Wireless Video Tele-operation using Internet Protocols

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ABSTRACT

By definition, remotely piloted or tele-operated vehicles require a wireless link between the vehicle and the operator. The wireless link will carry control commands from the operator to the vehicle, telemetry data from the vehicle back to the operator and frequently also a real-time video stream from an onboard camera. In many cases these requirements are met by a number of radio subsystems; typically one for control and telemetry data and another, high-bandwidth radio subsystem, for analogue video. This paper proposes that for *short-range* applications the use of Wireless Local Area Network (WLAN) technology would enable these diverse communications requirements to be integrated into a single radio subsystem, with significant benefits to cost and performance.

Wireless Local Area Network technology, developed primarily to extend wired networks to allow, for instance, roaming network nodes within a building, is now relatively mature. Typically a WLAN connection will employ spread spectrum modulation over a 2.4GHz RF carrier, with a raw data rate of 1-2Mbits/s. A number of manufacturers have adopted the recently agreed IEEE 802.11 standard for the physical and access layer protocols which, significantly, allow for straightforward integration with TCP/IP: the *Internet Protocols*. Thus a tele-operated vehicle employing WLAN technology becomes, from a systems design perspective, a node on a Local Area Network, which can with relative ease be bridged from the base-station to a Wide Area Network or even the Internet. Remarkably, therefore, this opens up the possibility that the tele-operated vehicle could be operated from anywhere with Internet access. One could envisage a scenario in which a robotic hazard inspection vehicle could be tele-operated by an expert via an international Internet connection.

In the Intelligent Autonomous Systems laboratory at UWE, Bristol, we have already demonstrated the feasibility of these ideas on a number of mobile robotic platforms. This paper reports on current work to develop adaptive video compression tools in order to enable practical video tele-operation of robotic vehicles over any TCP/IP connection.

BIOGRAPHY

In 1984, shortly after completing a PhD in Digital Communications Dr Winfield resigned his lectureship at the University of Hull, to co-found a company on the then newly established Hull University Science Park. Although created to exploit research work in high performance computer architectures, the company found itself delivering contract research and development in software for safety-critical communication systems, primarily for the public safety sector. Dr Winfield established the company, APD Communications Ltd, as one of the key UK providers of software for mobile radio data systems, notably leading contracts to design a fault-tolerant radio communications infrastructure for the Channel Tunnel. He left the company in 1992 to take up appointment as Head of Research and Hewlett-Packard Professor of Electronic Engineering at Bristol Polytechnic, but remains a non-executive director of APD.

As Head of Research Professor Winfield has actively pursued technology transfer opportunities with industry, believing strongly in the value of university-industry partnership, and now leads a Faculty wide engineering research activity with some 50 research staff and students, and a substantial portfolio of research grant and contract awards. Moving into the field of mobile robotics, he co-founded the Intelligent Autonomous Systems Laboratory at the University of the West of England in 1993. Current research is focussed on software and communications architectures for Distributed Mobile Robotics, in collaboration with the Electrical Engineering Department of the California Institute of Technology.

1. Introduction

Consider the scenario illustrated in figure one. Here we have a remotely piloted helicopter 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 helicopter, and a separate high-bandwidth analogue radio link for the video camera.

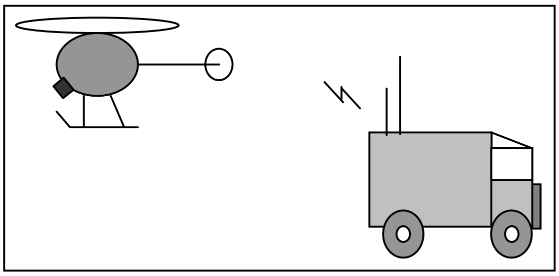


Figure 1

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 is based upon the IEEE standard 802.11 for the physical layer of Wireless LANs (1), and if higher layers utilise 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 two. 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.

A potential drawback of the approach proposed in this paper is that the bandwidth available from current wireless LAN devices falls short of the 5MHz bandwidth needed for a live video feed from the robot's on-board camera. This problem can however be addressed through the use of video compression techniques, and this paper reports on current work to develop adaptive video compression techniques tailored for tele-robotics applications.

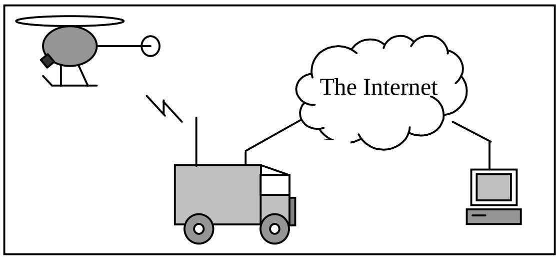


Figure 2

The paper proceeds as follows. First we review the current state-of-the-art in wireless local area networking, and comment on limitations in range and power. The paper then describes, with reference to the OSI 7-layer network reference model, the computer, communications and networking elements of the proposed tele-operated robot control architecture. Finally, the paper describes current work on adaptive video compression tools which should lead to practical video tele-operation of robotic vehicles over any TCP/IP connection.

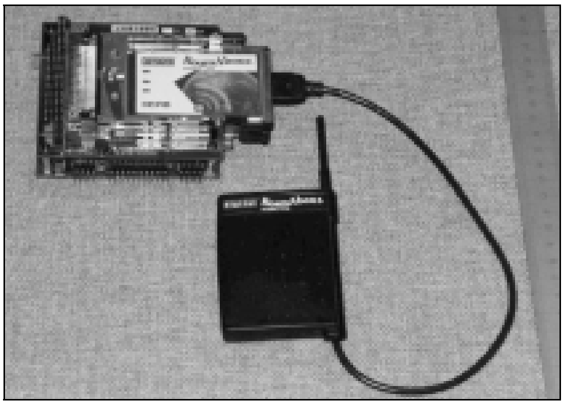
2. Wireless Local Area Network Hardware

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 (2). 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 be useful in the application described in this paper.

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) (3). 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. Two additional implementations are available: an ISA-bus plug-in card for desktop computers, and a standalone wireless-wired network bridge, sometimes known as an Access Point.

It is the PCMCIA wireless network interface that is of particular interest here, since its compact size and standard interface makes it ideal for integration into an embedded micro-controller suitable for tele-operated robotics applications. Photograph one 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 photograph one conform to the PC/104 (also IEEE Std P996.1) standard, which covers both the bus interconnect and the card form factor (4).



Photograph 1

We have successfully employed the controller shown in photograph one in two tele-operated mobile robot applications: one a proof-of-concept automated letter carrier for mail sorting office applications (5), and the other a miniature mobile robot platform for conducting laboratory experiments in distributed mobile robotics (6). Additionally, we are 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 we have 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. Network Software Architecture

7 Application	Man Machine Interface
6 Presentation	e.g. FTP
5 Session	e.g. Telnet
4 Transport	TCP/IP
3 Network	
2 Data Link	Network Device Driver
1 Physical	Hardware Interface

Figure 3

Consider the Open Systems Interconnect (OSI) 7-layer network reference model shown in figure three. 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 two). 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 (6). (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. For a detailed description of the applications layer code in a mobile robot employing WLAN technology refer to Winfield and Holland, 1999 (8).

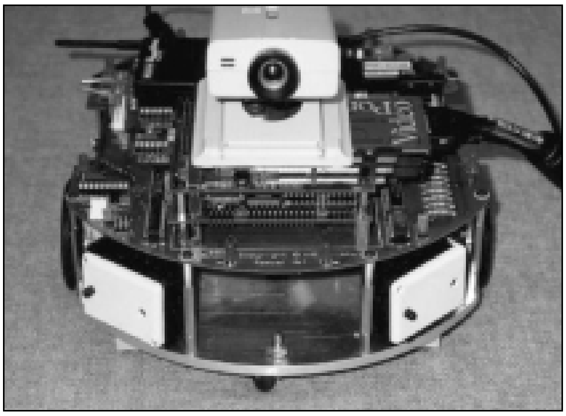
It is worth noting also that, depending upon the operating system employed in the robot, we may be able to utilise standard TCP/IP tools such as *telnet*, for remote debugging of the robot, *File Transfer Protocol (FTP)* for software upload, or even *Java* for exotic Web-based interaction with the robot.

4. 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.

Photograph 2

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, as shown in photograph two. Note that 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 tele-robotics applications. Photograph three 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.

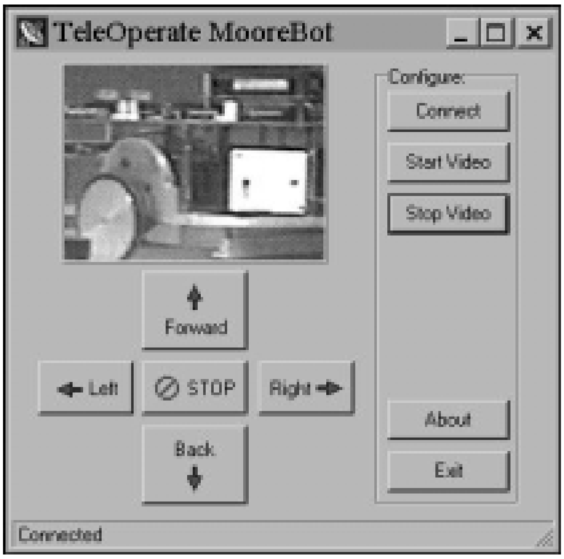


Photograph 3

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 proposed here is currently undergoing development trials on a miniature differential-drive wheeled robot in the Intelligent Autonomous Systems (Engineering) Laboratory at UWE. Photograph four 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.



Photograph 4

5. Conclusions

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.

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