SHARED CONTROL BETWEEN HUMAN AND MACHINE: USING A HAPTIC STEERING WHEEL TO AID IN LAND VEHICLE GUIDANCE

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When humans interface with machines, the control interface is usually passive and its response contains little information pertinent to the state of the environment. Usually, information flows through the interface from human to machine but not so often in the reverse direction. This work proposes a control architecture in which bi-directional information transfer occurs across the control interface, allowing the human to use the interface to simultaneously exert control and extract information. In this alternative control architecture, which we call shared control, the human utilizes the haptic sensory modality to share control of the machine interface with an automatic controller. We present a fixed-base driving simulator experiment in which subjects take advantage of a haptic steering wheel, which aids them in a path following task. Results indicate that the haptic steering wheel allows a significant reduction in visual demand while improving path following performance.

INTRODUCTION

In man-machine systems, the mechanical response of the control interface (e.g., knob, mouse, joystick, steering wheel) to the action of a human is not typically considered as a feedback signal to the human operator. Rather, a visual or auditory sensory input closes the loop in the traditional manual control analyses (Sheridan & Ferrell, 1974). In many cases, the response from the control interface does not carry information pertinent to the execution of manual control. We propose the explicit design (and analysis) of the response signal from a control interface to take advantage of the haptic (tactile and kinesthetic) sensory capabilities of the human. The haptic information will supplement the traditional sensory inputs (visual, auditory) and will be designed to improve the human/machine system performance. To synthesize the haptic feedback, we propose the use of a haptic interface (sometimes called "force-reflecting interface") as the control interface of the machine. In the following sections, we develop the idea of a haptic control interface in the context of ground vehicle steering.

SHARED CONTROL OF STEERING

Mechanized control has many advantages over human control including tireless vigilance, increased precision, fast processing, and fast response. Drivers use automatic control of speed today in autos (cruise control). GPS-guided control of both heading and speed for agricultural vehicles is also under development (Bell, 2000; O'Connor, Elkiam, & Parkinson, 1996). Humans, on the other hand, can quickly develop and use models that predict system behavior and have access to a rich set of sensory inputs. Thus, a challenge in man-machine system design is to combine the advantages of human and mechanized control.

Supervisory control, espoused by Sheridan (1992) combines human and mechanized control as depicted in Figure 1 (dotted lines represent signals or information, while solid lines represent power exchange). As a supervisor, the human makes changes to the state of a controller through a control interface and monitors the system for unexpected changes. Generally, the human turns knobs to adjust gains or set points in the controller while the controller closes the primary feedback loop around the machine (supervisory control describes the architecture used for cruise control in automobiles).

We propose an alternative control architecture, which we call shared control. In shared control, depicted in Figure 2, the human effectively "shares" control of the interface with an automatic controller or virtual agent. The agent is placed in the perceptual space of the human through the use of haptic display: the human feels the agent through a motorized steering wheel.

Thus, both the human and controller exchange power with the control interface, which in turn drives the vehicle. Because the human and controller are mechanically coupled to the interface, this scheme allows the human to seize control of the system and override the controller if necessary. It also allows for the surrender of control if it is decidedly safe to do so. If successful, the driver would be able to simultaneously feel the action of the agent and the tire/road interaction through the steering wheel and would be able to distinguish the two. Further, he or she would be free to override the agent or the tire/road interaction by increasing his or her own action.

Our ideas about shared control are drawn from virtual fixtures, which has found wide application in the fields of teleoperation and haptic interface (Rosenberg, 1994). Virtual fixtures are objects synthesized by a controller and rendered through a force-reflecting master (in teleoperation) or haptic interface. Shared control makes use of "live" fixtures, which we call agents. The virtual agent can be thought to have its hands on the wheel at the same time the human does, in much the same way a teacher would guide a student learning to drive. The efficacy of virtual fixtures (and we hope shared control) rests in the innate human tendency to perceive sensory inputs (even if they are computer-synthesized) as if they were due to objects (or agents) in the environment (White, 1970).

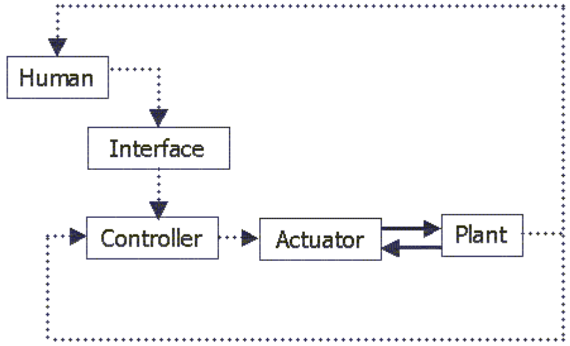


Figure 1. Supervisory Control of a Control Interface

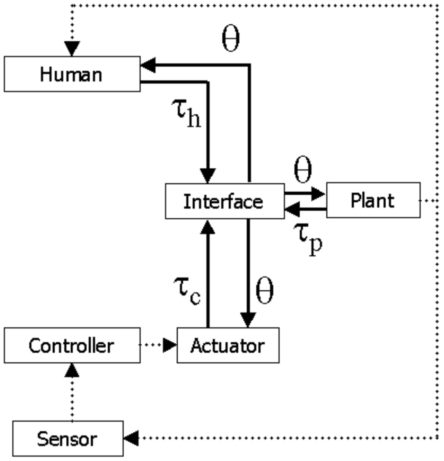


Figure 2. Shared Control of a Control Interface

We have designed a controller that can autonomously steer a vehicle along a pre-defined path. Our controller uses lateral displacement (sensed with GPS) to calculate a desired steering angle appropriate for good path following performance. Through a motor, it then applies a torque to the steering wheel that is proportional to the difference between the actual and the desired steering angle. Thus, a virtual "detent" is created and centered at the desired wheel position. The detent moves as the controller-generated steering angle set-point changes during path approach and following. By feeling this detent, the driver becomes aware of the actions of the agent.

Currently, in autos and off-road vehicles, drivers are loaded to a large extend with visual information. The haptic (tactile) modality, on the other hand, is a relatively underused sensory modality. In the first part of our experiment, we test our first hypothesis: that shared control architecture will relax the load on the driver's visual modality resource, reducing the demand for visual cues in the environment. This hypothesis is rooted in the multiple resource theory (Wickens & Liu, 1988). Because the controller aids the human in the driving task, we also imagine that some of the load on the driver's cognitive processing resources will also be relaxed. In the second part of the experiment, we tested our second hypothesis: that shared control will also unload on the driver's cognitive processing resources, freeing up cognitive processing capacity for other thinking tasks.

Related Work

The feasibility of an active steering wheel that communicates with a driver has been studied to a limited extent. Schumann, Godthelp, and Hoekstra (1992) investigated the use of an active steering wheel for lateral control of an automobile. They used a fixed base simulator composed of a Volvo 240 mock up that was equipped with a motorized steering wheel. Their results showed that a steady torque shift led to significant improvment, but that neither a short vibratory stimulus nor a steady, continuous torque feedback led to any improvement in vehicle control.

Schumann & Naab (1992) investigated the use of an active steering wheel for lateral control of a car, specifically in curve driving and overtaking (passing). They conducted a field experiment in a BMW 730i, which was outfitted with a heading control system making use of machine vision. In the first half of the experiment, a control system was able to provide haptic information cues to aid a driver in following a curve. The results showed no significant positive effect on control performance or control strategy for either of two variable factors: steering support strategy (short torque shift versus continuous torque feedback), and task demand (easy versus difficult). In the second half of the experiment, the control system provided two types of warning that were designed to interrupt and prevent the overtaking of a vehicle ahead of the driver. One was an auditory signal and the other was a vibratory haptic stimulus. Drivers were given a warning triggered by a time-to-lane-crossing, which is defined as the time remaining until the left fender of the car would cross over the center line of the road. They found that drivers were more likely to react to the haptic warning than to the auditory warning, though more than 50% of the subjects did not respond to either warning at all.

Of these papers, one had a positive result (Schumann, Godthelp, & Hoekstra, 1992). It suggested that a haptic device could improve the performance of a driver in avoiding dangerous lane changes. The other investigation showed no significant change in control strategy or control performance with the use of a haptic wheel, but significant results when using haptic feedback to interrupt a dangerous overtaking maneuver (Schumann & Naab, 1992). At least these studies provide encouragement for further research, but they also leave a significant volume of work left undone. Based on these papers, we know that a haptic steering wheel can communicate some sort of information to the human, and that we can use that mode of communication to present valuable vehicle guidance information to the human.

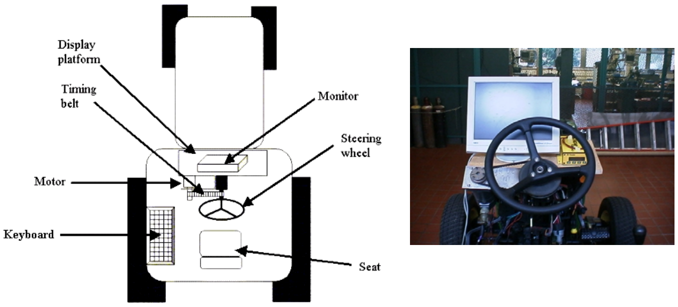
METHOD

Description

The overall experiment was divided into two distinct experiments. The first was aimed at quantifying the ability of the intelligent haptic interface to aid subjects in a path following task while reducing demand for visual cues. The second experiment was aimed at quantifying the ability of the haptic interface to aid the subject in a path following task while reducing the load on a driver's cognitive processing capacity. Both were conducted on a stationary John Deere 4700 tractor. To simulate the visuals of a driving task, a 15-inch monitor was placed before the subjects as they sat in the driver's seat. Subjects were presented with a wire-frame model of two curbs on either side of the vehicle and a dotted line down the middle of those lines, delineating a desired path. The path was straight throughout the course and was 2600 meters in length. The obstacles consisted of 1-meter cubes that sat on the path and were centered on the reference path. In all trials for all subjects, the obstacles were placed at 100, 500, 750, 1500, and 2500 meters from the start point.

Tasks

Drivers were asked to steer the vehicle with a motorized steering wheel and follow the straight path as closely as possible without colliding with any of the obstacles. In both cases, subjects were instructed that their highest priority should be obstacle avoidance and their second priority should be their performance in following the reference path.



(a) (b)

Figure 3. Experimental apparatus diagram (a) and photo (b)

Equipment

Using a desktop PC and an I/O card to communicate between the PC and a servo motor/encoder pair, a haptic steering wheel was created for use in the experiment. The motor was coupled to the shaft of the steering wheel with a timing belt and pulleys. All hardware was mounted upon the John Deere 4700 series utility tractor.

Participants

22 subjects, 19 men and 3 women, were recruited to participate in this study on a voluntary basis with no monetary compensation. All had been licensed drivers for at least 2 years.

Experimental Design

Experiment 1. The first experiment measured three dependent variables. The first two were performance measures – measures of performance on two typical driving tasks (obstacle avoidance and path following). The simulator logged the number of obstacle collisions and the vehicle's lateral deviation from the reference path. The third metric was visual demand. To measure the participants' demand for visual cues, the visual occlusion method was used (Green, 1998). In this method, participants pressed a button to get a half-second glimpse of the road and desired path whenever they felt that they needed to in order to successfully follow the path or avoid an obstacle. Outside of those half-second intervals, their vision of the environment was occluded (the screen was blank). Visual demand was directly related to the frequency at which the subject pressed the button during the trial. Each subject performed the trial once with no haptic feedback and once with haptic feedback in randomized order.

Experiment 2. The second experiment measured the subjects' overall performance on three time-sharing cognitive tasks. The first two tasks were identical to those in Experiment 1 (obstacle avoidance and path following) but the third task required cognitive processing: mental arithmetic. Subjects were required to orally count backwards from 1000 by 3's throughout the duration of the trial while their voices were recorded on tape. This tertiary task was used as a measure of reserve cognitive processing capacity of the human. Each subject performed the trial once with no haptic feedback and once with haptic feedback in randomized order.

Procedure

Experiment 1. The participants were instructed about the tasks they would perform and that they were to follow as closely as possible the dotted line with the center of their vehicle without colliding with any obstacles. They were explicitly instructed that they should avoid the obstacles at all costs, and that path following could be considered the second priority. Each subject practiced until indicating that he or she was comfortable with the experiment and its setup. Once the recorded trials began, each subject navigated the course twice, once with and once without the intelligent haptic interface (in alternating order for each successive subject).

Experiment 2. The participants were instructed about the tasks they would perform and that they were to follow as closely as possible the dotted line without colliding with any obstacles. They were instructed that their performance on the mental arithmetic task should be considered of lowest priority and that they should not sacrifice performance on the two primary tasks in order to improve performance in the arithmetic task. Each practiced until comfortable with the experiment and its setup. Once the recorded trials began, each subject navigated the course twice, once with and once without the intelligent haptic interface (in alternating order for each successive subject).

RESULTS

After experiment 1, the following data were compiled across all subjects:

1) Number of obstacles collided over entire course (0-5)
2) Mean lateral deviation from desired path (meters)
3) Number of key presses

	No Haptic Feedback		Haptic Feedback	
	Mean	StDev	Mean	StDev
Ratio Collisions to Potential Collisions	0.045	0.105	0.009	0.042
Lateral Deviation (m)	1.551	0.903	0.745	0.448
Key Presses	199	52.2	116	44.9

Table 1. Average performance metrics for experiment 1

After experiment 2, the following data were compiled across all subjects:

1) Number of obstacles collided (0-5)
2) Mean lateral deviation from desired path (meters)
3) Number of mental arithmetic calculations performed
4) Number of mistakes made during mental task

	No Haptic Feedback		Haptic Feedback		% Change in Mean
	Mean	StDev	Mean	StDev	
Ratio Collisions to Potential Collisions	0.01	0.04	0.01	0.04	-
Lateral Deviation (m)	1.02	0.71	0.53	0.23	-48.0%
Calculation Performed	118.3	44.2	123.1	39.7	+4.0%
Mistakes Made	2.55	1.63	2.00	1.45	-21.6%

Table 2. Average performance metrics for experiment 2.

Table 1 shows the average performance results for experiment 1, in which visual demand was measured, while Table 2 shows the average performance results for experiment 2, in which cognitive processing capacity was measured.

Each key press gives us an instantaneous measure of visual demand as defined by Shafer, Brackett, and Krammes (1995), and shown in Equation 1. Equation 1 defines $VisD_i$ as the visual demand over the time interval from one key press to the next. Figures 4 and 5 show profiles (averaged across all subjects) of visual demand plotted against longitudinal position of the vehicle.

$$VisD_i = \frac{0.5}{t_i - t_{i-1}} \tag{1}$$

Visual demand in the case without haptic feedback in Figure 4 seems to be roughly the same near obstacles, marked with vertical lines on the plots, as it is away from obstacles. However, in the case with haptic feedback in Figure 5, there are distinct crests in visual demand near the obstacles and the nominal visual demand is reduced. Table 3 shows average visual demand parsed into the two phases described earlier – near obstacles and away from obstacle.

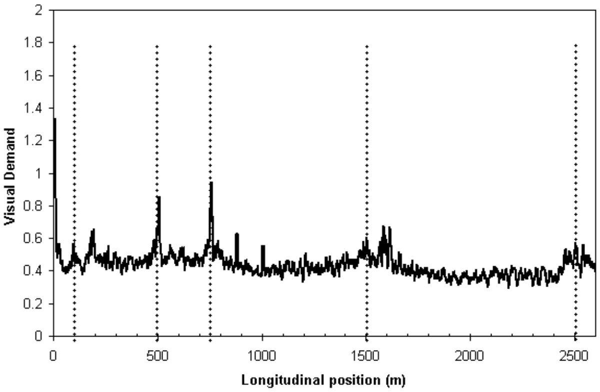


Figure 4. Visual demand profile without haptic feedback. Vertical lines represent positions of obstacles

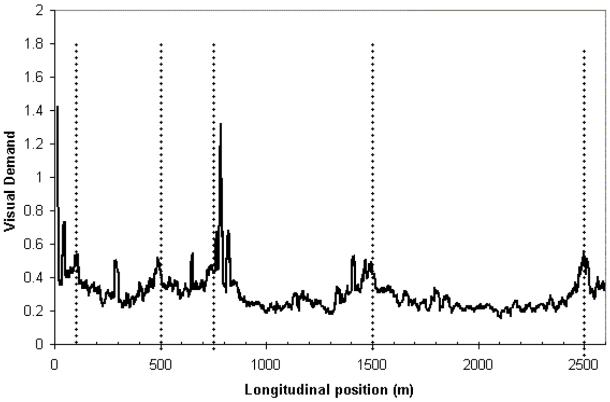


Figure 5. Visual demand profile with haptic feedback. Vertical lines represent positions of obstacles

These results suggest that, without the benefit of haptic feedback, the subjects experienced visual demand while they were away from any obstacle that was similar to the demand they experienced near obstacles. However, when the subjects have the benefit of haptic feedback, their visual demand was much lower when away from obstacles than it was near obstacles. From this result, we can conclude that the subjects allowed the controller to aid in their path following while they were not near obstacles and therefore needed fewer visual cues to perform the job at hand.

	Without Haptic Feedback	With Haptic Feedback
Within 50 meters of obstacles	0.44	0.35
Outside of 50 meters from obstacles	0.37	0.19

Table 3. Average visual demand near and away from obstacles

DISCUSSION

Experiment 1. The data suggest that, using an intelligent, haptic steering wheel rather than a traditional passive steering wheel, subjects are better able to closely follow a reference path while requiring fewer visual cues. T-tests were performed on the mean lateral reference path deviation and visual demand metrics to evaluate the significance of the mean differences between the two groups (with haptic feedback/without haptic feedback). Subjects had 42% lower visual demand with the use of the haptic feedback, $p < 0.0001$. They also cut their path following error (lateral deviation from desired path) by 50% when they had the advantage of the haptic feedback, $p < 0.0001$. This reduction in visual demand was seen after just a few minutes of using the haptic steering wheel, which was very new to the subjects. It is quite possible that, given time to learn how to use the wheel and how to optimally share control of the vehicle with the controller, the visual demand would drop even further.

Of particular interest is the difference in visual demand between the two "phases" described in the previous section (near obstacles/away from obstacles). When the haptic feedback was used, and during the periods in which there were no obstacles near, the subjects were able to trust the controller/intelligent wheel to guide them toward the path with little or no visual input. However, when the haptic feedback was off, the subjects had nearly as much visual demand away from obstacles as they did near obstacles because they needed visual cues in order to follow the reference path.

Experiment 2. We see a 48% reduction in mean lateral deviation from the desired path across all subjects, $p < 0.0007$. However, the difference from one group to the other in number of calculations performed is small and should not be considered statistically significant, $p < 0.1517$. So there is no evidence to suggest that the subjects had a significantly increased availability of cognitive processing capacity when they had the benefit of the intelligent steering wheel.

The reasons for this phenomenon in the results can probably be explained by one (or both) of two theories. It is possible that the driving task was too easy and highly learned to demand significant cognitive workload, which would explain the lack of improvement in the cognitive counting task between the two groups. Driving, for those who have accumulated experience for several years, is a highly learned task. One attribute of learned tasks is that they require a minimal amount of cognitive processing to perform. In case of this experiment, in which subjects performed a simple, highly learned task, an assist device like the haptic steering wheel may not lead to a significant reduction in cognitive loading. We also know that a task requiring verbal recitation of numbers makes use of the verbal cognitive processing code. However, driving tasks are clearly tasks that made use of the subjects' spatial central processing code. Given the lack of competition for central processing code resources, the humans were likely able to perform the spatial driving task with little interference with the verbal counting task.

SUMMARY

We have demonstrated the feasibility of a haptic steering wheel as a method of providing bi-directional information transfer between a human and a machine. In a path following task for land vehicles, we see significantly less visual demand with the aid of a haptic steering wheel. We envision the development of shared control for agricultural vehicles, where the driver must simultaneously control many machines, and the extension of this idea to other applications.

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