Anticipation as a Method for Overcoming Time Delay in Control of Remote Systems

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In this paper an original model is presented for human compensation for time delays when controlling remote vehicles. It is based upon a series of human experiments involving subjects driving a small rover with a joystick and video display system while under the effects of round-trip time delays ranging from 0 to 2.5 seconds. It is demonstrated that human behavior can be successfully replicated across a range of delays by a control system which relies on anticipating future control needs based solely upon information provided by the time-delayed video feed. A statistical analysis of the results of the human study are presented as well as a comparison of experimental and simulated trajectories and an analysis of controller performance.

I. Introduction

The problem of time delay compensation is of concern to both military and civilian systems. Delays can be introduced into the feedback loop either because of communication lag caused by the remote distance of exploratory vehicles, or by the extensive processing requirements required for complex terrestrial applications. For example: while the recent robotic exploration of Mars has been a dramatic success, it has also illustrated a number of problems inherent in the current paradigm. The rovers currently employed depend on detailed supervisory control from ground stations,[1] with one consequence being that the rate of exploration remains low. One approach has been to increase the automation onboard the vehicles.[2] Unfortunately doing so requires dramatic increases in local processing power and associated resource costs. Indeed, even were fully autonomous robots to be widely used for exploration, it is likely that there would remain tasks which were either sufficiently complex or sensitive as to require human control. However, in order to use direct control for remote vehicles, systems must be constructed so as to mitigate the inherent instabilities that are present due to time delay in communication. Accurate models of human adaptation and behavior when presented with time delays are essential in the design process for such systems. By determining what information humans use in compensating for time delay it will be possible to design systems which more effectively display useful data.

Figure 1. Pioneer 3-DX rover with custom camera mounting. The luminescent circles are retro-reflectors used for motion capture. The sonar panels on either end of the rover were not used during this study.

Although both the problem of time delay in human control of remote systems and the modeling of human drivers have been studied extensively over the past 60 years, most such work has either been concerned with the control of remote manipulators[3456] or with human driver models that only incorporate the short delays due to reaction time.[7]

Those that have studied remote control of vehicles in the context of adapting to time delay[8910] have typically allowed the human operator complete control over vehicle velocity and have found that when allowed to do so humans

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use a ”‘move and wait”’ strategy that combines open-loop maneuvers with pauses of at least the time delay in order to update position information. In such a context human models have focused primarily on predicting the time required to complete a task given a fixed time delay. This limits the applicability of such systems to situations in which intermittent control is necessary.

In contrast, the approach presented in this paper is to demonstrate that when operating in a continuously closed-loop manner; human operators rely upon the anticipation of future control requirements in order to overcome the challenges due to system time delays.

In order to accomplish these goals a series of experiments was conducted in which human subjects guided a remote ground vehicle around a fixed course while varying levels of time delay were imposed upon the system. The resulting input-output data was then used to extract control gains for two computer controllers which were able to mimic the human response to varying degrees. The time delays used were in the range of zero to 2.5 seconds, which is on the order of those experienced by remote systems on the moon or in the deep ocean when relying on acoustic communications.[5]

II. Experimental Setup

A. Hardware

A Mobile Robots Pioneer 3-DX differential drive rover mounted with a custom micro-ITX computer and an angled video camera was used as the experimental platform for this study, as shown in Fig. 1. Although the rover is differential drive, the onboard micro-controller automatically converts between translation/rotational velocity and the necessary wheel velocities. The rover was controlled wirelessly by means of a joystick outputting velocity commands. In order to enforce a continuous closed-loop response by the human subjects, we programmed the vehicle to move at a constant translational velocity of $0.2\,m/s$. The subjects were thus only able to control the desired angular velocity, which was limited to $\pm 0.5\,rad/s$. These speeds were chosen to allow an operator to follow the route with relative ease when no delay was introduced into the system. Naturally the ability for subjects to adapt to time delays would depend on the rate of travel, however an examination of the relationship between translational velocity and delay compensation is outside the scope of this study.

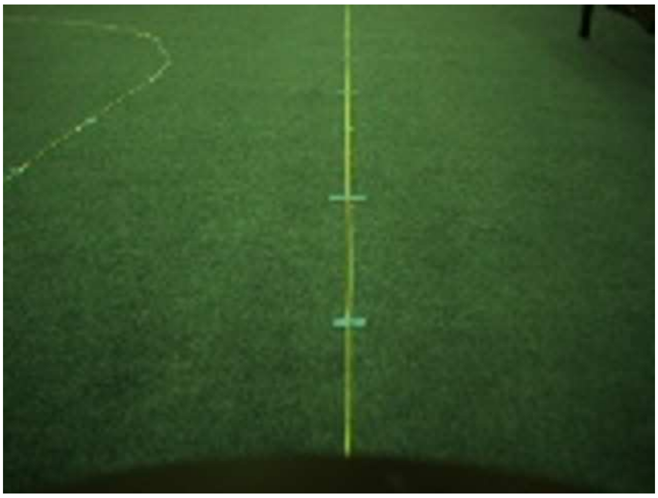


Figure 2. Example of a camera image seen by subject at the beginning of a lap. The yellow line is the reference route the subject has been instructed to follow. The models presented in this paper assume that subjects ignore later sections of the route that may come into view as seen in the upper left.

The rover-mounted camera records video at a resolution of 640x480 pixels and broadcasts a series of compressed 160x120 pixel jpeg images (see Fig. 2) at a rate of ∼20Hz to a video monitor placed so that the subject could not directly observe the workspace in which the rover operated. This reduction in quality was necessary due to processing and bandwidth limitations, but should have had no effect on subject performance.[11] The camera has a 50° field of view and can see objects lying between 0.4m and 1.4m from the rover’s kinematic center.

In order to track the location and orientation of the rover the workspace was outfitted with a 24 camera near-IR motion capture system produced by Vicon, inc which operates at 100Hz. This system is able to localize the position of spherical retro-reflectors mounted on the rover to within 1mm, allowing the system to calculate the rover pose at each instant in time. This system also allowed us to record the exact location of the reference route which had been laid out on the ground with cord.

A pair of symmetric time delays were introduced into the system: one between the joystick and the rover and another between the camera and the monitor. These delays were enforced by means of time-syncing the two systems and maintaining an image and control buffer. The round trip delay was allowed to range between 0 and 2.5 seconds, which was the maximum delay at which the rover could be driven safely given the space constraints on the experiment. For the remainder of this paper all time delays discussed are stated in terms of the round trip delay imposed by our software. It is assumed that any additional delays due to

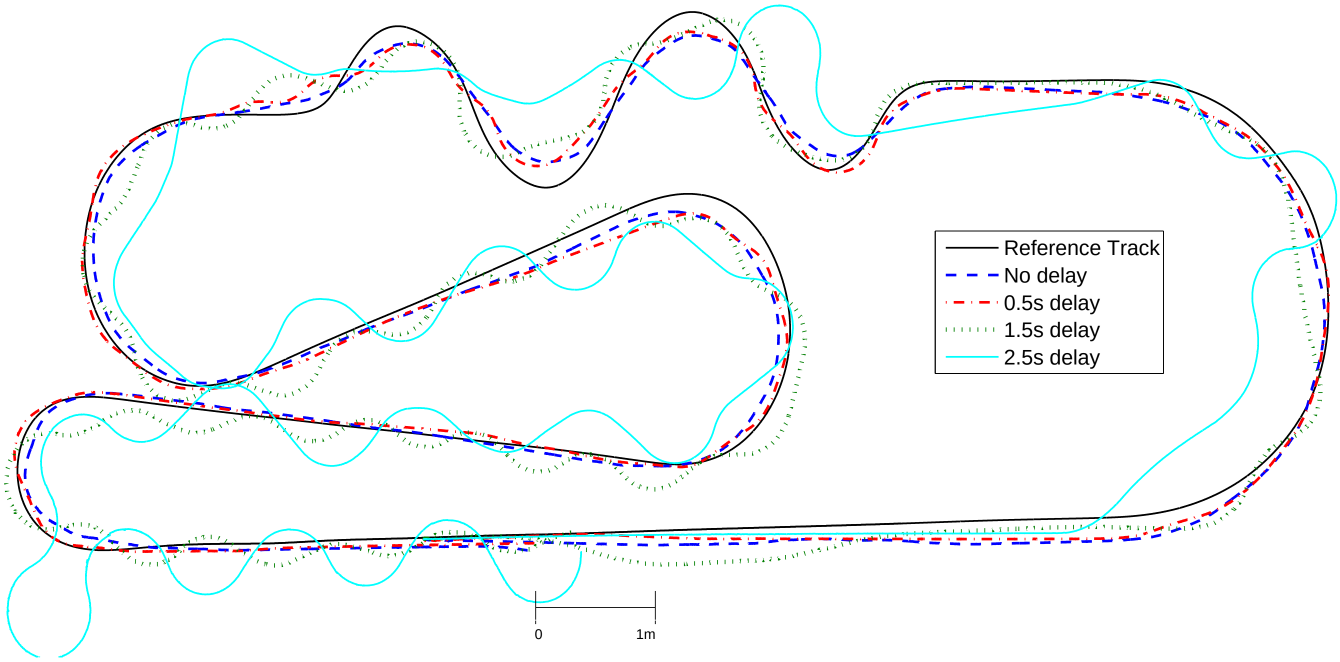


Figure 3. Experimental rover trajectories for 4 laps at differing time delays as compared to the reference route. Note the increasing instability at 1.5 and 2.5s

human reaction time are sufficiently small as to have negligible effect.

B. Research Subjects

20 volunteer research subjects between the ages of 20 and 40 were recruited for these experiments. The subjects consisted primarily, but not entirely, of students in the Department of Mechanical and Aerospace Engineering at Cornell. The gender breakdown was 7 women and 13 men. Each subject was run through the experiment individually over the time-span of approximately 2 hours.

C. Route Layout

As seen in Fig. 3, the route consisted of five sets of curves connected with straight segments. The inclusion of the straight segments was intended to assist the subject in returning to the route between sections. For the purpose of this analysis these five sections were as follows:

1. The initial large semicircle
2. The switchback
3. The first medium semicircle
4. The second medium semicircle in the opposite direction
5. The ending small semicircle

D. Experimental Process

Each subject was first asked to drive a single lap at no time delay in order to familiarize themselves with the control system. They were then directed to conduct three laps at time delays ranging from 0 to 2.5 seconds in half-second intervals, pausing between each lap to allow the system to be reset. The objective given to each subject was to attempt to keep the vehicle center as close to the reference route as possible. Subjects were informed of the current time delay and the same sequence of increasing delays was used for each subject.

At every time step the following data was recorded:

1. The 2D position of the vehicle kinematic center with regards to the fixed coordinate system of the workspace.
2. The vehicle heading expressed as a direction-cosine matrix with regards to the fixed coordinate system.
3. The control action of the human operator expressed as a desired angular velocity.

Given this complete history of vehicle pose and the known geometry of our system it was also possible to determine what portions of the reference route were visible to the camera at every time step of the experiment.

III. Human Performance

An example of the paths taken by one subject for four different time delays is shown in Fig. 3. The degradation of tracking performance with increased time delay is characteristic of all of the subjects. Over the course of this study it was noted that the primary cause of performance loss was due to the over-correction of small errors, with larger deviations occurring due to subject disorientation if these over-corrections caused the camera to lose sight of the route for more than brief periods of time.

For the following analysis performance was measured by finding the root mean square (RMS) off-track error over each segment, determined from the Euclidean distance between the rover position and the nearest point on the reference route in the same section at every time step. The effect on tracking error of time delay, route section, and which lap the subject was on are shown via the results of a 6 (Time Delay) x 5 (Route Section) x 3 (Lap Number) ANOVA test in table 1. As expected the effect of time delay meets the criterion for statistical significance ($p < 0.05$). Likewise the effect of which route section a subject was on had a significant effect on performance, indicating that different maneuvers had significantly different difficulties. The effect of lap number on RMS error is seen to not be statistically significant, which suggests that there is little to no short term learning demonstrated between laps at the same time delay. Consequently, for the rest of this analysis the results of different laps within the same time delay will be considered independent measurements. However, it is possible that there are learning effects across the full duration of the experiment that are being masked by the more dominant effect of increasing time delay on performance. Finally, the ANOVA results show that there are no higher order interactions between variables, indicating that the relative difficulty of route sections was independent of time delay.

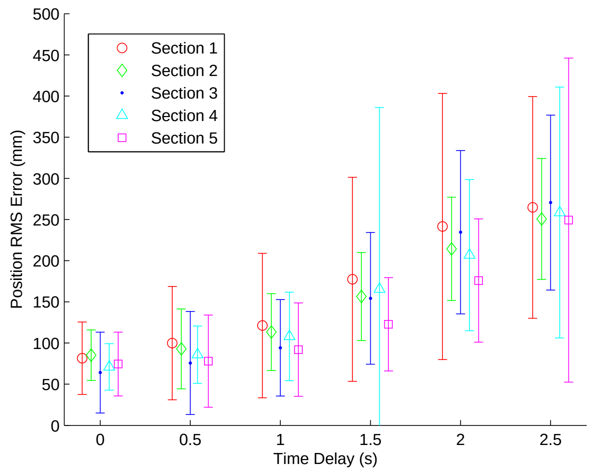


Figure 4. Human performance as a function of time delay and route section. Performance was measured by finding the RMS off-track error over each segment at each time delay.

Table 1. Results of the 6 x 5 x 3 ANOVA test for the effects of time delay, route section, and lap number on human RMS tracking error.

Independent Variable	F	p
Time Delay	$F(5,1518) = 237.66$	$p < 0.001$
Route Section	$F(4,1518) = 8.9$	$p < 0.001$
Lap Number	$F(2,1518) = 1.2$	$p > 0.30$
Time Delay + Route section	$F(20,1518) = 1.18$	$p > 0.26$
Time Delay + Lap Number	$F(10,1518) = 0.94$	$p > 0.49$
Route Section + Lap Number	$F(8,1518) = 0.46$	$p > 0.88$

The means and standard deviations for RMS error across subjects are shown in Fig. 4, sorted by time delay and route section. It is worth noting that while subject reported that section 1 was the easiest part of the route, it had the

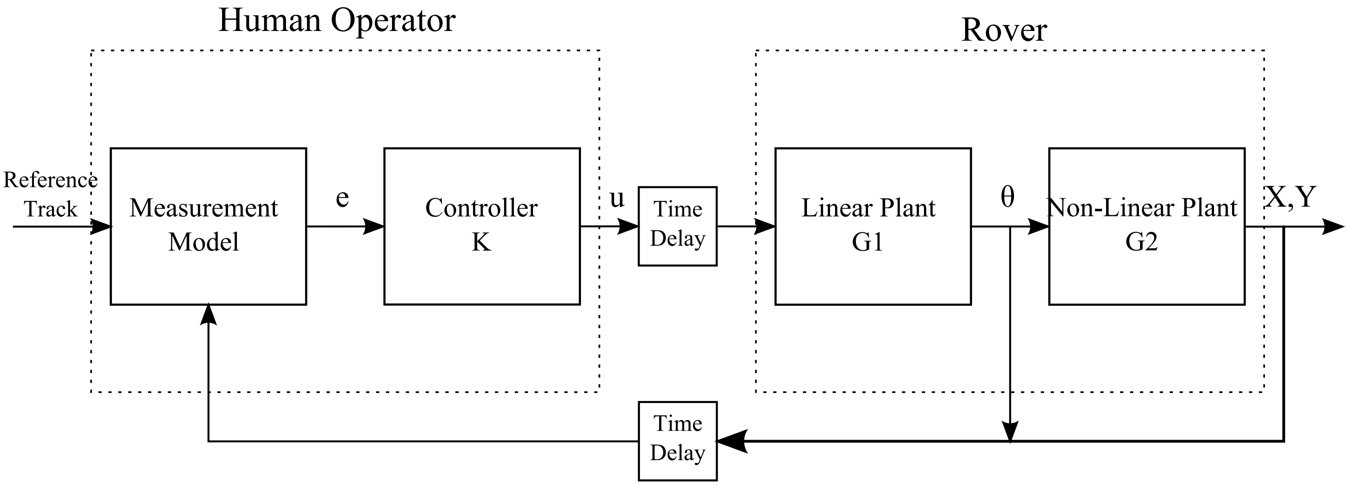


Figure 5. Feedback Control Framework. Note that the camera mounted on the rover and the human observer have been combined in the measurement model.

highest mean error for delays of $T = 0.5s$ and above. This is likely due to subjects driving routes that had roughly similar curvatures to the reference but with a large offset, giving the illusion of ease.

IV. Model

A. Control Framework

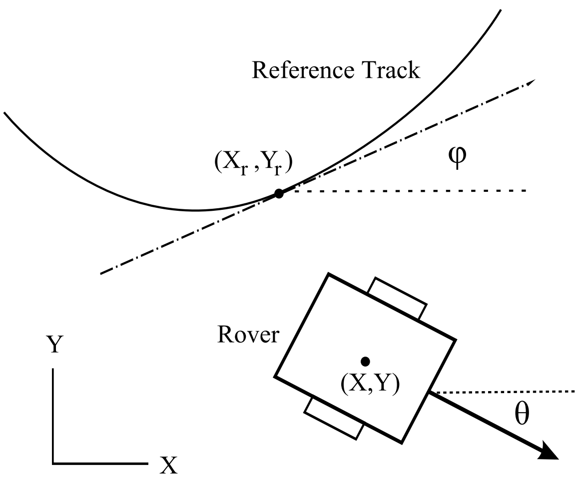


Figure 6. Schematic of rover and reference route at time k. (X_r, Y_r) is the closest point on the reference route to the rover position (X, Y).

The interaction between the rover and the human operator can be conceptualized as a feedback control loop with four subsystems (Fig. 5):

1. A combined camera + human measurement model
2. The human controller
3. The rover rotational dynamics
4. The rover translational dynamics

1. Plant

The Pioneer 3-DX rover can be modeled as a pair of discrete time state-space models linked in series with a time step of $\Delta = .0156$. The first is a 2 state black-box model developed using the N4SID method implemented in Matlab's system ID toolbox that determines the change in rover heading given the angular velocity commands input by the controller. This allows us to encompass the inner loop control of the rover into the model without explicitly considering the motor and wheel dynamics. A schematic of these coordinates is shown in Fig. 6. The first system (G1) is defined as:

$$\begin{bmatrix} x_1(k+1) \\ x_2(k+1) \end{bmatrix} = \begin{bmatrix} 1 & -.0003 \\ .004 & 0.924 \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix} - \begin{bmatrix} 1.3 \cdot 10^{-5} \\ 0.0135 \end{bmatrix} u \tag{1}$$

$$\theta(k) = [461\ 0.0326] \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix}, \tag{2}$$

where u is the control input, θ is the difference in heading angle relative to the initial rover heading in radians and $[x_1\, x_2] = 0$ when $\theta = 0$. The second system (G2) models the rover's translational dynamics and is defined as:

$$\begin{bmatrix} x(k+1) \\ y(k+1) \end{bmatrix} = \begin{bmatrix} x(k) \\ y(k) \end{bmatrix} + \Delta \cdot 200 \cdot \begin{bmatrix} cos(\theta(k)) \\ sin(\theta(k)) \end{bmatrix} \tag{3}$$

where $[x(k)\ y(k)]$ is the rover position at time k and a constant translational velocity of $200\,mm/s$ is assumed. Experimental data confirms that this is a reasonable assumption so long as we begin our simulation once the rover has reached its maximum velocity along the initial straightaway.

2. *Measurement Model*

The combination of the human and camera system is modeled as a non-linear observation which takes as inputs the reference trajectory and the position and heading of the rover at time $(k - T/2)$ and outputs the following values to the controller at time k, where T is the round-trip time delay:

1. The Euclidean distance to the nearest point on the reference route that lies within a 2 meter window of the previous time-steps nearest point. This allows the system to ignore later parts of the route that may happen to fall within the camera field of view due to the limited space for the experiment. If (X_r, Y_r) is the nearest point on the reference route and (X, Y) is the location of the rover at time $(k - T/2)$, then

$$E_d(k) = \left(\begin{bmatrix} X - X_r & Y - Y_r \end{bmatrix} \begin{bmatrix} X - X_r \\ Y - Y_r \end{bmatrix} \right)^{1/2}. \tag{4}$$

   The sign of E_d is defined to be positive if the rover is to the right of the reference trajectory, negative if to the left.

2. The difference in angle between the current rover heading and the tangent line to the reference trajectory at the nearest point (ie the heading the rover would have if it were following the reference perfectly). If the rover heading is ϕ and the tangent line to the reference route at (X_r, Y_r) is ϕ then

$$E_h(k) = \phi(k - T/2) - \theta(k - T/2) \tag{5}$$

3. The average signed curvature values c_j for the next five 0.2m sections of a cubic spline which is fit to the portion of the reference route visible to the camera at time $(k - T/2)$. The curvatures are defined as $c_i = 1/R_i$ where R_i is the radius of the circle which most closely fits the curve in the neighborhood of the point i. The sign of the curvature indicates the direction in which the reference is turning, positive for left turns, negative for right. $c_j = 0$ if no part of the corresponding 0.2m section lies in the camera field of view at time $(k - T/2)$. This metric was chosen to numerically represent how "‘sharp"’ or "‘gradual"’ an upcoming turn would appear to the human subject. Let

$$E_c(k) = \begin{bmatrix} c_1 & c_2 & c_3 & c_4 & c_5 \end{bmatrix} \tag{6}$$

4. The average "heading errors", for the next five 0.2m sections of the spline fit as previously defined. These "heading errors" are set to zero if no part of the reference trajectory lies in the camera field of view at time $(k - T/2)$. If ψ_j is the average heading error for spline section j, then

$$E_\psi(k) = \begin{bmatrix} \psi_1 & \psi_2 & \psi_3 & \psi_4 & \psi_5 \end{bmatrix} \tag{7}$$

   As before, $\psi_j = 0$ if no part of the corresponding 0.2m section lies in the camera field of view at time $(k - T/2)$.

3. *Controller Models*

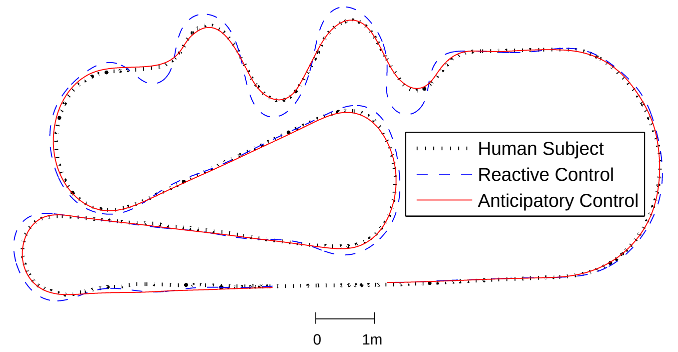
We consider here two controller models. The first, which we shall term reactive, utilizes only the knowledge of the state at time $(k - T/2)$ encoded in $E_d(k)$ and $E_h(k)$. Its control law is specified as

$$u(k) = \begin{bmatrix} k_{11} & k_{12} \end{bmatrix} \begin{bmatrix} E_d(k) \\ E_h(k) \end{bmatrix}, \tag{8}$$

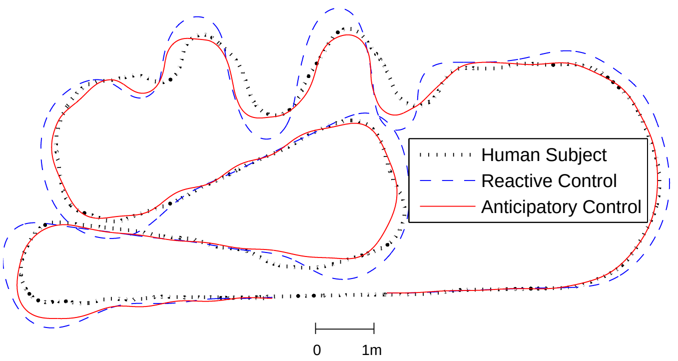
where k_{11} and k_{12} are scalar control gains that are calculated based on experimental data. This can be thought of as a form of PD control as the heading error is based on the derivatives of the reference input. The purpose of this controller is to serve as a baseline for examining the performance of the second model, which we shall call anticipatory, which leverages the predictive information provided by the camera system and has a control law specified as

$$u(k) = \begin{bmatrix} k_{21} & k_{22} & k_{23} & k_{24} \end{bmatrix} \begin{bmatrix} E_d(k) \\ E_h(k) \\ E_k(k) \\ E_\psi(k) \end{bmatrix}, \tag{9}$$

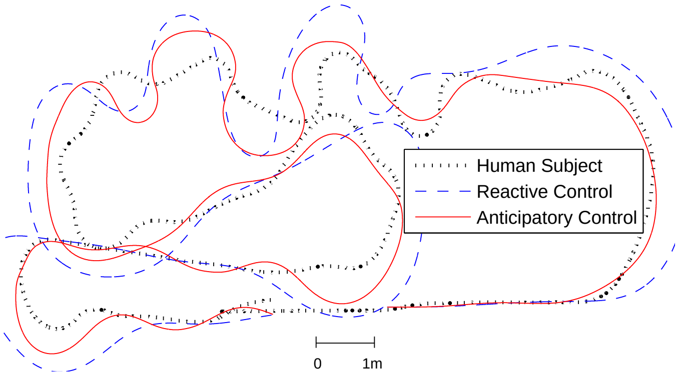
where k_{21} and k_{22} are scalar control gains and k_{23} and k_{24} are 1x5 row vectors of control gains



(a) 0s time delay



(b) 1s time delay



(c) 2s time delay

Figure 7. Comparison of simulated trajectories for reactive and anticipatory controllers. The feedback gains for both controllers were extracted from the human subject's trajectory shown for reference.

By incorporating the information of the route ahead provided by the camera, the control system is able to predict what future control inputs will be required and is thus able to mitigate the effect of time delays. The key detail here is that this form of anticipatory control relies only upon limited knowledge of the reference trajectory in the near future and has no memory of past control actions, even though the results of these actions may not yet be apparent due to the time delay. Each control output is then applied at time $(k+T/2)$.

The controller gains for each lap, time delay, and subject were calculated by using the Moore-Penrose pseudo-inverse to solve the over-determined least squares problem defined for the reactive and anticipatory controllers respectively as

$$min\,Norm\left(E \begin{bmatrix} k_{11} \\ k_{12} \\ 0 \\ 0 \end{bmatrix} - U \right) \tag{10}$$

and

$$min\,Norm\left(E \begin{bmatrix} k_{21} \\ k_{22} \\ k_{23}^t \\ k_{24}^t \end{bmatrix} - U \right), \tag{11}$$

where E is a matrix whose j^{th} row is

$$E_j = \begin{bmatrix} E_d(j) & E_h(j) & E_k(j) & E_\psi(j) \end{bmatrix} \tag{12}$$

and U is a column vector of the human controller output at each time step. The behavior of these controllers was then simulated at each time delay and compared against the rover trajectory from the data set used to calculate the control gains. Characteristic simulated rover trajectories are shown in Fig. 7 in comparison with the corresponding experimental rover trajectory.

V. Model Performance

The performance of the two controllers is evaluated based on their simulated trajectories using the same metric of RMS error used in judging human performance, with the modification that error is determined by measuring distance from the simulated trajectory to the experimental rover trajectory rather than to the reference route. Consequently large errors indicate poor ability in replicating human behavior. The means and standard deviations of these errors are shown in Fig. 8 for both controllers. The reactive controllers is able to do reasonably well at low time delays, but shows rapidly increasing error as the time delay increases. In contrast the anticipatory controller is able to mimic human performance almost perfectly at low delays, and is still able to do a reasonable job at delays above 1.5s. These different performances might be expected given that the anticipatory controller uses a significantly larger number of fitting parameters. However, the key detail is that these extra parameters are not additional knowledge of the system state at time $(k-T/2)$, but constitute a set of predictive information extracted from an interpretation of the desired trajectory as seen with the camera. The increasing difference in performance between the reactive and anticipatory controllers with increased time delay suggests that . This confirms statements made during the study by human subjects regarding their reliance on anticipating the control inputs required in the future in order to stay on course.

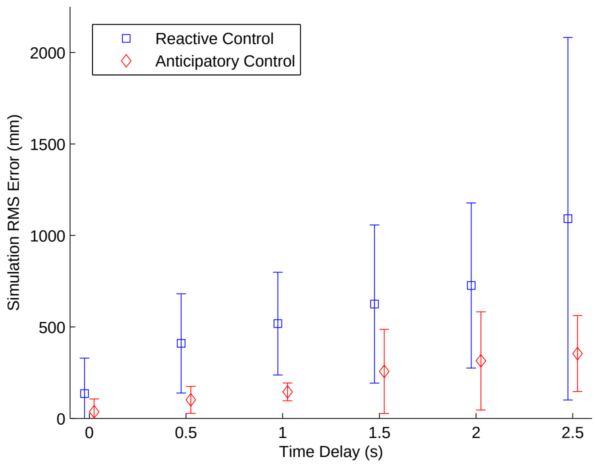


Figure 8. Simulated controller performance as measured by average distance from associated trajectories generated by human subjects. Reactive control utilizes only time delayed position and heading errors, while anticipatory control also incorporates time-delayed predicted average heading errors and reference route curvatures over a 5s horizon.

VI. Conclusions and Future Work

A. Conclusions

It has been demonstrated that human tracking performance degrades slowly for closed-loop time delays between 0 and 2.5s, indicating that humans are able to adapt to the errors induced by delay. This increasing error is primarily due to instabilities in the system that arise from operator over-correction. It was determined that while human subject tracking error had statistically significant dependencies on time delay and route section, there was no significant learning effect present between repeat laps at the same time delay. The performance of controller models derived in this paper show that while human behavior can be approximated by a simple PD controller at no delay, in order to adapt to increasing time delays it is necessary to incorporate predictive information concerning the route ahead provided by the camera. It should be noted that this system maintains no control history, thus confirming that humans rely primarily on anticipation of future requirements in order to adapt to small time delays. The reduced performance of our anticipatory controller at delays over 1.5s indicates that there are additional factors present at higher delay times that are not present in our model.

B. Future Work

In order to we intend to develop a model-predictive control system with a variable horizon distance whose parameters are again extracted from the human response data used for this paper. This would allow a determination of whether the human subjects shift attention from near to far parts of the visible track as time delay increases. By adding a variable length fading memory of past control actions it is hoped that we will be able to determine whether or not human operators estimate the effects of past actions at higher time delays. We also plan on conducting a longer set of experiments with more subjects that should allow us to probe a number of factors which were limited by the size of this preliminary study. By varying the order of time delays we hope to both determine whether having driven the rover at one time delay improves performance at different time delays and to isolate long term training behavior caused by learning the route vs. adapting to the time delay.

Acknowledgments

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