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

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ABSTRACT

The inertial forces acting on operators of joystick controlled machinery in moving vehicles can produce unwanted 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 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 unwanted control signals that degrade tracking performance. The phenomenon has been called vibration feedthrough or biodynamic feedthrough. If the controlled plant is the vehicle itself (in which case the operator may be considered a pilot or driver), then a closed loop exists that involves the biomechanics of the operator's body. These closed loop dynamics may give rise to unstable vehicle oscillations that jeopardize safe operation of the vehicle. Examples of vehicles whose piloting may suffer from vibration feedthrough include tanks, electric wheelchairs, frontloaders, fighter jets and helicopters [1]. But even when the controlled plant is a remote vehicle or on-baord machine, where no closed loop involving the human biomechanics exists, tracking performance will be degraded by vibration feedthrough.

The present study focuses on vibration feedthrough, and it does not include pilot induced oscillations. The first one is caused by inertial effects, typically in the frequency range between $1Hz$ and $5Hz$. The second one is caused by the instability of the system comprised by the vehicle and the volitional control activity of the pilot on frequencies below $1Hz$.

To eliminate the effects of vibration feedthrough, the use of a motorized, force-reflecting joystick has been proposed [2]. The aim is to cancel the non-volitional force caused by inertial effects with a torque injected by a DC motor on the force-reflecting joystick. This is expected to improve tracking performance in both the open loop (remote control) and closed loop (driving) cases and to improve stability in the closed loop (driving) case.

Force feedback in manual control interfaces has been shown to improve human/machine performance in various tasks. The

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classic example of the benefits of force-feedback is the bilateral telemanipulator, wherein force feedback in a local "master" manipulator carries information about the interactions taking place between the remote "slave" manipulator and its environment. 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 [3], enabling improved operation of the vehicle and improved performance in tracking tasks. Yuhara et al. [4] 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 [5]. The force-feedback system improved the performance of the pilot and reduced the mental workload associated with maneuvering a simulated UAV. Parker et al. [6] 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. A comprehensive overview of biodynamic effects on continuous tracking performance is available in Griffin [7]. The dynamics of both motion-type and force-type joystick interfaces and the associated human-machine system was analyzed by Hess [8], [9]. 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 analysis and simulation of vibration feedthrough and feedthrough cancellation through signal processing of a joystick controlled aircraft is presented by Verger et al. [10]. 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 were published in another paper by Verger et al. [11]. A joystick controlled motion platform was used for demonstrating the solution.

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 modeling 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. HessModel. McRuer et al. [16] 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 [17]. 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 [18]. McRuer and Schmidt [19] investigated the behavior of pilots when carrying out a secondary task in addition to tracking.

To eliminate vibrations induced by inertial effects, adaptive filtering of the control signal was implemented by Verger et al. [10], [11]. 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. [2] A robust controller was implemented using force-feedback by Sirouspour and Salcudean, [20]. An alternative approach involving increased joystick damping with decreased loop gain was proposed by Arai et al. [21]. Venneri and Noor [22] predict the appearance of EMG signal detectors mounted on the pilot's hand for obtaining vehicle control signals in the future. This solution is expected to eliminate biodynamic feedthrough, however, as pointed out by Xu and Hollerbach [23], voluntary and nonvoluntary movements can not be separated based on EMG using current technology.

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 nonvolitional moment imposed on the joystick will be determined based on human subject tests. The proposed controller will identify this transfer function and will impose a moment 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 principles of modelling the human/machine dynamics are explained. The next section presents how vibration feedthrough was reproduced experimentally and in simulation for the closed loop case in which the human biomechanics were modelled using a stand-in physical second order system. Also for this case, a vibration feedthrough cancellation controller was tested using a force reflecting joystick and the stand-in model for the biomechanics. At last, 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 a 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.

MODELING THE HUMAN/MACHINE COUPLED DYNAMICS

We are interested in developing a haptic or force-reflecting interface for the purpose of suppressing biodynamic feedthrough and thereby imp roving human/machine performance on-board moving vehicles. We have chosen to investigate 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*, which involves tracking, from on-board a moving host vehicle, of a moving target with a piece of machinery whose motion is independent of the motion of the host vehicle. The motion (or vibration) of the host vehicle can be considered a disturbance to the task. The second type of tracking task, which we call *driving*, involves tracking of a moving target with the vehicle itself. In the driving task, the motion of the machinery used for tracking is intimately coupled to the motion which acts as disturbance to the tracking task: they are one and the same. We consider a 'motion stick', a joystick with a pivot that rotates around one axis without dead-zone and without backlash, giving 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. Our joystick can be modelled as a second order transfer function from the force 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 controlled plant has no dynamics, thus our tracking task is zeroth order.

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 acting on the joystick T, has two components, one of them we call the *nonvolitional torque T_{nv}* which is the output of the transfer function $H_{nv}(s)$ describing the nonvolitional 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 *volitional torque T_v*, which is the output of the transfer function describing the action of the volitional controller $H_v(s)$ (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 to produce a command X_c of the plant $P(s)$.
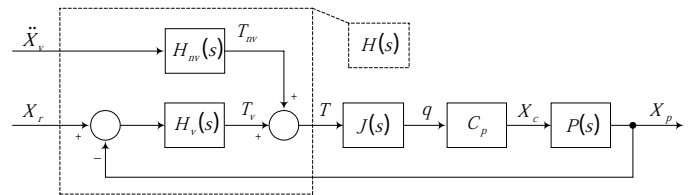

Figure 1.   Human in the loop control system with vibration feedthrough, remote control

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.
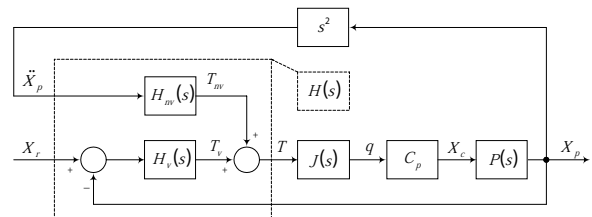

Figure 2.   Human in the loop control system with vibration feedthrough, piloting task

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

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the effective mass of the hand and arm of the pilot. A local feed-back controller on the joystick DC motor was programmed to re-alize 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 appara-tus 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 track-ing performance of the human operator was first characterized without motion disturbance and then tracking during motion dis-turbance 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 in-vestigated in systems comprised of 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 in-ertial moment on the joystick by means of a DC motor.
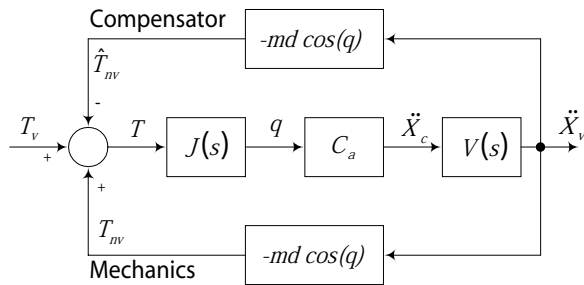

Figure 3. Feedthrough cancellation of local control system, realized on the RMS

The RMS shown 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 at-tention to vibration feedthrough occurring in a single axis: lat-eral 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 trans-mits position, velocity, and acceleration analog signals back to the control PC. The joystick box is equipped with its own ac-celerometer, and it sends acceleration signal and joystick angle data to the process control PC. The control PC uses a $1kHz$ sam-pling frequency, it calculates the RMS acceleration reference sig-nal and it records the joystick angle and RMS acceleration with a sampling frequency of $100Hz$. The motion of the platform is limited to $\pm0.50m$ whereas the rotation of the joystick is limited to $\pm30°$. The parameters of the joystick are: $k = 2.0Nm/rad$, $I = 0.019kg \cdot m^2$, $b = 0.0167Nm/(rad/s)$. The moment of in-ertia, I includes the equivalent inertia of the DC motor rotor as coupled through the mechanical advantage (realized using a cap-stan drive) between the joystick and the motor.
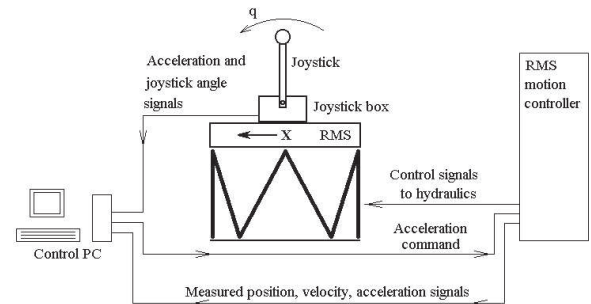

Figure 4. Experimental apparatus with RMS and second order operator model

Figures 5 through 8 present simulated and experimental time histories of the joystick angle. Figures 5 and 7 demonstrate vibra-tion feedthrough (no compensator in place) with simulated and experimental data, respectively. Figures 6 and 8 show results for the same system with a feedthrough cancellation compensator in place with simulated and experimental data, respectively. The acceleration command of the RMS was set to be 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 length $0.29sec$ in both the case of feedthrough and feedthrough cancellation. In simulation the impulse was applied at 2.5 sec, then the RMS and joystick os-cillation amplitude started to grow exponentially. In the case of feedthrough cancellation the torque impulse of the experimen-tal apparatus was applied at $52sec$. The responses in the case of feedthrough cancellation are determined by the natural response of joystick alone. This is because the effects of platform mo-tion on that of the joystick are compensated for, so the joystick moves independently of platform accelerations, as though it was fixed with respect to the ground. No actuator saturation occurred while the data shown on the graphs was recorded.

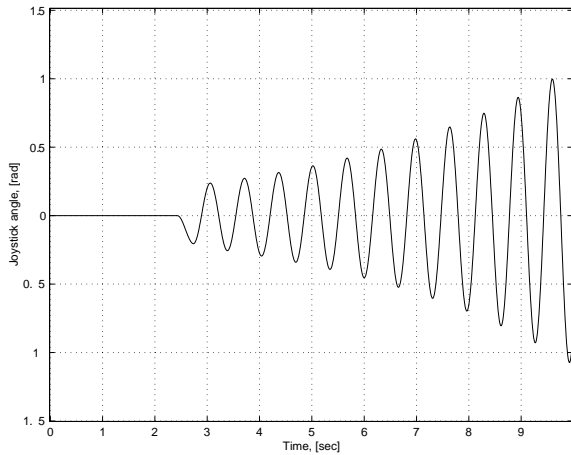The increasing amplitude oscillations in Figures 5 (simula-
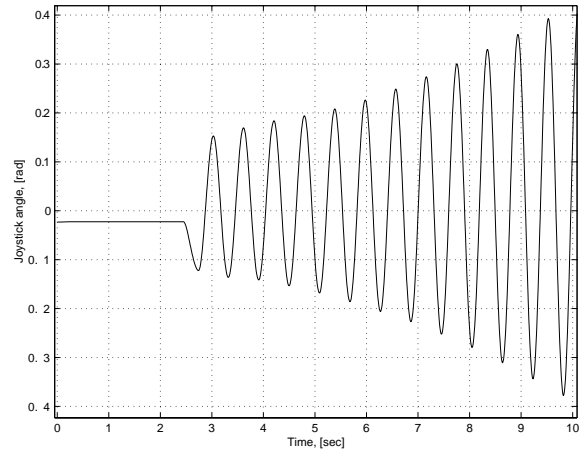
Figure 5. Feedthrough simulation
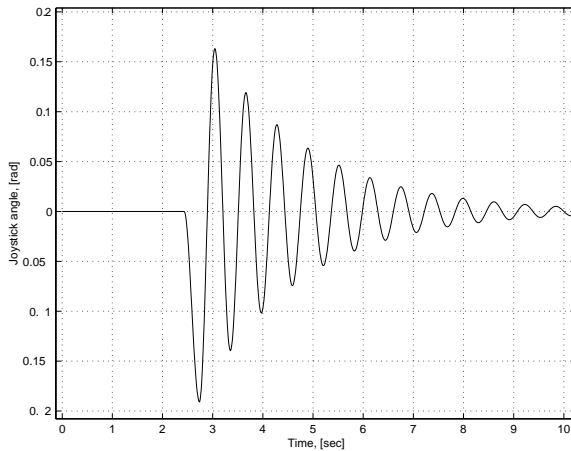

Figure 7. Feedthrough on the RMS

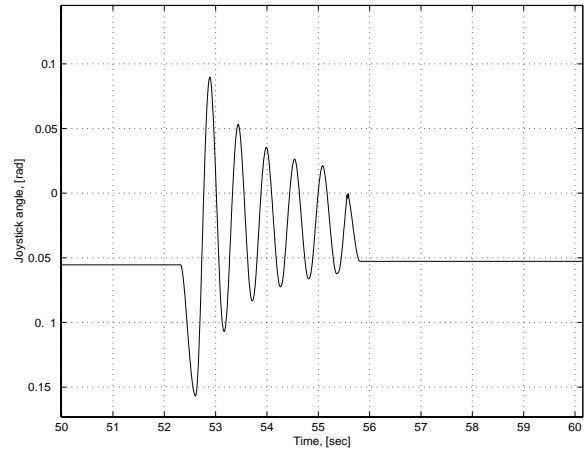Figure 6. Feedthrough cancellation simulation

Figure 8. Feedthrough cancellation on the RMS

tion) and 7 (experiment) demonstrate feedthrough and the decreasing amplitude oscillations in Figures 6 (simulation) and 8 (experiment) indicate successful feedthrough cancellation.

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 nonvolitional 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 nonvolitional 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 nonvolitional torque and the platform acceleration were recorded with a sampling rate of $100Hz$. The estimate of the transfer function from acceleration to nonvolitional 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.

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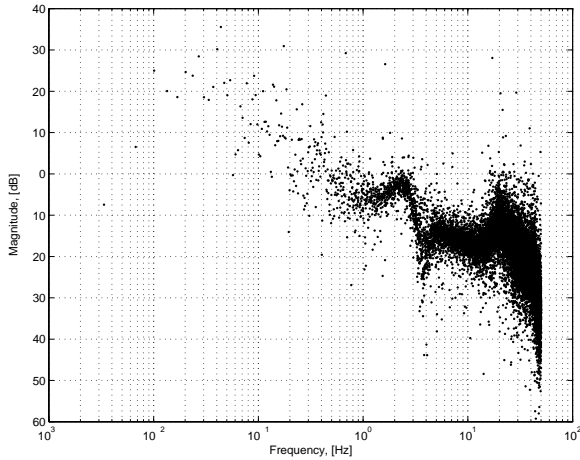The result can be seen in Fig. 9.

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 Fig 10.
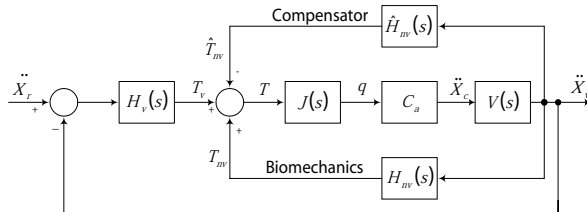

Figure 10.   Proposed solution for feedthrough cancellation

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. The cancellation torque was equal to the product of sensed vehicle acceleration and a constant.

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 tracking open loop 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 reference signal and the plant output were recorded with a sampling rate of $100Hz$. 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 crosscorrelation 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.
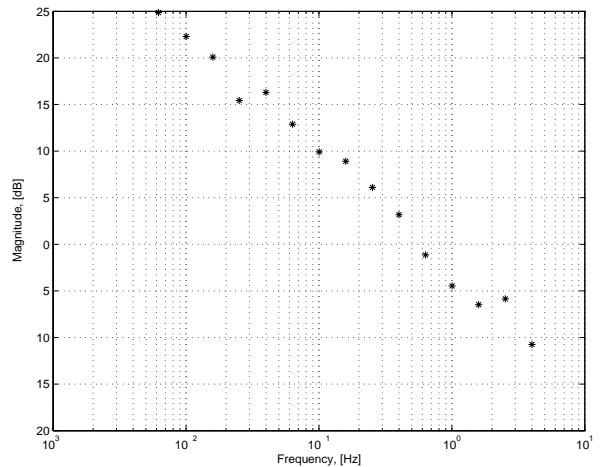

Figure 11.   Open loop transfer function of tracking

Three performance metrics were used, the crossover frequency f_c, the rms average of the tracking error, e_{RMS} and the arithmetic average of the Bode magnitude of the open-loop tracking transfer function above the crossover frequency, where tracking takes place. These are shown in Table :

The numbers indicate performance degradation as a consequence of platform motion and performance improvement due to
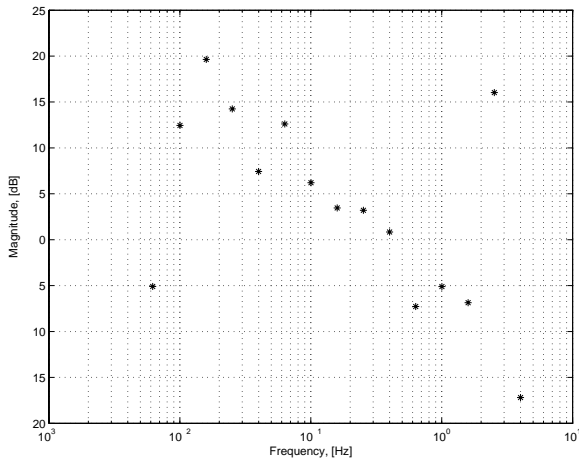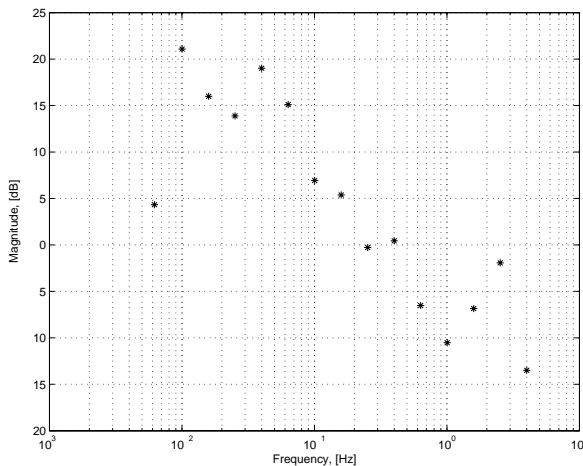
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Figure 12. Open loop transfer function of tracking

Figure 13. Open loop transfer function of tracking

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
magn [dB]	13	7	10

the cancellation controller.

McRuer's crossover model states that the open-loop transfer function of the HO has a $-20dB/dec$ slope in the crossover region, with a crossover frequency in the range of $0.5 - 1Hz$ in case of unpredictable reference signals. The output is delayed with respect to the input by $150 - 300ms$ 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 an inconsistent 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 case of an unpredictable tracking reference signal this can not be a consequence of volitional tracking activity due to its high frequency. Instead, because of the coincidence 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 can not be caused by joystick resonance, hence it is suspected to belong to that of body-parts. 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 9 between $6Hz$ and $10Hz$. This frequency range coincides with that of the resonances caused by stretch reflexes of the hand and the arm. It may not be possible to attribute this coincidence to causality 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.

The plot corresponding to acceleration compensation is a transition between the other two.

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

SUMMARY AND CONCLUSIONS

In the present work the existence and cancellation of unstable, closed loop vibrations was simulated and demonstrated on a vibration test bed and on a RMS in case of a second order operator model. Initial human subject test results were obtained. The harmful effect of vehicle vibration on human operator tracking performance was demonstrated by human subject tests. The implementation of a simple cancellation controller improved the continuous pursuit tracking performance of a human operator in a remote control task.

FUTURE WORK

In forthcoming studies the torso and the arm of the operator will be modeled 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

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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.

Further plans include carrying out more human subject tests, realizing feedthrough and feedthrough cancellation in piloting tasks on an RMS with motion and force sticks. Force sensing joysticks are more prone to beget unstable oscillations according to Griffin [7].

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