Telerobotics –Control over the Internet

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Abstract: - Web Telerobotics is a new and rapidly growing field of *telerobotic* research. Initially it was considered a novelty, but developments in the field combined with rapidly improving Internet technologies have opened up new application areas. The most promising area is the use of web devices as teaching aids in school and university course work. Given that web telerobots are appearing in increasingly large numbers with many varying applications, the motivation for this research was to identify, implement, and evaluate techniques for controlling robots (and other devices) over the web. Of particular importance was the *identification* of a set of *requirements* that all web telerobot applications require. A solution to these requirements could then be encapsulated in a form that is easily reusable in other web control projects.

Key-Words: - Telerobotics, Web, Internet, Control, TCP/IP, UDP

1 Introduction

The field of telerobotics grew out of the need to perform operations where it is difficult to place a human being, due to constraints such as cost, safety or time. Telerobotic systems need to be able to perform tasks that a human would normally do. Due to limitations in robot autonomy, this often has to be achieved by using human operators to control the remote robot (via a communication link). Such a system is a telerobot. The human operator is responsible for high level control such as planning and perception, while the robot performs the low level instructions at the remote site.

An aspect of web telerobot systems that affects the choice of control scheme is time delay. Shared continuous control is less sensitive to these problems and has been demonstrated over the Internet (Tzyn-Jong and Brady, 1998; Brady and Tzyn-Jong, 1998, 1999), but only on short, high bandwidth Internet links. Discrete command control schemes and above are free of any time delay based instability problems as all closed loop control is performed locally. They are therefore the most appropriate choice for web telerobotic systems.

2 Transmission Delay

Transmission delay, sometimes also termed as latency, of a communication line is the time from the start of data packet transmission at the source to the start of data packet reception at the destination. The source of the latency can vary from the speed of the signal to how the signal is relayed among various gateways. In many instances this delay can become significant enough to become noticeable by a human.

Dedicated algorithms are specially designed for and tested with the Internet as the communication medium, although in principle they are applicable to any sort of transmission delay. The Internet is a complex network of servers and clients where data transmission is not direct but is forwarded over many links via many gateways. This can produce significant latency especially at certain times of the day with heavy network congestion and in areas with poor network infrastructure. The unpredictability of the Internet can result in variations in latency as well as lost data packets. To perform bilateral teleoperation over the Internet, the system must solve the problems posed by these pure delays in what is effectively a closed-loop system.

2.1 Types of Transmission Delays

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The International Telecommunication Union Telecommunications Standardization Sector (ITU-T) noted that with voice calls, most callers notice round trip delays when they exceed 250mS. As a result the ITU-T G.114 recommend the maximum desired one way latency to achieve high quality voice is 150mS. With Round Trip Time (RTT) delays of 500mS or more, a 'natural' phone conversation becomes very difficult. These figures for voice traffic will be used as an initial starting guide for our implementation of timely and realistic force feedback.

2.1.2 Random Time Varying Delay

The Internet is a best effort service that offers no upper bound to response time or bandwidth guarantees. The result is a service that is time varying in a random nature. This fact introduces an extra level of complexity in the teleoperation of a system. A control engineer can deal with the problem of compensating of a constant delay with relative ease. However, a random time varying delay is very difficult to compensate for. Such a situation can often result in destabilising the overall system. The key to timely and stable control of a closed loop system over the Internet is to effectively reduce the variance of the delay.

The problem of controlling a real time tele-system using the Internet as the link has been studied extensively over the past few years. Most researchers have tended to use TCP/IP (with its inherent short comings in ability to deliver data in a timely fashion), seemingly without firstly looking deeply into the IP protocols options available.

Generally this past research has concentrated on a variety of complex control methods in order help stabilise a telecontrol system in the presence of TCP/IP delay. Essentially the results have traded off a large amount of system response (delays of 5-6 seconds are not uncommon) in order to achieve stability.

2.1 TCP/IP Delays

T TCP is a connection orientated protocol. Possible congestion due to TCP traffic flows is controlled by the congestion control mechanism that is native to TCP. This congestion control can inflict serious problems on real time applications. In addition to this, TCP has an error correction arrangement in the forms of:

- Ordered delivery
- Duplication detection
- Crash recovery
- Retransmission strategy

By TCP addressing these above issues, TCP offers a guarantee for the reliable transport of packets to destination, thus, shielding the data users from the unreliable nature of the underlying IP network. The downside is the fact that these flow and error control techniques employed by TCP present a major obstacle to achieving time guarantees over the Internet. For example, the TCP slow start mechanism is used to discover the channel throughput during the initial connection setup and for resumption of a broken connection. This is done by first sending a packet across the channel and waiting for a response. If a response is received, the next packet is sent a bit faster. This procedure is repeated until the speed of the link is discovered. With the half-second delay between responses, throughput is significantly slowed.

Since this process can take 7-15 Round Trip Times, for a link with a propagation delay of 500ms this can mean that for 3-7 seconds, the link is underutilised. (See figure 1)

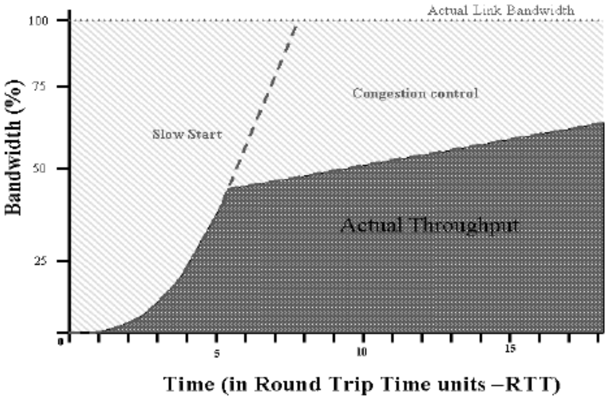

Fig 1. TCP/IP True Throughput

To further add to overhead, every TCP connection is established by a "3-Way Handshake" between the Receiver and Sender. On links with long propagation delays, this fixed overhead means that even very short data exchanges take at least a few seconds to be completed. Data links can be noisy, and this has profound effects on the performance of TCP/IP throughput because the slow start congestion control mechanism wrongly detects the noise as network congestion. Hence, from a real time viewpoint, TCP fails to provide an adequate solution, largely due to the enormous processing overhead it employs in order to provide a reliable path for data.

2.3 UDP/IP and RTP/UDP/IP Delays

Seemingly, none of the present online tele-operated systems to date have used Real Time Protocol (RTP) running over User Datagram Protocol/ Internet Protocol (UDP/IP). This is probably largely due to the fact UPD/IP is seen an unreliable data medium, whereby data could arrive out of order or not at all. Even so, RTP/UDP/IP is fast becoming the popular protocol arrangement for streaming data in real time over the Internet. UDP is a connectionless protocol. This fact gives it very different characteristics to TCP. UDP is an unreliable service due to the fact that delivery and duplication of packets cannot be guaranteed. In addition it is likely that packets will arrive at the destination out of order. Even so, UDP with RTP is a far better option than TCP for realtime applications such as voice or video. Retransmission of a packet 1-2 seconds after it was sent when it contains a 20mS sample (as is the common case for voice) would produce disastrous implications to the real-time voice stream. In addition the cost in time for TCP to detect a packet loss, stop the data stream, request a resend from the point of loss and then finally receive the lost packet can be in the order of several seconds. As stated, packet loss is unavoidable with UDP/IP, but it can be compensated for in voice streaming by codec loss-concealment schemes. One such codec is G.723.1, which has the ability to interpolate a lost frame by simulating the vocal characteristics of the previous frame and slowly damping the signal. It has been shown that packet loss rates up to the order of 10 percent have little noticeable impact on the audible quality of the speech. It should be noted also that the connectionless quality of UDP/IP reduces the overhead of the protocol (from TCP/IP 40bytes to UDP/IP 28bytes) and this makes UDP a further preferred choice for constant flow applications such as multimedia and control sessions. Even though a UDP/IP implementation has a lesser header overhead than that of TCP/IP, the RTP/UDP/IP implementation returns the header overhead back to 40bytes since the RTP component adds an additional 12bytes to the header. Now 40-45 bytes of overhead would not be an issue if the data packet were in the order of 1500 bytes. The problem is that our implementation only involves packets with a data size in the order of 10-20bytes (due to the sampling rate). Hence a whopping total of 40-45bytes of overhead to transmit a 10-20byte payload. There are two possible solutions to this problem:

1. Increase packet size, at the expense of sample rate and potential delay jitter.
2. Use header compression. In the case of voice packets it has been shown that the increased delay incurred from increasing the packet size is unacceptable. For this reason a great amount of research is being undertaken into optimizing header compression.

In summary, utilising UDP/IP in place of TCP/IP will greatly increase network efficacy by:

- Removing the need for having a connection setup before data can start to flow.
- Removing the slow ramping up of
- Low rate packet loss does not halt transmission of the streaming data.

In real time operations such as online gaming, some programmers would prefer to use user datagram protocol (UDP). This protocol eliminates the need for confirmation where the transmitting computer keeps sending the data packets with no regard as to whether the receiving computer has received the data. This means that all the data are sent in a timely fashion, an important feature for real time operations. But the lack of confirmation also means that it is less reliable. Figure 2 shows a typical TCP/IP transmission and Figure 3 shows an UDP round trip transmission delay as tested by Munir and Book. The experiment was performed in a similar fashion as the TCP case. As we can see, even though not all the data packets made it through the Internet, the basic shape of the sine wave is still recognizable. The transmission delay is also more stable than TCP.

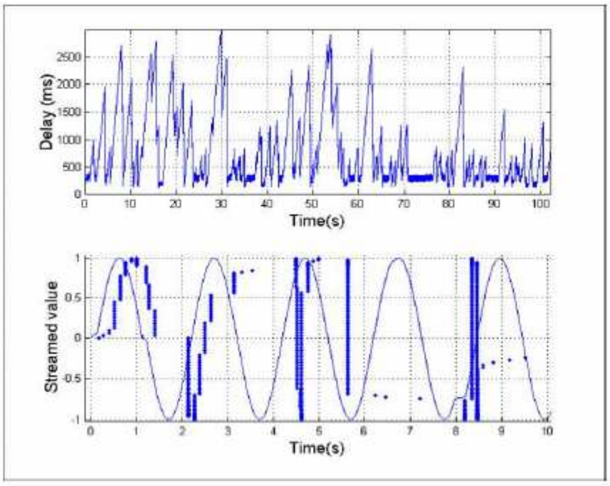

Figure 2: TCP Transmission Delay

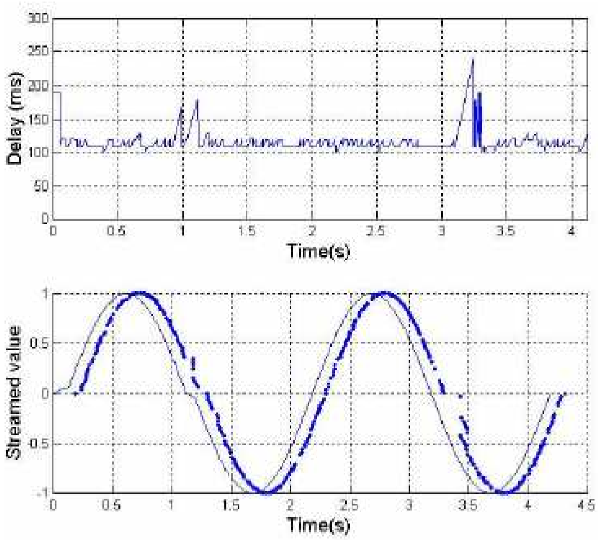

Figure 3: UDP Transmission Delay

3 Control of web-based Telerobotics equipment

From the previous discussion, it is clear that an Internet-based control system must face the variable time delay and the packet losses introduced by the computer network. We are interested in evaluating the feasibility of Internet-based, force-feedback telerobotics equipment, in which the control loop between master and slave robots is closed across Internet. This is equivalent to deal with the stability of telerobotic equipment with a variable communication delay and data losses.

3.1 Predictive Control

Predictive Control (BGPC) proposed in (Slama et al., 2007), which is base don an extension of Model Predictive Control.

Model Predictive Control (MPC) is an advanced method for process control that has been used in several process industries such as chemical plants, oil refineries and in robotics area. The major advantages of MPC are the possibility to handle constraints and the intrinsic ability to compensate large or poorly known time-delays. The main idea of MPC is to rely on dynamic models of the process in order to predict the future process behavior on a receding horizon and, accordingly, to select command input w.r.t the future reference behavior. Motivated by all the advantages of this method, the MPC was applied to teleoperation systems (Bemporad, 1998, Sheng, and Spong, 2004). The originality of the approach proposed in (Slama et al., 2007) lies in an extension of the general MPC, so-called Bilateral MPC (BMPC), allowing to take into account the case where the reference trajectory is not a priori known in advance due to the slave force feedback. The bilateral term is employed to specify the use of the signal feedback, which alters the reference system dynamic in the controller.

3.1.1 Generalized Predictive Control

Generalized Predictive Control (GPC), suggested in (Clarke et al., 1987), is one of the most popular predictive control strategies. GPC is based on the minimization of a quadratic cost function of the form (1) including a future control sequence on a receding horizon.

$$J=\frac{1}{2}\left(\sum_{j=H_w}^{H_p}\left\|\hat{y}(k+j|k,W)-(k+j\right\|_{Q(j)}^{2})+\sum_{j=1}^{H_u}\left\|\Delta w(k+j-1)\right\|_{R(j)}^{2}\right)$$

Predictive control, commonly grouped as model predictive control (MPC), uses a model of the plant to predict the output in the future $y\hat{}(k+j\ k)$. The GPC uses the Controlled Auto-Regressive and Integrated Moving Average (CARIMA) structure which is an input-output formalism taking into account the noise influence on the system through the *C* polynomial:

$$A(z^{-1})\Delta y(k)=z^{-\tau}B(Z^{-1})\Delta w(k-1)+C(z^{-1})\xi(k)$$

where *y(k)* and *w(k)* are respectively the output and the control of the system. $\Delta(z^{-1})=1-z^{-1}$ is the differencing operator. The τ parameter, a multiple of the sampling period, is the pure system delay and *ξ(k)* is an uncorrelated random sequence. *A*, *B*, *C* are polynomials of the backward-shift operator *z-1* with respectively the following degrees *nA*, *nB* and *nC*. *A* and *C* have unit-leading coefficients. The *C* polynomial may be used as a tuning parameter, since its identification is usually avoided. It has been shown by that the *C* polynomial plays a crucial role in the robustness and disturbance rejection of the control law. More generally, this polynomial influences the robustness and disturbance rejection.

Bilateral Generalized Predictive Control Design. Due to the slave force feedback, the master trajectory is not a priori known in the future. Therefore, we cannot determine a control sequence that minimizes the (1) cost function. To overcomethis difficulty, the Bilateral GPC (BGPC) approach proposes to rewrite the master model according to the slave control via the slave force feedback in order to determine the master output optimal prediction (Slama et al., 2007a).

Having determined the master and slave CARIMA models for the BGPC, the minimization problem (3) is solved, where *ym* and *ys* are respectively the positions of the master system and of the slave robot end-effector.

$$J = \frac{1}{2}\left(\sum_{j=H_w}^{H_p} \left\| \hat{y}_s\left(k+j|k,W_{ms}\right) - \hat{y}_m\left(k+j|k,W_{ms}\right) \right\|_{Q(j)}^{2} + \sum_{j=1}^{H_u} \left\| \Delta w_{ms}\left(k+j-1\right) \right\|_{R(j)}^{2} \right)$$

The objective is to determine the control sequence ***Wms*** minimizing the quadratic error between the future predictions of the master system output and the future predictions of the slave system output; both of these two outputs depend both on the control sequence. The plant output predictions *ŷm(k+j)* and *ŷs(k+j)* are obtained by solving two Diophantine equations for each incremental models. *Control law.* The receding horizon principle assumes that only the first value of the optimal control sequence resulting from the minimization of (3) is applied. At the next sampling period, the same procedure is repeated. This control strategy leads to a 2-DOF predictive RST controller, implemented through a difference equation:

$$R\left(z^{-1}\right)\Delta w_{ms}\left(k\right) = T\left(z^{-1}\right)y_m\left(k\right) - S\left(z^{-1}\right)\hat{y}_s\left(k+\tau_g\right)$$

By appropriate choices of the horizon lengths *Hw, Hp, Hu* and of the weighting matrices **Q**, **R** in BGPC, an excellent master reference trajectory tracking may be obtained for the slave system. It is interesting to note that *T(1) = S(1)* to guarantee offset-free response and that the polynomial *T(z-1)* does not contain a non-causal structure generally inherent in the polynomial predictive control. This major difference, in comparison to the standard GPC, is due to the future reference trajectory, which is not a known priori. The experimental validation of the proposed BGPC approach is presented in the next section. *A robust approach.* Stability conditions for constant and time-varying transmission delays of the nominal overall transfer function from the input force of the operator to the environment contact force have been determined on a frequency-domain approach in (Slama et al., 2007a). These conditions are derived by the small-gain theorem. Moreover, the proposed BGPC approach, which has taken into account the slave force feedback, introduces a new prefilter polynomial *Csem* (Slama et al., 2007b). This *Csem* polynomial plays a role in robustness and disturbance rejection of the overall system. The advantage about of the proposed approach is to impose the desired behavior at remote system, to ensure a robust stability of teleoperation in the presence of environment and transmission timedelays uncertainties.

Delay jitter compensation. A different solution, proposed in (Luck, and Ray, 1994; Oboe, and Fiorini 1998), is to even out the delay jitter by storing the incoming packets in a memory buffer. Given the standard deviation σ of the delay, a queue capable of absorbing a +/- 3σ variation of the delay is set up on both sides of the communication channel. This is realized with a FIFO queue with a length N=6σ/T, where 1/T is the transmission rate, as shown in fig.4.

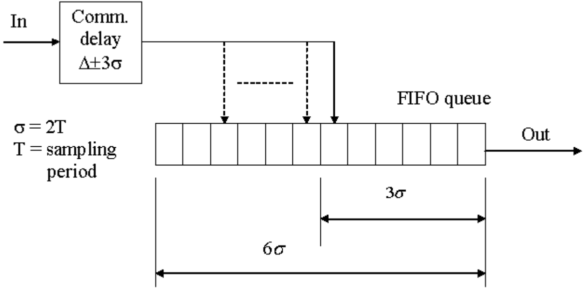

Fig.4 – Delay jitter compensation via buffering Data extraction begins when the queue is filled up to half of its length. This mechanism introduces an additional delay of 3σ to the transmission delay, but this can be easily handled by simply designing the control algorithm considering an augmented delay or by using an IOD control technique.

With this solution, the connection results to have a constant delay, for which one of the standard control techniques for time-delay teleoperators can be used.

4 Applications

There exist many other Web robots on the net, performing a variety of tasks such as those described in [13]. The NASA Space Telerobotics program website (http://ranier.oact.hq.nasa.gov/telerobotics page/realrobots.html) currently lists over 20 Real Robots on the Web. Reviewing all those web-based teleoperation systems, it is clear that the main problem is of course the unpredictable and variable time delay for communication over the Internet, which calls for the use of some form of supervisory control or off-line teleprogramming scheme to ensure stability.

Most of the systems currently available on the web incorporate user interfaces, which implement basic functionalities, such as enabling the user to choose from a prespecified set of tasks (e.g. target locations). These interfaces use some combination of HTML forms or Java consoles to enter data and issue simple commands for immediate or future execution (the requests issued by different client sites are scheduled by the robot server). Sensory feedback is usually limited to the display of images that are captured at the remote site, and the presentation of some status information in text form. It is obvious that this separation between the actions of the human operator (user) and the response of system fed back by the remote/slave robot deteriorates the transparency and telepresence characteristics of the teleoperation system. In other words, the user feels distant from the teleoperated system, and is forced to employ some form of move and wait strategy.

5 Conclusion

The Internet protocols do no guarantee a maximum delay for a message to be carried across a network link, which means that the control scheme must work under variable (and possibly large) time delays. Continuous control is not well suited, as it is prone to instability problems under time delayIn spite to all limitations, however, it is possible to realize reliable systems that in future will help in improving everyone's quality of life. In fact, remote diagnosis and rehabilitation, access to dangerous and/or remote sites will be more and more accessible and more applications are going to appear, all aimed at easing the interaction between distant worlds.

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