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AN INVESTIGATION OF VIBRATION FEEDTHROUGH AND FEEDTHROUGH CANCELLATION IN JOYSTICK CONTROLLED VEHICLES

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ABSTRACT

The inertial and applied forces acting on operators of joystick controlled machinery in moving vehicles can produce unintentional control signals through the joystick. These forces tend to deteriorate continuous tracking performance and further, when the machinery in control is the vehicle itself, they may lead to unstable oscillations that jeopardize that vehicle's safe operation. In this paper, we propose the use of a force-reflecting joystick and a model-based controller to cancel the effects of inertia forces. Using a simple physical model of human biomechanics, we experimentally investigate the effectiveness of a cancellation controller in stabilizing a driving task. A second experiment involving a human subject on board a motion base investigates the ability of the cancellation controller to improve performance in a continuous tracking task. Results indicate that the cancellation controller enhances stability and improves tracking.

INTRODUCTION

Human operators onboard moving vehicles are subjected to inertial forces due to vehicle accelerations, and these forces, when they are coupled through the operator's body into the control interface, induce unintentional control signals that degrade tracking performance. This phenomenon has been called vibration feedthrough or biodynamic feedthrough [1], [2] and [3]. We are investigating biodynamic feedthrough and its cancellation in the context of human tracking performance. We distinguish between two types of tracking task. The first we call *remote control* or *open loop* which involves tracking of a moving target while onboard a moving host vehicle using a piece of machinery whose motion is independent of the motion of the host vehicle. The motion (shock and vibration) of the host vehicle acts on the joystick through the biodynamic system of the operator, and it can degrade tracking performance. The second type of tracking task, which we call *driving*, or *closed loop*, involves tracking of a moving target with the vehicle itself. In the driving task, the motion of the machinery used for tracking is the same as the motion which acts as disturbance to tracking. In this case the operator may be considered a pilot or driver. A loop is closed through the biomechanics of the operator's body, and this may result in unstable vehicle oscillations that jeopardize the safe operation of the vehicle. Examples of vehicles whose piloting may suffer from vibration feedthrough include tanks, electric wheelchairs, frontloaders, fighter jets and helicopters [4].

The present study focuses on eliminating vibration feedthrough. The use of a motorized, force-reflecting joystick has been proposed for this purpose [1]. The aim is to cancel the unintentional force caused by inertial effects with a torque injected by a DC motor on the joystick. This is expected to improve tracking performance in both the remote control and driving cases and to improve stability in the driving case.

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We consider a *motion stick*, a joystick with a pivot that rotates around one axis without dead-zone and without backlash, that produces an electrical signal as a function of angular displacement. By contrast, a *force stick* is a rigid joystick providing electrical signals as a function of the force imposed on it. The latter is often used in airplanes. At this stage of our work only a motion stick is used for the investigations.

Force feedback in manual control interfaces has been shown to improve human/machine performance in various tasks. The classic example of the benefits of force-feedback is the bilateral telemanipulator, wherein force feedback from a local *master* manipulator carries information about the interactions taking place between the remote *slave* manipulator and its environment and thereby enables improved task performance over telerobots without force feedback. But force-feedback has also proven beneficial in the performance of vehicle control tasks. Force-reflecting devices improve the information content of manually controlled vehicles within virtual environments according to Repperger and Chandler [5], enabling improved operation of the vehicle and improved performance in tracking tasks. Yuhara et al. [6] used a structural driver-vehicle model to design a force feedback steering wheel. The added kinesthetic information improves vehicle handling, improves lane following both in compensatory and in pursuit control, and reduces the mental and physical load of the driver. A force feedback joystick was used to give information about the motion of an unmanned air vehicle (UAV) to its pilot operating from a remote site in the work presented by Korteling and Borg [7]. The force-feedback system improved the performance of the pilot and reduced the mental workload associated with maneuvering a simulated UAV. Parker et al. [8] built a force feedback system for heavy duty hydraulic machines. The system gives a feel to the human operator for the load acting on the tip of the boom of an excavator. The benefits of force-feedback in these examples, however, accrue because of the improved information about the controlled element's behavior available to the human operator. We are interested in benefits to be reaped by motorizing the interface device that do not involve cognitive control or volition on the part of the human operator. Vibration feedthrough can occur (and, with a motorized interface can be compensated) without any participation of cognitive processing.

Vibration feedthrough has been identified as a cause of deteriorated human/machine performance and investigated in various scenarios, including force and displacement sensing joysticks scenarios. A comprehensive overview of biodynamic effects on continuous tracking performance is available in Griffin [9]. The dynamics of both motion-type and force-type joystick interfaces and the associated human-machine system was analyzed by Hess [10], [11]. A structural pilot-aircraft model was constructed to analyze the roll-ratchet phenomenon. This includes a simple biodynamic feedthrough model, a continuous tracking model, a model for manipulator-feel system dynamics and a model for vestibular motion feedback. The resulting

Bode magnitude plots of the pilot-vehicle transfer functions follow trends similar to those of experimental Bode plots.

The need to predict the continuous tracking performance of pilots of vehicles and machine operators was first identified during the second World War [12]. Since that time, ever more accurate models of human tracking performance have been sought by the military and by industry [13]. A comprehensive summary of such models is given by Reid [14] and by McRuer [15]. The most frequently used types of models are the structural model and the optimal control (also known as algorithmic) model. Alternative modelling approaches also exist, e.g. the fuzzy control model [12]. The structural model evolved from McRuer's crossover model, and methods for measuring or estimating its parameters have been documented in numerous articles, e.g. [16]. McRuer et al. [17] describes new experimental results in the context of this model. The human operator is modeled as a linear, time invariant system in most of the studies. The algorithmic model uses LQR techniques and Kalman filters, and its implementations both in simulation and hardware are described in great detail in the literature [18]. The tracking performance of human operators has been investigated for a variety of scenarios, including tracking tasks carried out in more than one dimension at a time [19]. McRuer and Schmidt [20] investigated the behavior of pilots when carrying out a secondary task in addition to tracking.

The analysis and simulation of vibration feedthrough and feedthrough cancellation through signal processing of a joystick controlled aircraft is presented by Verger et al. [21]. In that work, the inertial effects acting on the pilot are estimated by an adaptive filter and they are subtracted from the control signal. The results of an experimental study in which a joystick controlled motion platform was used for demonstrating the solution were published in another paper by Verger et al. [2]. As mentioned above, to eliminate vibrations induced by inertial effects, adaptive filtering of the control signal was implemented by Verger et al. [21], [2]. In this work, however, the cancellation was effected by injecting a cancelling signal to the joystick output, rather than imposing a cancelling torque on the joystick. Thus the feel of the joystick to the operator was not affected directly. Also, this signal processing solution cuts off the high frequency components of the control signal above 1Hz, which somewhat deteriorates the performance of the vehicle. An acceleration feedforward control approach that imposed a cancelling torque on the joystick using a force-reflecting joystick was proposed by Gillespie et al. [1] A robust controller was implemented using force-feedback by Sirouspour and Salcudean, [3]. An alternative approach involving increased joystick damping with decreased loop gain was proposed by Arai et al. [22].

In this paper, the use of a force reflecting joystick and a model based controller is further investigated as a means of solving the vibration feedthrough problem. The transfer function of the human operator from vehicle acceleration to unintentional

torque imposed on the joystick will be determined based on human subject tests. The proposed controller will identify this transfer function and will impose a torque on the joystick in the opposite sense as a function of measured vehicle accelerations. This approach is expected to improve tracking performance and improve safety.

The body of this paper is organized in three parts. First, the modelling approach of the human/machine dynamics are explained. Second, the experimental and simulated demonstration of vibration feedthrough for the closed loop case in which the human biomechanics were modelled using a stand-in physical second order system is presented. Also for this case, a vibration feedthrough cancellation controller was tested using a force reflecting joystick and the stand-in model for the biomechanics. Finally, human subject tests of tracking performance carried out on a single axis motion platform are discussed. The degradation of tracking performance in moving vehicles and the effectiveness of a simple cancellation controller were demonstrated by these tests. This is groundwork for the investigation of vibration feedthrough in the driving task, the results of which are expected to lead to the design of a feedthrough cancellation controller.

MODELLING THE HUMAN/MACHINE COUPLED DYNAMICS

Our joystick can be modelled as a second order transfer function $J(s)$ from the torque applied on it to angular displacement which involves its moment of inertia and a virtual return spring and a virtual damper. The joystick angle is multiplied by a scalar to produce the output of the virtual plant to be controlled. The investigation is mainly concerned about the dynamics of the joystick and the pilot, not that of the plant or the plant controller, so the simplest plant of unity gain was selected for the experiments, thus our tracking task is zeroth order. This also results in a more straightforward identification of the operator's transfer function as a controller.

Fig.1 shows the block diagram of a general system operating in remote control mode. The human operator (HO) is characterized by the double input, single output transfer function $H(s)$, with the reference signal of the tracking task X_r and vehicle acceleration $\ddot{X}_v$ as inputs and a torque T as output. The quantity the HO intends to control by acting through the joystick is the output of the plant, that is, the plant position X_p. The torque T acting on the joystick $J(s)$ has two components, one of them we call the *unintentional torque T_{ui}* which is the output of the transfer function $H_{ui}(s)$ describing the unintentional effects of the vehicle acceleration $\ddot{X}_v$ on the torque T. This is a consequence of the biodynamic (primarily inertia) forces acting on the pilot in the moving vehicle. The other component we call the *intentional torque T_i*, which is the output of the transfer function describing the action of the intentional controller $H_i(s)$ (involving perception, cognition and muscle action) on an error signal or other combination of X_r and

X_p. Finally, a gain C_p multiplies the joystick angle q to produce a command X_c imposed on the plant $P(s)$.
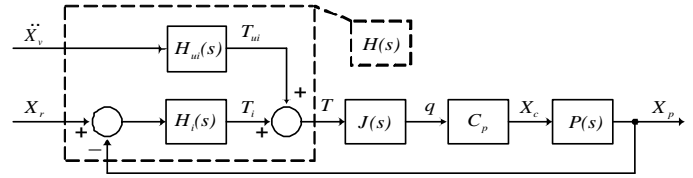

Figure 1. Vibration feedthrough in remote control systems

A special case of this system is obtained when $\ddot{X}_p = \ddot{X}_v$, that is, when the HO is subjected to the accelerations of the plant he or she controls with the joystick. This case is the piloting task and its block diagram is shown in Fig. 2.
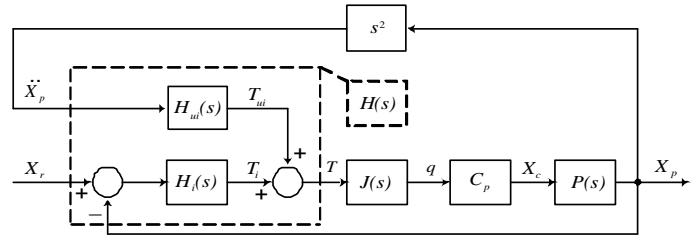

Figure 2. Vibration feedthrough in piloting tasks

The lower feedback loop we call the tracking loop, whereas the upper feedback loop we call the disturbance loop.

Prior to carrying out experiments with human subjects, we designed a set of experiments involving only hardware. These hardware experiments featured stand-in inertia, damping, and stiffness components to capture the role of the human arm and hand in biodynamic feedthrough. In particular, a dummy mass was attached to the end of the joystick to capture the effects of the effective mass of the hand and arm of the pilot. A local feedback controller on the joystick DC motor was programmed to realize a rotational spring and a rotational damper. Thus the second order system $J(s)$ captures some of the coupled dynamics of the joystick and human arm/hand, including inertial, damping, and restoring force characteristics of the human operator. The goal of the simulations and experiments carried out on this apparatus was to demonstrate the phenomenon of feedthrough and test a feedthrough cancellation controller in the case of the piloting task. Two experimental platforms were used, a vibration testbed and a ride motion simulator (RMS). Experiments with the RMS are discussed below.

Following the experiments involving hardware alone, a pilot study was completed with a single human subject. The tracking performance of the human operator was first characterized

without motion disturbance and then tracking during motion disturbance was tested for the case of remote control on-board a moving vehicle.

VIBRATION FEEDTHROUGH SYSTEM INVOLVING HARDWARE ALONE

At first feedthrough and feedthrough cancellation were investigated in systems comprising hardware components only. The tests and simulation carried out on the vibration test bed served to prepare for those carried out on the RMS. The control system used with the RMS experiments is shown in Fig. 3. The vehicle operates in acceleration control mode, and feedthrough is cancelled by applying a moment equal and opposite to the inertial moment on the joystick by means of a DC motor.
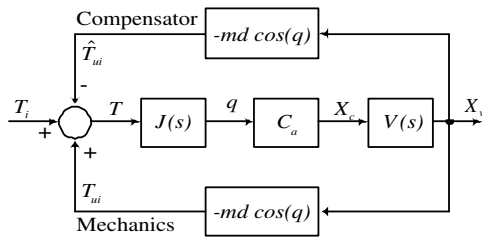
Figure 3.   Feedthrough cancellation of local control system

The RMS shown schematically in Fig. 4 is capable of producing motion in six axes (three displacements, three rotations) using a hydraulic Stewart-Gough platform. We have, however, restricted our attention to vibration feedthrough occurring in a single axis: lateral displacements in the direction labelled X in Fig. 4. The angle of the joystick is denoted q. The RMS motion controller takes acceleration commands from the control PC, and it sends control signals to the hydraulics of the platform. It also transmits position, velocity, and acceleration analog signals back to the control PC. The joystick box is equipped with its own accelerometer, and it sends acceleration signal and joystick angle data to the control PC. The control PC uses a $1kHz$ sampling frequency, it calculates the RMS acceleration reference signal and it records the joystick angle and RMS acceleration with a sampling frequency of $100Hz$. The motion of the platform is limited to $\pm 0.50m$ whereas the rotation of the joystick is limited to $\pm 30°$. The parameters of the joystick are: $k = 2.0Nm/rad$, $I = 0.019kg \cdot m^2$, $b = 0.0167Nm/(rad/s)$. The moment of inertia, I includes the equivalent inertia of the DC motor rotor as coupled through the mechanical advantage (realized using a capstan drive) between the joystick and the motor.

Figures 5 through 8 present simulated and experimental time histories of the joystick angle. Figures 5 and 7 demonstrate vibration feedthrough (no compensator in place) with simulated and experimental data, respectively. Figures 6 and 8 show results for
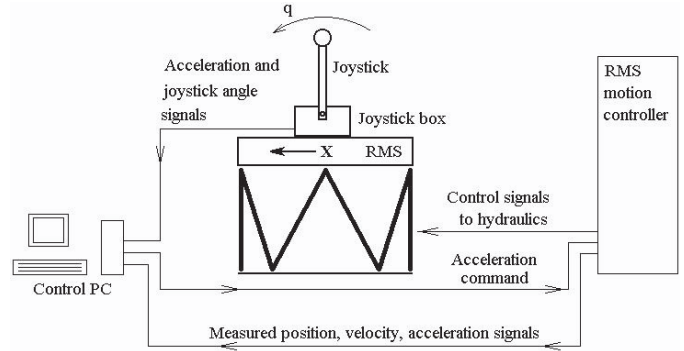
Figure 4.   Test apparatus with RMS and second order operator model

the same system with a feedthrough cancellation compensator in place with simulated and experimental data, respectively.
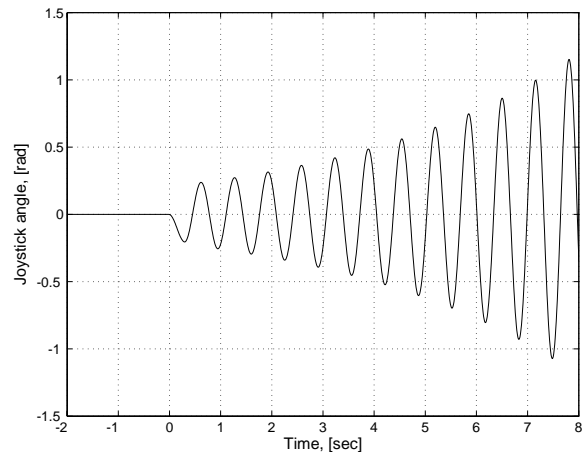
Figure 5.   Feedthrough simulation

The acceleration command of the RMS was proportional to joystick angle. The joystick/platform oscillatory motion was initiated with a torque impulse applied to the motorized joystick of magnitude $-0.2Nm$ and of duration $0.29sec$ in both the case of feedthrough and feedthrough cancellation at $t = 0s$. Both in simulation and during the tests, joystick oscillation amplitude started to grow exponentially. In case of feedthrough cancellation the responses are determined by the natural response of joystick alone. This is because the effects of platform motion on that of the joystick are to a large degree compensated, so the joystick moves independently of platform accelerations, as though its base was fixed to ground. No actuator saturation occurred while the data shown on the graphs was recorded. When the joystick virtual spring moment is less than the friction moment at the extremity of the oscillation, the joystick oscillation ends with an offset.

The increasing amplitude oscillations in Figures 5 (simulation) and 7 (experiment) demonstrate feedthrough and the decreasing amplitude oscillations in Figures 6 (simulation) and 8 (experiment) indicate successful feedthrough cancellation.
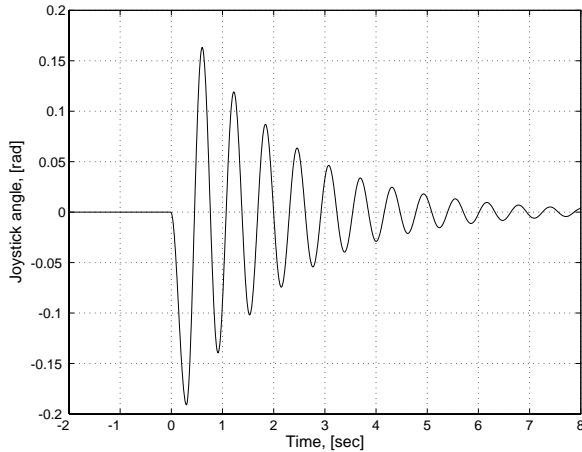
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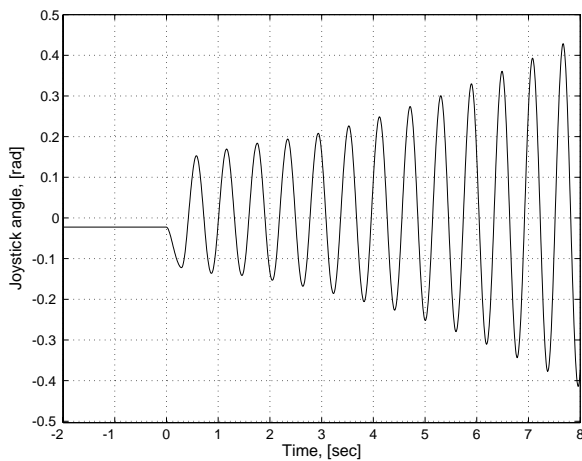
Figure 6. Feedthrough cancellation simulation
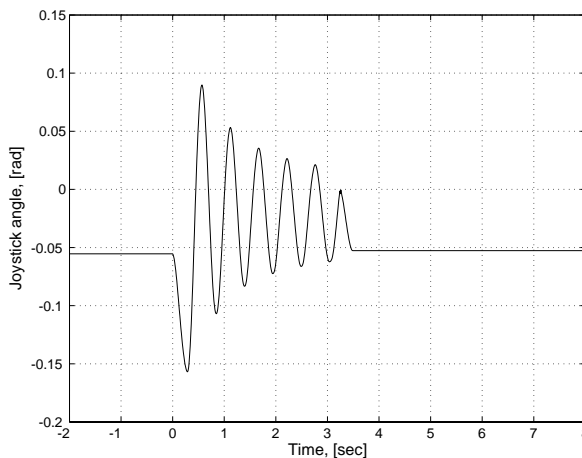

Figure 7. Feedthrough on the RMS

Figure 8. Feedthrough cancellation on the RMS

VIBRATION FEEDTHROUGH IN REMOTE CONTROL TASKS

The feedthrough cancellation method discussed in the previous section is based on the assumption that the response of the operator to vehicle acceleration is at least in part predictable.

This is easily accomplished in the case of the second order operator model, since it only relies on an estimate of the unintentional transfer function. The HO performing a task such as tracking, however, has two inputs and one output, as shown in Fig. 1. This section is devoted to the experimental investigation of the behavior of the coupled human-machine system theoretically and experimentally.

To demonstrate the degradation of tracking performance due to vehicle motion and the concept of feedthrough cancellation using a force reflecting joystick, four tests were carried out in a single axis motion platform. The first test was designed to explore the relationship between vehicle acceleration and unintentional torque imposed on the joystick. The pilot held a force stick in his hand while being shaken sideways by the platform. The platform moved according to a filtered white noise velocity control command filtered using a first order band pass filter. The high and low pass cutoff frequencies were $0.3Hz$ and $5Hz$, respectively. The unintentional torque and the platform acceleration were recorded with a sampling rate of $100Hz$. The estimate of the transfer function from acceleration to unintentional torque was then obtained by applying the method of averaged, modified periodograms of Welch on the two time functions. The test lasted for 5 minutes. The result can be seen in a Bode plot in Fig. 9.
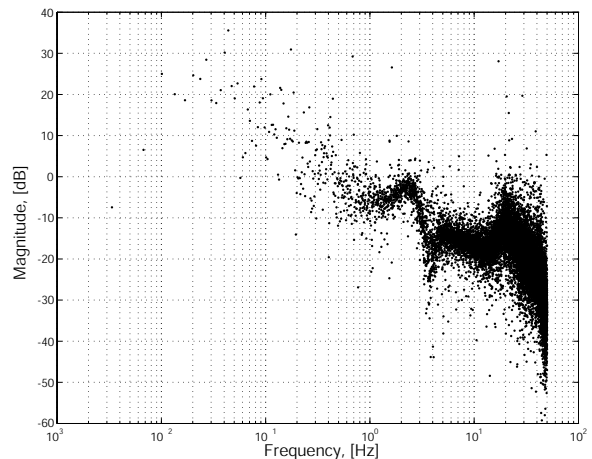

Figure 9. Transfer function from platform acceleration to joystick torque

The cancellation controller is supposed to imitate this transfer function, and apply a torque on the joystick as a function of platform acceleration, as shown in the block diagram of Fig. 10.

As a first attempt, the transfer function from acceleration to torque was modelled by the product of the distance between the joystick pivot and the center of the palm of the pilot ($0.08m$) and an equivalent mass. The latter was $0.95kg$, and it was determined experimentally by adjusting the virtual mass until the operator felt it was optimal. The cancellation torque was equal to the product of sensed vehicle acceleration, and a constant of
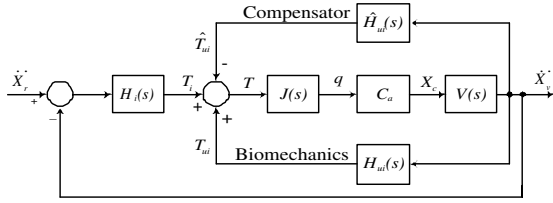
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Figure 10. Proposed solution for feedthrough cancellation

$0.08 * 0.95$. This would correspond to a $-22.4 dB$ straight line on Figure 9.

During the last three tests a human subject carried out a pursuit tracking task with a motion stick. The goal of these tests was to obtain an estimate for the human/machine open loop tracking transfer function under different test conditions. The first test involved tracking a reference signal in a steady platform. The platform moved in the second test, with the cancellation controller turned off. The platform moved and the controller was turned on in the last test. The reference signal of the tracking tasks was a sum of 15 sinusoids, with amplitudes decreasing with angular frequency. The plant output was the joystick angle multiplied by a constant gain, hence the task was again zeroth order. To reduce the effect of joystick dynamics on the pilot's performance, the joystick was programmed to zero stiffness and damping. Each test lasted for 5 minutes. The test subject saw two cursors representing the instantaneous values of the reference signal and the plant output on a computer screen, hence the task was a pursuit tracking task with no preview. The data was evaluated based on the following considerations. The reference signal has a discrete frequency content corresponding to the 15 sinusoids. The pilot is assumed to behave linearly, so the transfer function has to be obtained for these and only these frequencies. The method of modified periodograms of Welch (tfe command in Matlab) does not allow the specification of the frequencies for which to obtain transfer function values. Therefore, first the cross-correlation function of the input and the output, and the autocorrelation function of the output were obtained. Then the Fourier transform of these was computed using numerical integrals, which yielded the cross correlation spectral density of the input and the output, and the power spectral density of the input for the specified fifteen frequencies. The ratio of these yields the transfer function in the frequency domain. The results are shown for the three tests in Figures 11, 12, and 13.

Two performance metrics were used, the crossover frequency f_c and the rms average of the tracking error, e_{RMS}. These are shown in Table 1.

The numbers indicate performance degradation as a consequence of platform motion and performance improvement due to the cancellation controller.

McRuer's crossover model states that the open-loop transfer function of the HO and the plant has a $-20 dB/dec$ slope in the crossover region according to Levine [12], with a crossover
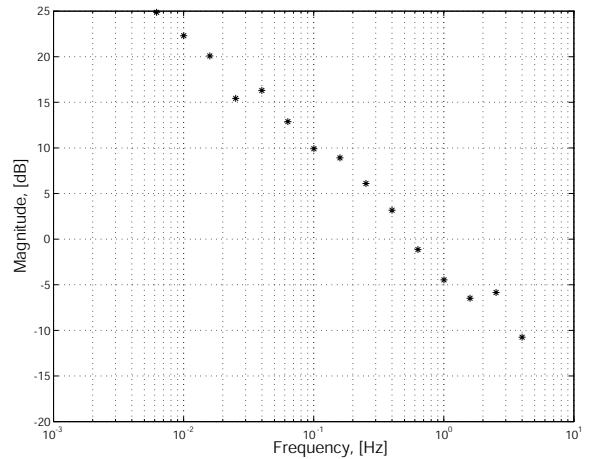

Figure 11. Open loop transfer function of tracking in steady platform
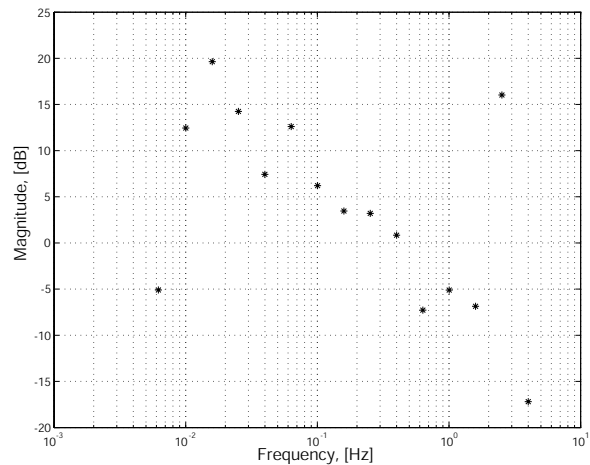

Figure 12. Open loop transfer function of tracking in moving platform without compensation

Table 1. Tracking performance under various test conditions

	Steady	No comp	Comp
f_c [Hz]	0.55	0.35	0.35
e_{RMS}	6.6	21.8	12.9

frequency in the range of $0.5 - 1 Hz$ in case of unpredictable reference signals. The output is delayed with respect to the input by $150 - 300 ms$ in case of zeroth order systems. The crossover region is observable on all the three plots. The dots line up when the platform is steady, while they are somewhat scattered when the platform moves, indicating a less consistent tracking performance. Platform motion causes a peak at 2Hz, at the frequency where the transfer function from acceleration to joystick torque also has a peak. In the case of an unpredictable tracking reference signal this can not be a consequence of intentional tracking activity due to its high frequency. Instead, because of the coin-
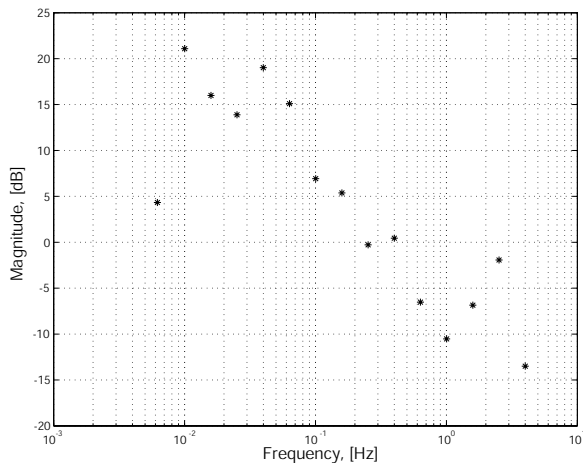
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Figure 13. Open loop transfer function of tracking in moving platform with compensation

cidence with the peak mentioned, this is suspected to be a consequence of inertial effects. A stiff stick was used to obtain the test data shown in Fig. 9, so the peak cannot be caused by joystick resonance, hence it is suspected to be due to the motion of segments of the operator's arm. The drop of the transfer function at $0.006Hz$ and at $0.01Hz$ also takes place during disturbed tracking only. The correlation between a motion disturbance that is high-pass filtered at $0.3Hz$ and a performance degradation at and below $0.01Hz$ is yet to be explained. There is another peak in Figure 9 between $5Hz$ and $10Hz$. This frequency range coincides with that of resonances caused by stretch reflexes of the hand and the arm. It may not be possible to attribute this coincidence based on a single human subject test only, nevertheless, this can be a starting point of further investigations. The scatter of the points in the plot becomes greater above about $15Hz$. This is to be disregarded, since sampled time functions allow us to identify system behavior up to only about one fifth of the sampling frequency.

Several trends are evident when comparing Figs. 11 through 13 that indicate the deterioration of tracking performance by vehicle motion, and the restoration thereof by the compensator. One important difference between the figures is the magnitude of the transfer functions for frequencies less than the crossover frequency. Since the error signal and the output have a small phase shift below the crossover frequency, a greater magnitude in the open loop transfer function indicates that the closed loop transfer function is closer to unity, that is, indicates better tracking. On average, the magnitude data indicate the greatest magnitude in case of a fixed platform (Fig. 11), the lowest in case of a moving platform without compensation (Fig. 12) and an intermediate value in case of a moving platform with the controller turned on (Fig. 13). Also, the scatter of the points is the largest in case of a moving platform with the controller turned off (Fig. 12), indicating the least consistent tracking performance. The scatter is the

smallest in case of a fixed platform case (Fig. 11), and the scatter is intermediate for the compensated case (Fig. 13). Monotonicity (or consistency) of decreasing gain as frequency increases is at least partially restored by the compensator.

As far as the performance metrics are considered, the changes in e_{RMS} and f_c indicate that platform motion deteriorates tracking performance. Compensation does not change f_c significantly, but it brings about a significant reduction in e_{RMS} which indicates that compensation aids disturbance rejection.

Two human subjects were tested for concept demonstration. The first subject was one of the authors, who had previous experience with tracking tasks, but was not told when the compensator was turned on. The results presented in this paper were based on the tests with the first subject, the results obtained with the second subject were much the same.

CONCLUSIONS AND FUTURE WORK

Vibration feedthrough has long been known to deteriorate the tracking performance of operators in moving vehicles and to cause unstable oscillations. The present paper summarizes a concept demonstration solving the feedthrough problem using acceleration feedforward and a simple controller. The cancellation of unstable, closed loop vibrations was simulated and demonstrated on a vibration test bed and on an RMS in case of a second order operator model. Initial human subject test results were obtained. The harmful effect of vehicle vibration on tracking performance was demonstrated by human subject tests. The cancellation controller improved the continuous pursuit tracking performance in a remote control task.

In forthcoming studies the torso and the arm of the operator will be modelled as a multi-body linkage, yielding a nonlinear system. The torque to be applied on the joystick will be calculated from the inertial properties of the body and from the motion of the vehicle. This will yield a cancellation controller. Experiments will be used to verify the theoretical operator model and the effectiveness of the cancellation controller. A compensator with a third order numerator and denominator has already been successfully implemented in human subject tests.

Further plans include carrying out more tests with untrained human subjects realizing feedthrough and feedthrough cancellation in piloting tasks on an RMS with motion and force sticks. Force sensing joysticks are more prone to produce unstable oscillations according to Griffin [9].

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