Buffering Time Optimization for Path Tracking Accuracy in Remote Vehicle Control with Digital Twin Computing

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Abstract: On path tracking control of vehicles via the Internet, transmission delay and jitter prevent them from tracking a target path accurately. To improve the control accuracy, it is effective to apply digital twin computing and jitter buffer to the control system. The control system with jitter buffer has an issue of optimizing buffering time. Through simulations by using some realistic transmission delay models, we quantitatively evaluated the control accuracy depending on the buffering time. As a result, we showed that buffered packet rate (BPR) can be a key index to optimize the buffering time according to transmission delay.

Keywords: unmanned vehicle, remote control, transmission delay, jitter buffer, state-predictive control

Classification: Navigation, guidance and control systems

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1 Introduction

With the spread of the Internet of Things, the demand for applications utilizing communication networks has increased. Autonomous driving of unmanned vehicles (UVs) is one of the technologies that have been attracting attention in recent years. The technology is expected to be applied not only to automobiles but also to various small vehicles, such as patrol vehicles [1] and goods delivery vehicles [2].

Remote control by cloud computing is effective to realize an application that autonomously controls a large number of UVs over a wide area. Centralizing control functions into a cloud server (CS) has advantages of system cost reduction, easy update of the functions and utilization of information collected through the network. We investigate the feasibility of a CS-based UV remote control system for path tracking control [3]. On the control via the Internet and wireless access, transmission delay and jitter prevent the UVs from tracking a target path accurately. Applying digital twin computing (DTC) [4] to the CS improves UV remote control accuracy even with transmission delay. By applying jitter buffer [5] to the UV, the control accuracy improves further.

The control system with DTC and jitter buffer has an issue of optimizing buffering time. The jitter buffer absorbs transmission delay fluctuation of control signal from the CS. It increases the average control delay between the CS and the UV. When a digital twin model (DTM) can not perfectly simulate a controlled UV, a prediction error by the DTM increases as the control delay increases. Therefore, too long buffering time deteriorates the UV control accuracy. On the other hand, too short buffering time also deteriorates it because the jitter buffer can not absorb the delay fluctuation sufficiently.

To achieve accurate UV control, it is necessary to optimize the buffering time according to transmission delay characteristics through communication network. In this letter, we proposed to use buffered packet rate (BPR) as a key index to optimize the buffering time according to transmission delay through simulations of UV remote control. This letter provides more detailed descriptions of the system and explanation of simulation results than our conference publication [6].
2 Simulator of remote path tracking control by cloud server

For path tracking control via a network, we assumed that a CS and a UV formed a feedback control loop. The UV travels following control signal from the CS, and cyclically sends its current traveling state as a status information packet. The CS has target path information, and sends control signal referring to the status information to make the UV travel along the path. Transmission delays of control signal and status information are unavoidable when communicating via the Internet. As these delays increases, the accuracy of the path tracking control deteriorates and the UV deviates largely from the target path.

By applying DTC and jitter buffer, the control system can reduce the deterioration of UV control accuracy. To quantitatively evaluate the control accuracy, we created a UV remote control simulator. Figure 1 is an overview of our simulator. In the simulator, the UV is a program that simulates a small four-wheeled vehicle. To focus on evaluating the effect of transmission delay on UV control, we assumed that the UV can track the target path accurately when there is no transmission delay between the CS and the UV.

During the simulation, the UV receives control signal of UDP packet including values of traveling speed ($v$), front wheel steering angle ($\theta$) and sending time of the CS ($t_{cs}$). Received signals are temporarily kept in a jitter buffer. The jitter buffer has parameter $D$ that represents the maximum buffering time. When a control signal is transmitted with a delay $d$, the jitter buffer outputs the signal to the UV at time $t_{cs} + \max(d, D)$. The UV simply calculates its own position $(x_t, y_t)$ on a virtual plane every 1 ms according to values of $v$ and $\theta$. When $\theta \neq 0$, the position is calculated as follows.

$$ r = \frac{WB}{\sin \theta} \quad (1) $$

$$ \delta = \frac{v}{r \times 1000} \quad (2) $$

$$ x_t = x_{t-1} + r(1 - \cos \delta) \cos \phi_{t-1} + r \sin \delta \sin \phi_{t-1} \quad (3) $$

$$ y_t = y_{t-1} + r \sin \delta \cos \phi_{t-1} - r(1 - \cos \delta) \sin \phi_{t-1} \quad (4) $$

$$ \phi_t = \phi_{t-1} + \delta \quad (5) $$
Here, $r$ and $\delta$ are a turning radius and a rotation angle of a virtual vehicle, respectively. $WB$ is a wheelbase of the virtual vehicle. $v/1000$ indicates the distance traveled in 1 ms. The UV sends status information of UDP packet including its position and direction to the CS every 100 ms.

Before the remote control starts, the CS gets a target path data. To apply DTC to the control system, we implemented a DTM in the CS based on the UV program. After sending a control signal, the CS uses the DTM to predict the UV traveling state that received the signal. Instead of status information from the UV, the CS cyclically refers to the prediction by the DTM to calculate a new control signal. Receiving the status information from the UV, the CS corrects the prediction based on the actual UV traveling state. The above procedures allows the CS to perform the state-predictive control of the UV.

3 Transmission delay models and target path in simulations

![Fig. 2. Simulation conditions](image-url)
In each simulation, we used one of three transmission delay models described in Fig. 2(a) for packet transmission delay between the CS and the UV. These delay models reproduce the realistic transmission delays through the Internet and Wi-Fi. Ranges of delay fluctuations in delay model A, B and C were from 3 to 254 ms, 54 to 296 ms, and 120 to 363 ms, respectively. Each delay model consists of Internet and Wi-Fi delays. The three models have different characteristics of the Internet delay and the same characteristics of Wi-Fi delay. The Internet delays was created by fitting the Pareto distribution [7] to delay measurements with three cloud servers in Tokyo, San Francisco and Frankfurt in July 2021. The Wi-Fi delay was measurements in IEEE 802.11ac with coexisting 300 Mbps background traffic.

The target path was as shown in Fig. 2(b). To evaluate UV control accuracy, we defined parameter \( MLD \) as the maximum lateral deviation between the target path and a UV trajectory in each simulation. A small \( MLD \) means that the UV could travel along the target path accurately.

### 4 Simulation result and discussion

Through simulations, we quantitatively evaluated the UV control accuracy depending on the \( D \) value. We carried out ten simulations for each condition.
$D$ was set between the minimum and maximum values of the reproduced transmission delay model. The traveling speed $v$ was set to 2.0 m/s.

Figure 3(a) illustrates $MLD$ characteristics for each delay model. Every point indicates the average of $MLD$ for each condition. The vertical axis indicates $MLD$ value. The horizontal axis indicates $D$ value. For reference, we also carried out the UV remote control simulation without DTM and jitter buffer. In these simulations, the sending cycle of status information by the UV was 10 ms. The $MLD$ values were much larger than those in Fig. 3(a). Specifically, at $v = 2.0$ m/s, $MLD = 0.16, 0.65$ and $1.57$ m for delay model A, B and C, respectively. From those results, we confirmed effectiveness of DTM and jitter buffer to improve the accuracy of path tracking control.

Figure 3(a) shows that $MLD$ decreases as $D$ increases. As described in Section 1, $D$ should be small as long as $MLD$ does not increase greatly. To realize accurate UV control, it is effective to adaptively determine $D$ according to transmission delay characteristics. We considered that buffered packet rate ($BPR$) is an appropriate parameter to determine the optimal value of $D$. $BPR$ indicates a rate of control signal packets with the transmission delay of $D$ or less. Figure 3(b) is a graph in which the horizontal axis of Fig. 3(a) is replaced with $BPR$. This graph shows that the UV control accuracy did not deteriorate much for any transmission delay model even when $BPR$ decreased from 100% to 96%. Between 100% and 96% $BPR$, the variations of $MLD$ were 1.9, 1.7 and 1.0 cm for delay model A, B and C, respectively.

In this study, the DTM accurately simulates the UV and does not include any prediction error. For accurate UV control, $D$ value depends not only on transmission delay characteristics but also on modeling accuracy of the DTM. Our simulation results suggest that $BPR$ can be a key index to optimize the buffering time of control signal.

5 Conclusion

On CS-based path tracking control of UVs, DTC is effective to improve the UV control accuracy. By applying jitter buffer to absorb transmission delay fluctuation of control signal, the control accuracy further improves. To achieve the accurate control, buffering time of the jitter buffer should be adaptively optimized according to transmission delay.

In this letter, we quantitatively investigated how to optimize the buffering time by using some realistic transmission delay models based on actual measurements. The result showed that buffered packet rate ($BPR$) can be a key index to optimize the buffering time. Our simulations showed that maximum lateral deviation from a target path varied by only 1.9 cm at most between 100% and 96% $BPR$.

On UV control system with DTC, a prediction error caused by modeling accuracy of the DTM affects the control accuracy. In our future work, we will investigate the effectiveness of optimizing the buffering time using $BPR$ under various conditions of modeling accuracy.