimbursement will be forthcoming.

Technical Barriers: Here, at least, the science and engineering communities do have some control of the issues, these include:

The human-machine-interface is the dominant technical barrier to widespread use of telerobots in rehabilitation. Text, voice, graphic and kinematic command-control interfaces are very cumbersome for robot motion specification, planning and supervision. This forces the user to be overly dependent on pre-programmed motions and the technicians who create them. We must work towards "instructable" telerobots.

The machine-environment-interface is the second most deficient aspect of telerobotics in rehabilitation. The absence of sensor driven grasp and object approach-avoidance reflexes forces the user to directly control end-effector motion under difficult observational circumstances and without "natural kinesthetic cues". We must develop robust sensate end-effectors and the "reflexes" to make them useful. Force (impedance) control will be a requirement for advanced user support tasks.

Mobility, or the lack of it, defines the telerobot's work space and, in part, its ultimate utility. One can not reasonably expect general cost-effectiveness when people must be available to bring work to the telerobot. Raw mobility is, however, not enough. Remote presence makes much greater demands on the user-interface and telerobotic sensory capability. A more "intelligent" robot may, in fact, be the greatest challenge yet to the user-interface designer.

Fault-intolerance is an overriding shortcoming of almost all robots. As programmable electro-mechanical systems, they are inherently subject to a very wide variety of fault modes. Not even the digital controller in current machines take advantage of computer fault-tolerance architectures (which themselves make no provision for sensor and actuator failure modes). Widespread personal use of telerobots will require fundamental progress in design for fault-tolerance (we must get well beyond just being careful).

Telerobotics in Rehabilitation: Once Around the World

A small number of underfinanced telerobotics teams around the world are attempting to overcome these barriers. The most recent compilation of papers are in the Proceedings of the "First International Workshop on Robotic Applications in Medicine and Health Care" (1988). The next edition will grow out of the International Conference on Rehabilitation Robotics (sponsored by the A. I. duPont Institute, June, 1990). The following synopses highlight some of the ongoing R&D (see Table-4 for a technical comparison of the telerobots used.

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) project (Schneider et al., 1981) concentrated on the implementation of a workbench-mounted robot intended to perform activities of daily living (ADL) tasks. The design (initially 4 degrees-of-freedom then extended to 5) was derived from prosthetic arm technology. Control is accomplished by a head-motion (chin) controlled joystick for joint specific motion. Pre-programmed motions are invoked by menu-selection and input command via a sip-and-puff switch.

The Tufts-New England Medical Center robotics project (Gilbert and Foulds, 1987; now at the A I duPont Institute) concentrated on the design of a universal robot programming language, CALVIN, to provide a common interface to the many different manipulators available. Using CALVIN, they set up a variety of small, low cost, robot work cells (typically 4 and 5 degree-of-freedom manipulators) in clinical rehabilitation settings for disabled children. The clinical objective is to foster intellectual development of the child.

The Boeing Company developed a voice-controlled workstation using the Universal Machine Intelligence RTX (5 degree of freedom) manipulator (Fu, 1986). The distinctive feature of this project is that it's user interface is a voice query system for large data bases developed by Boeing. Prab Command, Inc., began marketing the system in 1988 for vocational applications. There is very little telerobotic function beyond pre-programmed diskette loading. The internal project at Boeing has ended and Prab sold the technology to the Zenith-Heath.

From 1980 through 1988, the Veterans Administration sponsored a collaborative effort with Stanford University (Leifer, 1982; Hammel et al., 1989) to test the hypothesis that industrial manipulators could cost effectively serve the needs of severely impaired spinal cord injury patients. The project demonstrated that, through voiced commands, the utility and reliability of a high performance manipulator (PUMA-260) and control language (VAL-2) can yield attractive cost-to-benefit performance ratios when the telerobot is able to operate for four hours without attendant intervention. Sensate end-effector, mobility, 3D point designation and natural language studies laid the foundation for further R&D. A desktop vocational assistant robot (DeVAR) version of the system is available commercially.

Outside the United States, the Canadian Neil Squire Foundation has developed a low-cost manipulator designed for desktop applications in rehabilitation (Cameron, 1986). The system is being sold by the foundation. At the Institute for Rehabilitation Research in the Netherlands, Hok Kwee (previously with the French Spartacus project (Kwee, 1983) and his colleagues have developed a wheelchair mounted, joystick-controlled, manipulator (MANUS, Kwee, 1987). They are particularly interested in collocation of the robot and user at all times. The manipulator is expected to function as an arm, not really a telerobot.

While human attendant care is the norm today, and telerobotics technology promises to release some attendant time cost effectively, there is a third alternative. Capuchin monkeys have been trained to provide attendant services from feeding to appliance operation (internal VA program review, 1988). Monkey training is expensive, labile, and done by methods objectionable to the animal rights community. Program retention (to a maximum of 12 short tasks) and willfulness remain significant obstacles to the monkey assistant concept. The approach is particularly limited by the fact that monkeys can only work one-on-one with their user. The distractions of institutional and vocational settings render the monkey ineffective.

Table 1 presents an extended comparison of the strengths, capabilities and limitations of five approaches to augmenting the independence of severely impaired persons. Supported by a growing body of experimental evidence, this comparison strongly suggests that telerobots can become cost-effective personal and vocational assistants. Table 2 lists many of the feeding, personal hygiene, vocational, and recreational tasks that have been demonstrated over the past 8 years by four generations of the Stanford-VA Rehabilitation R&D Center's Telerobotic systems. Table 3 identifies the technical functions required to perform these tasks.

A Partial View of the Future

The operator interface will remain the dominant problem. It is so difficult that most systems designers prefer to ignore it and focus on "tangible" technical specifications. It is likely to use multiple-channels in the sense of incorporating a "natural robot instructional language" and bi-directional pictographic dialog between the operator and the system. Increasingly "autonomous" telerobots will actually increase the burden on this interface.

Sensor driven motion planning and autonomous grasp/avoidance reflexes will become commonplace. The rate of introduction of such features will, however, be much slower than expected. In part, this is due to the fact that system architectures will continue to be "fault-intolerant" such that the introduction of both sensors and programmed reflexes will bring new reliability problems with them.

Force (impedance) control of telerobots will continue to evolve slowly even thought this capability is a fundamental requirement for any robot that must work intimately with humans. Physical therapy by robots is both needed and impossible without force control. These lines of technical evolution will themselves depend on getting more applications feedback from telerobots in the clinic, home and office. In combination, we see a rather daunting challenge.

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Table 1a In-depth Review of the Capabilities, Strengths and Weaknesses of Five Basic Approaches to the Restoration of Manipulative Function for People with Severe Physical Limitations (none = -, limited = *, usable = **, good = ***, excellent = ****).

	Environment Controllers	Prosthetics Workstations - Seamone	Monkeys - Willard	Robots - Leifer	People
Human Input/Output Factors					
COMMAND	*	**	*	***	****
Substitution errors	5%	5%	10%	10%	1%
Detection errors	10%	10%	25%	15%	2%
Number of commands	10	20	12	100	2000
Syntax options	-	menu	menu	program	English
User programming	-	-	-	yes	yes
CONTROL	-	-	-	***	-
Real-time	-	-	-	yes	-
Degrees of freedom	-	-	-	7	-
Flexible	-	-	-	yes	-
User programmable	-	-	-	yes	-
DIALOG	*	*	*	***	****
Feedback modes	lights	lights	noises	voice	voice
Explanations	-	-	-	status	unlimited
Inference	-	-	-	limited	unlimited
Rule based	-	-	-	limited	general
User adaptive	-	-	?	limited	unlimited
Model based	-	-	?	sensory	general
Machine Input/Output					
AUTONOMOUS PLANNING	-	-	-	**	****
Path	-	-	-	limited	general
Strategy	-	-	-	limited	general
Data driven	-	-	-	limited	general
PROGRAMMABLE REFLEXES	-	-	*	**	****
Force compliance	-	-	**	**	***
Contour following	-	-	-	**	****
Proximity sensing	-	-	-	***	-
Collision avoidance	-	-	***	*	****
POSITION/ORIENTATION	-	*	**	***	****
Degrees of freedom	-	4	9	7	9
Radius of working volume	-	40cm	30cm	40cm	55cm
Precision	-	low	low	high	flexible
Repeatability	-	2mm	3mm	0.2mm	3mm
Strength	-	low	low	low	flexible
Speed	-	low	moderate	flexible	flexible
MOBILITY	-	-	***	**	****
Degrees of freedom	-	-	6	4	6
Range	rooms	desk	room	rooms	unlimited
Remote control	IR link	-	voice	voice	voice
Autonomous	-	-	?	limited	unlimited
GRASP	-	*	***	**	****
Degrees of freedom	-	1	6	1	6
Grip force	-	1kg	1.5kg	3kg	25kg
Dexterity	-	minimal	good	minimal	excellent
SENSATION	-	-	****	**	****
Tactile	-	-	****	*	****
Force	-	-	****	**	****
Proximity	-	-	-	**	-
Vision	-	-	****	-	****
Audition	-	-	****	-	****

Table 1b

Assessment	Environment Controllers	Prosthetics Workstations - Seamone	Monkeys - Willard	Robots - Leifer	People
PERFORMANCE	**	**	**	***	***
Task time	seconds	minutes	minutes	minutes	seconds
Training time	2hrs	30hrs	20hrs	40hrs	4hrs
Number of tasks	10-20	15-30	10-20	20-200	40-400
Commands per task	1	1-4	1-4	1-20	1-2
Precision	-	5mm	2mm	0.2mm	2mm
Repeatability	-	1mm	3mm	0.2mm	3mm
Reliability	high	good	fair	good	fair
Accessibility	24hrs	24hrs	12hrs	24hrs	8hrs
SAFETY	****	***	**	**	****
Intention errors	5%	10%	5%	10%	4%
Intrusion errors	0%	4%	5%	5%	2%
Contact errors	0%	2%	4%	2%	1%
COST	****	**	**	**	*
Hardware	low	medium	medium	high	low
Software	low	low	high	high	low
Training	low	medium	high	medium	low
Maintenance	low	medium	medium	low	high
Cost/hour of use	$1/hr	$4/hr	$10/hr	$5/hr	$25/hr

Table 2 Meal preparation and service, vocational material handling, personal hygiene, and recreational tasks that have been performed for and with disabled individuals across four generations of desktop robotic assistants (DeVARs I, II, III, IV)

Meal preparation and service

- arrange table setting
- open and close microwave door
- open and close refrigerator door
- manipulate containers
- set appliance timer
- pour liquids and solids
- beat eggs
- toss salad
- soup preparation and service
- heat and serve casseroles
- serve pudding
- serve fruit
- prepare and serve spaghetti
- prepare and bake a cake
- use knives, forks and spoons
- retrieve drinks
- mix drinks
- lock and unlock cabinet doors
- light and extinguish candles
- light and extinguish cigarette
- open and close storage drawers
- room lights
- window open and close

Vocational material handling

- write with pen and/or pencil
- retrieve books and manuals
- set up books for reading
- turn book and report pages
- turn on-off computer equipment
- type on keyboard
- adjust keyboard position
- operate private and speaker phones
- insert and retrieve diskettes
- insert and retrieve audio tapes
- operate dictation equipment
- manipulate printout
- voiced control of generic software
- load and operate printer
- retrieve and serve medication
- circuit boards for inspection
- operate electronic control units:
- door operation
- security system
- stereo equipment

Recreation

- paint and sketch
- arrange flowers
- hand out flowers
- hand out candy and souvenirs
- perform one armed ballet
- checkers
- monopoly
- television
- operate video games
- pac-man
- invaders
- play board games:
- chess

Personal hygiene

- wash and dry face
- brush teeth
- dispense toothpaste
- use electric shaver
- retrieve mouthstick
- comb and brush hair
- blow nose
- apply makeup

Table 3. Several functional capabilities are needed in a Telerobotic Assistant to achieve utility in the performance of independent living tasks, not needed ( ), should have (□), must have (■)

	COMMAND	CONTROL	DIALOGUE	PLANNING	GRASP	MANIPULATION	REFLEXES	MOBILITY
MAINTENANCE Tasks								
Food Preparation	■	■	□	□	■	■	□	■
Food Service	■	■	□	□	■	■	□	□
Personal Hygiene	□	■	□	□	■	□	■	□
Personal Grooming	■	■	□		■	■	■	□
Clothing Management	□	□	□	■	■	■	□	■
Appliance Usage	■	■	□	■	■	■	□	■
VOCATION Tasks								
Storage & Retrieval	■	□	□	□	■	■	□	■
Equipment Operation	■	□	□	□	■	■	■	■
Assembly	■	■	■	■	■	■	□	□
Word Processing	■	□			□	□		
Computing	■		□					
Materials Processing	■	□	□	□	■	□	■	■
RECREATION Tasks								
Reading	■	□		□	□	□	□	
Film & Video	■				■	■	□	■
Performing Arts	□	■	□	□	■	■	□	■
Graphic Arts	□	■	□	□	■	■	□	
Sports	□	■	□	■	■	■	■	■
Social Interaction	□	□	■	□	□	□	□	■

Table 4 The performance and technical features of selected Rehabiliation Robotics projects are reviewed in an approximately chronological order. Legend: DF = degrees of freedom; R = rotational joint; T = translational (linear) degree of freedom.

	PROJECT	ARM TYPE	HAND TYPE	DISCRETE INPUTS	CONTINUOUS INPUTS	CONTROL MODES	AUTO. ROUT.	PROGR CAPAB	SENSORY FUNCTION	LEARN DIFFIC	MANIP. CAPAB	RELIA-BILITY	ARM and CONTROL
1.	CASE ceiling mnt.	industrial 8DF: 5R,3T. 1kg	2-finger vice	7 levers keyboard	none	joint velocity	position replay	limited	none	very high	med	med	high very high
2.	RANCHO chair mnt.	orthosis 6DF: 6R,0T. 1kg	2-finger hook	6 tongue switches	2DF manip.	joint on/off velocity	none	none	none	very high	very low	high	low very low
3.	HEIDELB. floor mnt.	industrial 5DF: 5R,0T. 20kg	pneumatic 2-finger vice	2 tongue sw 1 sip/puff	3DF mouth manip.	cylindrical velocity	none	none	none	med	med	med	very high very high
4.	VAPC chair mnt.	rehab 6DF: 5R,1T. 2kg	2-finger hook	5-position switch	2DF chin manip.	world velocity	none	none	none	low	low	med	medium medium
5.	JHU/APL table mnt.	prosthesis 5DF: 5R,0T. 1kg	2-finger vice	1 chin switch	1DF chin control	joint position	limited	limited	none	med	low	med	low low
6.	SPARTAC. floor mnt.	industrial 6DF: 6R,0T. 3kg	2-finger gripper	16 voice, 1 switch	2DF head pos 1DF elbow	world/tool velocity	limited	none	grip/vert force	low, flexible	high	high	very high very high
7.	BOEING table mnt.	UMI/RTX 5DF: 4R,1T. 1kg	2-finger pinch	voice vocab.	none	joint/world/ tool speed	good	good	none	high	med/ high	med/ high	medium high
8.	TUFTS table mnt.	SCORBOT 5DF 5R,0T. 0.5kg	2-finger pinch	8 switch	none	joint velocity	good	limited	none	low	med	med	low med
9.	PAVA desktop	PUMA-260 6DF: 6R. 1kg	2-finger Otto-Bock	VOTAN 128-word	none	joint/world/ tool speed	excellent	limited	none	low	very high	very high	high med/high
10.	SU mobile manip.	9DF:3DF-Omni PUMA-260. 1kg lift	2-finger pads. prototype	Kurzweil 1000-word	2DF head pos.	joint/world/ tool/room velocity	excellent	good	6DF force, 12 prox, 14 bumper sigs laser scanner	med/ high	very high	high	very high very high