

Future Directions in Tele-operated Robotics

Alan FT Winfield, BSc, PhD, CEng, MIEE

Intelligent Autonomous Systems (Engineering) Laboratory
University of the West of England, Bristol

ABSTRACT

This paper examines a number of key areas of current research in tele-operated robotics that could have a significant impact on future directions and applications. Although accurate prediction is notoriously difficult the paper will aim to ground its conclusions through reference to current research literature. Following a generic description of the key elements in tele-robotic systems, the paper briefly reviews two areas of relevance to future directions: semi-autonomous tele-operated robots and the miniaturisation of tele-operated robots. The paper then takes a third key area and describes, in greater depth, current work in the author's laboratory in integrating wireless communications, Internet protocols and adaptive video compression.

1. INTRODUCTION

Tele-operated Robots (although not necessarily named as such) have, in recent years, come to prominence in a number of esoteric spheres of application. Notably, in Space, in Underwater Exploration, in Military Aerospace, and in Robot-assisted Surgery. Planetary exploration has had remarkable success with the tele-operated deep space probes Pioneer and Voyager, and more recently the Mars Pathfinder Microrover 'Sojourner' (1). Such is the success of this technology that NASA has declared its intention of meeting 50% of its "EVA-required operations on orbit and on planetary surfaces" with tele-operated robots by the year 2004 (2). Undersea Remotely Operated Vehicles (ROVs) are now a routine technology for deep-sea exploration, salvage and maintenance. In the field of military aerospace, tele-operated Unmanned Air Vehicles (UAVs) have, since 1990, assumed considerable importance in aerial reconnaissance (3). Tele-robotic devices are finding acceptance by surgeons and might soon be regarded as key surgical tools for certain procedures (4).

Tele-operated robotics or tele-robotics for short, describes the class of robotic devices that are remotely operated by human beings. Tele-operated robots thus contrast with ‘autonomous’ robots that require no human intervention to complete the given task. The distinction between autonomous- and tele-operated robots is however blurred since some tele-operated robots may have a considerable degree of local autonomy, thus freeing the human operator from low-level control decisions.

It is useful to distinguish between two classes of tele-operated robot: those that are physically fixed or anchored, in space, and those that are not. The former includes multi-axis manipulators (robot ‘arms’) which might, for instance, be used for the remote handling of dangerous materials. The latter class, of tele-operated *mobile* robots, covers a much larger group, including for instance land-based vehicles for inspection and manipulation of unexploded ordnance, Unmanned Airborne Vehicles (UAVs) for surveillance or reconnaissance applications, or undersea Remotely Operated Vehicles (ROVs). A further useful distinction may be made between those tele-operated robots whose sole function is to provide the human operator with a passive ‘tele-presence’ and those that additionally allow action at-a-distance. Indeed tele-presence, generally provided by means of a camera mounted on the tele-operated robot, is practically a defining feature of tele-robotics. An underlying assumption of tele-robotics is that the objects that need to be inspected, manipulated or surveyed are too complex for (current) autonomous robot systems yet too hazardous, remote or inaccessible for human beings. A human expert is needed to *interpret* the objects, make *judgements* and perhaps also *direct actions*, yet all of this must be carried out remotely. A tele-operated robot might thus be regarded as an extension of the senses and (perhaps) also the hands.

Current and potential applications of tele-operated robotics cover the full spectrum of operating environments, including land, sea, air and space; and *in-vitro* applications for robot-assisted surgery. Given this wide potential range of applications and operating environments, it follows that the primary limits to tele-operated robotics lie with current technology. As the enabling technologies improve then the range of feasible applications for tele-operated robotics will in-turn increase.

A complete review of the enabling technologies would need to cover a considerable range of topics, including power and energy sources; motors and actuators; sensors; microelectronics; control and communications technologies; software and man-machine interfaces. Such a wide-ranging review is beyond the scope of this paper. Instead the paper overviews two areas which are of interest to current research within the field. Firstly, developments in semi-autonomous tele-operated robotics and, secondly, the miniaturisation of tele-operated robots. The paper then describes in detail a third area of interest: the integration of wireless networked communications, Internet Protocols and adaptive video compression, leading to a generic ‘smart vision’ systems for tele-operated robotics

1.1 A Generic Tele-robotic System

Before proceeding, it is useful to establish a generic description for tele-operated robotic systems in order to identify their key elements, or sub-systems. These will be referred to throughout this paper. The three main elements that, in a sense, define a tele-operated robot system are:

- the Operator Interface
- the Communications Link, and
- the Robot

In-turn we can break down each of these three elements into their essential components.

The Operator Interface: this will generally consist of one or more *displays* for the video from the robot's onboard camera(s) and other sensor or status information. In addition the interface will require *input devices* to allow the operator to enter commands (via a keyboard), or execute manual control of the robot (via a joystick, for instance).

The Communications Link: this might utilise a wired connection for fixed tele-operated robots, or wireless for mobile robots. In either event the communications link will need to be two-way (full duplex) so that command data can be transferred from the Operator Interface to the Robot, and at the same time vision, sensor and status information can be conveyed back from the Robot to the Operator Interface. Often, the communications requirements are diverse, requiring both digital and analogue channels and high bandwidths, especially for real-time video from the Robot back to the operator.

The Robot: whether it is a fixed manipulator (robot arm), or a mobile robot, the tele-operated robot will integrate mechanical and electronic components. Its design will vary enormously over different applications and operating environments. However, the robot is likely to require:

- Onboard power and energy management sub-systems;
- Communications transceivers to interface with the Operator Interface via the Communications Link;
- Embedded computation and program storage for local control systems, and to interpret commands from the Operator Interface and translate these into signals for motors or actuators, and
- Video camera(s) and other distal sensing devices.

In fact, many of the requirements of tele-operated robotic systems are sufficiently generic to merit research into abstracted modular architectures that can be re-applied to diverse system requirements (5).

Two aspects of the generic tele-operated systems architecture merit further discussion. The first is that the human operator is an integral part of the overall control loop. Video from the robot's onboard camera is conveyed, via the communications link, to the human operator. He or she interprets the scenario displayed and enters appropriate control commands that are transmitted, via the communications link, back to the robot. The robot then acts upon (or moves in) its environment, in accordance with the control demands and the outcome of these actions is reflected in the updated video data to the operator. Hence the control loop is closed. Recognition that the human operator is an integral part of the control loop underlines the key importance of good design in the Operator Interface. This leads to the second observation, which is that no part of the overall system should be designed in isolation. A successful tele-operated robotic system must be designed from an overall systems-engineering perspective. It would be easy, for instance, to focus all of the design effort into the robot,

neglecting the operator interface and hence compromising the operational effectiveness of the overall system.

2. DIRECTIONS IN TELE-OPERATED ROBOTICS

In reviewing both actual and potential future directions for tele-operated robotics, we could adopt either an *applications* or a *technology* perspective. An applications viewpoint would consider future directions for each discrete applications domain, and it is certainly true that different arenas present unique design challenges. Tele-operated Unmanned Air Vehicles (UAVs), for example, present very different design and operational criteria than fixed tele-operated multi-axis manipulators for processing hazardous materials. This paper is, however, concerned with *generic* issues and challenges in tele-operated robotics. Especially those advances that might have a significant impact on a wide range of application domains, or even open up completely new or hitherto infeasible applications for tele-operated robotics. We shall therefore adopt a technology focus in this section.

2.1 Local Intelligence for Semi-Autonomous Tele-operated Robots

By definition, a tele-operated robotic system includes a human operator. A well-designed system should, however, aim to reduce the workload on the human operator so that he or she can focus on the overall task or mission objectives. If the human operator has to manually control every aspect of the tele-robot's operation, then they can easily become overwhelmed by the minutiae of low-level control actions, to the detriment of the high-level mission goals. A radio-controlled helicopter provides an example of a system that is notoriously difficult to fly. A remotely piloted rotary-wing aircraft fitted with a camera for surveillance tasks typically requires one operator to fly the vehicle, while another observes the scene from the onboard camera and directs the pilot. This is less than ideal, since it relies on verbal communication between observer and pilot; undoubtedly the weakest link in the control loop.

While it is self-evidently true that the human operator should, ideally, be relieved of very low-level control actions for mobile tele-operated mobile robots, it is equally true for fixed tele-operated multi-axis manipulators. A system that requires the human operator to control each axis of the manipulator separately in order to move the end-effector would clearly be extremely slow and cumbersome in operation. A far better solution is to provide the operator with a single manual control for the position of the end-effector, and rely on a control system to compute the inverse kinematics necessary to bring about the required end-effect translation (6).

There may be other factors in the overall tele-robotic system that demand a degree of local autonomy in the robot. In orbital tele-operated robotic systems, or in tele-operated planetary exploration, propagation delay times for the communication systems become so significant that it is impossible to operate the robot, from an earth ground-station, in real-time. By the time the human operator has seen an obstacle in the path of the planetary rover, for instance, it is too late to take avoiding action since the rover has either already struck the obstacle, or it will have by the time the command signal reaches it. One approach to this problem is simply to not operate the vehicle in real-time, but execute each movement of the vehicle as a series of carefully planned and very slow discrete segments. A better approach would be to command

the vehicle to make its own way to a given target location, perhaps with reference to an object of interest within the visual field shown by the onboard camera, and then rely on local intelligence to plan and execute a trajectory to that target location, with local sensing and avoidance of obstacles (7).

A great deal of effort has gone into semi-autonomous control for tele-operated Unmanned Air Vehicles (UAVs). The particular demands of semi-skilled operation in a military context have led to the development of a number of fixed-wing UAVs with automated launch and recovery, and semi-autonomous flight control (8). Thus the operator has only to mark the required target location and flight path (with way points) on a map display and the UAV will, once airborne, follow the specified flight plan without the need for 'hands-on' control by the human operator. The operator is then free to focus entirely on the images from the onboard camera(s). The design of navigation systems for semi-autonomous UAVs is relatively straightforward thanks to the Global Positioning Satellite (GPS) system, and the availability of compact modular GPS receivers.

Semi-autonomous control and navigation of land-based tele-operated mobile robots is, by comparison with fixed-wing UAVs, much more demanding. The chaotic and cluttered terrain, with both static and moving obstacles, through which a mobile robot may be required to navigate means that a pre-planned trajectory is generally impossible. The development of semi-autonomous control for mobile robots has therefore focussed on layered, modular architectures in which low-level 'reactive' control decisions are based upon local sensors and small control loops within the vehicle (9). Thus the mobile robot will have low-level local control of motors and actuators, steering, and navigation around or over obstacles (for instance), but the architecture must allow the higher control layers (including the human operator) to modify, inhibit or override these low-level control decisions. A good deal of current research in robotics is concerned with adaptive control; that is control systems that are able to learn and adapt to the environment in which the robot finds itself (10). Such controllers will undoubtedly find application in tele-operated mobile robots, although the critical nature of most tele-operated robotic applications demands a cautious approach to the adoption of greater levels of autonomy in the robot. One interesting area of current research is one in which the tele-operated robot is able to progressively learn from its human operator, so that the degree of local control autonomy in the mobile robot is, with human supervision, cautiously increased (11).

2.2 Scaling: the Down-Sizing of Tele-operated Robots

There is very considerable interest in the potential of miniature tele-operated robots. Tele-operated robots with dimensions of the order of a few centimetres might address a wide range of potential applications including inspection and maintenance of plant and machinery, pipes or other inaccessible spaces. Alternatively such machines could be used to aid search and rescue within collapsed or dangerous buildings, or for covert surveillance. Even smaller tele-operated robots, measured in millimetres, could revolutionise robot-assisted surgery or diagnosis.

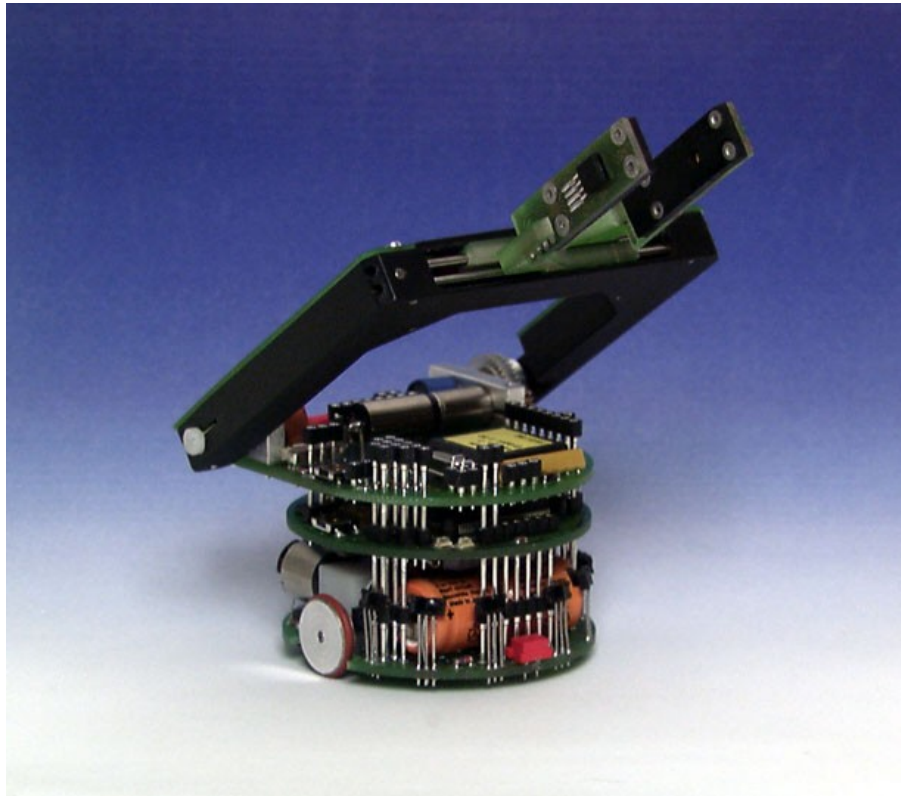


Figure 1: The Kephera Robot¹

Conventional mechanical and electronics technologies place a practical minimum size limitation on tele-operated mobile robots of a few centimetres. The Kephera robot, at 30mm high (without gripper), is probably the world's smallest commercially available mobile robot, shown in figure one. Technology places a similar minimum size limitation on flying (micro-) UAVs, although the problem of providing sufficient power for flight within the limited payload of these vehicles presents unique difficulties. Interestingly, because the payload of micro-UAVs is limited to just a few grams, some researchers argue that this limit precludes tele-operation altogether and that such robots would have to be fully autonomous (12). Micro-UAVs would be particularly useful for operation within buildings or confined spaces but such vehicles would need to be able to hover. Fixed-wing approaches are therefore regarded as inappropriate and current research in this area is focussed on insect-like flapping flight (13).

Tele-operated robots smaller than 1 cm require a technology which integrates mechanical and electronic components onto a single substrate. The new technology of Micro-Electro-Mechanical Systems (MEMS) utilises conventional Integrated Circuit (IC) fabrication techniques to 'etch' mechanical components onto silicon, and has already successfully demonstrated working motors and actuators measured in micro-metres (14). There is little doubt that MEMS technology will result in practical millimetre sized tele-operated robots within a few decades.

3. NETWORKING, COMMUNICATIONS AND SMART VISION

¹ Photograph courtesy of manufacturer's K-Team (<http://www.k-team.com/>).

Two of the key sub-systems of tele-operated robotic systems identified at the start of this paper are communications and vision. While these may be treated separately as discrete sub-systems, there is considerable merit in regarding communications and vision as tightly coupled. Not least because the vision system generally places the greatest demand on the communications link, between operator interface and robot, due to the high bandwidth required for real-time vision relative to the generally modest bandwidth needed for robot control. The conventional approach to the high bandwidth required for vision is to employ video compression techniques to reduce the bandwidth required without seriously compromising image quality. While there are a number of well-known and highly effective video compression algorithms for vision systems (15), none of these were designed for tele-operated robotics. In particular, conventional algorithms are not design for continuously varying compression rates that can be linked to vehicle motion. This section proposes an adaptive video compression scheme which is tightly coupled to both the communications link and the motion of the robot and hence optimised for tele-robotics, especially tele-operated *mobile* robots.

Consider the scenario illustrated in figure two. Here we have a small tele-operated rotary-wing UAV fitted with a video camera for inspection or surveillance. Conventionally the vehicle will be operated from a mobile command centre with a number of separate radio links between the robotic vehicle and the command centre. Typically there will one or more low-bandwidth telemetry radio links to provide control data to and from the UAV, and a separate high-bandwidth analogue radio link for the video camera.

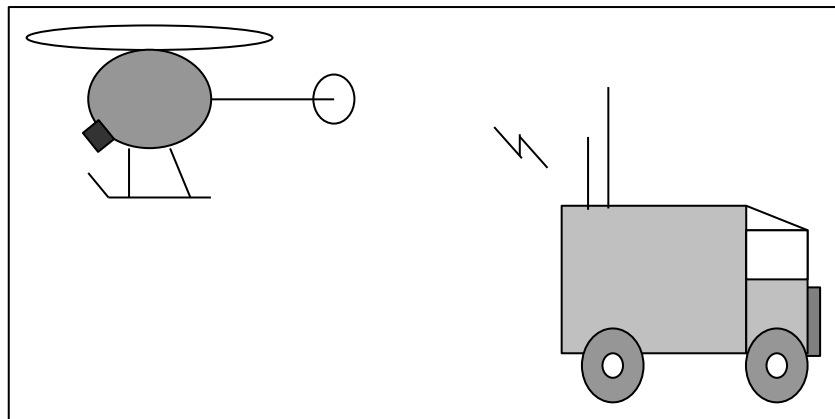


Figure 2: Tele-operated rotary-wing UAV

This paper proposes an alternative communications architecture, in which all of the radio links between the tele-operated robotic vehicle are replaced with a single high-bandwidth wireless Local Area Network communications (LAN) link. If this link makes use of the TCP/IP (or Internet) protocols, then a number of significant advantages follow. In essence, the tele-operated robotic vehicle becomes a *node* on a Local Area Network that may, in turn, be bridged onto the Internet from the mobile command centre, as illustrated in figure three. This means that the robotic vehicle could be tele-operated from anywhere with Internet connectivity, i.e., globally. Operationally this would mean that the human expert (in Unexploded Ordinance, for instance) need not be physically on-hand, but could be brought to bear on the situation from anywhere with Internet access. Apart from this operational benefit,

there is a significant benefit in terms of engineering development effort. The use of standard devices and protocols means that the design engineer can use off-the-shelf hardware and, more significantly, software. The use of standard and proven software components for the communications and networking means that the new software design effort needs only to focus on the top level ‘applications layer’ for robot control and the Man-Machine Interface.

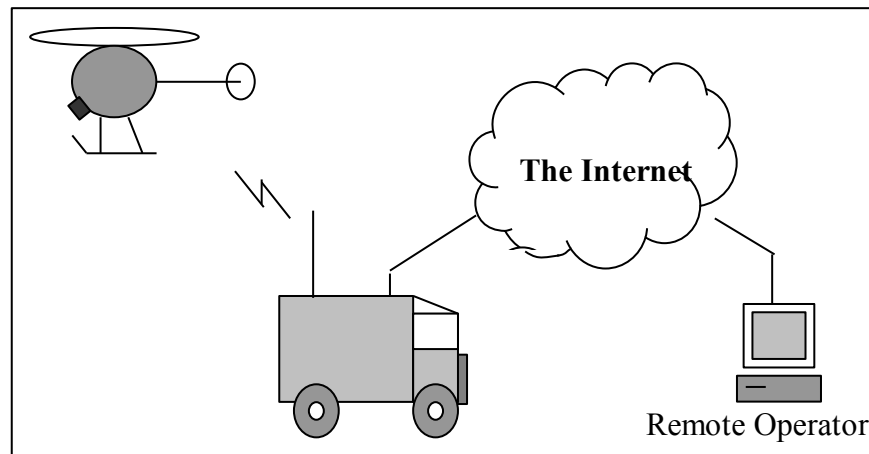


Figure 3: Rotary-wing UAV using Internet Protocols

3.1 Wireless Local Area Network Hardware

Wireless Local Area Network (WLAN) technology, developed primarily to extend wired networks to allow, for instance, roaming network nodes for portable computers within a building, is now relatively mature (16). Typically a WLAN connection will employ spread spectrum modulation over a 2.4GHz RF carrier, with a raw over-air data rate of 1-2Mbits/s. Spread spectrum modulation is a technique that, as the name implies, disperses the modulated signal over a much wider RF bandwidth than using conventional modulation techniques. Spread spectrum modulation is particularly appropriate for a conventional WLAN environment, because it helps overcome problems that would normally be associated with multiple transceivers sharing the same RF spectrum and high levels of multi-path interference. Spread spectrum modulation also confers a high degree of noise immunity, including immunity to accidental or deliberate interference. A benefit that may well be useful in tele-operated robotics applications.

There are two variants of spread spectrum modulation in common use. Frequency Hopping (FH) spreads the spectrum by rapidly switching the carrier frequency. The more sophisticated Direct Sequence (DS) technique achieves the same effect by multiplying the message data with a pseudo-random bit sequence (PRBS) (17). Both variants have the same overall characteristics outlined here, but DS typically will allow a higher over-air data rate than FH.

Because of their intended application with portable or notebook computers, manufacturers have produced remarkably compact wireless network interface hardware. Typically these employ the Personal Computer Memory Card Interface Association (PCMCIA) interface, which is a de-facto standard in portable computers, and usually have a two-part construction consisting of a PCMCIA card with a separate similarly sized wireless transceiver. Its compact size and standard interface makes it ideal for integration into an embedded micro-controller

suitable for tele-operated robotics applications. Figure four shows a complete Personal Computer (PC) compatible controller board, together with a PCMCIA adapter and a wireless network interface. This complete package provides a remarkably powerful controller for mobile robotics applications which occupies about 10cm x 10cm x 10cm. The fact that the processor board is architecturally a PC means that standard network software components can be utilised. Applications software can be developed and tested in a desktop PC environment, using standard tools, thus easing the task of software development considerably. The processor and PCMCIA adapter cards in figure four conform to the PC/104 (also IEEE Std P996.1) standard, which covers both bus connections and card dimensions (18).

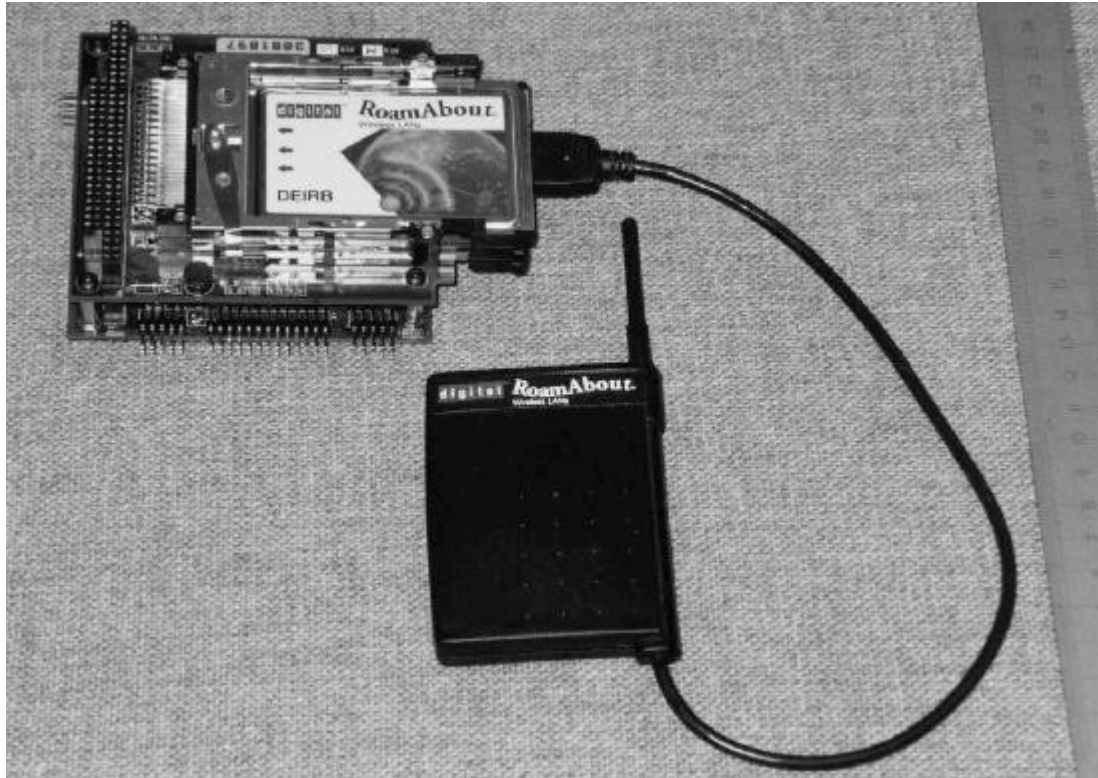


Figure 4: PC/104 controller and wireless LAN

We have successfully employed the controller shown in figure four in two tele-operated mobile robot applications: one a proof-of-concept automated letter carrier for mail sorting office applications (19), and the other a miniature mobile robot platform for conducting laboratory experiments in distributed mobile robotics (20). Additionally, the author is currently investigating the integration of this controller package into a remotely piloted helicopter. The modest weight of the overall package, about 300gm excluding battery, makes this a feasible option.

The relatively low transmitted power output of the wireless network interfaces described here, typically 100-250mW, clearly places a major limitation on the operational range of any tele-operated robotic vehicle employing this technology. Manufacturers quote the maximum range in a building as 100-250m, although the author has found this to be a conservative estimate; empirically we have found the maximum line-of-sight range in open air to be much greater. This does of course limit tele-robotic applications using this technology to short-range applications such as robotic inspection of suspect packages or hazardous materials, or over-

the-building surveillance using a remotely piloted helicopter. Notably, manufacturers of WLAN devices are introducing higher power variants for bridging wireless networks between buildings. Any such improvements will clearly increase the range and hence scope of potential applications. Importantly, the architecture proposed here is clearly scalable up to longer-range applications, simply by increasing the transmitted power of the wireless network interface hardware. All other aspects of the architecture remain the same.

3.2 Network Software Architecture

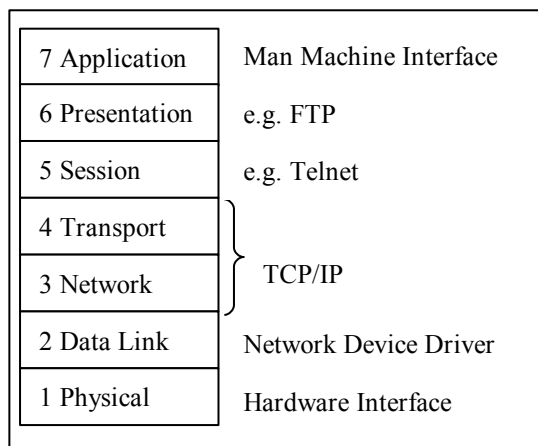


Figure 5: OSI 7-layer reference model

Consider the Open Systems Interconnect (OSI) 7-layer network reference model shown in figure five. This provides a powerful model for describing discrete network ‘layers’ which allows us to ‘mix-and-match’ different network software components. The interchangeability of network software components is achieved by the adoption of standard interfaces between each layer. An implementation of the network layers (3 and 4) is sometimes referred to as a ‘protocol stack’, which needs to be present at both ends of the communications link; in our case the robot and it’s command centre. Any message from the applications layer at one end of the link (an instruction from the command centre for the robot to move, for instance), is transferred down the protocol stack at the originating end of the link. Then across the physical network interface (in our case the wireless connection), and finally up the protocol stack at the destination (i.e. the robot). While this may appear cumbersome it does mean that the same network protocols can be employed over radically diverse hardware communications links. The Internet clearly provides a remarkable example of the success of this approach.

Layer 2, the data link layer, is represented in software by the ‘device driver’ which a manufacturer needs to supply with the network interface hardware. Layers 3 and 4 are frequently grouped together and given a generic network description. Appletalk and DECNet are two proprietary examples. However, the group of protocols known as the Internet Protocols, or (Transmission Control Protocol/Internet Protocol - TCP/IP), have arguably become the most widely used for both local and wide area networks. Clearly, the most interesting operational benefit that might flow from the adoption of TCP/IP is that the tele-operated robot could, if necessary, be controlled from anywhere with Internet connectivity (as illustrated in figure three). Any concerns over security could easily be met by employing any

one of a number of strong cryptographic techniques (in layer 6) that are already commonly employed within the Internet. A description of these techniques is beyond the scope of this paper.

Even if remote tele-operation via the Internet is not a requirement, there are still strong technical arguments in favour of the use of TCP/IP. One is the fact that the protocols are well known and understood, with well-established libraries to support the applications programmer. Another is that standard and proven software components to implement TCP/IP are available for practically every Operating System in common use. We have, for instance, employed MSDOS in the mobile robot controller, with TCP/IP software components from FTP Inc. The command centre computer may typically employ MS Windows 95/98 or NT, which has built-in support for TCP/IP (21). (The fact that different operating systems can be employed at each end of the link might also be regarded as an advantage.)

A particularly strong argument in favour of TCP/IP is that the Transmission Control Protocol (TCP) employed in the transport layer provides us with a robust and reliable data connection. Error detection and repeat request mechanisms are built into TCP so that, providing the connection is not physically broken, reliable data delivery is practically guaranteed. This means that the applications programmer does not need to be concerned with data integrity. Once a TCP connection has been established data can be transmitted without the need for acknowledgements or other such handshake mechanisms in the applications layer code. In short the development engineer does not need to 'invent' a reliable communications protocol, as would be the case for a completely bespoke radio telemetry link.

It is worth noting also that, depending upon the operating system employed in the robot, we may be able to utilise standard TCP/IP tools such as *telnet*, for remote debugging of the robot, *File Transfer Protocol (FTP)* for software upload, or even *Java* for exotic Web-based interaction with the robot.

3.3 Adaptive Video Compression for Tele-Robotics

The requirement of this application is for a live video feed from the robot back to the mobile command centre. The architecture proposed in this paper assumes that the video data will be digitised and relayed from the robot to the command centre, via the WLAN TCP/IP connection.

The hardware required for this operation is relatively modest: a *frame grabber* capable of accepting the analogue video signal from a miniature CCD camera and capturing images one-frame-at-a-time, is readily available in PCMCIA format. The combination of the WLAN interface, the frame grabber, the PC/104 PCMCIA adapter and the PC/104 processor card presents a remarkably compact generic building block for mobile tele-robotics applications. Figure six shows an example of this configuration mounted on a miniature differential-drive wheeled laboratory robot. The same configuration has been successfully integrated into a tracked vehicle, and is currently being mounted into a remotely piloted helicopter.

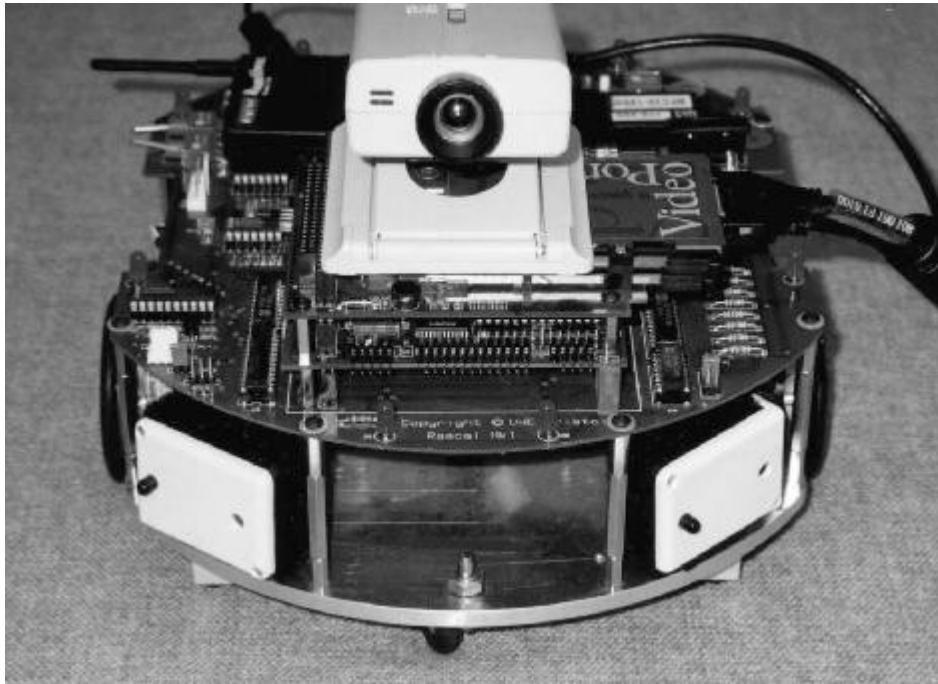


Figure 6: Laboratory platform for adaptive video compression trials

The availability of digitised video data allows great scope for the use of compression techniques, necessary to allow a real-time video feed via the somewhat restricted bandwidth of the WLAN connection. This paper proposes an adaptive video compression scheme, which exploits the fact that the robot's operator makes different demands of the video information at different operational phases. Accepting that this is a gross over-simplification, we can describe a mission as consisting of two phases: *navigation* and *inspection*. The navigation phase describes the part of the mission during which the operator is commanding the robot to move toward the object of interest. During the inspection phase, the robot is either static (or hovering in the case of a helicopter) or moving very slowly, and the operator is primarily concerned with inspecting the object of interest.

From a vision perspective, during navigation the operator requires a high frame rate so that obstacles can be seen and evasive actions taken in time to avoid collision. During navigation a high frame rate is much more important to the operator than high resolution. If the robot is approaching a wall, for instance, then the operator needs a good sense, in real-time, of where the wall is in relation to the robot's current trajectory, but does not need to see the fine detail of the wall itself. During inspection however, high video resolution is likely to be much more important than frame rate, in order to give the clearest possible image of the object under inspection. Because the robot is static, or moving slowly during its inspection phase, then the frame rate can be sacrificed to increase the video resolution. Thus, in the proposed video compression scheme, the vision system continuously adapts both the frame rate and the video resolution according to the current speed of the robot. When the robot is moving at speed, resolution will be sacrificed in favour of a high frame rate, but as the robot slows (under operator command) the frame rate will reduce in favour of increased video resolution. In the limit, when the robot is stationary, the vision system will automatically deliver maximum resolution at a reduced frame update rate. Since transmission bandwidth is a product of frame rate and resolution, then the proposed scheme should manage the communications bandwidth over a wide operational range.

The adaptive video compression scheme has been successfully demonstrated on a miniature differential-drive wheeled robot in the Intelligent Autonomous Systems (Engineering) Laboratory at UWE, Bristol. Figure seven shows a screen shot of a prototype Man-Machine-Interface (MMI) for the test system, which integrates the video display from the robot with the robot's motion control system. In this prototype system vision data and robot commands are successfully integrated into the single TCP/IP connection between the command PC, and the robot.

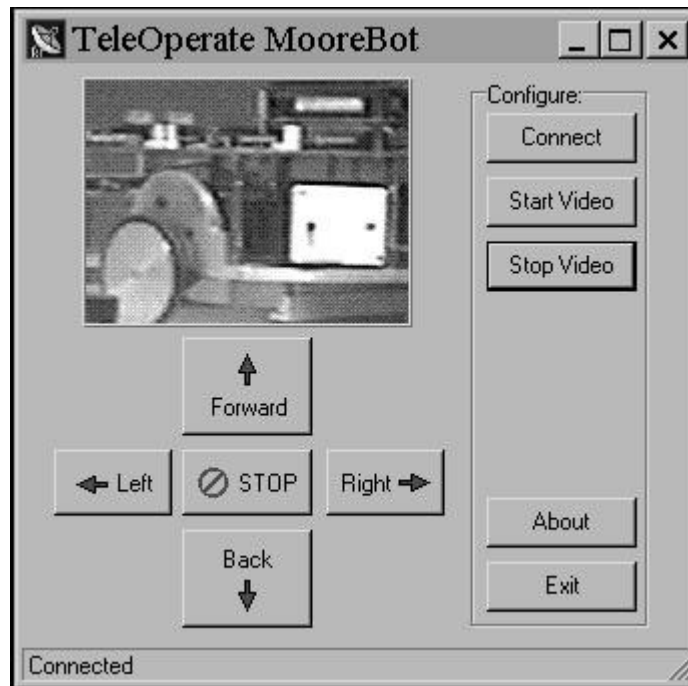


Figure 7: Man machine interface for video tele-operation

4. CONCLUSIONS

This paper has taken a generic technology perspective and examined a number of key areas that, in the author's opinion, could have a significant impact on future directions – and applications – in tele-operated robotics. The paper has briefly reviewed two areas of considerable interest to current researchers in the field:

- the increasing use of local intelligent control systems within the tele-operated robot and hence the development of semi-autonomous tele-operated robots, and
- the down-sizing of tele-operated robots to centimetre sized, and ultimately, millimetre sized robots (micro-bots).

The paper then takes a third key area and examines, in greater depth, current work in the author's laboratory, in integrating wireless networked communications, Internet Protocols and adaptive video compression. Work that should lead to the development of a generic 'smart vision' sub-system optimised for tele-operated mobile robots. In particular, this paper has argued that the use of standard hardware and software components, including Wireless Local Area Network technology, and Internet Protocols, can bring considerable benefits to the

design of tele-operated robots for applications in inspection or surveillance. The benefits include substantial reductions in design and development effort through the use of standard hardware and software components, and potentially far-reaching operational benefits; in particular the possibility of remote operation from any location with Internet connectivity.

Power limitations of current WLAN hardware devices clearly place a severe restriction on potential applications of the technology, as described in this paper, to short-range line-of-sight applications. However, the paper argues that the principles described are scalable up to much higher transmitted power levels, and hence longer-range, applications. This generic and modular architecture means that replacement of the lowest level (physical and link layer) network components would only require, at worst, re-coding of the device driver software component to suit the new hardware. All other hardware and software components of the system described would remain completely unchanged, thus minimising the cost and effort of scaling the architecture for long-range applications.

This paper has not attempted a comprehensive review of all of the key technologies that could impact future directions in tele-operated robotics. Two further areas that do, in the author's view, merit a brief mention include:

- the Man-Machine Interface: Virtual Tele-presence
- the Impact of Collective, or Distributed Mobile Robotics

Since the aim of a number of tele-operated robotic systems is to provide the human operator with a 'virtual' tele-presence, then it would appear logical to merge the technology of Virtual Reality (VR) (22), into the Operator Interface for tele-operated robots. In such a system, the operator would be provided with an 'immersive' man-machine interface, in other words stereo vision within a VR headset that can be remotely steered by simple head movements. Graphical objects overlain onto the real video within the VR headset would provide other control interfaces, and manual controls would be provided by joystick-like 'haptic' interfaces. Haptic interfaces would provide the operator with tactile feedback from force sensors within the robot (23).

Undoubtedly, *Collective Robotics*, represents one of the most exciting current areas of research within the field of robotics. Collective robotics, also known as Distributed Mobile Robotics, is concerned with how a number of robots might co-ordinate their actions, or co-operate, in order to achieve a given task (24). One particularly interesting collective robotics paradigm is based upon the observation of social insects in nature. Engineering systems based upon a number of identical, or near-identical individual agents would be particularly robust to failure or deliberate attack, and would be cost-effective in comparison with conventional robotic approaches if the individual robots were simple (25). While the potential impact of collective robotics to tele-operated robots may not be immediately obvious, this author is convinced that there could be significant benefits from crossover between the two fields. Consider, for instance, tele-operated UAVs. These are at present operated as individually piloted vehicles (albeit remotely). There might however be operational benefits from operating a squadron (or 'flock') of UAVs. It would clearly be infeasible to remotely pilot each UAV when operating in close formation, and a more sensible approach would be to remotely pilot only one 'lead' vehicle with the others 'autonomously' flocking. Alternatively consider a remote search or surveillance task using multiple tele-operated robots. The use of semi-autonomous control of individual robots, together with video data fusion in the Operator Interface might allow the operator to survey a much larger area than would be possible with a

single vehicle. In effect, the tele-operated robot 'collective' would appear, to the human operator, as a single large 'virtual' tele-operated robot. While these scenarios are presented as pure speculation, they are certainly feasible, in the author's view, given the current rate of research in collective robotics.

In conclusion, there is no doubt that the field of tele-operated robotics provides a rich arena for future developments, both in the near- and long-term future.

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