Perception of motion-lag compared with actual phase-lag for a powered wheelchair system

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***Abstract* — As analogue powered wheelchair systems are digitized and sensors and other systems are added then a lag can be introduced into the control of the wheelchair. This paper discusses phase lag in a powered wheelchair system and when a wheelchair driver might begin to perceive a lag in the motion of the wheelchair. The reduction of any time lag is important for driving performance and ability. The threshold of allowable time lag for a wheelchair driver has not been explored and this work investigated the minimum time lag before a wheelchair driver perceived a lag.**

I. INTRODUCTION

Performance is important when driving a powered wheelchair. Time lag between the input (usually a joystick) and desired output (usually motor control) is one of the factors influencing driving performance. If the driver is able to perceive a time lag then their driving performance is affected. A threshold value of perceived time lag exists t_{minlag}, after which a user realizes that a lag exists. Perception may also depend on phase lag as well as time lag because as an input frequency increases, system phase lag may increase. So, a driver may perceive a motion lag even if the system only has arelatively small time lag. In this research, the threshold value of the time lag is t_{minlag}, the "perceived lag time". The threshold value of the phase lag is ϕ_{minlag} "perceived lag phase". Time lag in a driving system has been studied by Chang [1], Kawamura [2] and Sanders [3]. But, perceived lag time has only rarely been considered, an exception being Toyoda *et al* [4] who considered motion lag in a tele-operated robot system. It has never been considered for a powered wheelchair. In addition, little attention has been given to the perceived effect of phase lag [4].

II. THE POWERED WHEELCHAIR SYSTEM

The apparatus consisted of a dedicated controller with analogue interfacing, DC servo-amplifiers and joystick, and a BobCat II powered wheelchair modified to include extra control and sensor systems. Two driven wheels were at the front and two trailing castors at the back. Ultrasonic sensor pairs were mounted over each driving wheel. Altering the differential of rotational speed of the driving wheels affected steering and direction of movement.

Sonar sensors have been widely used for powered-wheelchairs and mobile powered wheelchairs [5],[6] and ultrasonic ranging was selected, as it was simple, cost effective and robust. Ultrasonic transmitter and receiver pairs were mounted at the front of the powered-wheelchair. With suitable processing the ultrasonic signals were converted to a simple representation of the environment ahead of the wheelchair. An integral function was used with the joystick signals so that the tendency to turn when approaching an object could be over-ruled by the user, for example to reach a light switch on a wall.

Software algorithms to intelligently mix the inputs to the powered wheelchair (joystick and sensors) were described in [7]–[11] and the wheelchair was driven under computer control by "fly-by-wire". The direct link between the powered wheelchair and joystick was severed and a computer processed control information. Sensors were activated and interrogated by the computer and the computer was programmed to modify the powered-wheelchair path. Alternatively, joystick control data could be processed and sent to the wheelchair controller without modification. In this case the powered-wheelchair responded to joystick inputs as if it was an unmodified wheelchair system. Software systems were constructed using methods discussed in [12]-[14]. Systems had three main levels: supervisory, strategic and servo control. These were similar to the levels and sensor systems described or used in [15]-[17].

Algorithms applied the following rules: (1). User remained in overall control. (2) Systems only modified the trajectory of the powered-wheelchair when necessary. (3) Movements of the wheelchair were smooth and controlled.

III. EXPERIMENTS

A. Description

In this research, experiments were performed in using a dead-time simulator able to make arbitrary time lags [18][19]. Users performed driving experiments and the effect of motion lag was evaluated in the driving experiments to reveal the threshold value of the time lag, t_{minlag}. The magnitude estimation method [20] was used. Furthermore, a phase lag was obtained for each perceived time lag when the input frequency was switched. Perceived phase lag was obtained from the time lag value. The finally evaluated value was the perceived phase lag related to each input frequency.

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B. *Dead-time simulator*

The powered wheelchair system was modeled as a dead-time system [4] because the system gain was 1 at any frequency so that wheelchair motion response was confined to being affected by the time lag. So the motion lag indicated dead-time. A dead-time simulator created a virtual time lag and delayed the commands to the powered wheelchair. Random inputs were generated to test the operation of the simulator using:

$$G_S(s) = \exp(-\Lambda s) \tag{1}$$

C. *Magnitude estimation*

The magnitude estimation method [4] was used to provide a quantitative evaluation of the effect of motion lag and perceived lag time was delivered by this evaluation. The magnitude estimation method revealed the effect due to various stimulations. The method was stable for quantitative evaluation of psychological reaction such as the effect of motion lag. The magnitude estimation method was one of the sensory assessments used in ergonomics [4][21]. S.S.Stevens [21] showed that a human psychological value ψ related with certain magnitude of physical stimulus I had the relationship:

$$\Psi = kI^{n} \tag{2}$$

Where:

ψ: psychological value
I: magnitude of physical stimulus
k: gain
n: power index

Equation (2) is Stevens' power law [4]. In the work described in this paper, the stimulation physical value is time lag. The psychological value ψ was evaluated from relating driving motion lag and the effect of the motion lag.

D. Method

The method was similar to that used by Toyoda *et al* [4] with a tele-operated surgical robot used for coronary artery bypasses.

1. The simulator was set to operate at 0.1 Hz.

2. A metronome made a sound at 0.1 Hz rhythm and the sound and simulator were synchronized.

3. The dead-time was varied across 10 levels in a random order as shown below in table1.

4. The magnitude of time lag effect was recorded based on the magnitude estimation method.

TABLE I

Level	1	2	3	4	5
Dead time (mS)	1	2	3	4	5
Level	6	7	8	9	10
Dead time (mS)	7	10	14	19	25

Test subjects driving the wheelchair were eight men and women in their early 20's.

E. *Results*

Perceived lag time for 0.1 Hz input frequency was transformed to a common logarithm and showed a linear curve. A linear curve indicated the response after an operator perceived a time lag. An approximate line was drawn to estimate the relationship. This result indicates that the perceived lag time is 80ms when input frequency is 0.1Hz. Equation (3) shows the relation between dead-time more than 80ms and magnitude of time lag affection.

$$\Psi = 25 * I^{0.35} \tag{3}$$

When dead-time was less than 80ms, a driver did not perceive any motion lag. The perceived lag time was obtained when input frequency varied from 0.1 Hz to 1Hz and Stevens' power law was calculated for those input frequencies. The relation between the dead-time, magnitude of time lag effect and the approximate power function after a driver perceived the motion lag were considered.

For example, phase lag was considered once a driver had perceived a motion lag. The phase difference of the dead-time system is shown by (4).

$$\angle G(j\omega) = -\omega\Lambda \tag{4}$$

So, the phase lag was determined by ω which was the input angular frequency when operator perceived the motion lag and Λ which was the perceived lag time.

Perceived lag time, perceived lag phase and power index are shown in table II.

TABLE II

Input frequency (Hz)	Perceived lag time (ms)	Perceived lag phase (deg)	Power index
0.1	80	-6	0.35
0.2	70	-7	.4
0.5	50	-9	.41
1	25	-8	.35

IV. DISCUSSION

Perceived lag time was obtained by the quantitative evaluation of the effect of motion lag using a magnitude estimation method. Table I shows that perceived lag time differs for each input frequency; if input frequency increases then perceived lag time decreases.

This result coincides with sensory prediction which is that during slow movements it is difficult for an operator to perceive any motion lag [4].

After a driver perceived a motion lag, that is when dead-time was greater than t_{minlag}, the magnitude of the effect of the time lag changed. The power index after the perception was an average of 0.36 which had no relation to input frequency. From this result, it was concluded that perceived lag time differs between each input frequency but after perception the magnitude of the time lag effect has no relation to input frequency.

Because the power index was less than 1, the effect of motion lag becomes insensitive as motion lag increased.

Considering perceived phase lag, when phase lag was less than -7 deg, a driver perceived the motion lag. As perceived lag time became larger perceived lag phase remained small. The difference for perceived phase lag is smaller than the perceived lag time. These results relate to the phase lag of the dead-time system (4). A driver had a threshold of phase lag in perception and then perceived lag time could be obtained in inverse proportion to the input frequency.

The threshold of motion lag perception was related to the system's phase lag. Therefore if a powered wheelchair driver does not perceive motion lag, it is important that the control system is designed so that the system's phase lag is less than the perceived lag phase. In this research, the perceived phase obtained was about -7 deg.

V. CONCLUSION

The relation between motion lag and the magnitude of a time lag effect has been investigated and described and the perceived time was was obtained. Perceived time lag determined perceived phase lag.

A perceived threshold value of the time lag, t_{minlag}, the "perceived lag time" appears to exist and was estimated. After a driver began to perceive the motion lag, the magnitude of the time lag effect increases in relation to Stevens' power law. In this research, the Stevens' power index was an average of 0.36.

Perceived lag time was different for each input frequency and perceived time lag became smaller as input frequency increased. Regardless of input frequency, a driver tended to begin to perceive the motion lag if the phase lag became less than -7 deg.

Variation of perceived phase lag was smaller than that of time. When phase lag exceeded perceived phase lag then a driver began to perceive the motion lag in driving.

Reliability of perceived phase lag depended on t_{minlag}. To improve the reliability of the results, more drivers need to be tested with the powered wheelchair system.

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