Haptic Guidance, Interaction Between the Guidance Model and Tuning

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A haptic interface, also called haptic display, is a system that informs and aids a human operator by forces on the control device (stick, steering wheel or other). These interfaces are being explored for many fields, e.g., for UAV control, (tele-)robotics, automotive control and flying. The force feedback helps in control tasks and increases the operator's awareness. Proper design of such interfaces promotes "shared control", where an autonomous agent and the human operator can jointly exercise control on a dynamic system. The human's flexibility and adaptivity of his neuromuscular system offers ways to override the haptic support, should this be necessary. Haptic interfaces require design decisions on three issues: ***(a)*** The appropriate guidance laws should be developed, thus the behavior of the automated agent must be defined. This guidance should be inherently safe and useful, and it should be compatible with human control strategies, ***(b)*** The guidance should be translated to haptic input on the control device. Here additional force and modification of the control device's apparent properties (mass, damping, spring coefficients) can be used, and ***(c)*** The scaling between the guidance and the haptic input should be tuned to the proper level. From the above, it appears possible to break down the design process into individual steps. However, in a recent research project in which individualized guidance laws were investigated, we discovered an interaction between the guidance laws and the perceived haptic feedback strength, where variation in the guidance laws produced an apparent change in haptic authority by the automation. This paper discusses this experiment – car driving with lateral support – and analyses the causes of the interaction. The results include recommendations for removing this interaction.

Introduction

Recently, an increased interest is signalled for haptic interfaces (or haptic displays) for vehicles. These interfaces use an operator's sense of feeling or touch to display information about the environment or about the device that is being operated. NISSAN for example markets a haptic gas pedal, that can provide force feedback to the driver about obstacles or vehicles detected in front of one's car. In aviation, research has been performed on UAV control and in-aircraft haptic feedback (Lam, Mulder, van Paassen, Mulder, & van der Helm, 2009; de Stigter, Mulder, & van Paassen, 2007; Goodrich, Schutte, & Williams, 2011). When the forces created by the haptic display can influence the input to the controlled system, a *shared control* situation is created. Both the human operator and the system's automation, through the haptic interface, exert an influence on the control input.

The advantages of haptic shared control over conventional assistance by automation are that the actions of the automation are easily observed by the human operator, and, since the display is through the control device, the often overloaded visual channel is not further taxed. However, a shared control situation is in principle still a situation where a human operator is using automation to perform a task. Issues identified in similar situations, such as supervisory control, still apply. Thus reliability of the automation, complacency, (over-)reliance, transparency, and level of automation are relevant issues (Abbink, Mulder, & Boer, 2012). In addition to that, new aspects in shared control are ***(a)*** the continuously variable balance between the human operator's and the automated controller's contributions, and ***(b)*** the fact that the control input is now the sum of the individual inputs of human and automation.

An implication from the first aspect is that the authority of automation versus the authority of the human operator must be made explicit in the design of the haptic device. The choice for device parameters such as stiffness, and the tuning of the device's force feedback, affect this balance. Combined with the fact that the human's neuromuscular system can also adapt, this means that this tuning is not easily arrived at by trial and error. Human adaptability means that a large range of tuning setting produce acceptable behavior for nominal conditions, and an argued choice needs conscious selection of a setting based on neuromuscular system characteristics and task requirements. This issue was explored for a system with haptic feedback for a UAV (Abbink, Cleij, Mulder, & van Paassen, 2012; Sunil, Smisek, van Paassen, & Mulder, 2014).

The consequence of the summing of control forces through the haptic interface means that shared control situations need to be analysed with respect to their control properties. One of the issues is that the control actions by the human and automation must be complimentary, and not counteracting each other. We explored this in a car driving experiment on curve negotiation with haptic support. It is well known that drivers do not follow the center of the road in corners, but slightly "cut" the corners resulting in better driving comfort, and individual differences exist. In our research, we fit a guidance model to drivers' natural preferences, and evaluated the difference between individualised guidance (IG), in which the guidance model was fit to a specific subject's behavior, and a "one size fits all" (OSFA) variant. The surprising result was that many subjects rejected the individualised guidance in favor of the OSFA variant (Boink, van Paassen, Mulder, & Abbink, 2014).

This paper discusses the experiments and investigates the causes for its findings. Then it lists an overview of the design considerations for haptic shared control that were discovered after analysing our results. In addition to the abovementioned experiment, available descriptions in literature of shared-control set-ups are considered and analysed in the light of these design considerations.

Haptic shared control

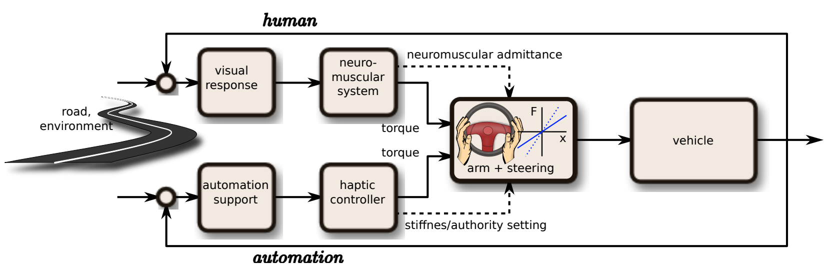

Figure 1. Schematic representation of haptic shared control. Both the automation and human user formulate an input, which is implemented by the combined torque on hands and steering wheel.

In a vehicle with haptic shared control, both the human operator and an automated agent influence the control input; the human through exerting a torque on the steering wheel, and the automation through an additional torque on the wheel from, e.g., an electric motor. In addition, the wheel may have its own dynamic characteristics, typically mass and damping, and the torques on the front wheels (self-aligning torque) are passed through the linkage, resulting in an apparent stiffness of the steering wheel(K_s). Figure 1 depicts this situation. This is effectively the same as the set-up described in Fig. 2 in (Griffiths & Gillespie, 2004), which has a slightly different format for the block diagram, since it expressly shows how the self-aligning torque in a simulation is implemented by the electric motor.

When the steering wheel – or another control device – is held by the human operator, the human's muscular force and the torque from the haptic feedback system act on the combined dynamic properties of that coupled system. A human can generally influence the dynamics of his/her limb, by changing the setting of the neuromuscular system, effectively increasing or decreasing limb stiffness. If properly equipped, the haptic device's stiffness (and possibly damping and mass as well) can be modified in an analogous manner. Such modifications serve to shift the weight of the human contribution to the system input versus the haptic automation's contribution (Abbink & Mulder, 2010); this modulation is indicated by the dashed arrows in Fig. 1.

An important component in the haptic shared control is the generation of the guidance. Two situations are generally distinguished. The shared control may have the purpose of avoiding collisions with obstacles, in that case the haptic display shows *virtual fixtures*, virtual obstacles and boundaries simulated through repulsive forces. In the case of car driving, when only one lane is considered – or a mechanism is provided to detect the desire for a lane change, and the automatic controller can switch lanes – the guidance can be continuous, and the goal of the automation can be defined as keeping the vehicle on an "optimal" track. Rather than virtual fixtures that the vehicle can "hit", a continuous virtual fixture is implemented that pulls the vehicle to a specific target.

For an effective haptic interface, this target should coincide with the driving behavior that a human driver would find acceptable. In curves, assuming a position of the car on the center of the road does not reflect how human drivers will negotiate a curve. In our experiment (Boink et al., 2014), we identified the manner in which drivers negotiated a curve, and fit this with a simple model that calculates the steering wheel angle given the difference between the nominal track and the lateral position of the car at some look-ahead time t_{LH}:

$$\delta_{wt}(t) = K_\delta E_{t_{LH}}(t) \tag{1}$$

Here $E_{t_{LH}}(t)$ is the lateral error of a predicted position of the car created by integrating a model with the car's current velocity and rotational rate over a prediction time t_{LH}. The K_δ and T_{LH} parameters were identified for each subject individually, and Eq. 1 was used to create the nominal path for the haptic control. In addition a version of the controller was tested which used parameters in the center of the parameter space observed for all participants ("One Size Fits All", indicated with the red circle in Fig. 2).

To convert the nominal path into a guidance force, a scaling gain needs to be determined. Here, this gain is based on the stiffness of the steering wheel (K_s), on the assumption that torque from the haptic feedback system should generate the proper steering wheel angle when the user does not hold the steering wheel:

$$F_{wt}(t) = K_s\left(K_\delta E_{t_{LH}}(t)\right) \tag{2}$$

Experiment

To test our hypothesis that inddividual guidance (IG) would be preferred over OSFA, an experiment with 24 subjects was performed in a fixed-base driving simulator. The simulator was equipped with a Nissan steering wheel actuated by a Moog-FCS ECol-8000 S actuator. In a first session, participants drove a track with alternating left and right curves over 45 degrees, with a 250 m radius. No haptic feedback was provided in this session. A visual scene was projected on the walls in front and to the side of the simulator, providing a field-of-view of almost 180 degrees. The velocity of the simulated car was fixed to 80 km/h. An individualised model (IG) as in Eq. 1 was fit to the data of this run. On the basis of the IG model fits, also an OSFA fit was determined. In a second session, subjects performed runs with haptic guidance, with either the IG or the OSFA tuning. Figure 2 shows the spread of the tuning parameters and the OSFA tuning. After each pair of runs, subjects were asked to indicate their preference for either the first or second run.

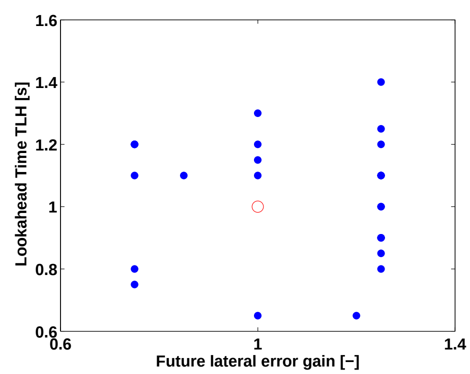

Figure 2. Individual fits of look-ahead time and lateral error gain ($K_S K_\delta$) used in the experiment (Boink et al., 2014).

Results and Discussion

Figure 3 gives an example of a single curve driven by a "medium-gain" subject, in the OSFA condition. In addition, the curve driven by the subject in the absence of haptic support, and the result of letting the haptic support system "drive alone" is given. A number of surprising results can be noted ***(a)*** The lateral error (note that this is the lateral error at the look-ahead point) is fairly small when the human is driving – with or without haptic support –, indicating a successfully driven curve; ***(b)*** When the haptic automation drives alone (hands off steering wheel), the errors are fairly large, indicating that the control law in Eq. 2 is actually not effective; ***(c)*** Finally, the force from the guidance actually seems to oppose the human torque over a large stretch of the curve.This latter result was found with multiple subjects, and often with subjects with curve negotiation behavior that resulted in model fits with high gains and large look-ahead times.

The experiment expressly adressed one of the design decisions in creating a haptic support system, namely the question of *what should be the reference trajectory for the haptic support system*. Rather than taking the lane's center, which would result in unnatural driving behavior, a simple control law is fitted to observed control behavior.

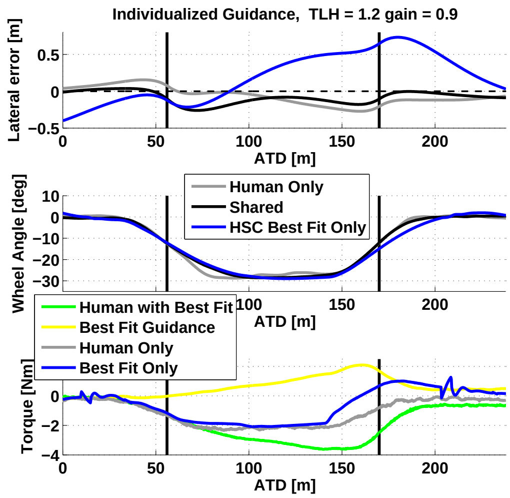

Figure 3. Example run from a subject with and without individualised haptic shared control, illustrating in this case initially no, and later negative contribution of the guidance to the steering wheel torque.

Compared to an older experiment (Abbink, Cleij, et al., 2012), in which the reference was created by averaging a number of previous runs, the present approach is more general.

One of the other surprising results from this experiment was that more subjects preferred the OSFA tuning of the controller over the adaptive tuning. Upon further inspection, it proved that this correlated with the gain of the individual tuning; subjects which had a lower gain, preferred the individualised tuning settings, and subjects with higher gain preferred the OSFA tuning. To investigate possible causes for this, a further analysis of the controller and the haptic feedback it provides was done.

Given that the log data indicates that the haptic guidance often counteracts the human control input, it could be expected that a weaker haptic guidance is to be preferred over a stronger one. This was also found by Mars et al., 2014, although that research in addition forced unnatural curve negotiations, since the haptic feedback was based on the lane center. However, why would the haptic guidance not contribute to the control goal or even counteract the human control? And also, why would haptic guidance alone not create a proper control of the vehicle?

To analyse the effect of the control law, a small-angle approximation is used for the future lateral position error $E_{t_{LH}}$:

$$\tilde{E}_{t_{LH}} = V t_{LH} \left(\Psi(t) - \Psi_r(t) \right) + \left(y(t) - y_r(t) \right) \tag{3}$$

To determine the effect on haptic feedback, consider a run in which the subject exactly replicates the steering commands, as measured in the runs without haptic support and as captured in the model in Eq. 1. In that case, the lateral error at the look-ahead point ($E_{t_{LH}}$) is minimal; the only source of deviation between the reference model and the user's run would be the remaining variation in the user's driving that could not be captured by the model. According to Eq. 2 the haptic feedback force would be nearly zero in this case. Inspection of a similar architecture in literature (Griffiths & Gillespie, 2004) suggests that the same occurs in that set-up; with successful control by the human, and a zero control error, there is no torque contribution from the haptic support for curve negotiation. This relates to a second design decision that needs to be made, *how much should the haptic support system contribute to the control effort in nominal (no-deviation from target) cases?*. The haptic support system tested in our experiment relied on error between the determined nominal path and the driven path. In this case, subjects who seek support from the haptic system need to allow deviations from the nominal path before getting this support. The hands-free runs in Fig. 3 are an illustration of this point. If the haptic support system needs to supply a contribution to the steering input, it needs separate information from both the target signal and the current error signal; enabling the calculation of separate haptic support torques for following the track (feed-forward of the target signal, block *LoHS* in 4) and for correcting deviations from the track (feedback of remaining execution errors, block *SoHF*).

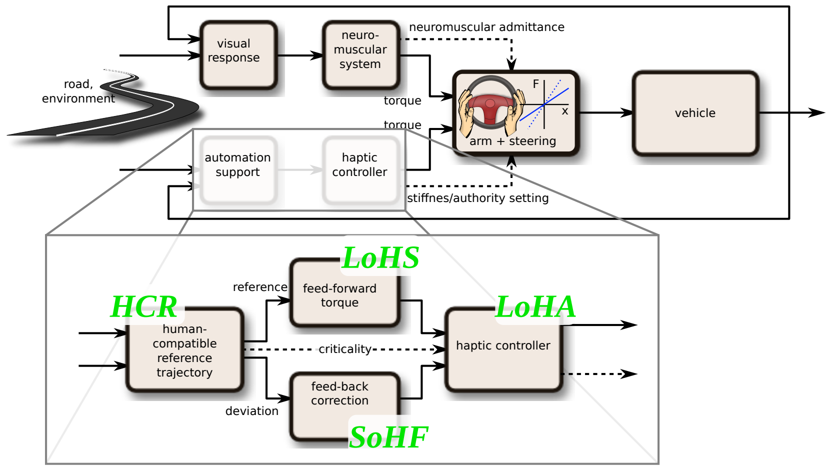

Figure 4. Schematic representation of haptic shared control, detailing the four design choices identified in this paper.

Now consider a lateral error in the car position $y_r(t) - y(t)$. For each unit in lateral deviation, a feedback force of $K_s K_\delta \left(y_r(t) - y(t)\right)$ [Nm] will be generated. A lateral deviation in car heading has a similar effect, now with a gain of $K_s K_\delta V t_{LH} \left(\Psi_r(t) - \Psi(t)\right)$. However, in this case both the gain K_δ and look ahead time t_{LH} are parameters from the individual lateral guidance model fit to the subject's runs without haptic guidance, and not parameters chosen to tune the strength of the haptic feedback. The experiment thus had a confounding effect, in that the preference for curve negotiation influenced the strength of the haptic feedback to deviations from the nominal path. This amounts to the third design decision, *how strong should be the feedback to deviations from the nominal path?* A related decision is the weighting of what constitutes a "deviation". In this case, deviation can be expressed in lateral position and in heading deviation. A control law needs to determine how these are weighed; such a control law depends on the dynamics of the controlled system, required performance and the comfort levels that one wants to attain.

The final design decision concerns the *authority of the haptic controller*. In analogy to the Level of Authority in supervisory control (Parasuraman, Sheridan, & Wickens, 2000; Sheridan & Parasuraman, 2005), Abbink et al. (Abbink, Mulder, & Boer, 2012) coined the phrase Level of Haptic Authority (LoHA). By selecting the control device's stiffness settings – fixed or possibly variable – one can influence the weight of the automation in determining the final control input. Given that the human operator has the means to adjust the settings of their neuromuscular system, this will result in a range of division of LoHA between automation and human.

Note that with a high level of haptic authority, in a system designed without haptic support, the haptic interface will still push the system towards the reference, however before that happens a control error needs to build up in the system, and the path that results will no longer match the subject's curve negotiation strategy. This behavior annoyed some of the subjects in our experiments, since when subjects implement the proper control strategy, the automation does not contribute to the control signal, except to correct any deviations.

Conclusion

Haptic shared control is common practice in training settings in aircraft; typically the instructor's and student's controls in a trainer aircraft are mechanically linked, and a good instructor can make a student feel the necessary inputs, reduce their LoHA – both in generating feed-forward and corrective feed-back inputs, and there is a common and compatible (visual frame of) reference. Such a situation can be seen as a reference for haptic shared control. An implementation of haptic shared control with automation requires that such an instructor's behaviour be made explicit with a number of design choices:

Human Compatible Reference (HCR) Generation of a reference for the control, compatible with user strategies and the device and environment constraints.

Level of Haptic Support (LoHS) A choice for the Level of Haptic Support; i.e., by how much will the automated system contribute to implementing a path that follows the reference (feed-forward).

Strength and Strategy of Haptic Feeback (SoHF) A choice for the strength of the haptic feedback and the control law upon which this feedback is based (in this case, weighing lateral and heading error); i.e., by what control law / aggressivenes will the automation provide corrective inputs to reduce the difference between the reference and the vehicle's path.

Level of Haptic Authority (LoHA) A choice for the level of haptic authority; i.e. how is the balance between human input and automation. A high level of authority is implemented by choosing a large base stiffness of the control device. In that case the feedback and autonomy signals (since they are adapted to the joint control device and human operator stiffness) scale too.

The first and fourth issues have been addressed in literature. Independently tuning the level of haptic support and the strength of the haptic feedback is a step that is still lacking in many designs.

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