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Compensation of Time-delay for Internet-based Mobile Robot Using Fuzzy Logic

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Abstract

Recently, internet-based applications can be found easily in various fields. Internet-based telerobot system becomes one of important applications of internet. Among many important technological issues on the internet-based telerobot, time-delay is inherently critical problem to be solved.

Time-delay is classified as micro time-delay and macro time-delay in this paper. Algorithms for compensation of path-error and time-error are proposed for the both types of time-delays using fuzzy logic since fuzzy logic is one of the best tools to represent expert's knowledge. Simulation results show the validity of the proposed algorithms.

Key Words : internet, time-delay, mobile robot. teleoperation. telerobot, fuzzy logic

1. Introduction

Recently, internet-based applications can be found easily in various fields. A lot of applications can also be found in the field of robotics. Many researchers have been trying to develop internet-based telerobots and several successful results have been reported in the literature. Most of researches on the internet-based telerobot in the early stage was focused to manipulators[1, 2, 3, 4]. Mobile robot system is, however, the major application of the internet-based telerobot[5], recently.

Time-delay due to the natural characteristics of internet is serious especially for mobile robot systems. Several researchers focused on this problem. Imad[6] improved reliability of a remote control system using the so-called event based control algorithm. The mobile robot halts when the time-delay is larger than the pre-set time interval and the mobile robot is closer than the pre-set distance to the nearest obstacle simultaneously in the event based control algorithm. Ohba[7] investigated internet-based MOMR (Multi Operator Multi Robot) with time-delay. Virtual thickness modification algorithm is proposed to avoid collision due to time-delay between cooperating robots. However, most of the researches on the time-delay deal with relatively large time-delay from the view point of sampling time of the system.

Nowadays, development of hardware technology related to internet is very rapid. Therefore, the time-delay becomes shorter and shorter. Furthermore, operating speed of mobile robot becomes faster due to the rapid development of H/W and S/W technologies of mobile robot. Therefore, diverse investigations on the time-delay are becoming necessary.

The time-delay is classified micro and macro time-delays and the error due to time-delay is also classified path-error and time-error in this paper. Algorithms compensating path and time errors under micro and macro time-delays are devised using fuzzy logic. Simulated examples verifies the validity of the proposed algorithms.

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2. Classification of Time-delays of Internet-based Mobile Robot

2.1 An Internet-based Mobile Robot System

Figure 1 shows a typical internet-based mobile robot system.

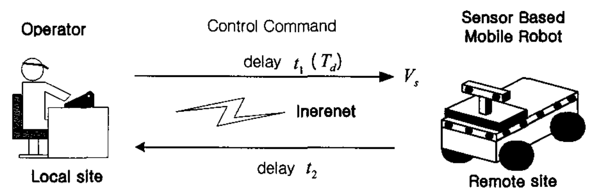

Fig. 1 A typical internet-based mobile robot system

An operator at local site sends control command to the mobile robot at remote site through internet. The mobile robot sends its position information back to the operator through internet. Time-delay between local and remote sites, however, is a serious problem of internet-based mobile robot systems.

An internet time server can be used as a reference to compensate time-delay by synchronizing the local and remote sites. Equation (1) represents the amount of time-delay.

$$T_d = T_m - T_c \tag{1}$$

where T_c, T_m, and T_d represent the time at which the control command is sent to the remote site from the local site, the time at which the remote site received the control command from the local site, and the amount of time-delay, respectively.

It is assumed that

① *the control command is sent to the remote site* at the constant time interval T_s, referred to the sampling time in this paper, from the local site,

② the control command consists only of the next direction of the mobile robot.

2.2 Classification of Time-delay

Time-delay is classified as micro time-delay and macro time-delay in this paper as shown in the figure 2.

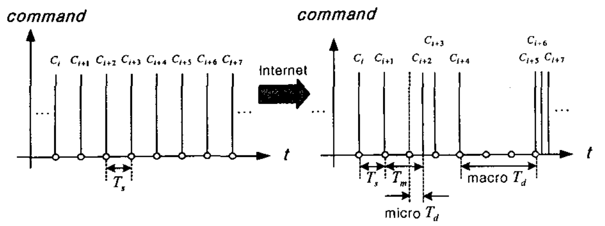

Fig. 2 Micro and macro time-delay

The micro time-delay represents the case of the shorter amount of time-delay T_d than the sampling time T_s. It means that the control command is received before the second sampling time even though it was not received at the first sampling time. However, the macro time-delay represents that the control command is not received after the second sampling time.

If the speed of the mobile robot is low, the distance traveled during the micro time-delay will be very short. Therefore, the robot may not deviate so much from the desired path. However, in the case of high speed, the deviation may be very large. Compensation for the micro time-delay becomes important since the speed of mobile robots goes fast due to the rapid development of hardwares.

Error due to micro or macro time-delay is classified path-error and time-error in this paper. Figure 2 shows typical pictorical representations of path and time-errors.

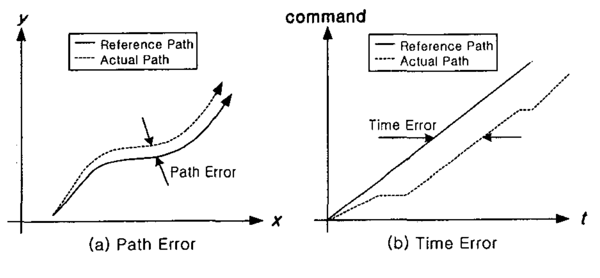

Fig. 3 Definitions of path-error and time-error

3. Proposed Compensation Algorithm for Time-Delay

3.1 Conceptual Description of the Compensation Algorithm

Figure 4 shows the conceptual description of the proposed compensation algorithm.

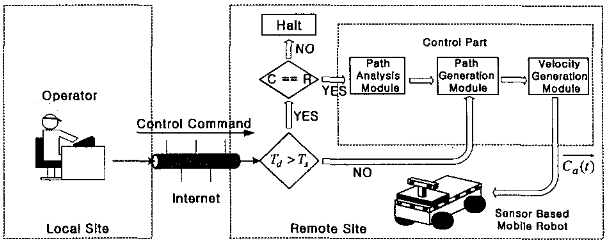

Fig. 4 Conceptual description of the proposed compensation algorithm (C==R means the mobile robot received the delayed control command)

An operator at the local site sends the control command to the mobile robot at the remote site through internet. If the amount of delayed time T_d is greater than the sampling time T_s, i.e., if the macro time-delay is occurred, the mobile robot halts its motion until it receives the control command. After receiving the delayed, i.e., macro time-delay, control command, the path analysis module produces a new control command according to the amount of delayed time. This new control command is now input of the path generation module. The path generation module yields the final control command which compensates the path-error due to the time-delay. The final control command goes to the velocity generation module. It gives a new velocity command to reduce the time-error due to the time-delay. In the case of micro time-delay, the received control command enters directly to the path generation module.

3.2 Implementation of the Proposed Compensation Algorithm Using Fuzzy Logic

Figure 5 represents the assumed mechanism for the occurrence of path-error due to time-delay.

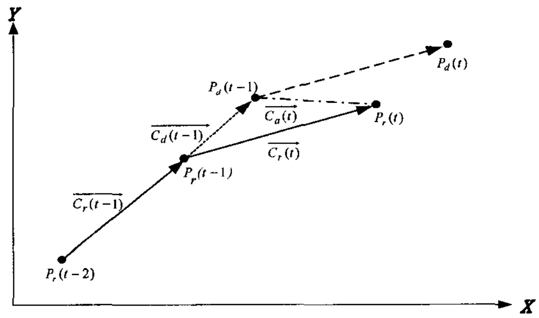

Fig. 5 Mechanism for the occurrence of path-error due to time-delay

$P_r(t-2)$ is the point where the mobile robot received the current control command. $P_r(t-1)$ represents the point where the next control command supposed to be received. $P_d(t-1)$ is the point where the mobile robot received the next control command actually due to time-delay. $P_r(t)$ shows the point where the mobile must arrive when there is no time-delay and it can be calculated. $P_d(t)$ represents the point where the mobile robot will arrive due to time-delay when there is no compensation for time-delay.

Now, the simplest algorithm to compensate the path-error due to time-delay may be to control the mobile robot to move along the path $C_a(t)$. It causes, however, abrupt turning motion at the point $P_d(t-1)$ and it could be dangerous to the mobile robot. Therefore, a smooth compensated path is more desirable than such a abrupt turning motion.

The compensation algorithm for path-error proposed in this paper yields a smooth compensated path as shown in figure 6.

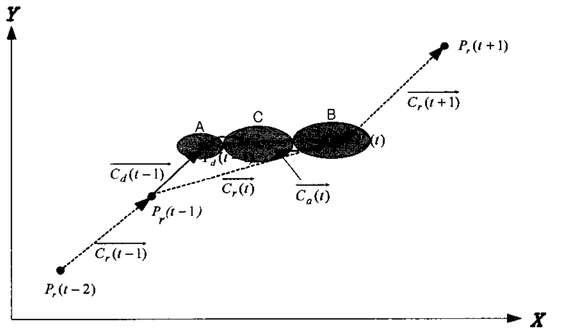

Fig. 6 Proposed path for compensation of path-error

The basic idea is to move the mobile robot nearly tangent to $\overrightarrow{C_d(t-1)}$ at the beginning of the region A and nearly tangent to $\overrightarrow{C_r(t)}$ at the end of region B. Region C is the smooth connection between A and B regions.

3.2.1 Generation of a compensated path at region A

Cubic spline interpolation is used to produce a path at the region A, i.e., $P_A(t)$, in this paper as shown in figure 7.

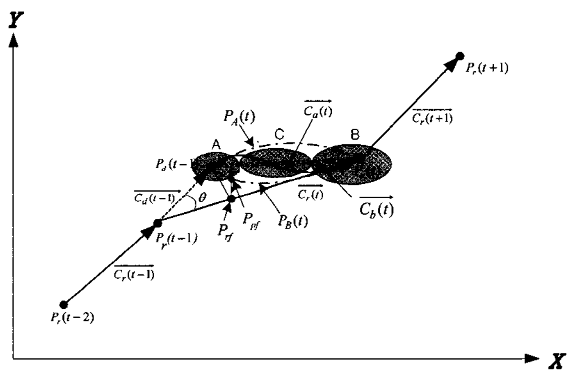

Fig. 7 Cubic spline interpolation for path generation at regions A and B

Points $P_r(t-1)$, $P_d(t-1)$, and $P_r(t)$ are used for cubic spline interpolation. More weight is given at the point beginning of $P_A(t)$ in order to produce a path nearly tangent to $\overrightarrow{C_d(t-1)}$.

3.2.2 Generation of a compensated path at region B

The compensated path at the region B is obtained from $P_B(t)$ by giving more weight at the end of $P_B(t)$. The path $P_B(t)$ is produced by using cubic spline interpolation from $P_d(t-1)$, $P_r(t)$, and a point P_{bf} between these two points. As shown in the figure 7, P_{bf} is calculated from P_{rf}. Choice of the point P_{rf} plays an important role to the path-error. It is, however, not so easy to determine the point in closed form since there are many factors to be considered. Fuzzy logic is used to determine P_{rf} in this paper since the fuzzy logic is relevant to implement the expert knowledge of human being. The generic form of the fuzzy rule is as follow

Rule I : If Dist is Ai and Angle is Bi
Then P_{rf} is Ci, i=1,...,n

and the full set of fuzzy rules is shown in the Table 1.

Table 1 Fuzzy rules determining P_{rf}

Dist \ Angle	NB	NS	ZR	PS	PB
ZR	ZR	P1	ZR	P1	ZR
P1	P1	P3	P2	P3	P1
P2	P2	P4	P3	P4	P2
P3	P3	P5	P4	P5	P3
P4	P3	P6	P5	P6	P3

The term sets for the linguistic variables "Dist", "Angle", and "P_{rf}" are {ZR, P1, P2, P3, P4}, {NB, NS, ZR, PS, PB}, and {ZR, P1, P2, P3, P4, P5, P6}, respectively. The corresponding membership functions are shown in figures 8, 9, and 10.

The lingustic variables "Dist" and "Angle" in the premise part represent "traveled distance during the time-delay" and "deviation angle θ" as shown the figure 7. The membership

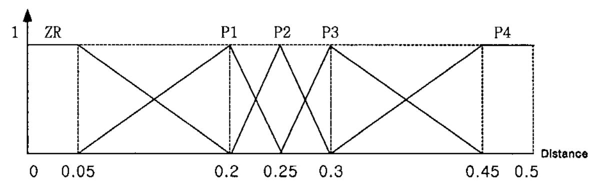

Fig. 8 Membership functions for term set of the linguistic variable "Dist"

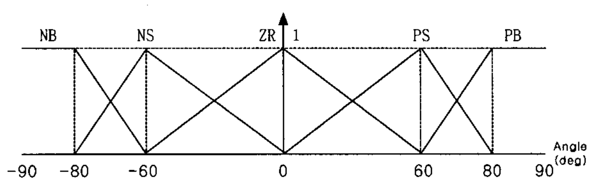

Fig. 9 Membership functions for term set of the linguistic variable "Angle"

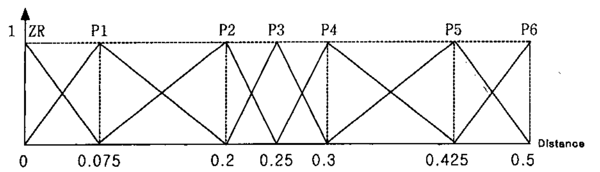

Fig. 10 Membership functions for term set of the linguistic variable " P_{rf}"

functions are determined heuristically. It should be noted that the discourse of universe of lingustic variables "Dist" and " P_{rf}" is possible maximum travelled distance during one sampling time T_s.

Now, P_{bf} is obtained from P_{rf} by choosing middle point of the line segment which is drawn from P_{rf} to $\overrightarrow{C_b(t)}$ perpendicularly. Cubic spline interpolation using $P_d(t-1)$, P_{bf}, and $P_r(t)$ gives a compensated path in the region B.

3.2.3 Generation of a compensated path at region C

Compensated path $C_a(t)$ at the region C is determined by interpolating $P_A(t)$ and $P_B(t)$ using fuzzy logic which is designed deliberately to yield smooth path. y-axis component of $C_a(t)$ is defined as follows:

$$C_{a_y}(t) = P_{B_y}(t) + (P_{A_y}(t) - P_{B_y}(t)) \cdot \alpha \tag{2}$$

where subscript y represents y-axis component corresponding to the equally spaced x-axis values between $P_d(t-1)$ and $P_r(t)$ and where α is obtained from the following fuzzy rules.

Rule 1: If X is Start, Then α is 1

Rule 2: If X is End, Then α is 0

Figure 11 shows the membership functions "Start" and "End".

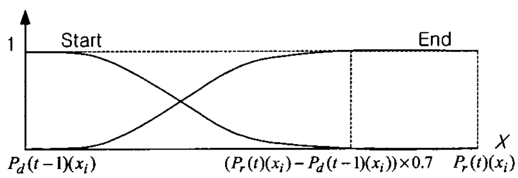

Fig. 11 Membership functions for "Start" and "End"

3.2.4 Compensation Algorithm for Time-error

As mentioned before, not only path-error but time-error also occurs due to time-delay. The time-error is reduced by varying the speed of the mobile robot on the basis of the compensated path in this paper.

As shown in the figure 12, the mobile robot decelerates when the time-delay is occurred and accelerates from the point $P_d(t-1)$.

Figure 13 shows velocity profiles for time-error compensation. Solid lines represent the cases of constant acceleration which is a direct implementation of the idea in the figure 12.

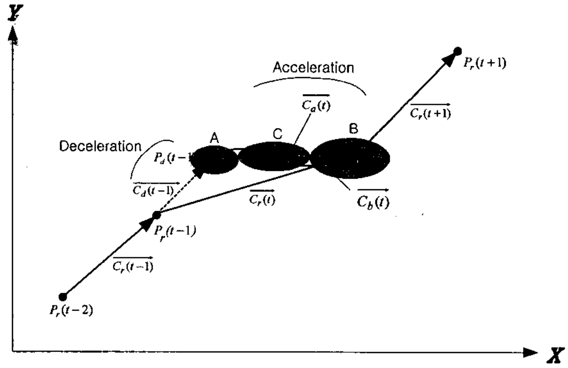

Fig. 12 Representation of deceleration and acceleration regions for time-error compensation

. $V_{\max}$ and $V_{\min}$ mean the predefined maximum and minimum velocities of the mobile robot. $V_{\max_i}$ and $V_{\min_i}$ are actual maximum and minimum velocities of mobile robot during compensated motion.

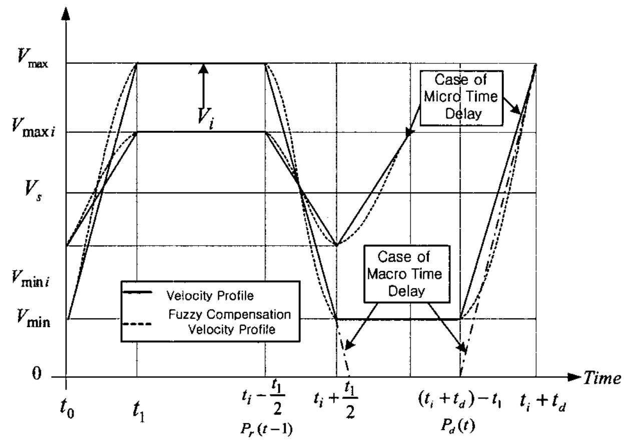

Fig. 13 Velocity profiles during time-error compensation

The solid lines in the figure 13 show abrupt change of velocity. It means rapid acceleration and deceleration of mobile robot. Proper fuzzy rules are designed in this paper to reduce rapid acceleration and deceleration. The corresponding velocity profile is represented as dotted lines in the figure 13. Equation (3) is proposed as a compensation algorithm to reduce time-error.

$$newV_i = V_{\min i} + (V_{\max i} - V_{\min i}) \cdot \beta \tag{3}$$

where $newV_i$ is the compensated velocity command and β is determined from the following fuzzy rules.

Rule 1 : If Time is Short, Then β is 0

Rule 2 : If Time is Long, Then β is 1

Figure 14 represents membership functions for "Short" and "Long".

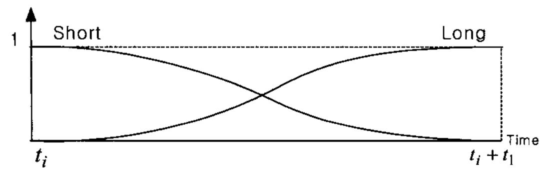

Fig. 14 Membership functions for "Short" and "Long"

4. Simulations

4.1 Parameters for Simulation

The validity of the proposed algorithm is verified through simulations in this section. The sampling time T_s is set to 0.5 second. Therefore, T_d which is less /greater than is treated as the micro/macro time-delay. It is assumed that the speed of the mobile robot during the normal operation is 1m/sec.

Table 2 shows the time table used for simulation. As shown in the Table 2, micro and macro time-delays are mixed on purpose.

Table 2. Time table used for simulation

#	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
T_c	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
T_m	0.0	0.67	1.30	1.75	2.20	2.83	3.26	3.90	5.37	5.37	5.37	5.77	6.37	6.89	7.0
T_d	0.0	0.17	0.30	0.25	0.20	0.33	0.26	0.40	1.37	0.87	0.37	0.27	0.37	0.39	0.0

4.2 Simulation results without compensation for time-delay

Figure 15 shows the simulation results when the proposed compensation algorithm is not used.

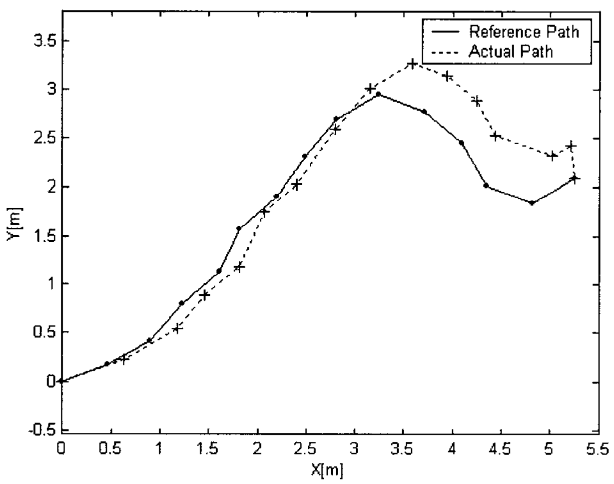

Fig. 15 Simulation results without compensation

As can be seen in the figure 15, there is large deviation between the reference path and actual path. If the speed of the mobile robot is increased, the result will be more serious and even dangerous for some applications.

4.3 Simulation results with compensation for time-delay

Figure 16 represents the simulation results when the proposed path-error and time-error compensation algorithms using fuzzy logic are used.

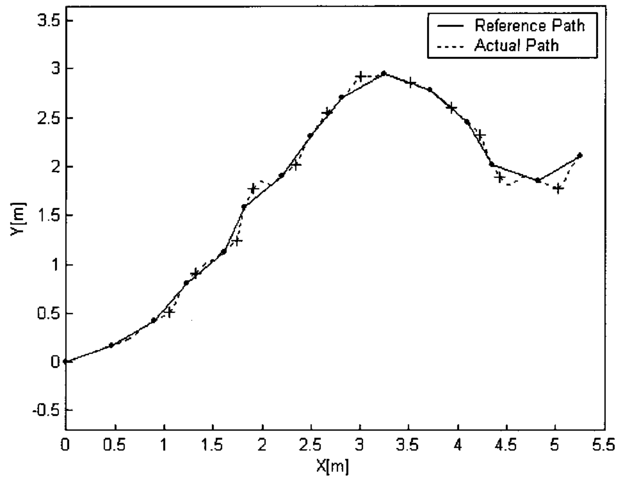

Fig. 16 Simulation results with compensation

Figure 16 shows that the path-error is greatly reduced. Furthermore, the actual path is very smooth, i.e., there is no abrupt motion as expected. It is also found that the compensated path is tangential to the reference path when crossing is occurred. It verifies that the proposed fuzzy rules work well.

Figure 17 represents velocity profiles obtained as a result of compensation action.

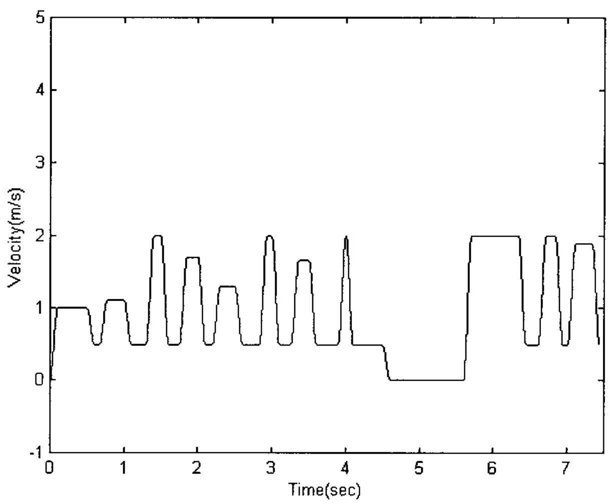

Fig. 17 Velocity profiles obtained after simulation

It can be seen easily that acceleration and deceleration are occurred as a compensation action for time-error. It can also be found that the velocity profile is somewhat smooth. It is the evidence of the validity of fuzzy rules. The smooth velocity profile reduces rapid acceleration and deceleration.

Quantitative comparison is performed for the above simulation results. As a performance index for path-error, area between the reference path and actual path is used. Traveling time from the starting point to the destination is used as a performance index for time-error. Table 3 shows the results.

Table 3. Comparison of performance index

	Without Compensation	With Compensation
Path-error	1.1056 m^2	0.3218 m^2
Time-error	1.7015 sec	0.4400 sec

As can be seen in the Table 3, path-error and time-error are reduced greatly. This simulation results verify the validity of the proposed algorithm.

5. Concluding Remarks

This paper proposes a compensation algorithm for time-delay of internet-based mobile robot. The time delay is further classified as micro time-delay and macro time-delay in this paper in order to reflect rapid development of internet and hardware technologies.

Basically, the path-error is compensated using cubic spline interpolation and fuzzy logic is used deliberately in order to prevent abrupt turning motion.

Time-error is compensated by decelerating and accelerating the mobile robot properly. Fuzzy logic is also played important role in reducing rapid acceleration and deceleration of the mobile robot.

Simulated results verify the validity of the proposed compensation algorithm for time-delay.

References

[1] K. Goldberg, M. Maschna, S. Gentner, et al., "Desktop teleoperation via the www," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 654-659, Japan 1995.

[2] http://telegarden.aec.at

[3] K. Taylor and B. Dalton, "Internet Robotics : A New Robotics Niche," IEEE Robotics and Automation Magazine, Vol. 7, No. 1, pp. pp. 27-34, March 2000

[4] Riko Safaric, Karel Jezernik, D. W. Calkin, R. M. Parkin, "Telerobot Control via Internet," Proceedings of the IEEE International Symposium on Industrial Electronics, Vol. 1, pp. 298-303, July 1999,

[5] D. Schulz, W. Burgard, Dieter Fox, S. Thrun, and A. Cremers, "Web interfaces for Mobile Robots in public places," IEEE Robotics and Automation Magazine, Vol. 7, No. 1, pp. 48-56, March 2000

[6] Imad Elhajj and Ning Xi, Yun-hui Liu, "Real-Time Control of Internet Based Teleoperation with Force Reflection," Proceedings of the 2000 IEEE International Conference on Robotics and Automation San Francisco. CA, pp. 3284-3289, April 2000

[7] K. Ohba, S. Kawabata, N. Y. Chong, K. Komoriya, T. Matsumaru, N. Matsuhira, K. Takase, and Tanie, "Remote Collabroation through Time Delay in Multiple Teleoperation," Proceedings of the 1999 IEEE/RSJ International Conference on Intelligent Robotics and Systems, Vol. 3, pp. 1866-1871, October 1999

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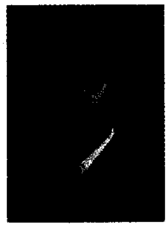

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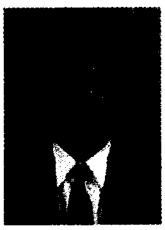

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