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Toward a Remotely-Manned Energy and Production Economy

Marvin Minsky

ABSTRACT. We can solve many problems of Energy, Health, Productivity, and Environmental Quality by improving the **technology of remote control.** This will produce

- Nuclear Safety and Security.
- Advances in Mining.
- Increases in Productivity.
- Economies in Transportation.
- New Industries and Markets.

By creating "mechanical hands" that are versatile and economical enough, we shape a new world of health, energy and security. It will take 10 to 20 years, and cost about a billion dollars.

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Marvin Minsky
M.I.T.

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1. The Idea.

A person wears a comfortable jacket lined with sensors and muscle-like motors. Each motion of arm, hand, and finger is reproduced at another place by mobile, mechanical hands. Light, dexterous and strong, those hands have their own sensors, through which the operator sees and feels what is happening. Using such an instrument, you can "work" in another room, another city, or another country. Your remote "presence" can have the strength of a giant or the delicacy of a surgeon. Heat or pain is "translated" into informative but tolerable sensation. Dangerous jobs become safe and comfortable.

We can do a little of this today, using the crude machines made for handling radioactive materials. But once we improve those clumsy instruments -- the basic point of this proposal -- we will gain in many ways:

ENERGY: Safe and secure nuclear power generation and waste processing. Safe and efficient land and sea mining. Low cost space stations.

PRODUCTIVITY: Advances in fabrication, assembly, inspection and maintenance systems - in both light and heavy industry - could restore US eminence in this area.

HEALTH: Elimination of all chemical and physical hazards will make many old jobs more tolerable, create new processes and technologies.

TRANSPORTATION: Besides reducing cost, energy and time, one person will be able to do different jobs in different places.

To do this we must improve our "telepresence" instruments -- that is what I will call them -- so that they feel and work like our own hands! This could take 20 years and cost a billion dollars. It will repay itself a hundredfold. Three Mile Island showed the absurd inflexibility of current nuclear technology. We still wait (8/79) until men can rush in to look -- and absorb a year's dose in a few minutes. Ridiculous! With better ***telepresence*** tools we could quickly inspect and repair, perhaps reducing losses from a billion to a few millions.

Many experts liked the ideas in an earlier draft of this essay. But, because US "energy policy" was yet to be formulated, no agency was empowered to deal with such issues. Here is what happened:

INDUSTRY people thought GOVERNMENT should do it.
DEFENSE suggested ENERGY.
ENERGY suggested NASA.
NASA suggested COMMERCE.
(No one suggested Labor.)
COMMERCE suggested NSF.
NSF wished it had funds, suggested DEFENSE.

I am sure the President himself would like these ideas, but they can reach him only if a distinguished group of backers support it. ***Energy Problems threaten more than just the economy and quality of life. Conservation and self-denial will help only for a moment. In the end, discomfort and hostility could turn to starvation and war. If this consumes our remaining resources, the human race may have no second chance to reach the stars.***

EXAMPLE 1: MINING AND PETROLOGY

It is easy to talk of digging more coal or shale, but Labor will never again tolerate the old mining methods. Remote-controlled mining instruments can exploit buried resources more efficiently and humanely. In a "remotely manned" mine, ***there are no people to be hurt.***

SAFETY. No one is exposed to any danger of dust, collapse, or explosion. Costs are lower, more can be extracted.

ACCESSIBILITY. We will be able to exploit meter-thin mineral deposits, e.g., much anthracite coal, that remain in formations we cannot now reach.

INTEGRATION. We can reconsider underground combustion and gasification schemes that never "made it" because they could not be controlled. Remotely-manned mines need less cooling, ventilation, safety, or escape provisions.

RESERVES. With remote mining, single deep shafts can have many branches, to ***extract more from each reservoir.***

EXAMPLE 2: NUCLEAR TECHNOLOGY

Present nuclear plants have inadequate provisions for maintenance or intervention. With telepresence technology, we could service them more like normal industrial plants, preventing problems before they start. Diagnosis and repair is easier when people can work as though they were on the spot. With *no one at all in the building*, we gain in::

SAFETY. No one is exposed to any radiation. We can stop quarreling about "tolerable" and "threshold" doses!

SECURITY. If nothing enters or leaves except via telepresence machines, it is easier to secure critical materials. No person can steal anything, and the machines can be monitored by computers programmed to detect unusual activities -- and by skeptical citizens encouraged to use the viewing channels. Few opportunities for sabotage.

RELIABILITY. Mobile probes (that can repair one another) permit easier inspection and repair.

INTEGRATION. All this makes it easier to combine Power Generation, Fuel and Waste processing and temporary waste storage in a single plant. Many objections to *breeder* technology are overcome.

ECONOMY. Materials are more easily recycled and replaced. We can use cheaper and stronger but shorter-lived materials.

EXAMPLE 3: UNDERSEA EXPLORATION AND EXPLOITATION

Most of our planet is ocean. Remotely manned "sea-floor construction crews" could bypass the prohibitive hazards of manned exploration, avoiding the cost and risk of weather-troubled ships and treacherous towers in Continental-Shelf Mining. As I write this, the Gulf Coast is threatened by an undersea oil blowout that promises billion dollar losses. Advanced telepresence technology would have little trouble repairing the damaged well.

Manned exploration is more technically difficult in the ocean than in outer space; "moonwalks" are harder there! ONR already has a project for a remote controlled deep-sea laboratory. Larger such systems could *exploit* as well as *explore* the resources of the deep -- to mine, drill, and operate other systems now considered impractical.

The new technology touches everyday life. Today, one has to dig up the city to repair underground systems; via telepresence we can do much from the inside. This applies to sewers, telephone lines, steam tunnels, fuel pipelines, and nuclear waste tanks. Boston loses half of its water supply, it has been estimated, to water main leaks that will cost billions to repair by present methods.

2. *Proposal for A BILLION DOLLAR PROJECT*

We can have this in 20 years -- but only if we immediately start an energetic, well supported project. This is a large project because many different technologies must be merged. The technical scale resembles that of designing a new military airplane. The size of the effort suggests the strategy wherein MIT's Project Lincoln coordinated a wide variety of technical research groups to develop our early Air Defense Systems.

COST. Developing these super-instruments could cost 50 million dollars/year for 10 years. This might seem expensive, but compares with the cost of an automotive model change, or a single nuclear power station. Any complex, well-engineered, new device can cost a million dollars of R&D; many such will be needed for sensing the motions of a person's hand, and for sending signals back to that hand. New kinds of motors will be needed, new sensors, lightweight actuators, low friction linkages, special materials for surface coverings; all must tolerate bad environments. Other "components" are also costly -- mathematical theories for feedback control of new complex mechanical systems, novel computer languages and systems.

PAYOFF. This investment could restore the United States' traditional positions in Energy and Production Technology. The Appendices promise benefits in other areas, such as Transportation and Medicine.

UNIT COST. First prototypes will be costly but as designs mature most of the complexity will move from expensive hardware to easily copied computer software; mass production will bring costs down further. The goal should be to make them as cheap as cars.

SCHEDULE. It will take 20 years to do all this: one decade for developing the basic instruments, the second for refining and adapting them to their applications. The ***first decade*** is concerned with issues like:

Design of advanced teleoperator geometries.
Research on sensors and effectors.
Experimental and theoretical work on control theory.
Development of automatic monitoring methods.
Development of automatic manipulation processes.
Research on "responsible" software generation.
Development of good human report interfaces.
Prototype software for plant operation procedures.

A first decade annual budget that allows for "redundant" parallel efforts on critical facets would allow for:

10M	Teleoperator Mechanical Engineering
10M	New Sensors and Effectors.
5M	Research on Automatic Control and Monitoring.
5M	Research on Sensori-Motor Psychology.
5M	Research on Programming and Semantics.
15M	Adapting Prototypes to Applications.

The ***second decade*** will further refine the instruments to make their operators more comfortable and effective, to improve materials and reliability, and to adapt the systems to different pilot systems and plants. The second decade budget will depend on how fast different industries adapt to exploit the new technology. The two phases are not really separate, for some early work will quickly find many important applications to urgent and critical problems.

1980: Organization of design projects.
1984: Completion of several experimental prototypes.
1986: Refining and improving human factors.
1988: Second generation prototypes.
1990: Thermal and radiation-hard prototypes.
1994: First pilot mining and nuclear plants.

SUMMARY

*Telepresence technology can solve many **Energy** and **Productivity** problems. The project seems foolproof because **this new technology will pay off**, whichever energy sources -- Coal, Fission, Fusion, Solar, or whatever -- wins the competition. It will further profit us in **Industry, Agriculture**, Transportation, and Health. It promises many rewards in general science, practical engineering, computer science, medicine, physiology, and psychology. The appendices will discuss these sciences in more detail.*

APPENDICES

0. TECHNICAL PROBLEMS. Early telepresence systems used cables and pulleys to sense a person's motions and duplicate those motions elsewhere; later versions used electric motors. None had enough dexterity or intimate sensory feedback. We explain the problems.

1. ORGANIZATION. The project should be organized as ***a league of Working Centers connected by a computer communication Network.*** This will attract first-class specialists, support the technical goals, and allow other research centers to participate.

2. WHERE TO START. A new, dedicated project is needed because no existing center has the required resources. The field needs strong support, deliberate and courageous long-range planning.

3. STATE OF THE ART. The clumsy claws of present systems cannot "feel" and their joints are too awkward; this makes simple jobs take too long and complex jobs hard to do at all. This is why no plants are designed to exploit them.

4. INDUSTRIAL APPLICATIONS. Telepresence will open a new era of productivity. It will save many old jobs, and create many new ones.

5: NUCLEAR SAFETY AND SECURITY. We detail a wide range of ways in which telepresence will minimize present dangers.

6: SPACE. Telepresence will make practical many schemes for orbital, lunar, and planetary exploration and exploitation.

7: BIOLOGY AND MEDICINE. Miniaturized telepresence systems will lead to medical and surgical techniques that today seem impossible.

8: TRANSPORTATION. Both human and material time and cost will be saved by applying manual labor at a distance.

APPENDIX 0. TECHNICAL PROBLEMS TO BE SOLVED

A telepresence system must sense a person's motions and duplicate them elsewhere. Such systems have been called "*Teleoperator*", ***"Telefactors"***, or *"Waldos"* (after an inventive hero in a 1940 novel by Robert A. Heinlein). I prefer "telepresence" to emphasize the importance of high-quality sensory feedback.

The first ones were built around 1946 at Argonne National Laboratory, using cables and pulleys. Later, these were replaced by electric motors. There have been few advances since then. To explain what needs to be done, here is some background:

"Force-Reflection". The electric-motor systems were stronger and could work at greater distance, but they lost the sense of "feel" that had come through the cables. To restore some of this, later models measured forces at the output and used additional motors to "reflect" these forces back to the user's hand.

"Supervisory Control". Telepresence systems can be controlled by computers instead of people, if we can write appropriate programs. Then the human operators can become "supervisors", merely indicating higher level goals. Workers in the field of "Artificial Intelligence" have already demonstrated systems that can grasp and move objects in accord with *verbal commands*.

"Robotics": Such devices have been programmed to complete simple jobs automatically. A complicated precision bearing was so assembled at MIT, an entire water pump assembly at Stanford, a toy automobile at Edinburgh. But such programs are not yet dependable, versatile, nor easy enough to construct.

But present-day telepresence systems have disabling limitations:

Clumsiness. The mechanical hands have but two inflexible fingers, poor elbows and shoulders, unnatural wrists. None can use an ordinary pair of pliers. Appendix 3 explains why engineers have been been reluctant to work in this area.

Sensory Limitations. No present system has any true sense of "feel". We must set high objectives for the senses of touch, texture, vibration and all the other information that inform our own hands.

Control Systems. Once we make these improvements, the new systems will be more complex and will need better control systems to exploit their expanded capacities.

Reliability. Critical applications will demand new orders of reliability. We should be able to exploit the new concepts of "responsible software" now emerging from Computer Science. Such systems will maintain the coherence and reliability of a program by continuously comparing what it actually does against explicit statements of its "intentions" -- of what it is *supposed* to do. While such programs are yet in experimental stages, the concept is clearly sound.

The sensible course is to try to ***make an instrument that compares well to human arms and hands.*** This goal is ambitious, but we should compromise only when necessary -- and not before trying hard. We should set ourselves a level of aspiration like this:

General configuration:. The system should have two humanoid arms and five-fingered hands, able to imitate natural motions. It should be mobile; legs surpass wheels in most environments. Many design and control concepts for the new arms could be so adapted, to yield a system able to work whenever a person could -- not just on carefully prepared floors.

Man-Machine Interface. Control should be via an instrumented sleeve, light and articulated with little friction. It must include effectors to transmit "reflected" forces to the operator. To do this will require advanced composite materials and new muscle-imitating devices -- challenging engineering research problems. Visual feedback could use slender fibre-optic probes, articulated to emulate the operator's head motions.

Special Application Problems. For exotic operations, e.g., undersea, we may want to extend the telepresence to the entire body, perhaps controlled by a submerged, instrumented wet-suit. This simplifies control problems, uses bouyancy against weight, drag against inertia. Nuclear and deep-sea systems will have special architectural and materials problems.

APPENDIX 1. ORGANIZATIONAL IDEAS

SCALE. The needs of the project suggest models like RAND or LINCOLN, with strong technical groups in sensors, effectors, materials, artificial intelligence, software engineering, psychology, control theory, reliability, and other specialties.

SECRECY. It is in everyone's interest that safety-related technologies be public -- especially since the project's principal applications will be industrial, economic, and medical. The US is fast losing its traditional eminence in advanced machinery -- and attempts to hide progress from foreigners will only retard dissemination at home.

NATIONALITY. Foreign contributions should be encouraged. JAPAN and UK are advanced in robotics and computation; France, Canada and Italy have much manipulator capability. All nuclear nations with facility in teleoperators can contribute -- and it is in our self-interest to make things safe everywhere.

COMPUTER-NETWORK BASE. In the Lincoln or RAND model, one assembles the entire staff in a single, central place. A more practical and modern scheme is to ***center the project around a Computer Network.*** This reduces recruiting problems and enhances the development of foolproof remote technology. Such a Network would contain:

- A ***Central Resource*** somewhere in the US, combining administrative and engineering resources that need centralization.
- Several ***Working Centers*** near university or industrial locations, that work together or separately as appropriate, via a computer-communication network like the ARPANET.
- Many ***Associate Centers*** of fewer people, playing effective roles via the computer network.

A Computer Network enhances communication -- both personal and publication -- to a degree that newcomers find hard to appreciate. It provides better computational and engineering services than can any traditional "computation center". And it has obvious special values to a telepresence research project.

Two scientific communities already successfully operate this way. Stanford's SUMEX coordinates computational research for many small medical projects in many locations. The ARPA-supported network of ***Artificial Intelligence Laboratories*** have worked together effectively for a decade. (In fact, the technology of networking itself was developed within that community -- along with much of modern robotic science. As this community will play a key role, it would make sense to grow the Project Network as an extension of ARPANET.)

STAFF. The project needs first class engineers and scientists, and technical managers of great skill and vision. To recruit them, it must offer real long-term commitments. It is fortunate that we need not assemble the entire staff in a single place.

START-UP. Often, a large new project can grow from an existing one. In the present case I incline toward a new start, because this field has stagnated for so long (20 years) that its once most productive institutions are now generally inactive. The present scene looks to me like this:

Industry. Many major companies were involved at various times -- IBM, AMF, Hughes, General Mills, and others -- but none ever reached "critical mass". Many smaller firms are active, and there is much precious "knowhow" at Unimation, Central Research (CRL), Programmed and Remote (PaR), and others.

Government. ONR has a substantial activity, in submarine exploration and rescue. ARPA was for a decade "the" sponsor of research in robotics, but withdrew in recent years. The Army joined ARPA for a time in work on powered armored suits. NASA gave telepresence little attention until recent concerns with shuttle cargo handling and space station fabrication. NBS has made useful studies. Except for ONR there is no current government leadership center in this area.

University. Rich in ideas and plans, no university project could ever afford to engineer complete systems, but they produced many important designs and prototypes. Generally, these were concerned more with computer control than with human telepresence. There are important projects at Carnegie, Case, MIT, Rochester, Stanford, etc., and at quasi-university laboratories like SRI, JPL, and Draper.

In view of this I incline toward a fresh start. It would seem natural to explore the subject in an NAS-type study committee but, frankly, I am uneasy about its domination by conservative old-timers.

FACILITIES. The project needs first-class equipment for Mechanical and Electrical Engineering, Materials Science, Psychology, Mathematics, and Control Theory. Developing the real-time man-machine interfaces will need the most advanced Interactive Computation resources -- like those at XEROX, MIT, or Stanford. It needs powerful "number-crunching" computers for realistic, real-time physical simulation. The Research Centers must be linked by a video-bandwith computer network, so that telepresence systems can be operated and coordinated from different locations. (Satellite links are too slow for natural human feedback, so microwave or cable links are required.)

APPENDIX 2: Why a Special Project?

If telepresence technology is so useful, won't it appear when needed? The answer is "no"; its "natural" evolution stopped nearly twenty years ago! Even as needs grew, research costs grew faster, but funding declined; by 1960, no laboratory could afford to take another major step. Today, one can buy more than a hundred commercial teleoperators -- mostly from Japan -- but all of them are of the crude six-jointed, two-fingered gripper type. This stagnation, since Argonne's 1954 "force reflecting" instruments, was due to endless repetition of this scenario:

1. *Some application seems to need a better manipulator, e.g., to join two pipes in a certain way.*
2. *An existing Mechanical Hand would help -- but only if it had another joint in one of its "fingers".*
3. *But making that improvement causes complications:*
    The control system needs another channel.
    The output needs a new sensor.
    Another input feedback device is required.
    A microcomputer program must be modified.
    Some operator retraining is necessary.
    Several older tools must be re-engineered.
4. *While no one of these is very serious, the totality lies outside the company's mission and budget. So they decide to "make do". The pipe fittings are redesigned so that the old, clumsy hand can manage.*

A good production engineer can solve any specific problem by finding some specific trick: use a special jig; prefabricate some new parts; develop a special tool for the hand; replace the hand with a special tool. Each little problem is thus solved, but the technology becomes antiquated. The overall problem becomes visible only in incidents like Three Mile Island -- when we suddenly find no way to turn some valve from afar!

Unless some agency takes responsibility, nothing will change. Perhaps this is part of the larger pattern in which, according to Tesar (**Science**, 1978), the US has acquired a profound general weakness in technically intricate, machinery, which has already disturbed our international trade balance.

This deficiency has already cost billions in our nuclear technology, for it complicates everything from minute details of fittings and connectors to overall plant architecture. It creates policies in which lives are shortened and sometimes lost, when humans have to intervene in emergencies. A single malfunction can entail operating losses that dwarf all the costs of our project.

APPENDIX 3. STATE OF THE ART

A typical contemporary teleoperator has three basic elements:

Input: a handle attached to a jointed arm-like linkage. Moving it makes the Output move similarly. Squeezing the handle closes a gripper at the output.

Output: The remote gripper follows the motion of one's hand, but not the curve of the arm -- so it cannot always reach around obstacles; there are too few joints to emulate our shoulder, elbow and wrist. The "force-reflection" feedback is sometimes adequate, but for delicate work one needs better senses of touch and shape.

Compensation: If the work is too large, small, heavy or light for human hands, the system needs a psychologically natural computational compensation in force and time scales, so that the operator can distinguish the inertia and elasticity of the instrument from that of the workpiece. No current systems do this well enough.

Ill-suited for delicate assembly work, all work goes slowly -- typically, easy jobs take 8 times longer than "by hand", hard jobs much more. The two "fingers" can pinch or clamp, but cannot twist, shear, roll, or bend. One cannot use ordinary pliers or scissors; instead, one removes the hand and replaces it by a special tool. This is fun to watch, but it takes time. Engineers must often design new end-tools for new jobs.

We should supply as many natural sensory channels as practical -- touch, pressure, textures and vibration -- and in comfortable, natural ways. Where we cannot reach perfection, we must learn which "sensory deficits" are most tolerable in which kinds of applications. The systems must be able to reconfigure the perceived workspace to make the operator comfortable, e.g., so that a remote "miner" could dig a narrow seam without himself stooping or crawling. To learn how to do this -- a problem in many everyday procedures from dentistry to microsurgery -- the project must support psychological research on how physical situations are represented in our minds.

Some exceptions to this bleak picture: The "Handiman" system developed around 1958 by Mosher at G.E. had good dexterity and compensation. Hitachi has developed a 12-joint hand that can "roll" a baton between three fingers. I built a 14-joint multi-elbowed arm that could reach easily around obstacles. Several projects have pursued radical "tentacle" designs. NASA Ames has an exciting "augmented" space-suit design. The prosthetic "Ranchos Los Amigos" arm has a humanoid geometry. But no project has had the resources to perfect any such ideas. The References summarize a wealth of such ideas.

APPENDIX 4: INDUSTRIAL APPLICATIONS

Industry uses some teleoperators and computer controlled "general purpose" manipulators -- mainly in hazardous or unpleasant jobs like spray-painting, or handling hot objects. But, as noted in Appendix 3, Industry has found it hard to apply these to new jobs because they arrive without hands, feedback sensors, or automatic programming aids. If each machine must be rebuilt, programmed, and debugged for each particular situation, it is no wonder that production engineers find it better to "start from scratch". The field is immature.

Our project should change this, for its will be mechanically versatile and will arrive with adequate programming aids. Eventually, their computer programs will have enough "common-sense" to deal with normal problems of shape, support, and obstacles; they will be able to recognize objects with their computer eyes and manipulate them, verifying that the expected really happens. Today, such jobs are major programming projects; with the "sensible software" of tomorrow they will involve less programming, more "explaining" and "showing by example."

Though this sounds like Science Fiction -- centuries away, much of it has ***already*** been done in years past at the "Artificial Intelligence" projects at MIT, Stanford, Carnegie, SRI, and Edinburgh. At these and several other centers around the world computers, equipped with hands and eyes, are able to recognize and orient certain kinds of objects, interpret simple mechanical assembly instructions, and cope with changing spatial relations or moving obstacles.

However, while these demonstrate the possibilities, such things are still too hard to program to be practical for industry. As automatic programming methods mature, it will become easier and less costly. To be sure, this new generation of "software" will be expensive to create. So it is important to remember that ***software -- unlike anything else -- can be duplicated without cost.***

Those better programs will come the sooner we embark on the Telepresence Project. Then, instead of using different machines for each operation, many assembly-lines will use general-purpose manipulators to do more jobs at each station. Their smarter programs will need less precise uniformity of components and their placement -- very costly constraints. Finally, where "mass-production" is now a synonym for "uniformity"; the new machines will be able to make each produced item to better suit its individual purchaser.

Appendix 5: Nuclear Safety and Security

Like it or not, we are becoming dependent on nuclear power. All present reactors have toxic radiation by-products, and Fusion's shielding and activation problems may be just as serious. All reactors have these fundamental problems:

Thermal: High temperatures weaken all structural materials and exclude most materials entirely.

Mechanical: All efficient generators apply high pressures and forces to those weakened structures.

Radiation: Causes cumulative structural damage, corrosion, and interior flaws that make inspection difficult and hazardous.

Because of inaccessible to humans, designers today must demand long component life and high reliability. The resulting materials problems are expensive and almost unsolvable, and any design must compromise between two extremes:

Permanence: Build each part with monumental toughness -- and hope the system never fails.

Maintenance: Build a modular system that permits periodic inspection, maintenance and replacement of parts.

Because they must minimize human exposure, today's nuclear designs lean toward *permanence*. But this is the wrong choice from the view of structural engineering, because of the scarcity and expense of materials to resist corrosion, heat, pressure, and radiation. In the end, breakdown and failure occurs anyway, requiring manned intervention. ***Maintenance*** is basically better -- but requires adequate telepresence -- and the problem today is a vicious circle: ***facilities are not designed for telepresence, because telepresence technology is too primitive --- and vice versa***! (I realize that on the surface ***maintenance*** appears to entail a problem of more waste materials. My intuition is that it can be solved by recycling and refabrication, but the issue is complex.)

The aircraft industry's outstanding safety record is based on maintenance; instead of relying on material life, they use regular disassembly and inspection -- expensive, yet cost-effective. Present-day nuclear designs do not permit this. Yet, even a small failure that would be repairable in hours with telepresence is cause to shut down a present-day reactor for months. Now, it may be too difficult to place teleoperators within the core itself, but other maintenance inside containment vessels should be much easier than it is now.

WASTE PROCESSING. Dealing with large masses of radioactive materials entails problems so serious that the US now has a critical deficit of Fuel and Waste processing resources -- with no prospect of relief. Industry dislikes building them, regardless of budget. Clearly, better remote technology would help -- for example, to repair the leaking Hanford tanks from the inside.

SECURITY. Justified fears about security of weapon-grade material are so strong as to set our national policy against fuel-efficient breeder reactors. The remotely-manned concept could change this perspective, for it permits potent new provisions:

Limited Access. Since all actions happen via servo channels, we can easily monitor *all* physical operations! There is no way to observe "everything" in a manned environment, but it is practical in the remotely manned plant.

Public Monitors. All operations can be made public via video, so that any suspicious citizen could contribute free time for surveillance. Of course, the public monitors would not be able to perform any motor actions.

Automatic Detectors. To guard against attack ***through*** the remote control system, critical operations would be monitored by programs sensitive to "unusual activities". The quality of these programs would grow over the years, as we learn more.

Reduction of traffic. More self-contained, it is easier to control all that enters and leaves such plants, there are no problems about personnel or their supplies. With maintenance equipment inside, little need pass but consumables and wastes.

Integration of procedures. Eventually, integrated plants will combine generation, separation, reprocessing and waste concentration at the same site. This will further reduce safety, transportation and theft problems.

When a geologically acceptable disposal site is finally agreed upon, we can envision a completely isolated, remotely manned, system that provides also for waste disposal and security against attack and sabotage. Wastes are concentrated, separated, cooled and buried -- in disposal wells adequate for the installation's lifetime. Isolation need ***never*** be broken if a lifetime of fuel is provided; this would be practical with a breeder reactor.

Such a scheme sounds absurd today, because nothing we could now build would work long enough -- nor are we yet sure enough of basic geological mechanics to select the sites. But plate tectonics itself is only two decades old; in another two -- at the rate Geophysics is moving -- we should know enough to be quite certain about some sites. And just about then, we would be able to build such systems, with teleoperators able to repair each other.

APPENDIX 6: SPACE

Planetary Exploration: Vikings I and II show how much can be done even with crude teleoperators, day-long transmission delays that used conservative "supervisory" control involved week-long administrative wait-and-see cycles. Yet Viking had pathetic limitations. It could not reconfigure on-board equipment to exploit what it learned. It took weeks of breath-holding planning just to turn a rock. When a Mars Rover is launched, it should have better manipulators; if we can supply enough "supervisory" computer control, they could erect large antennas, make extensive excavations, and reconfigure scientific equipment.

Near-space exploitation. Think how much more we could have learned with a crude remote vehicle on the Moon. Short Earth-Moon transmission delays permit direct human teleoperator control. With traverses of a kilometer per day, in the ten years that have slipped by, we could have surveyed a substantial portion of the lunar surface. It was often said, during Apollo, that "machines could not replace men". But via telepresence, those people could have done much more, in most phases of Lunar exploration. I fully support the non-scientific motives of manned space exploration, but that is not here the issue. The subject was examined thoughtfully by T. Gold [Ref.]

Space stations. Orbiting space stations may be important some day for power. Building them via earth-based teleoperators would cost far less than via large orbiting worker colonies, though it would help to have a substantial group of on-site participant supervisors. As envisioned by O'Neill, the economics of large near-earth systems might well gain by using Lunar construction materials. Again, this might best have a small on-site colony supervising a large earth-based telepresence labor force to build and operate lunar mining, fabrication, and mass-projector systems. Similarly, planetary exploration is best done by people in orbiting spaceships controlling ground-based teleoperators; Earth-Mars delays are too long to work directly from earth.

Appendix 7: Micro-Applications in Biology and Medicine.

Construction cranes are just giant teleoperators, and Industry already appreciates them. At the other end of the size spectrum, biologists have long used "micromanipulators" -- very small teleoperators. But none have any sensors. If we can miniaturize teleoperators, there are clear and urgent applications in surgery and biology:

Vascular micro-surgery. Surgeons today can repair and replace small blood vessels -- except where the need is greatest, in the brain and other organs where scalpel and forceps cannot reach. For that, the micro-vascular surgeon would need touch-reflecting micro-hands, on slender probes that reach through very narrow passages.

Semi-automation. Along with its technical difficulty, microsurgery has a time problem; one can replace two or three major coronary vessels, but not a hundred smaller ones. A surgeon could direct a semi-intelligent procedure to swiftly make many more small repairs. The device would interrupt to ask about unexpected difficulties, and not all the small operations need be successful.

Coronary circulation repair. The US annual budget for coronary vessel repair already exceeds a billion dollars, despite some remaining questions about its value. Again, micro- telepresence could permit more extensive, multiple, repairs with less trauma.

Cerebral circulation repair. Recent progress in surgery for stroke (and, more important, for *impending* stroke) means this, too, will become a national expense. The myth is false that senility is a normal part of "aging"; it most often comes to healthy brains with failing arteries. A small repair can yield an extra decade for an intellect that took a lifetime to build.

General Surgery. Many procedures could be done via mini-hands that enter small incisions and traverse natural pathways. Today, especially in Japan, stones and emboli are removed, and pacemakers implanted, with simple, remote controlled probes. These limit repairs to a narrow spectrum of cutting, crushing, and stretching operations, but we would change that.

Medical Procedures. Telepresence technology will make many procedures more accurate and tolerable, e.g., in radiotherapy and other motion-intolerant situations -- the instruments would be "slaved" relative to the patient. Instead of rationing CT scanners because of cost, HEW should help make them cheaper to build and use; a CT scanner is only a radiation source, a sensor array, and a manipulator to move them. Source and sensors need not stay expensive, and our project will lower manipulator costs.

"Dangerous" Microbiology. Public dread of genetic research, quiescent at this writing, will return some day with more real dangers. How to make a really secure laboratory? Seal it in with a telepresence.

Ordinary Biology: In normal biology, better micromanipulation will bring us into better direct contact with the basic structures and processes of life. Eventually it should let us rearrange the internal structures of single cells.

APPENDIX 8: TRANSPORTATION

MASS TRANSIT. The current move toward mass transit threatens to move masses of people through places they don't want to go, wasting their time and mental energy. Why not instead work toward an ultra-efficient and safe car, with advanced semi-automatic features? I would not be surprised to find them as energy efficient per person-trip as current mass-transit schemes. Automatic cars are not the same as teleoperators, but could be approached by a related program. They will come eventually -- and what a waste if just after two decades and a hundred billion dollars of trolley-building! For then the public will reject the "mass" system that must in its nature poorly serve the busy, elderly, handicapped, or very young.

REDUCING TRANSIT. Much work-related travel and traffic can disappear as we move toward telepresence; much office and factory work can proceed via this and computer networks. This will change attitudes about manual labor, for many "dirty" jobs would become tolerable with teleoperators -- and downright interesting with semi-intelligent supervisory controls.

GEOGRAPHICAL IMPLICATIONS. With teleoperators much manual work could be done from home or elsewhere instead of mines and factories. But ***if one can so do the job at all, one can as easily work from a thousand miles as a thousand meters***! Underdeveloped and underprivileged regions can exploit and export any high-earning skills they have -- any laborer in Africa or India can market her or his ability in Japan or Antarctica.

SOCIAL MOBILITY. If fewer workers will need physically to travel "to work", many may not want to stay home either, for our "home vs. work" system releases us from the constraint of a single environment. Perhaps people will invent "work clubs". On the other side, telepresence users can enter ***wider*** universes, working with others from diverse backgrounds. Persons with unusual talents can reach larger opportunities. Time-sharing multiple jobs will become more practical.

How much is telepresence like really "being there"? Joking aside, we know little about it. People have reported strong illusions, even with limited equipment. In fiction, the teleoperator experience was treated thoughtfully in novels by James Blish, Robert Heinlein and Frank Herbert, among other writers.

NOTES

This proposal is dedicated to two friends. The late Ray Goertz developed in 1954 the first electric force-reflecting teleoperator, and he talked of such ideas as these a long time ago. My first vision of a teleoperator-based economy came from Robert A. Heinlein's 1940 novel, ***Waldo***. The first such instruments were built in 1947. Forty years after writing ***Waldo***, Heinlein helped me sharpen up this paper.

If Teleoperator technology promises wealth beyond dreams, is there a dark side? People who make proposals should think about such matters, but all I find to say is that we must try to help those who want to live in the "old ways" to have their chance, while those who want the new gifts should also have theirs. In my personal view, the gifts promise better, richer and longer lives. Might telepresence have a special tendency to make workers feel "alienated"? I would suppose yes, even with superb technology. In compensation, many jobs will become intensely more "interesting" and creative, and many persons' worlds will be enlarged.

Each step toward telepresence is a step toward automation, and that raises problems; everyone knows the economic pain and psychic grief unemployment causes, and some would try to slow change to reduce it. Yet already, for other reasons, a generation of reforms are eliminating many unsafe jobs -- ***many of which telepresence could "save"***! And because with telepresence a person can offer a skill, part time, to several employers, that worker becomes less vulnerable to the fortunes and moods of one employer. In any case, one must weigh the insidious losses to all of us, that stem from decreasing productivity, against the acute loss for one person of a particular unproductive job.

Finally, in a queer sense, the question of "technological unemployment" may be becoming moot. Many of the new generation consider it demeaning to be bound to any single employer, occupation, or even culture. I suspect this is because we all today understand -- at least on some level -- that most of what we do does not (in the last analysis) really have to be done! Today, how we perceive our work as essential, and how we feel about changing it, depends more on nuances of our dispositions than on the jobs themselves. In effect, most of us already feel technologically unemployed.

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