This is a preprint. The DOI for the final published version is available at https://doi.org/10.1109/ICKII58656.2023.10332694.

State Estimation Predictor with Stochastic time-delay Based Framework for Teleoperated Vehicle

1st Eugene Kim
Automotive Materials & Component
Korea Institute of Industrial Technology
Gwangju, South Korea
egkim@kitech.re.kr

2nd Taeyoon Lim
Automotive Materials & Component
Korea Institute of Industrial Technology
Gwangju, South Korea
limty226@kitech.re.kr

3rd Myeonghwan Hwang
Automotive Materials & Component
Korea Institute of Industrial Technology
Gwangju, South Korea
han9215@kitech.re.kr

4th Hyunrok Cha
Automotive Materials & Component
Korea Institute of Industrial Technology
Gwangju, South Korea
hrcha@kitech.re.kr

***Abstract*—The recent automotive industry has consistently focused on autonomous driving technologies for their potential chances to free human drivers from tedious maneuvering labor. Although the commercialized so-called full-driving automation vehicles are thought to be capable of replacing human drivers, many disengagement reports of autonomous driving make doubt about its safety-integrity levels to fulfill the minimum risk to be acceptable. As a countermeasure and backup plan for the disengagement of autonomous driving, recent approaches have focused on the teleoperation method to collaborate with humans and vehicles. However, the performance of the teleoperation method largely relies on the communication quality between the control center and the vehicle. Due to this fact, the communication delay has to be preliminarily investigated and profiled to be used as a boundary to classify as a communication outlier. This study involves a real-time communication delay classification scheme using a state estimation predictor with a stochastic time-delay-based Framework. The proposed framework is tested with an actual human-vehicle interface using a lte/5G network with a GNSS system. The communication delay was classified according to the level of the potential risk considering the magnitude of the communication delay. The result shows in accordance with the estimation of the state space model, the total amount of the communication delay was compensated by considering the communication time delay.**

***Index Terms*—Teleoperation, Autonomous vehicle, Communication delay, Outlier detection, Kalman filter**

I. INTRODUCTION

Due to the emergence of the autonomous driving system (ADS), numerous concern about the potential risk of disengagement of the ADS is rising. As the California state transportation agency points out (CalSTA), there seems not much doubt about ADS can face hazardous situations during urban driving scenarios [1]. Due to this fact, SAE J3016 and ISO 22736 guide to execute a DDT fallback scheme to take the ego-vehicle into minimum risk state [2], [3]. On the other hand, from the viewpoint of feasibility, recent research focused on the functionality of the teleoperation system considering the edge scenario of vehicles and pedestrians being congested [4]. However, despite dedicated efforts to utilize teleoperation to enhance the mobility of the ego vehicles, safety issues due to a communication delay still remain a major concern [5].

According to some of the literature regarding teleoperation of the UGVs, significant degradation in driving performance was monitored when the communication delay was coexisting [6]. In order to improve the performance when communication delay is underlying, some studies introduced compensation methods based on passivity and predictive displays against robot manipulators [7]–[10]. Furthermore, it was also shown that haptic feedback can aid the performance of teleoperation of the robot in terms of transparency [11]. However, in the case of handling ground vehicles, it was pointed out that teleoperator more relies on vision, not haptic feedback [12]. On the other hand, it has been proved that a predictive display approach is effective to compensate the influence of communication delays and even improve the mobility of the teleoperated vehicles in human in loop systems [13]–[15]. The core idea of manipulating predictive display lies in the modification of camera vision by forecasting the likely state based on the communication delay [13], [16]. However, in order to apply a predictive display approach, limitations exist where a full-vehicle model is required and the accuracy of the prediction relies also on the model.

One other approach is a predictor-based framework that uses model-free dynamics to overcome the limitations identified above which has to know the full-vehicle model [17]–[21].

This study has been conducted with the support of the Korea Institute of Industrial Technology as "Development of Core Technologies for a Working Partner Robot in the Manufacturing Field"(KITECH EO-23-0009)

This is a preprint. The DOI for the final published version is available at https://doi.org/10.1109/ICKII58656.2023.10332694.

Within this framework, it does not require any information on the vehicle dynamics but only has to obtain the communication delay each time [21]. In addition, pilot studies were also conducted within constant round-trip delays [22], and further included blending architecture to improve the accuracy of the heading position of the predictor [23].

However, the developed methods above have not considered the effect of erroneous communication states such as the communication delay outliers. In this study, we focus on the communication delay which may degrade the performance even if the strategies mentioned above are applied.

II. METHODOLOGY

A. Communication delay measurement

In order to measure the communication delay between the vehicle and the control center, NTP (Network Time Protocol) was used which is one of the most effective time synchronization methods [24]. In the case where synchronizing the inner clock of the slave node to the clock of the master node, a timebase of the node n can be written as follow:

$$t_n = t + \delta_n \tag{1}$$

Let $t_n^{(a)}$ be a time of nth node slave's discrete-time when asking to synchronize, and $t^{(b)}$ is the timebase of the master node when $t_n^{(a)}$ has arrived to the master node. After receiving $t_n^{(a)}$, $t^{(c)}$ is sent from the master node to the nth slave node. Finally, $t^{(d)}$ is received to estimate the clock offset between the vehicle and the control center:

$$\hat{\delta}_n = \frac{t_n^a + t_n^d}{2}, \tag{2}$$

where $\hat{\delta}_n$ is the estimated clock offset. In order to minimize $\hat{\delta}_n$, constant or dynamic offset removal is used in general. Thus, by using the NTP protocol, the inner clocks of slave nodes can be synchronized with the master node.

B. State estimation predictor

Depending on the communication delay x_k where k is the discrete time k, the likelihood function of the Gaussian distribution can be written as:

$$L(\theta; x_1, ..., x_N) = P(x_1, ..., x_N; \theta) = \prod_i^N \mathcal{N}(x_i|\mu, \sigma^2), \tag{3}$$

where θ is the parameter of gaussian ($\theta = (\mu, \sigma)$), x_i is the ith sample, and N is the number of samples, μ is mean of samples, and σ is standard deviation of samples. After taking the logarithm, the maximum value does not change and can be written as:

$$\begin{aligned}\log L(\theta; x_1, ..., x_N) &= \sum_{i=1}^N \mathcal{N}(x_i|\mu, \sigma) \\ &= -\frac{1}{2}\sum_{i=1}^N \frac{(x-\mu)^2}{\sigma^2} - \frac{N}{2}\log(2\pi\sigma^2).\end{aligned} \tag{4}$$

Further, by using expectation maximization, M Gaussian distributions can be estimated:

$$P(j|\boldsymbol{x}, \lambda) = \frac{c_j \mathcal{N}(\boldsymbol{x}|\boldsymbol{\mu}_j, \boldsymbol{\Sigma}_j)}{\sum_{k=1}^M c_k \mathcal{N}(\boldsymbol{x}|\boldsymbol{\mu}_k, \boldsymbol{\Sigma}_k)}, \tag{5}$$

where λ is a parameter of Gaussians ($\lambda = \{c_j, \boldsymbol{\mu}_j, \Sigma_j\}$), and c_j is the weight of jth Gaussian among the M Gaussians which can be written as:

$$\hat{c}_j = \frac{1}{N}\sum_{i=1}^N P(j|\boldsymbol{x}_i, \lambda), \tag{6}$$

where $\hat{c}_j$ is the estimated weight of jth Gaussian. Finally, the means and variances are estimated as:

$$\hat{\mu}_j = \frac{\sum_{i=1}^N P(j|\boldsymbol{x}_i, \lambda)\boldsymbol{x}_i}{\sum_{i=1}^N P(j|\boldsymbol{x}_i, \lambda)} \tag{7}$$

$$\hat{\sigma}_j = \frac{\sum_{i=1}^N P(j|\boldsymbol{x}_i, \lambda)\boldsymbol{x}_i^2}{\sum_{i=1}^N P(j|\boldsymbol{x}_i, \lambda)} - \hat{\mu}_j^2, \tag{8}$$

where $\hat{\mu}_j$, and $\hat{\sigma}_j$ are estimated mean and standard deviation of the jth Gaussian among M Gaussians.

However, in terms of estimating communication delays regarding instant bad-quality communication status and erroneous wireless conditions, (5) can be discretized into certain sample intervals:

$$P(j|\boldsymbol{x}_{i-l|i-1}, \lambda) = \frac{c_j \mathcal{N}(\boldsymbol{x}_{i-l|i-1}|\boldsymbol{\mu}_j, \boldsymbol{\Sigma}_j)}{\sum_{k=1}^M c_k \mathcal{N}(\boldsymbol{x}_{i-l|i-1}|\boldsymbol{\mu}_k, \boldsymbol{\Sigma}_k)}, \tag{9}$$

where l is the sample interval. By use of (9), communication delays can be not only estimated in real-time but also can be used as a judgment criterion for whether the instant communication delay x_i.

III. EXPERIMENT

In this section, experimental setups and simulation criteria are presented.

A. General experimental setup

In order to estimate the communication delay with an actual teleoperation condition, the following experimental setup was used. Firstly, 5G/LTE communication was settled by the use of LG Service Korea. Secondly, in order to synchronize the inner clock system between the control center and the teleoperated vehicle, Chrony (4.3, stable release) was used as the NTP protocol demon. Next, to collect data from the GPS (Global Positioning System), the gpsd (3.22 stable release) package was used to extract time data and PPS data (Pulse Per Second). By using the both gpsd and Chrony package, the control center, and teleoperated vehicle was synchronized to the atomic clock system of the fixed satellites. Finally, the whole system was linked based on the ROS (Robot Operating System, noetic, Ubuntu 20.04) framework, and communicates with TCP/IP protocol. To gather the communication delay profiles, the teleoperated vehicle was driven to collect the communication delay for 30 minutes in the field of the parking lot of the Korea Institute of Technology (Seonam Division, Gwangju, Rep. Korea).

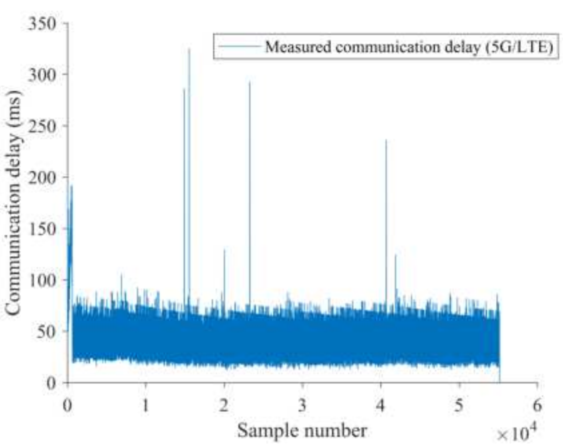

Fig. 1. Communication delay obtained during teleoperation of the vehicle. The teleoperated vehicle was driven to collect the communication delay for 30 minutes in the field of the parking lot of the Korea Institute of Technology

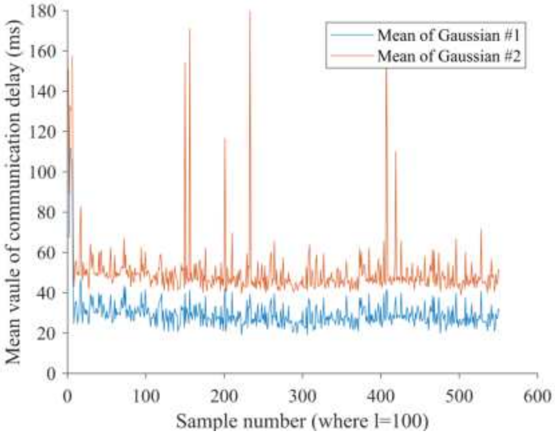

Fig. 2. Mean value of the communication delay where M was set as 2, and l was 100. It can be known that one of the means of the Gaussians largely differs from the previous samples which can be classified as a communication outlier

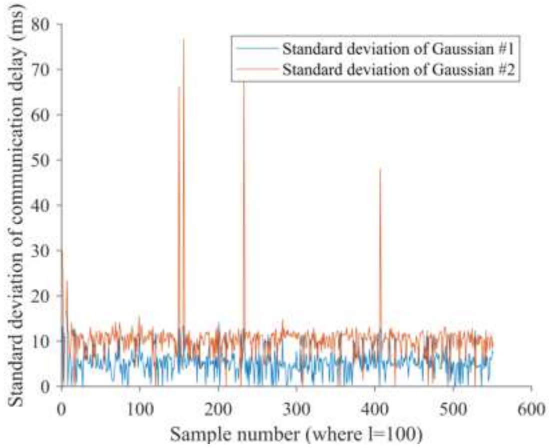

Fig. 3. Standard deviation of the communication delay where M was set as 2, and l was 100. It can be known that one of the means of the Gaussians largely differs from the previous samples which can be classified as a communication outlier

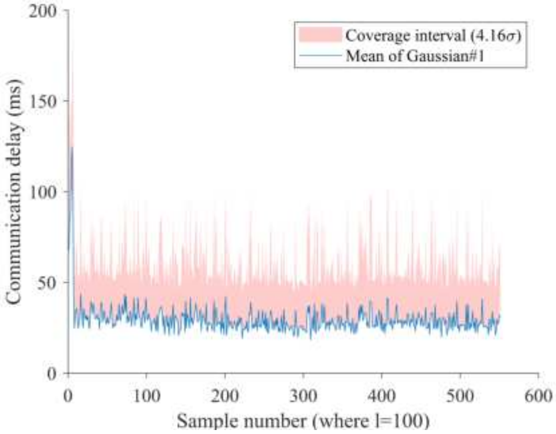

Fig. 4. Coverage interval computed with 4.16 σ which indicates acceptable uncertainty based on the safety integrity level of SIL2. It should be noted that the coverage interval can be changed according to the instant communication quality change

IV. RESULTS

In this section, the results of the experiment mentioned upper section III, and the analysis results are shown.

A. *Communication delay analysis*

Fig. 1 shows the result of communication delay measured within 30 minutes.

Fig. 2 shows the result of the mean value of the communication delay during the experiment. It can be known that the mean value of the second Gaussian occasionally has large deviations compared to the previous mean of the sampling trend. In addition, it should be noted that the length of the sample interval l was set as 100.

Fig. 3 shows the result of the standard deviation value of the communication delay during the experiment. It can be known that the standard deviation value of the second Gaussian occasionally has large deviations compared to the previous standard deviation value trend.

B. *Estimation results of communication delay*

Fig. 4 shows the coverage interval (4.16 σ) depending on the mean, and standard deviation of the instant communication delay. It should be noted that the coverage interval indicates acceptable uncertainty based on the safety integrity level of SIL2.

Fig. 5 Detected communication delay outlier which was detected by the computed coverage interval. The orange circle indicates the detected communication delay outlier.

V. CONCLUSION

In the field of autonomous driving, teleoperation is considered one of the options to take the vehicle into the minimum risk state. However, the teleoperation of the vehicle should

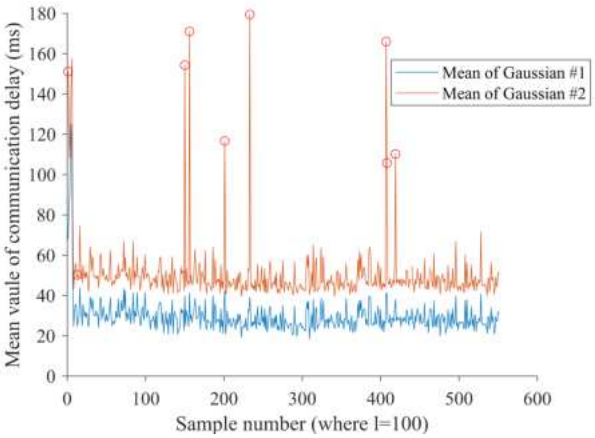

Fig. 5. Detected communication delay outlier which detected by the computed coverage interval. The orange circle indicates the detected communication delay outlier

be continuously managed to be controlled safely in terms of risk assessment. In this study, a state estimation predictor with a stochastic time-delay-based framework for teleoperated vehicles is introduced. By using the proposed technique, communication delays can be stochastically estimated in real-time and can detect communication delay. As for further research, based on the detected outliers, an effort is needed for actual teleoperation control should be mitigated with respect to the magnitude of the communication delay.

ACKNOWLEDGEMENT

This study has been conducted with the support of the Korea Institute of Industrial Technology as ”Development of Core Technologies for a Working Partner Robot in the Manufacturing Field”(KITECH EO-23-0009)

REFERENCES

[1] State of california department of motor vehicle, “Autonomous vehicle disengagement reports 2019-2020,” 2020.

[2] SAE-J3016, “Surface vehicle recommended practive, taxonomy and definitions for terms related to on-road motor vehicle automated driving systems,” 2018.

[3] ISO/SAE PRF PAS 22736, “Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles.”

[4] D. Majstorović, S. Hoffmann, F. Pfab, A. Schimpe, M.-M. Wolf, and F. Diermeyer, “Survey on teleoperation concepts for automated vehicles,” in *2022 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, pp. 1290–1296, IEEE, 2022.

[5] S. Hoffmann and D. F. Diermeyer, “Systems-theoretic safety assessment of teleoperated road vehicles,” *arXiv preprint arXiv:2104.06795*, 2021.

[6] L. H. Frank, J. G. Casali, and W. W. Wierwille, “Effects of visual display and motion system delays on operator performance and uneasiness in a driving simulator,” *Human factors*, vol. 30, no. 2, pp. 201–217, 1988.

[7] J. P. Luck, P. L. McDermott, L. Allender, and D. C. Russell, “An investigation of real world control of robotic assets under communication latency,” in *Proceedings of the 1st ACM SIGCHI/SIGART conference on Human-robot interaction*, pp. 202–209, 2006.

[8] F. Penizzotto, S. García, E. Slawiñski, V. Mut, *et al.*, “Delayed bilateral teleoperation of wheeled robots including a command metric,” *Mathematical Problems in Engineering*, vol. 2015, 2015.

[9] Y.-J. Pan, C. Canudas-de Wit, and O. Sename, “A new predictive approach for bilateral teleoperation with applications to drive-by-wire systems,” *IEEE Transactions on Robotics*, vol. 22, no. 6, pp. 1146–1162, 2006.

[10] A. K. Bejczy, W. S. Kim, and S. C. Venema, “The phantom robot: predictive displays for teleoperation with time delay,” in *Proceedings., IEEE International Conference on Robotics and Automation*, pp. 546–551, IEEE, 1990.

[11] D. A. Lawrence, “Stability and transparency in bilateral teleoperation,” *IEEE transactions on robotics and automation*, vol. 9, no. 5, pp. 624–637, 1993.

[12] S. Lichiardopol, “A survey on teleoperation,” 2007.

[13] F. E. Chucholowski, “Evaluation of display methods for teleoperation of road vehicles,” *Journal of Unmanned System Technology*, vol. 3, no. 3, pp. 80–85, 2016.

[14] S. Mathan, A. Hyndman, K. Fischer, J. Blatz, and D. Brams, “Efficacy of a predictive display, steering device, and vehicle body representation in the operation of a lunar vehicle,” in *Conference Companion on Human Factors in Computing Systems*, pp. 71–72, 1996.

[15] J. H. Hogema, “Compensation for delay in the visual display of a driving simulator,” *Simulation*, vol. 69, no. 1, pp. 27–34, 1997.

[16] M. J. Brudnak, “Predictive displays for high latency teleoperation,” in *Proc. NDIA Ground Veh. Syst. Eng. Technol. Symp.*, pp. 1–16, 2016.

[17] A. Tandon, M. J. Brudnak, J. L. Stein, and T. Ersal, “An observer based framework to improve fidelity in internet-distributed hardware-in-the-loop simulations,” in *Dynamic Systems and Control Conference*, vol. 56130, p. V002T21A004, American Society of Mechanical Engineers, 2013.

[18] X. Ge, M. J. Brudnak, P. Jayakumar, J. L. Stein, and T. Ersal, “A model-free predictor framework for tele-operated vehicles,” in *2015 American Control Conference (ACC)*, pp. 4573–4578, IEEE, 2015.

[19] X. Ge, Y. Zheng, M. J. Brudnak, P. Jayakumar, J. L. Stein, and T. Ersal, “Analysis of a model-free predictor for delay compensation in networked systems,” *Time Delay Systems: Theory, Numerics, Applications, and Experiments*, pp. 201–215, 2017.

[20] Y. Zheng, M. J. Brudnak, P. Jayakumar, J. L. Stein, and T. Ersal, “A predictor-based framework for delay compensation in networked closed-loop systems,” *IEEE/ASME Transactions on Mechatronics*, vol. 23, no. 5, pp. 2482–2493, 2018.

[21] Y. Zheng, M. J. Brudnak, P. Jayakumar, J. L. Stein, and T. Ersal, “Evaluation of a predictor-based framework in high-speed teleoperated military ugvs,” *IEEE Transactions on Human-Machine Systems*, vol. 50, no. 6, pp. 561–572, 2020.

[22] Y. Zheng, M. J. Brudnak, P. Jayakumar, J. L. Stein, and T. Ersal, “An experimental evaluation of a model-free predictor framework in teleoperated vehicles,” *IFAC-PapersOnLine*, vol. 49, no. 10, pp. 157–164, 2016.

[23] Y. Zheng, M. J. Brudnak, P. Jayakumar, J. L. Stein, and T. Ersal, “A delay compensation framework for predicting heading in teleoperated ground vehicles,” *IEEE/ASME Transactions on Mechatronics*, vol. 24, no. 5, pp. 2365–2376, 2019.

[24] D. L. Mills, “Network time protocol (ntp),” tech. rep., 1985.