Journal of Unmanned System Technology

Evaluation of Display Methods for Teleoperation of Road Vehicles

Frederic Emanuel Chucholowski

Institute of Automotive Technology, Technische Universität München, Germany

Abstract**—**During teleoperation of road vehicles, live images from the vehicle are sent to an operator via a cellular connection, who then inputs his control demands. Time delays resulting from signal processing and transmission times can cause instabilities in the control loop and decrease driving performance. To mitigate the negative effects of time delays, predictive displays have long been used in the field of robotics. This paper presents the "Frame Prediction" method for drawing a predictive display for teleoperation of road vehicles. It also shows the results of an experiment in a simulated environment which compared the presented method to 1) driving under the influence of time delays and 2) a display method where the video images are modified as if there was no time delay present. Results revealed that the Frame Prediction method significantly increases driving performance and decreases operator workload for delayed systems. For some scenarios it even supersedes the driving performance without delays.

Keywords**—**Teleoperation, predictive display, indirect vision driving.

I. INTRODUCTION

TELEOPERATION of road vehicles was developed to handle the driverless delivery of car sharing vehicles to the customer and to move electrical vehicles from customers to charging stations and back without requiring a human to sit inside the vehicle [1]. Therefore the vehicle is equipped with video cameras that transmit a live video feed from the vehicle to the operator workstation via mobile Internet connection [2]. The operator then inputs the control commands which are transmitted back to the vehicle. These transmission and signal processing times for video encoding and decoding lead to a time delay or time lag in the control loop, which affects the task of vehicle guidance. In addition to a delayed perception of traffic situations, it also leads to unstable control behavior [3]. One approach to combat time delays is the reduction of processing times by, for example, optimizing the video encoding and decoding process as described in [4]. But since time delays cannot completely be eliminated, it is important to assist the driver in stable and accurate vehicle guidance. Under the influence of long time lags, operators tend to use the move-and-wait-strategy [5] which increases task completion time. For short fixed delay times of about 200 milliseconds most operators are able to adapt to the delay and roughly predict the outcome of their control actions with some practice [6]. But especially for variable time lags, driving performance is still far below the performance without delays [3].

Besides other approaches to mitigate time lags in the teleoperation of robotic systems, such as wave-variable filters [7] or command displays with indirect control strategies [8], predicted displays have been used. Predictive displays were first investigated by Arnold and Braisted [9] for the teleoperation of lunar rovers. Later, research for predictive displays also focused on manipulators [10], underwater vehicles [11] and ships [12]. Davis et al. [3] proved for military vehicles that a predictive display can successfully mitigate the effects of constant and variable time lags.

This paper demonstrates two possible display methods to remotely control road vehicles using predicted vehicle states. It also shows the results of an experiment in a virtual environment comparing their efficacy to driving without time delays. Results revealed that while both demonstrated methods significantly increase directional stability, "Frame Prediction" has no disadvantage over the computational more complex and time consuming "Perfect Prediction" method.

II. PROCEDURES

A. *Participants*

One female and twenty-one male students and employees of the Technische Universität München participated in this experiment. Their ages were between 21 and 35 with an average age of 24.91 years and a standard deviation of 3.22 years. Four participants indicated that they already had experience with driving simulators and 15 participants had good or very good experience with computer games. With only one female participant and all participants having an academic and technical background, they do not represent the average population. However, this study aims to show tendencies for future development.

B. *Apparatus*

The simulator used in this experiment is also used for real world test drives at the Technische Universität München and can be seen in **Figure 2**. It has a fixed base driver's station with a vehicle seat and a G25 Logitech Racing Wheel, with steering wheel and acceleration and braking pedals, that serves as the input device. Three 22-inch flat screen computer monitors display the animated scenery with a wide angle field of view just as it would be shown using real world camera images. The

Corresponding author: Frederic E.C.(e-mail: chucholowski@ftm.mw.tum.de)
This paper was submitted on November 13, 2013; revised on August 7, 2014; and accepted on December 27, 2015.
DOI: 10.21535/just.v3i3.38

investigator can control the simulation and change parameters via a fourth computer monitor.

Figure 1 The simulator used for this experiment is also used for real world test drives

Figure 2 The simulated environment is shown as a 3D scene in DYNAanimation

The simulation environment consists of the real-time capable vehicle dynamics simulation environment TESIS DYNAware DYNA4 and the corresponding animation program DYNAanimation. The animation program shows the simulated environment as a 3D scene as in **Figure 2**. The participants have to complete a handling course with five left-turns and five right-turns and an overall distance of 1750 meters and a width of four meters. A city course was additionally implemented, which could be completed with 50 km/h if no time delays were present. This course consists of four crossings, five turns, one roundabout and one stop line. The street width is 6 meters but the participants are advised to keep on the right lane. At three points the street is narrow because of vehicles standing on the oncoming lane.

Each course is driven with the following three display methods in alternating order.

C. *Delayed Display (DD)*

The DD method delays the vehicle and camera position by the designated time delay before they are displayed by the animation program. This corresponds to a delayed visual feedback in a camera-based driving system. The 3D camera is hereby positioned in the top center of the delayed vehicle's windshield as it would be in the real vehicle.

D. *Perfect Prediction (PP)*

The PP display method assumes that we were able to perfectly predict the camera image that would be visible if there was no time delay in the visual feedback. Under this assumption, the image which has to be displayed in the animation is the same as driving without delay. The simulated camera and vehicle position are therefore not delayed and are directly displayed by the animation program. To accomplish a perfect prediction in reality, a 3D representation of the world has to be generated from the live video feed as in [13]. The video image can then be reconstructed as if it was captured from the predicted vehicle position. Although one can expect algorithms and image quality for this method to improve in the near future, we still wouldn't be able to show a predicted image of areas which have not yet been captured by the vehicle's cameras. This applies, for example, to objects or parts of the street behind corners or hill ridges. This is not accounted for in the simplification of only showing undelayed images. However, this experiment will find out if it would make sense to have a perfect prediction compared to a different display method with less computation effort. Thus if there is no significant advantage using the idealized perfect prediction, the advantage will be even less with the above mentioned restrictions.

E. *Frame Prediction (FP)*

The FP display method draws a predicted vehicle position into the live video feed. In [14] we showed how the predicted vehicle position can be calculated with sufficient accuracy using a single track vehicle dynamics model. For this experiment we assume that we were able to accurately predict the positions. We can therefore use the real vehicle position returned by the simulation to draw the predicted state. The camera in the 3D scene, however, is positioned at the 3D position where the vehicle was positioned the designated time delay before. That means that the camera position is equal to the camera position in the DD method.

Until now several possibilities have been developed to show predicted information on an operator's user interface. The most suitable ones for our task might be drawing an arrow indicating the direction as suggested for a predictive display for lunar rovers in [15]. Davis et al. [3] on the other hand, use a semi-transparent 3D chassis model similar to the real vehicle which is positioned at the predicted position. However, this method has the drawback that large parts of the image are obstructed, especially for low velocities. Therefore we developed the FP method, which shows the extent and orientation of the vehicle by drawing a rectangular frame. The vehicle path and the front position are visualized with virtual track marks as shown in **Figure 3**. The size of the frame and the angle and length of the track marks on the visible 2D image also support the driver in estimating the vehicle's velocity.

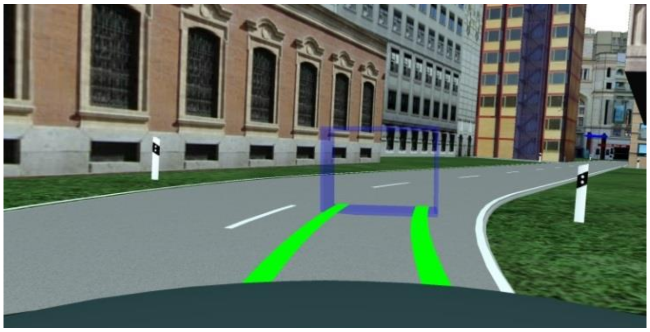

Figure 3 The Frame Prediction display method visualizes the vehicle path and the front position using virtual track marks and a rectangular frame

F. *Methodology*

At the beginning each participant fills in the first questionnaire before the investigator explains the usage and control of the simulator hardware and software. The participant then completes one drive for each course and each display method. All driving trials are driven with a delay of 500 milliseconds. The driver starts with the handling course using DD, FP and PP and finishes with the city course using DD, FP and PP. These first runs are not evaluated because pilot tests revealed that it is very difficult to keep the vehicle on track under the influence of time delays in the first minutes of driving. By driving each course several times, the participants learn about the characteristics of each course and improve their control skills for these. To eliminate this effect from the actual experiment, these practice drives are carried out before the actual experiment starts. They also help to get acquainted with the three display methods. In the following five minutes break, the rating scales are explained.

The whole group is split into two smaller groups with eleven participants each. Group A begins trials with the handling course followed by the city course, while group B begins trials with the city course followed by the handling course. Each course is then driven by each participant for each of the three display methods in alternating order. After each test drive the participant grades controllability and work load on the rating scales. This leads to a total of six practice drives and six driving trials for each participant. The participants have to control the steering wheel angle as well as the vehicle speed to be able to keep the vehicle on track. The participants are told that although it is important to complete the driving trial as fast as possible, lane accuracy is more important. The time for each drive varied between about eighty seconds and six minutes.

G. *Data Analysis*

We analyzed the experiment using both measured data during the driving trials as well as two questionnaires. One questionnaire is filled in before the driving trials begin. It is used to categorize the participants. The second questionnaire is filled in after the driving trials. It consists of questions with choice boxes to subjectively compare the display methods and open questions that will help for future development. After each driving trial the participants evaluate controllability and work load for the driven course with the display method used.

Often deviation from the center of the lane is used to evaluate lane accuracy as in [3, 5]. But since it is normal to deviate from the center of the lane during turns, we advised the participants to stay on the track instead of keeping to the center of the lane. We therefore calculate the distance from the center of the front axle to the edge of the lane. As long as the vehicle stays on the track, the lane deviation is set to zero. If at least one tire leaves the track, the deviation is accounted for in the average deviation and the average percentage that the vehicle stayed on the track.

To see how smoothly the participant is able to control the vehicle, we considered the number of times that the direction of the steering wheel rate changed. We therefore counted all steering wheel angle extreme points which were at least about 20° apart from each other.

We calculated the overall performance using both lane accuracy (the percentage of the drive that the driver stayed on the road) (*LA*) and task completion time (*T*). Since the participant's primary goal is to keep to the lane and only the secondary goal is a fast completion time, we weighed lane accuracy with two thirds compared to one third for completion time. The values for both are calculated using the quotient of the difference of the best value and the participant's value by the difference of best and worst value as shown in Eq. (1).

$$\mathrm{OP} = \frac{2}{3} * \left(\frac{\mathrm{LA}_{\mathrm{min}} - \mathrm{LA}_{\mathrm{Participant}}}{\mathrm{LA}_{\mathrm{min}} - \mathrm{LA}_{\mathrm{max}}}\right) + \frac{1}{3} * \left(\frac{\mathrm{T}_{\mathrm{max}} - \mathrm{T}_{\mathrm{Participant}}}{\mathrm{T}_{\mathrm{max}} - \mathrm{T}_{\mathrm{min}}}\right) \quad (1)$$

To evaluate the longitudinal control accuracy the distance from the vehicle's front to the stop line is also calculated.

III. RESULTS

A. *Workload*

Participants rated the workload after each driving trial on a scale from zero (lowest) to ten (highest) as shown in **Figure 4** and **TABLE** . Wilcoxon-tests revealed that the workload for FP was significantly lower in both courses (CC: p<0.001; HC: p<0.001) than for DD. While there was no significant difference of FP compared to PP on CC (p=0.207), the workload with PP is significantly lower than with FP on HC (p=0.005). The number of steering wheel changes on the CC with FP was significantly lower than with DD (p<0.001) and PP (p<0.001) according to t-tests. Wilcoxon-tests showed that also for the HC, the number of steering wheel changes with FP was significantly lower than with DD (p<0.001) and PP (p=0.001).

B. *Performance on Driving Tasks*

An overview of the values regarding the performance on driving tasks is shown in **Figure 5**, **Figure 6** and **TABLE II**. Participants rated controllability after each driving trial on a scale from zero (lowest) to ten (highest). Wilcoxon-tests revealed that controllability on both courses was rated significantly higher (CC: p<0.001; HC: p<0.001) with FP than with DD. While there is no significant difference (p=0.076) between FP and on the CC, the PP is rated significantly better (p=0.044) than FP on the HC.

Wilcoxon-tests for the CC showed that the average lane offset is significantly smaller with FP (p=0.001) and PP (p<0.001) compared to DD. However, there is no significant difference (p=0.385) between PP and FP. While the PP on the HC is significantly better (p=0.023) than DD, there is no significant difference between FP and DD or PP. The percentage that the vehicle stayed on the road according to Wilcoxon-tests is significantly higher with FP (CC: p<0.001; HC: p<0.001) and PP (CC: p<0.001; HC: p<0.001) than with DD on both courses. While for the CC the percentage with FP is also significantly higher (p<0.001) than with PP, there is no significant difference (p=0.555) for the handling course.

For both courses Wilcoxon-tests revealed that the task completion time is significantly shorter with PP (CC: p=0.003; HC: p<0.001) compared to FP, which is again significantly shorter than with DD (CC: p<0.001; HC: p<0.001).

Wilcoxon-tests showed that overall performance with FP is significantly better than for DD (p<0.001) and PP (p<0.001) on the CC. On the HC, there is no significant difference (p=0.211) between FP and PP. FP has a significantly higher (p<0.001) overall performance, however, than DD.

According to Wilcoxon-tests, the distance to the stop line is significantly shorter (p=0.042) with FP than with DD. Compared to PP, there is no significant difference (p=0.101).

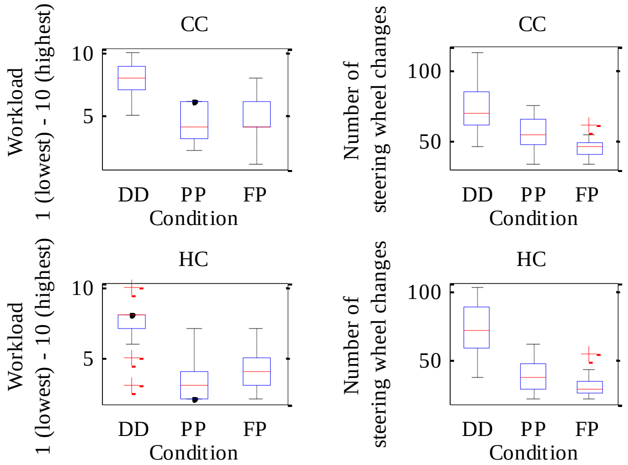

Figure 4 Workload and number of steering wheel changes on CC and HC

TABLE I WORKLOAD MEAN VALUES AND STANDARD DEVIATION

Criterion	Method	CC		HC		Scale
		μ	σ	μ	σ	
Workload	DD	7.91	1.23	7.23	1.41	0 (lowest) to 10 (highest)
	PP	4.18	1.44	3.23	1.51	
	FP	4.64	1.62	4.27	1.55	
Number of steering wheel changes	DD	73.68	17.76	71.73	17.23	Number of changes
	PP	55.05	11.90	37.45	11.49	
	FP	44.82	6.82	29.95	7.86	

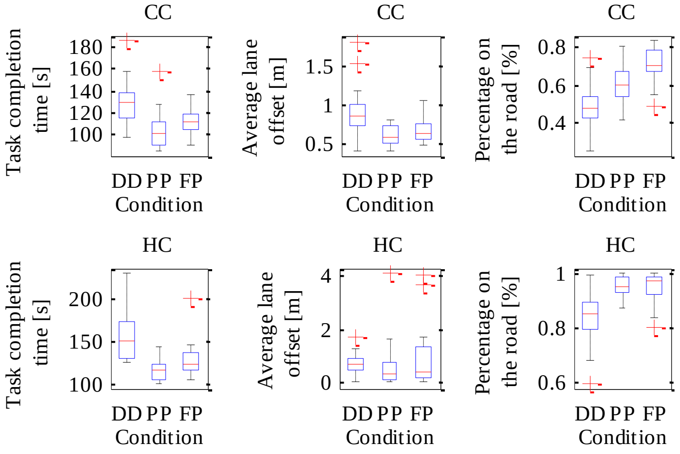

Figure 5 Task completion time, average lane offset and percentage on the road on CC and HC

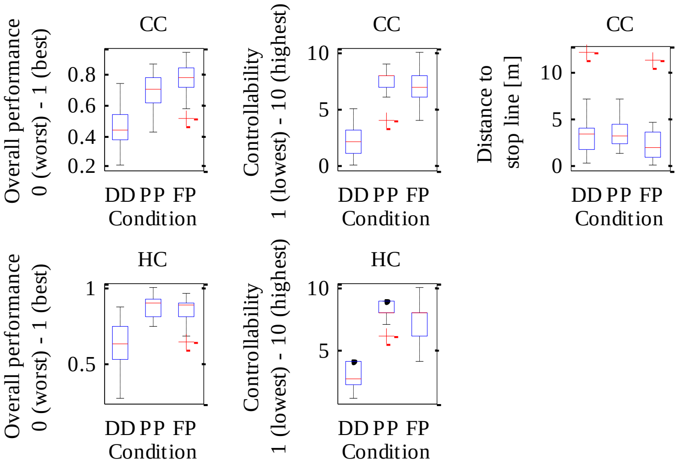

Figure 6 Overall performance, controllability and distance to stop line on CC and HC

C. *Sensation of Velocities*

Participants rated after each driving trial whether they had a good sensation of the vehicle's velocity on a scale from one (true) to six (not true), as shown in **Figure 7** and **TABLE III**. Wilcoxon-tests revealed that the participants had a significantly (p<0.001) better sensation of velocity with FP than with DD. Compared to PP there was no significant difference (p=0.572).

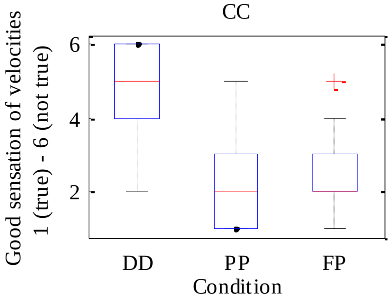

Figure 7 Rated values for good sensation of velocities

TABLE II DRIVING PERFORMANCE MEAN VALUES AND STANDARD DEVIATION

Criterion	Method	CC		HC		Scale
		μ	σ	μ	σ	
Task completion time	DD	128.7	18.73	156.1	28.48	Seconds
	PP	103.6	16.90	115.9	10.54	
	FP	111.1	12.13	128.6	19.82	
Average lane offset	DD	0.90	0.303	0.71	0.386	Meters
	PP	0.59	0.118	0.58	0.907	
	FP	0.65	0.170	0.86	1.101	
Percentage on the road	DD	0.48	0.117	0.85	0.098	Percent
	PP	0.60	0.096	0.95	0.039	
	FP	0.70	0.091	0.95	0.055	
Overall perfor-mance	DD	0.452	0.138	0.608	0.165	0 (worst) to 1 (best)
	PP	0.608	0.165	0.872	0.071	
	FP	0.762	0.108	0.849	0.086	
Controll-ability	DD	2.05	1.327	2.86	1.037	0 (lowest) to 10 (highest)
	PP	7.59	1.182	8.09	0.868	
	FP	7.09	1.540	7.45	1.471	
Distance to stop line	DD	3.65	2.66	-	-	Meters
	PP	3.50	1.63	-	-	
	FP	2.45	2.44	-	-	

TABLE III SENSATION OF VELOCITIES MEAN VALUES AND STANDARD DEVIATION

Criterion	Method	μ	σ	Scale
Good sensation of velocities	DD	4.73	1.24	1 (true) – 6 (not true)
	PP	2.27	1.12	
	FP	2.45	1.18	

IV. DISCUSSION

As shown in previous experiments [3], results from this experiment also demonstrate that time delays have a large negative influence on driving performance and operator workload. Results also proved that both can be improved using a predictive display.

The number of steering wheel turns could be decreased using PP. But the least amount of turns and therefore the smoothest driving was possible with FP. This might be due to the fact that most participants stated to have a good overview of the vehicle and were able to accurately determine the vehicle position on the track with FP.

The average lane offset could significantly be reduced on the CC with FP and PP compared to DD, whereas PP was only slightly better than FP. On the HC, there is no significant difference between FP and DD or PP. However, the percentage that the vehicle stayed on the track was best for FP. This might also be due to the good overview of the vehicle position on the lane. With PP, participants often left the lane only for a few centimeters. In the real world this would often be as bad as leaving the lane further.

Task completion time was lowest for PP, which was about 7 % faster than FP. FP however was still 14 % faster than DD. Overall performance of PP and FP were both significantly higher than with DD. The best overall performance for the city course was achieved with FP. On the handling course PP slightly outperformed FP however. With increasing velocity the predicted distance also increases, which requires a further forward visibility. Because of the idealized realization of PP, the forward view is always better than with FP. In the real world, however, forward visibility would be the same for all display methods. This might explain why PP is better with higher velocities.

This also complies with the subjective decrease of work load for FP and PP compared to DD. And while for the city course with slower velocities the work load of FP is similar to PP, it is higher for the handling course with higher velocities.

The distance to the stop line was about the same for PP and DD. Although with FP it could greatly be reduced - by 31 %. The reason for this might also be the good overview of the vehicle position on the lane with FP.

Participants stated that it was easier to estimate the velocity with FP compared to DD but it was not easier than with PP.

The open questions revealed that further improvements to the displayed frame in FP can be done, which is part of ongoing developments at the Technische Universität München. Fourteen out of twenty-two participants stated that they preferred FP over DD and PP. The evaluation shows that a predictive display greatly supports the driving tasks. The PP slightly supersedes the FP in some categories, but often both provide the same results or FP even supersedes PP. It is therefore not necessary to use the complex PP. The FP is our preferred display method.

Besides just predicting the remote controlled vehicle, it will also be necessary to predict other traffic participants and show their predicted positions on the video images. Combining these with FP might lead to the driver's confusion. This will require further experiments. Another aspect will be the attentional focus as already pointed out by [3].

V. CONCLUSION

By using a predictive display, time delays in the control loop of teleoperated driving can be mitigated. Both PP, which virtually repositions the camera in the 3D world, and FP, which draws a frame at the predicted position, increase directional stability compared to driving without predictive display. Since implementation, and most of all calculation, effort for PP is much higher than for FP and it doesn't show significant advantages, FP is the preferred method. Future work will therefore further improve the FP display method and combine it with the display of other predicted traffic participants.

ACKNOWLEDGMENTS

The work was conducted by basic funding of the Technische Universität München. Thanks are also due to TESIS DYNAware GmbH for providing us with their simulation framework DYNA4 and DYNAanimation.

REFERENCES

[1] F. Diermeyer, S. Gnatzig, F. Chucholowski, T. Tang, and M. Lienkamp, “Der Mensch als Sensor - Der Weg zum teleoperierten Fahren,” in *AAET*, 2011.

[2] S. Gnatzig, F. Chucholowski, T. Tang, and M. Lienkamp, “A System Design for Teleoperated Road Vehicles,” in *Proceedings of the 10th International Conference on Informatics in Control, Automation and Robotics*, 2013.

[3] J. Davis, C. Smyth, and K. McDowell, “Mitigating the Effects of Time Lag on Driving Performance,” *Proceedings of the 2009 Ground Vehicle Systems Engineering and Technology Symposium* (GVSETS), pp. 1–5, 2009. VIEW

[4] T. Tang, F. Chucholowski, M. Yan, and M. Lienkamp, “A Novel Study on Data Rate by the Video Transmission for Teleoperated Road Vehicles,” in *ICIUS 2013: 9th International Conference on Intelligent Unmanned Systems*, 2013.

[5] W. R. Ferrell, “Remote manipulation with transmission delay,” *Human Factors in Electronics*, vol. 6, no. 1, pp. 24–32, September 2013. CrossRef

[6] D. W. Cunningham, A. Chatziastros, Von Der Heyde, M, and H. H. Bülthoff, “Driving in the future: temporal visuomotor adaptation and generalization,” *Journal of vision*, vol. 1, no. 2, pp. 88–98, http://www.ncbi.nlm.nih.gov/pubmed/12678604, 2001. CrossRef

[7] G. Niemeyer and J.-J. Slotine, “Towards force-reflecting teleoperation over the Internet,” *Proceedings of 1998 IEEE International Conference on Robotics and Automation (Cat. No.98CH36146)*: IEEE, 1998, pp. 1909–1915. CrossRef

[8] S. Gnatzig, F. Schuller, and M. Lienkamp, “Human-machine interaction as key technology for driverless driving - A trajectory-based shared autonomy control approach,” in *2012 RO-MAN: The 21st IEEE International Symposium on Robot and Human Interactive Communication: Paris, France, 9 - 13 September 2012*, Piscataway, NJ: IEEE, 2012, pp. 913–918. CrossRef

[9] J. E. Arnold and P. W. Braisted, “Design and evaluation of a predictor for remote control systems operating with signal transmission delays,” NASA December, 1963.

[10] T. Burkert, J. Leupold, and G. Passig, “A Photorealistic Predictive Display,” *Presence: Teleoperators and Virtual Environments*, vol. 13, no. 1, pp. 22–43, 2004. CrossRef

[11] W. Verplank, “Display Aids for Remote Control of Untethered Undersea Vehicles,” in *OCEANS ’78*: IEEE, 1978, pp. 238–241.

[12] B. Sullivan, C. Ware, and M. Plumlee, “Predictive Displays for Survey Vessels,” *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 50, no. 22, pp. 2424–2428, 2006. CrossRef

[13] M. Jagersand, A. Rachmielowski, D. Lovi, and N. Birkbeck, “Predictive Display from Computer Vision Models,” in *The 10th International Symposium on Artificial Intelligence, Robotics and Automation in Space I-SAIRAS*, 2010.

[14] F. Chucholowski, S. Büchner, J. Reicheneder, and M. Lienkamp, “Prediction Methods for Teleoperated Road Vehicles,” in *Conference on Future Automotive Technology - Focus Electromobility*, Garching: Bayern Innovativ GmbH, 2013.

[15] 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 common ground - CHI ’96*, New York, New York, USA: ACM Press, 1996, pp. 71–72.