Internet-Based Bilateral Teleoperation: A Review and Future Directions with UDP and Event-Based Control

Kevin Walker*, Jason Gu†‡ and Ya-Jun Pan†‡
Kevin.Walker@dal.ca, Jason.Gu@dal.ca, YaJun.Pan@dal.ca

*Electrical and Computer Engineering, Dalhousie University, Halifax, Nova Scotia, Canada B3J 1Z1
†School of Control Science and Engineering, Shandong University, P.R. China 250100
‡Mechanical Engineering, Dalhousie University, Halifax, Nova Scotia, Canada B3J 1Z1

Abstract—A survey is done of various results in the control of bilateral teleoperation systems in order to determine the best control scheme for telesurgery over the Internet. Telesurgery is a particularly demanding application where the challenges imposed by the Internet, including time-varying delay, lost packets and out-of-order packets, must be addressed to try to maximize performance. The nature of delay on IP networks and the merits of UDP as a transport protocol are investigated and out-of-order packets are shown to have the same effect as lost packets. Stochastic models can be used to characterize packet delay. Passivity-based, predictive, robust & optimal and event-based control are discussed with respect to teleoperation. When time-varying delays are introduced, the system becomes a hybrid event-time based system. Future work is proposed that would consider a delay model that incorporates knowledge of lost and out-of-order packets to be incorporated into a hybrid event-time predictive control scheme.

I. INTRODUCTION

Teleoperation has a long history with much of the original work being devoted to outer-space applications and the handling of dangerous materials. More recently the Internet has become more popular for teleoperation as the available bandwidth increases and the cost decreases. One of the most attractive features, however, is its penetration, with high speed Internet being available in virtually every urban center. Connectivity between two points can be established quickly and inexpensively, especially when compared to higher performance dedicated networks. The Internet introduces a series of challenges to weigh off against these benefits. The transmission delay is time varying and random and the bandwidth is not guaranteed.

The health care sector has seen the potential of teleoperation in the field of telesurgery through various experiments. An actual operation has been performed across continents under unilateral control [1]. Bilateral telesurgery has not yet been performed on a human patient, but such functionality would aid surgeons in accomplishing the tasks at hand. Telesurgery is a challenging field because of the precision required. The scale of certain operations is quite delicate and the non-invasive techniques sometimes used makes it difficult to design instruments that are small enough to operate in the constrained workspace while stiff enough to exert the necessary forces, motivating the study of flexible link manipulators [2].

The basics of telesurgery are covered in brief in Section II. To accommodate the precision requirements of telesurgery, the User Datagram Protocol is considered as the transport protocol in a new force-reflecting teleoperation control scheme. The nature of the delay when taking into account out-of-order packets and packet losses is considered in Section III. Various teleoperation control schemes are considered in Section IV and ways to incorporate this new communication model are put forth in Section V.

II. TELEOPERATION & TELESURGERY

Teleoperation is the control of a remote system. This is often in the form of a human operator using an input device to issue commands that are then transmitted over a computer network to be obeyed at a distant location for the purpose of interacting with the environment. The feedforward scheme is said to be unilateral while the feedback case is bilateral. The configuration for a generic teleoperation control system is shown in the block diagram of Fig. 1. Visual feedback has been included because we rely mainly on our sense of sight for coordination.

The visual feedback of the environment to human operator introduces the need for a higher performance network. It is another stream of real-time data that usually shares the same network channel for transmission. This feedback is invaluable and it increases the immersion of the operator significantly. When combined with haptic feedback, complicated and delicate tasks can be performed. Sight and touch are by far the most common senses to be integrated into a teleoperation scheme, but are by no means the only ones. Audio and temperature can also be important in certain applications, e.g. when the sound produced by a drill changes pitch as it encounters increased resistance or a surgeon senses a change in the temperature of an organ as an indication of the flow of warm blood [3].

Teleoperation has been applied to numerous applications including mobile robot navigation, space applications and surgical procedures. A quick search on the Internet reveals all kinds of implementations that can be operated via a web browser, including remote controlled cars and robotic manipulators. Usually some form of supervisory control is used, where high-level commands are issued to instruct the robot to move to a certain position or assume a certain pose. An interesting example of this is the robotic tour guide that was used in the Smithsonian museum. It allows visitors on the web to tell the robot where to go, using cameras to display the various artifacts while avoiding obstacles in a dynamic environment [4].
Models of all aspects of the teleoperation scheme have been considered. The models of the input device (the master robot) and the output device (the slave robot) are generally fairly well defined. At the very least the general form of the model is known and adaptive control can be used to determine the exact parameters. Various models of the communication delay exist, including both deterministic and stochastic models. This leaves the outer blocks in the block diagram, which are the most unpredictable and hence most difficult to model, but in the pursuit of better performance there have been attempts to model both the human operator [5] and the environment [6].

Telesurgery is a particularly challenging field in teleoperation as the requirements require a high degree of precision, especially for in utero procedures on unborn children and neurosurgery. This translates into millimeter or sub-millimeter position error precision, good tracking and a high degree of transparency. Such precision has been attained in the unilateral case for cross-continental telesurgery, but has yet to be demonstrated in the operating theater for a bilateral operation [1]. In the unilateral case, it has been shown that delays of 250ms are noticeable by the operator and performance begins to markedly degrade after that [7]. The measure of such performance is usually the time required to complete a certain task as it is a very practical measure of the utility of a system.

The word haptics comes from the ancient Greek word for touch and is used to describe the forces that an input device can exert on the operator to give them a sense of feel as well as relaying texture and other mechanical properties of a real or virtual material. Most of the efforts have focused solely on forces as they are essential to complete dextrous tasks without exerting unduly large forces. Ideally, a haptic device used to convey such force feedback information will have no inertia or friction which makes them backdriveable (i.e. the operator can move the device without feeling any forces when the slave is moving through free space) and can be driven at high frequencies. Such properties are hard to achieve in highly geared robots, so cabled devices have become popular. When used in teleoperation schemes, the bandwidth of the system is often too low to convey all necessary information about the contact event. Methods have been proposed to provide a separate event-based feedback channel to relay such information without compromising stability [8].

These haptic devices have the goal of creating transparency in the teleoperation scheme, meaning that the operator feels the forces being applied on the environment as if the task were being performed locally. Different measures of transparency have been developed, including an impedance model relating the ratio of force and velocity at both master and slave sides for manipulators with different workspaces at the local and remote sites [9] and the direct correspondence of position and force for identically scaled workspaces [10]. Either definition is applicable to telesurgery depending on the application. Experiments suggest that impedance scaling may be of benefit in telesurgery to scale the amount of force being applied. Subjects took longer to perform robot assisted suturing with haptic force feedback over visual force feedback and the difference was attributed to the poor force resolution of our sense of touch compared to the level of detail presented by a graphical force meter [11].

There are however cases when transparency should be sacrificed. One such case is when delicate tools are being used that cannot tolerate forces above a certain threshold. On the other hand, we will not be able to maintain transparency when the forces exerted by the environment or the operator reach the physical limits of the input devices by either exceeding the maximum torque of the robot’s actuators or saturating the force sensors. In the first case, a force and position control scheme with full parallel composition can be used to introduce a compliant coordinate frame that would allow position errors in order to regulate a desired force and ensure safety operation [12].

The systems must be incredibly robust as the cost of failure is human life. This would involve a design procedure which focuses on safety, redundant systems and the detection of the loss of communications at the slave side to ensure safe operation, which is especially important when the environment is dynamic. It would have to maintain performance over a long period of time as surgical procedures can extend up to 8 hours or more, so if the velocity were being calculated from position data we would have to transmit the current velocity periodically to eliminate drift due to numerical integration.

III. Communication Model

Ideally the communication channel used in teleoperation would be lossless, error-free, without delay and with an infinite throughput. For dedicated communication links many of these qualities hold true thanks to a low bit error rate and near lossless transmission, but the delay can still be significant. On the Internet the conditions degrade from a control perspective. Both the delay and delay jitter are affected by the congestion in the network, the burstiness of traffic, the total physical distance traveled and the number of network hops between source and destination and you have no control over the intermediate nodes. The Internet cannot implement Quality of Service (QoS) guarantees, because an Internet Protocol (IP) network does not form an actual connection between hosts. Packets are sent via numerous forwarding intermediaries and we have no control over their route which can change from one packet to the next.

The two main transport protocols in use on the Internet are the Transmission Control Protocol (TCP) and the User Datagram Protocol (UDP). They differ in the services they provide: UDP will send a packet only once while TCP uses acknowledgments so as to retransmit lost packets [13]. The penalty for the extra services TCP provides is a larger average delay and larger delay jitter as well as greater communication overhead, as has been shown by multiple researchers including [14], [15]. To keep delay to a minimum, many real-time robotic development efforts have chosen a UDP based scheme for communications [16], [17]. Often a new protocol layer is implemented on top of UDP, like with the trinomial protocol defined in [18]. UDP has no inherent flow control, so the sender can easily cause congestion and hence worsen network performance by transmitting too many packets to the detriment of both the UDP stream and the streams of other users on the shared network. By regulating flow control, trinomial determines an optimal transmission speed which helps avoid excessive packet losses and ensures fairness among the protocols operating over the Internet.
It is essential to dynamically update the parameters of a delay model since the delay trend changes over time, especially with respect to the time of day and day of the week [14]. Since we have no QoS guarantees, systems have been designed that adapt to the current QoS conditions in an attempt to maximize the utilization of network resources in the control scheme. [19] implements a flow control mechanism similar to that of trinomial, but also uses the QoS information in a gain scheduling adaptive control law.

Since the delays one way are not equal to half of the round trip time (RTT) [20], higher precision is achieved by analyzing both transmission directions separately. To measure the one-way delay, the transmitter needs assistance from the receiver. The outgoing packets can be time-stamped so the receiver can calculate the transmission time if the clocks are synchronized. Certain solutions exist for clock synchronization, including the Network Time Protocol (NTP) that can help synchronize multiple clocks to a given reference [21]. For teleoperation, precision of tens or hundreds of microseconds would be sufficient. Often in experiments the master and slave controllers reside on the same computer and the delay is injected artificially or the packets are transmitted to a third party that will reflect them back, removing the issue of clock synchronization by design for testing purposes.

Some efforts simplify matters by using UDP with a receiver-side buffer to reduce the delay jitter. [17] uses a buffer long enough to accommodate a delay jitter of \( \pm 3\sigma \), where \( \sigma \) is the standard deviation of the delay. This significantly reduces the delay jitter, but comes at the expense of introducing an extra delay of \( 3\sigma \). The design of the control scheme becomes much easier and if the delay jitter is low enough, this will out-perform TCP as a transmission scheme.

For high quality haptic feedback that would cover the entire dynamic range of human perception, the control system must have a bandwidth of around 1kHz [22]. At such speeds, the time interval between packet transmission is going to be at most 1ms assuming all control signals can be multiplexed into a single IP packet. Given the typical delays of at least 100ms between two cities, this would mean that around 100 packets are in transit at any given time. With the introduction of a bounded delay jitter above \( \pm 1\% \), some packets will eventually arrive out of order. This is a rough example and many experiments achieve good results for much lower bandwidths, but at the same time we must realize that delay jitter can be much larger than \( \pm 1\% \).

The possibility of out of order packets and packet losses produce a few different transmission scenarios we will now consider. Fig. 2 (a) shows a signal being sampled at the master side. If the transmission experienced only small variances in the time delay, it would result in Fig. 2 (b) at the slave side using a zero order hold D/A. The delays are not always so similar from one packet to the next and in addition some packets may be lost. Fig. 2 (c) & (d) show the cases where a packet is lost and when a packet arrives out of order, respectively. Since the late packet is simply discarded, these last two cases have the same effect on the slave system and produce the same effective gap in time between the first and second packet at the destination. The packets used at the destination will have strictly increasing time stamps when out-of-order packets are discarded. This set will be referred to as "useful" packets. Formally, this can be written as

\[
P_{\text{sent}} = \{p_1, p_2, \ldots, p_n\} \tag{1}
\]

\[
P_{\text{useful}} \subseteq P_{\text{sent}} : \tau_i + T_s < \tau_{i+1} \tag{2}
\]

where \( p_i \) is the \( i \)-th packet, \( \tau_i \) is the delay of the \( i \)-th packet and \( T_s \) is the sampling period at the source. Note that although the out-of-order packets are considered lost for immediate control signal calculation, they may still be required for numerical integration where the current position is being derived from velocity data, for example.

![Fig. 2. Three Transmission Cases (a) Original Sampled Signal (b) In-order Arrival (c) Lost Packet (d) Out-of-Order Arrival](image)

The behavior of the network should be characterized using stochastic models, due to the random nature of the delay. The delay of an IP network like the Internet has been shown to be highly autocorrelated [15]. The mean delay varies slowly over time while the delay of two consecutive packets is random and unbounded and related only insofar as they relate to general network congestion. This is the consequence of the variation in routing between subsequent packets, where packets can experience route fluttering when their path oscillates between two or more routes [23].

Although the delay between the arrival of two useful packets is theoretically unbounded, a maximum bound may be introduced for performance's sake. Such a long delay may indicate the loss of network connectivity, and the slave should shut itself down as a failsafe or could transition to a different control law such as an event-based hold and wait control that would guarantee synchronization and stability [24] or some form of supervisory control. This allows us to impose an upper bound on the delay of useful packets without introducing undue optimism into the design.

**IV. CONTROL APPROACHES**

Various control strategies have been applied to the problem of teleoperation with time-varying delay. Most impose conditions on the derivative of the time delay to ensure in-order delivery, which no longer holds for UDP. Many also impose a maximum delay on the system. If TCP is used this is a reasonable assumption as lost packets will eventually be retransmitted, but
with UDP the packet is lost forever unless a retransmission scheme is built into a protocol on top of UDP. The packet that is lost has a theoretically infinite delay, although time-based systems would typically repeat the last received value in the event of a missing packet. By incorporating packet loss into our transmission model and using event-based controllers or event-time hybrid controllers this problem is avoided [25].

There are several common control approaches to teleoperation that will now be considered in view of UDP and its transmission characteristics.

A. Passivity Based Methods

This family of control methods is based on rendering the communication channel passive through the use of the scattering operator or some variation thereof. They assume that the environment and the human operator are passive so the system reduces to an interconnection of passive blocks which is also passive. It has been shown that wave variables, which are based on passivity methods, are stable for any delay [26] with performance degrading as the delay increases. The wave transform is shown in Fig. 3.

\[ \begin{align*}
  &\begin{array}{c}
    \bar{x} \\
    \downarrow
  \end{array} \\
  &\begin{array}{c}
    \bar{v} \\
    \downarrow
  \end{array} \\
  &\begin{array}{c}
    \bar{F} \\
    \downarrow
  \end{array}
\end{align*} \]

Fig. 3. One Side of the Wave Variable Transform

One of the challenges of such schemes are the reflections they create in the communication channel. Predictors have been used to try and improve performance, which is especially important for larger delays [27]. These can work well in structured environments but impedance estimation is difficult for unknown environments. Unmatched impedances lead to wave reflections, the same as in the analogue of mechanical waves, and can only be mitigated with extra damping. People may be able to adapt to these reflections with training, but they would serve as a distraction and the extra damping makes the system feel sluggish to the operator.

Wave variable schemes are build using time-based control and so impose an extra degree of delay that would serve to worsen the theoretical maximum possible performance independently of any other performance losses due to reflection filtering. Their attractiveness lies in the simple manner in which they guarantee stability using such a simple algebraic transformation that requires very little computational power to implement.

B. Predictive Control

Prediction based methods are based on the early work of Smith who developed the Smith Predictor [28]. Predictors break the model of the plant into two parts, consisting of the undelayed dynamics and a pure delay element. The predictor essentially extracts out a modeled version of the plant output while adding in a non-delayed plant response against which the controller is designed. This structure works well for networked control systems where the delay can be easily separated from the dynamics of the remote system.

In teleoperation there are two plants on either side of the communication channel with the control law and network in the middle. Some approaches have looked at predicting the state of the master side [29] or the slave side [30]. In teleoperation it is best if prediction takes place at both ends for the sake of both the master and slave controllers, although most efforts do not go as far as to model the operator as does [29]. To have a predictor in both the master and slave controllers, you need to know what the other side is predicting. This leads to four predictors where the slave is predicting the master side at the same time as the master duplicates the slave’s predictor so it can properly predict the slave’s behaviour and vice versa [31]. As can be seen in Eq. 3 [31] the master’s controller uses a prediction of the slave state, where \( u(t)_m \) is the master control signal, \( x_m \) is the master position, \( v_m \) is the master velocity, \( F_c(t) \) & \( F_c(t) \) are the actual and the predicted interaction forces at the slave side and \( T(t) \) are the actual and predicted delays. \( F_c(t) \) is calculated using a prediction of the slave state and it is this prediction that will be duplicated on the slave side to ensure accurate master prediction.

\[
  u_m(t) = -\alpha F_h(t) - B_m v_m(t) - K_m x_m(t) + \beta F_c(t) + \beta[F_c(t - T(t)) - F_c(t - T(t))] \tag{3}
\]

Predictors must know the time delay in the system, but no deterministic expression can be determined for the delay. This requires the use of stochastic methods as was done in [32] where the delay dynamics include a stochastic variable as in Eq. 4. This is where accurate knowledge of the time delay can be incorporated into the system.

\[
  \tau(t) = \tau_{avg} + \epsilon(t) \tag{4}
\]

Prediction is also used in a different form in predictive displays, where visual information is overlaid on the live video feed to show the operator where the robot currently is based on delayed data and predictions. This has been used especially in space applications where the delay is typically much longer than that experienced on the Internet and is particularly useful when the delay is greater than 0.5s [33], but has also been applied to Internet-based teleoperation [34]. This shows the operator where the robot is most probably located, preventing the operator from being forced to revert to the hold and wait strategy so that the delayed video can update with the current position. This usually involves a great deal of computational processing as the environment and slave robot are modeled in 3D in real time and overlaid on top of a normal video feed.

C. Robust H\(_\infty\)-Control and \( \mu \)-Synthesis

Robust control methods design for a family of systems, taking into account a nominal plant and all possible variations that would result from various perturbations. The controllers are then robust to these variations, from which the name of the control scheme is derived. Although most commonly used to tackle imperfections in a plant model or the variations between different plants of the same type, time delays can be thought of as another form of perturbation. Where H\(_\infty\) focuses on the stability of the closed-loop system, \( \mu \)-synthesis incorporates
performance optimization goals as well. These methods rely on the small-gain theorem to establish their results [35].

These techniques were applied to bilateral teleoperation with constant delay in [36]. The results are shown to be delay dependent, but they directly address performance criteria as a design constraint which is their main benefit over other control techniques like wave variables. Control for free-motion is tackled first and then control for constrained-motion is added in an outer loop so as not to interfere with free-motion to ensure performance in both scenarios.

D. Event-Based Control

Event-based control methods aim to eliminate the problems associated with delay by using events as a reference instead of time [25]. Supervisory control is one form of event-based control that uses commands that describe higher level tasks which the slave performs using the logic in the slave controller in a heuristic approach [33]. This method provides an easy way to eliminate the problems associated with delayed feedback since the higher level control does not require frequent back and forth communication and is not as sensitive to small time delays. The problem with this approach is that it requires an understanding of the environment to determine how to implement the high level functions. Such intelligence is difficult to construct in unknown environments and poses many challenges. As far as teleoperation is concerned, it dissociates the operator from the low level control, reducing transparency and immersion.

At a lower level, event-based control can be implemented so that it updates each system in the block diagram in a round-robin fashion. For example, the operator will respond to a force by generating a new joystick position. This generates a response from the master controller and the new event is propagated along the communication channel, arriving at the slave. The slave will act on this event and interact with the environment, generating feedback. This will eventually return to the master controller and hence to the operator who will react to the new force and the cycle repeats [37].

Teleoperation systems are hybrid systems. They have continuous time plants in their mechanical systems and discrete events in the packet arrivals at random times. Such hybrid systems need special consideration as presented in [38] which deals with long delays, i.e. where \( T > T_s \). Via discretization, the controller and plant of networked control system are modeled using discrete-time jump linear systems. Similar work can be found in [39] where the control of a PUMA robot via the Hypertext Transport Protocol (HTTP).

V. FUTURE WORK

With proper modifications, any of the control schemes considered here could benefit from knowledge about out-of-order packets. In future work, the predictive control case will be considered and amended to work under the new communication assumptions. Predictors at both the master and slave side will be used to attain a maximum performance for the given resources. Stability proofs will be derived and experiments will be carried out for simple linear robots. Eventually this work will be extended to the nonlinear case and an adaptive control law can be introduced to further reduce errors in the system.

As the slave robot interacts with its environment, the dynamics that the master must use for predictions sake change. Methods have been developed to estimate the stiffness and damping of the environment or even the hysteresis properties of the material in question [6]. One of the ongoing challenges for predictors is the discontinuity injected in transitioning between free motion and constrained motion or surface contact. The slave robot and its environment are mechanically coupled and when such a transition occurs the model that describes them changes in an unpredictable manner since the environment properties cannot be estimated until after contact has occurred. One possible option is to use remote sensing methods to determine when contact would occur. These include sonar, laser range finders or even electric field sensing for the case of telesurgery [40].

VI. CONCLUSION

The effects of time delay in teleoperation are impossible to eliminate. They will always impose certain performance limitations, although deriving expressions for these limitations would be difficult, especially in the time-varying delay case. The problem of stability has been tackled for many control schemes, and now work focuses on improving performance without comprising that stability.

Haptic feedback is difficult to render in unstructured environments, but is essential for intuitive interfaces and completing delicate or constrained tasks. Some force control techniques will permit a position error to maintain a desired force in the case where the physical limits of the teleoperation scheme are encountered.

Internet-based teleoperation schemes are hybrid systems, consisting of both discrete events and continuous processes. Such models provide an accurate means to describe the full dynamics of the system and yield high-quality controllers, especially when used with predictive control. Minimizing the communication delay by using UDP and considering it as a real-time system, we should be able to attain the best possible performance.

REFERENCES


