TELEROBOTIC REQUIREMENTS FOR SENSING, NAVIGATION, AND COMMUNICATIONS

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Abstract

The coming decade will see a wide variety of large and small unmanned vehicle systems emerging from laboratories to tackle real-world applications. These systems will not only perform reconnaissance and inspection tasks, but also do real physical work, such as installing subsea completions in offshore oilfields. This presentation is intended to promote an appreciation of the broad range of telerobotic systems which offer opportunities for microwave and analogous technologies to support required functions of navigation, sensing, and communication. One thrust is to identify some of the many significant dimensions of variability between different systems characterizable as "telerobotic" -- dimensions which accommodate a wide variety of system concepts not yet explored. The specific details of an application's requirements -- in terms of functionality, performance, and environment -- sensitively affect the tradeoffs leading to an optimally cost effective system design approach.

1. Introduction

The telerobotic systems of our interest must be distinguished both from the anthropomorphic robots of fiction and from the industrial manipulators of factory automation. We are discussing mobile robots which are situated, move, and navigate within some environment, and which are intended to perform some mission, which may involve sensors (such as surveillance), manipulators or other effectors (such as environmental remediation), and/or communications capabilities (such as communications relay).

2. Teleoperation, Autonomy, and Supervisory Control

Two radically different approaches to developing unmanned vehicle systems have been extensively explored. The first approach is **teleoperation**, in which a remotely located human operator drives or pilots the vehicle. The key to successful teleoperation is in providing the operator with enough data to permit him to successfully drive the vehicle -- typically video from the vehicle. The second approach is **autonomous** operation, in which the vehicle essentially drives itself with no operator intervention. The key to successful autonomous operation is to provide the vehicle with sensor subsystems, processing resources, and vehicle control loops based on the sensor data that can successfully drive the vehicle.

While teleoperation of a ground vehicle using video might seem to be a straightforward process, actual experience with developmental systems has indicated a number of significant problems: (1) the disparity between visual and inner ear cues can induce nausea and other symptoms in the remote human driver; (2) it is easy to get lost, since the line of sight of a camera mounted low to the ground may be impeded by grass or other obstacles; and (3) video alone does not provide the operator with critical orientation cues, leading to potentially severe problems in coping with sloped terrain.

On the other hand, fully autonomous ground vehicle operation has proved far more difficult than originally anticipated. "Simple" tasks such as autonomously driving down a paved road using visual cues to determine the road edges and centerline have not been reliably solved for the general case, due to such perturbing factors as changes in lighting due to cloudiness and shadows.

Supervisory control schemes integrate the strengths of both the teleoperated and autonomous modes of operation. Examples include: (a) JPL's CARD system, in which the operator designates an apparently traversable path to a target location on a video frame, and then the vehicle autonomously follows that path to the target, using its sensors to avoid obstacles; and (b) NRAD's "telereflexive" obstacle avoidance, in which the driving commands of a remote driver are treated as "suggestions" which the vehicle modifies based on local sensor information. Limited autonomy could also serve as a backup for a lost communications link; if the link is lost (as might happen with a broken fiber optic tether or eclipsed LOS RF link), the vehicle could autonomously drive (perhaps retracing its previously followed path) to a preassigned point.

The bottom line in considering the spectrum from teleoperation to autonomy is that it essentially boils down to a tradeoff between (a) implementing enough communications bandwidth to allow a remote operator to

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perform navigation and control functions, and (b) implementating processing algorithms of adequate complexity and throughput to perform the functions on the vehicle. Unfortunately, we encounter solid technical limitations in both arenas: in many situations we may not be able to realize the needed communications bandwidth over a non line of sight (NLOS) path, and we may not have the sensor processing capabilities (in terms of effective algorithms as well as of adequate throughput) needed to adequately "perceive" the features of our environment necessary for reliable navigation.

3. Current Programs

The Department of Defense has focused its efforts to develop telerobotic systems for military applications in three Program Offices (POs), for Unmanned Ground Vehicles (UGVs), Unmanned Undersea Vehicles (UUVs), and Unmanned Air Vehicles (UAVs). Since the formal development process for military systems involves establishment and validation of requirements and doctrine for deployment, logistical support, and so forth, each of the POs has targeted only a small number of system concepts for development. ARPA plays a key role in technology development in support of these development efforts.

The efforts of the Unmanned Vehicles/Systems Joint Program Office (UGV/S-JPO) are focused on two long term goals: the Tactical Unmanned Ground Vehicle (TUGV), which is intended to provide reconnaissance, surveillance, and target acquisition-designation (RSTA-D), chemical detection, and mine-countermine capabilities, and the Engineer Vehicle Teleoperation Capability (EVTC), which is intended to remove the human operator from existing military engineer vehicles during obstacle breaching operations. [1]

The Program Executive Office for Cruise Missiles and AUVs has structured requirements for a number of target systems in terms of operational range (radius of action) and endurance time: close range (30 km, 4 hours), short range (150 km, 8 hours), medium range (700 km, 4 hours), as well as long endurance (farther, longer), and vertical take off and landing (VTOL) systems. Heavy emphasis is placed on commonality of modular subsystems across system categories. [2]

As the deep water strategic threat of Soviet submarines has diminished in recent years, the UUV efforts of ARPA's Maritime Systems Technology Office (MSTO) and of the Navy's UUV Program Management Office (PMO 403) have been refocused on shallow water warfare, and especially on countermine capabilities. [3]

Other robotic efforts within DoD address warehouse security [4] and ordnance disposal. In addition, dual use and technology transfer have become important considerations for defense robotics programs. NASA's telerobotics efforts have included support for the construction of the Space Station (the now-canceled Flight Telerobotic Servicer program) and unmanned (i.e., low cost) planetary exploration. The Department of Energy is pursuing the development of robotic tools to help in the massive environmental remediation task it faces in cleaning up after the nuclear weapons industry.

4. Evolving Technological Opportunities

Several rapidly evolving branches of technology offer the promise of enabling great expansion in the range of feasible telerobotic systems. For the most part the importance of these technologies lies as much in realizing extremely low cost, compact implementations of previously expensive capabilities as in realizing previously infeasible functionality. The development of large scale commercial markets for these functions is critical to achieving these benefits.

VLSI Technology. As the costs of memory and of processing functionality and performance continue to decline, sophisticated high performance DSP functions will become available in inexpensive telerobotic systems. GPS receivers are one example; the "wireless" personal communications revolution will yield many more.

Behavior Based Intelligent Control and "Neural Structures". The introduction of low level "reactive" or "behavior based" [5] control processes in the late 1980s (as opposed to high level "deliberative" control) has demonstrated that even simple inexpensive robots can be provided with behaviors that effectively respond to their sensor inputs. Research on insect and other animal motor control systems points to the possibility of very inexpensive compact robotic control processing elements mimicking these neural structures.

Micro Electro Mechanical Systems (MEMS) Technology. The technology of manufacturing miniature electromechanical subsystems promises to revolutionize the sensor world; for example, MEMS approaches are now being applied to the fabrication of focal plane arrays (FPAs) of uncooled FLIR sensor elements; the promise is that the cost of IR cameras will drop from the $50K -$100K range down to below $1K, opening up tremendous new markets in law enforcement and other areas [6]. Another expected benefit of MEMS technology will be inexpensive miniature Inertial Measurement Unit (IMU) subsystems based on tiny gyros and accelerometers. MEMS technologies may soon enable the monolithic fabrication of a complete robotic system -- a "robot on a chip" -- at a cost so low that extremely large numbers of them could be applied to a single task such as cleaning a ship's hull or detecting intruders in a controlled area of interest [7, 8]. Supplying power to and communicating with [9] such tiny devices will present major challenges and opportunities.

The range of telerobotic systems that will soon be technically and economically feasible extends far beyond the relatively few concepts being explored by the military and other government agencies. The military system development cycle takes many years, while the state of the art in the key technologies which enable the development of telerobotic systems, especially sensor and processing technologies, are advancing very rapidly. Hence it is important to consider a much broader range of systems concepts than those being actively pursued by DoD.

5. Issues and Challenges

Sensitivity to Specific System Constraints. Determining the optimal design approach for a given telerobotic system requires careful consideration of the constraints and opportunities specific to the intended application. For example, it may well be possible for a robot which is carrying a communications relay mission package to exploit that package for its own communication needs. Similarly, if a heavy work system requires an umbilical to convey power to the robot during its operation, high bandwidth communications can be piggybacked at minimal additional cost, perhaps favoring a teleoperated approach. The use of multiple robots in an application can bring both opportunities (communications relay, sensor cooperation) and constraints (e.g., tether tie-ups, requirements for communications between platforms). The presence or lack of structure in the environment, the ability to add structure (e.g., passive retroreflective markers or active beacons), and the ability (or lack thereof) to summon a human backup can also critically affect the system design.

Communication. Humans are visual creatures, and teleoperated systems have relied heavily on the transmission of video to the remote operator, sometimes in color, and sometimes stereoscopic. Furthermore, imagery-based reconnaissance and surveillance ("RSTA") are common functions for autonomously navigating robots. This need for a video bandwidth communication channel has motivated the use of fiber optic cable for non-line of sight (NLOS) ground vehicle operations and for undersea systems. In ground applications where neither a fiber tether nor LOS relay is acceptable, video data compression is being explored to transmit reduced frame rate video over available tactical radio links (e.g., SINCGARS) at 16 to 64 kbps [10]. VLSI DSP spinoffs from the "wireless communications revolution" and HDTV should make this goal possible in the near future. The poor characteristics of seawater as a medium for the high fidelity transmission of both acoustic and electromagnetic energy make the communication problem especially acute for underwater systems; optical systems can provide short range transmission of video bandwidth signals (100 Mpbs at 100 yards), while acoustic systems are being refined to extend both bandwidth and range (on the order of 20 kbps at 4 nm). Barring major breakthroughs in the quest for truly autonomous systems operation, including AI techniques to reliably "understand" and reason about the world as sensed by video or IR imagery, increased bandwidth to return sensor information from the remote vehicle will remain a major goal.

Navigation. While the advent of mass production compact, inexpensive GPS receivers has essentially solved the problem of knowing where a vehicle is on a geographic scale, GPS is not available to UUVs (unless they come to the surface), can be less than useless in trying to get to a point whose LATLONG is in error (e.g., a remote island as located on an old nautical chart), and is not accurate enough to guide a mine detection sensor with a swath width of a few feet over a "lawnmower" style search pattern. When an application permits the installation of fixed beacons or receiver stations in the environment, this last type of navigation problem can be handled by an RF or optically based locating system. One example is Harris Technologies' Infogeometric Location and Communications System (ILCS) [11], which uses time of arrival measurements of spread spectrum RF signals to compute vehicle location. A second example is MacLeod Technologies' Computer Opto-Electronic Navigation and Control (CONAC) system [12], which is based on a rotating laser beacon. Both of these systems can be tailored to the requirements of specific applications to address communication and vehicle control as well as navigation.

6. Conclusions

The continuing rapid evolution of a number of enabling technologies ensures that the economic importance of telerobotic systems will expand drastically over the next decade, providing a host of opportunities in providing important subsystem functions, including sensors, navigation, and communication. One strategy for pursuing these opportunities is to avoid tackling the difficult generalized problems that others have stumbled over; instead identify specific application niches and then exploit the specific characteristics of these applications. It will pay to piggyback on the cost-optimized products of the consumer marketplace, and to anticipate the rapid differentiation of any really successful broad market niche that emerges.

7. References

1. Swinson, M.L. "Unmanned Ground Systems: The JPO Strategy for System Development and Fielding", **Proceedings of AUVS-93, 20th Annual AUVS Technical Symposium**, Washington DC, 28-30 June 1993, pp 947-953.

2. Brown, B. "Joint Unmanned Aerial Vehicle (UAV) Program Update", **Proceedings of AUVS-93, 20th Annual AUVS Technical Symposium**, Washington DC, 28-30 June 1993, pp 1-53.

3. Shotts, W.E. "Program Update-403", **Proceedings of AUVS-93, 20th Annual AUVS Technical Symposium**, Washington DC, 28-30 June 1993, pp 585-605.

4. Heath, T.A, and Everett, H.R. "Coordinated Control of Interior and Exterior Autonomous Platforms", **International Symposium on Robotics and Manufacturing**, Maui HI, August 1994.

5. Brooks, R.A. "A Robust Layered Control System for a Mobile Robot", **IEEE Journal of Robotics and Automation**, RA-2, April 1986, pp 14-23.

6. Gallo, M.A., Willits, D.S., Lubke, R.A., and Thiede, E.C. "Low Cost Uncooled IR Sensor for Battlefield Surveillance", **Proceedings of SPIE Infrared Technology XIX**, San Diego CA, 12-14 July 1993, Volume 2020-37.

7. Flynn, A.M. "Gnat Robots (And How They Will Change Robotics)", **Proceedings of the IEEE Micro Robots and Teleoperators Workshop**, Hyannis MA, 9-11 November 1987. Also appeared in **AI Expert**, December 1987, p 34 et seq.

8. Gage, D.W. "Command Control for Many-Robot Systems", **AUVS-92, 19th Annual AUVS Technical Symposium**, Huntsville AL, 22-24 June 1992. Reprinted in **Unmanned Systems** Magazine, Fall 1992, Volume 10, Number 4, pp 28-34.

9. Gage, D.W. "How to Communicate with Zillions of Robots", **Proceedings of SPIE Mobile Robots VIII**, Boston MA, 9-10 September 1993, Volume 2058, pp 250-257.

10. Noell, T.E., and DePiero, F.W. "Reduced Bandwith Video for Remote Vehicle Operations", **Proceedings of AUVS-93, 20th Annual AUVS Technical Symposium**, Washington DC, 28-30 June 1993, pp 479-486.

11. Harris, J.C. "An Infogeometric Approach to Telerobotics", **Proceedings of 1994 National Telesystems Conference**, San Diego CA, 26-27 May 1994.

12. MacLeod, E.N., and Chiarella, M. "Navigation and Control Breakthrough for Automated Mobility", **Proceedings of SPIE Mobile Robots VIII**, Boston MA, 9-10 September 1993, Volume 2058, pp 57-68.