Networked control methods robust to jitter and their evaluation by inverted pendulum

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Abstract

Control systems over the Internet often suffer from a peculiar transmission delay named jitter, which is an irregular variation of delay time due to network congestion. In order to make the closed-loop system robust to jitter, this paper proposes to apply two types of control methods; namely, i) a phase margin guarantee method known in control theory, and ii) a packet sorting method in network architecture. The paper evaluates the effectiveness of these methods through various experiments in stabilization of an inverted pendulum.

1 Introduction

Today the Internet provides a high-quality and wide-bandwith communication service, which enables us to access every device all over the world as far as it has the IP address [1]. In view of this situation, it is natural to expect that we may use this infrastructure as a means of feedback control. Future application will be found in various fields such as tele-operation, robots, and networked household appliances.

The Internet is, however, originally designed as a best-effort type network, and hence we can never avoid transmission delay nor data loss caused by traffic congestion. Evaluation and compensation of such phenomena are thus important issues for the purpose of practical use of control over the Internet [2, 3].

The objectives of this paper is as follows: We first propose to apply two types of methods, one from control theory and another from network architecture, in order to make the networked control system robust to the transmission delay peculiar to the Internet. Then we examine the effectiveness of these methods through various experiments in stabilization of an inverted pendulum.

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First, as a control-theoretic approach, we adopt the following:

- **Phase Margin Guarantee Method**

  We design a control law using a stability margin guarantee method recently proposed in literature [4, 5, 6]. Regarding the transmission delay as a phase-lag, we give a control system guaranteeing a desired phase margin of the loop transfer function.

  Delay compensation is not a new issue in control engineering. In networked control, however, the delay time is subject to an irregular variation named jitter, which has never appeared in conventional control problems such as process control. We thereby need a method robust to the jitter phenomenon. Another feature of the networked control is that there is no other uncertainty like gain variation in the transmission channel, because we can transmit exact signal values. In this context, the well-known $H_\infty$ criterion may be conservative since it evaluates uncertainty in terms of gain.

  In view of these aspects, the phase margin guarantee method is a promising tool in control over the Internet, although this has not been pointed out in literature [4, 6, 5]. For reference, we also examine an ordinary $H_\infty$ mixed-sensitivity method for robust stability as in [2].

Secondly, as a network-architecture approach we introduce:

- **Packet Sorting**

  Due to jitter, it is often the case that control signals do not arrive in the right order. Namely, a signal may overtake other signals, and in this case we receive older (useless) information. Since this causes a fatal effect in control, we avoid this phenomenon by numbering each packet and sorting it at the destination side.

  We now proceed to evaluation of the above methods. We first note that jitter can not be formulated as LTI (linear time-invariant) dynamical systems such as retarded and neutral delay-differential systems. It is a time-varying delay system with the delay time varying too irregularly to treat it theoretically. In view of this, we evaluate our control systems through real-world experiment.

  As a typical mechanical system, we adopt an inverted pendulum. Since this is an unstable system, we expect to observe the effect of transmission delay clearly. In order to facilitate real-time processing, we use RT-Linux (Fig. 1).

  The authors have succeeded in constructing a feedback control loop on the Internet and have made several types of experiment. For objective evaluation of the control methods, however, we should not use the Internet directly, since the result strongly depends on traffic conditions that we cannot control exactly. Hence we monitor the delay property in the Internet on various conditions, and then use the network emulator “NistNet” [7] which can produce the pseudo transmission delay based upon the observed data (Fig. 2).

  The remainder of the paper is organized as follows. In §2.1, we describe our network configuration. Then, in §2.2, we show our proposed control law. Finally, in §3, we describe experimental results with our two proposed methods.
Problem Setting

Network Configuration

The network system shown by Fig. 1 or 2 has two nodes. One node acts as a controller, and the other is connected to the plant. We call the controller node “local” and the other “remote”. The remote node gives the power value to the cart actuator and takes the pendulum angle and the cart position. The local node computes the actuator power from the angle and position signals received through the network.

These nodes communicate with UDP/IP via Internet for feedback path. Each signal is sent in a packet normally in a fixed sampling period. The remote node takes the angle and position signals with 10ms sampling time, and send these value messages to the local node. The local node receives messages from the remote node, determine the output value for torque motor according to the control rule and put this value in message packet and return to remote node. The remote node outputs power values to the torque motor at every sample point.

The authors have constructed a real system that uses the Internet as a feedback path with RT-Linux and NistNet for emulating the network cloud behavior. The message stack has been modified in remote node so that received packets are stacked in a buffer until next sample timing. When a return packet from the local node does not arrive at sample point due to transmission delay, remote nodes energize 0 voltage to torque motor and send angle position values to the local node. If, further, there are multiple message packets at local node
stacked, remote node selects the “freshest” message from stack and adopt this value. These strategies are countermeasures for packet disordering caused by jitter.

2.2 Control System Design

We can achieve the phase margin guarantee accordingly to the following idea. In Fig. 3, we set a “prohibited region,” namely, a disk into which the Nyquist plot must not enter. Let $P(s)$ be a plant to be controlled, and $K(s)$ be a controller. If all values of $K(s)P(s)$ for $s = j\omega$ do not enter into this disk, then the classical Nyquist stability theorem assures that the closed-loop system has a phase margin greater than $\phi$.

This idea is a generalization of the well-known circle criterion in LQ control: If $\sigma = r = 1$, then the prohibited region coincides with the unit disk which is tangential to the imaginary axis. By means of linear matrix inequality, it is feasible to compute a controller satisfying this “generalized circle criterion”. For details, see [4, 5, 6].

![Figure 3: Generalized Circle Criterion](image)

Now let us consider a networked control system with transmission delay. Suppose that we have obtained a controller for the specified phase margin $\phi$, and that this phase margin is attained at a frequency $\omega$. Namely, we have

$$K(s)P(s)|_{s=j\omega} = \exp(-j\phi'), \quad \phi \leq \phi'$$

Then it is easily verified that the closed-loop system will remain to be stable even if we insert a delay element of any delay time $L$ such that

$$L < \phi/\omega =: L_{\text{max}}.$$ 

We call $L_{\text{max}}$ the maximal acceptable delay time. We thus obtain a controller robust to the delay. It should be noted, however, that the above reasoning treats only perturbation due to an arbitrary but fixed delay time case, and does not directly treat jitter.

We can design another feedback system using the mixed sensitivity function in $H_\infty$ control theory. It is designed using the weighting functions shown in Figs. 4 and 5. Here, $r$ and $\theta$ respectively denote the cart position and the pendulum angle of the inverted pendulum under consideration. This design method is almost similar to the one proposed in [2].
3 Experimental Results

In order to evaluate our methods in a realistic condition, the authors have collected the “ping” measurement data from five (5) hosts for 30 minutes (1800 points probing). These hosts are located in various areas in Japan. We show the obtained data in Table 1.

Then, using NistNet with these parameter, stabilization experiment of the inverted pendulum has been conducted. For each condition, experiment has been repeated for 10 times, since the result varies statistically by nature. It has turned out that the pendulum is stable in each of the control methods.

For example, we show a behavior for the Case 5 in Figs. 6-9. In Figs. 6 and 8, the horizontal axis shows arrival packet sequence and the vertical axis means the pendulum angle. In Figs. 7 and 9, the horizontal axis shows arrival packet sequence and the vertical axis means the delay value of each packet. From these figures, we observe that our system remains stable even when the packet delay is larger than the guaranteed delay time.
Table 1: Ping Measurement.

<table>
<thead>
<tr>
<th>CASE</th>
<th>Destination</th>
<th>Mean delay[ms]</th>
<th>Standard Deviation[ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><a href="http://www.kyoto-u.ac.jp">www.kyoto-u.ac.jp</a></td>
<td>10.6</td>
<td>7.5767</td>
</tr>
<tr>
<td>2</td>
<td><a href="http://www.mainichi.or.jp">www.mainichi.or.jp</a></td>
<td>16.7</td>
<td>7.7995</td>
</tr>
<tr>
<td>3</td>
<td>aist.ring.gr.jp</td>
<td>18.9</td>
<td>11.002</td>
</tr>
<tr>
<td>4</td>
<td>ring.shizuoka.ac.jp</td>
<td>31.2</td>
<td>11.928</td>
</tr>
<tr>
<td>5</td>
<td><a href="http://www.2top.s-abe.or.jp">www.2top.s-abe.or.jp</a></td>
<td>34.1</td>
<td>32.425</td>
</tr>
</tbody>
</table>

The result of our detailed analysis can be found in the following Web site:

http://genesis.aist-nara.ac.jp/cc/cc-pend-e.html

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References


Figure 6: Pendulum angle for mixed-sensitivity method

Figure 7: Packet delay for mixed-sensitivity method

Figure 8: Pendulum angle for phase margin method

Figure 9: Packet delay for phase margin method