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HAPTIC ASSISTANCE TO MITIGATE DAMAGING VERTICAL ACCELERATIONS OF SMALL SHIPS IN HEAD WAVES

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SUMMARY

Crew of small fast ships often experiences excessive vertical accelerations when sailing in waves, leading to discomfort and injuries. In an attempt to avoid this, experienced operators reduce speed voluntarily when they anticipate that the next vertical peak acceleration will be unacceptably large. However, at night and during excessive spray, the operator can hardly see the environment which makes it almost impossible to anticipate wave driven events. On top of that, this approach carries the risk of operator misjudgement due to loss of concentration or fatigue.

The objective of this paper is to investigate the potential of using haptic assistance to support operators in preventing excessive vertical accelerations, by using haptic speed advice on the throttle based on experienced wave statistics.

A stochastic based approach was used to construct a haptic algorithm, which gives a maximum advisable propeller speed setting based on an estimate of the current sea state. To test the effectiveness of this approach, a human-in-the-loop experiment was conducted. The effect of haptic assistance was compared to manual control under both good and reduced visibility conditions.

No significant decrease in the number of excessive accelerations was achieved when comparing equal conditions in the current experiment, although subjects controlled the ship with reduced workload.

The lack of significance indicates a difference in control strategy between the participants, for 16 out of 22 participants experienced less excessive accelerations when sailing shared control.

1. INTRODUCTION

The FRISC or Fast Raiding Interception and Special forces Craft is a small fast (45kts) special forces craft that is used by the Royal Netherlands Navy for anti-smuggling, anti-piracy, counter-terrorism and patrol missions. In Fig. 1 the raiding craft version of the FRISC is shown. A tactical advantage of the FRISC is its ability to operate at high speeds in adverse weather conditions. However, the physical strain that accompanies operating high-speed vessels in adverse conditions now proves the limiting factor in the employability of the FRISC. Operating in extreme conditions, the crew can experience dangerously high slamming impact forces, potentially causing severe injuries to the crew, as well as damage to the structure. This problem is not exclusive to the FRISC but holds for most small fast vessels [4], [14].

Fig. 1 The FRISC raiding craft in action [19].

The FRISC is operated by a minimum of two crew members: a navigator and a helmsman. In restricted waters the navigator communicates the directions to the helmsman who is standing with one hand on the wheel and one hand on the lever and has to keep all of his/her attention on the water, especially at high speeds. Due to the high load on the visual system of the helmsman, additional information is preferably provided through other sensory channels. Therefore, in this paper the potential of using haptic shared control (HSC) to assist the operators of small fast ships when sailing in waves is investigated.

Several measures have been taken in an effort to reduce the possibility of injuries due to wave induced vertical accelerations. These measures include shock absorbing chairs, a responsible sailing behaviour table and an extensive exercise program for the FRISC crew. Furthermore, the exposure time is limited by implementing strict deck cycles and resting periods.

When operators control a complex machine, the addition of force feedback on the controls reduces the workload, increase task performance and situational awareness [6]. When using haptic shared control not only visual but also the tactile and proprioceptive senses are used, which allows for fast control using reflexes and increased awareness. Although literature has shown the benefits of applying haptic shared control for driving, flying and remote operation (tele-operation), little attention has been directed towards implementing this promising technology in the maritime domain. The human-in-the-loop maritime simulator setup used by Hoeckx et al. [1] is one of the first attempts to apply haptic shared control in the maritime domain. Their main goal was to see if it is possible to increase safety of shipping by the introduction of haptic ship control. Towards this end, two actuated 2-DOF azimuth control levers were designed. In this paper the same levers are used to control a small fast ship.

2. VERTICAL ACCELERATIONS

From previous work on fast ships in waves [2], [3], [4], [14] it is known that the excessive vertical accelerations are the limiting factor in operations. Furthermore, from on-board measurements it was found that vertical peak accelerations have a very short duration and a relatively low frequency of occurrence [4]. It can be concluded that not all wave encounters will lead to an excessive vertical acceleration.

Understanding exactly what influences the vertical accelerations is the first step towards finding a mitigation measure. Peaks in vertical acceleration levels are the result of complex interplay between geometry, incoming wave characteristics, motion before impact and forward speed at impact [20]. Of these variables the incoming wave characteristics and the relative ship speed are most dominant. The largest accelerations occur in head seas at high forward speed with a low average wave period, which causes steep waves [8], [9].

The injuries that result from extremes in accelerations and excessive exposure can range from joint pain to severe kidney injury and fractured vertebrae. However, not only the extremes in vertical acceleration can cause injury to the human body but also the vibration dose and exposure time affect injury severity. The vibration dose can be reduced by significantly reducing the vessel speed and exposure time, which is undesirable given the type of operations that are typical for the FRISC and similar small fast ships. Therefore, the focus of this paper lies on reducing the extremes in vertical acceleration level. Identifying the damaging accelerations is a key point in finding a solution to the wave slamming problem. When measuring onboard accelerations in practice, the acceleration signals are normally measured by an accelerometer mounted on the structure of the vessel. The resulting raw signal needs to be processed to find the accelerations that can cause injuries to the human body. For this purpose a set of three signal processing steps as proposed by Coe et al. [10] is used in this paper:

- *A 10 Hz low-pass filter* - This filter removes the high frequency structural vibrations and other components that might locally have the same magnitude but a much higher frequency. These high frequency vibrations are not damaging to the human body.
- *A vertical threshold* - This threshold signifies the minimum acceleration magnitude that is required to count it as being an acceleration. Usually this threshold is set to the Root-Mean-Square (RMS) of the signal.
- *A horizontal threshold* - This threshold is used to signify that there cannot be multiple harmful accelerations within one wave encounter. Usually this threshold is set to 0.5 [sec] for analysing small fast ship accelerations. The harmful accelerations can be distinguished from the raw signal using the signal processing steps defined above.

Note that in this paper these signal processing steps are applied to the vertical acceleration signal generated by the ship simulator and the results are used to construct the Rayleigh database, which is explained later.

3. CONTROL STRATEGIES

Experienced operators tend to reduce speed when a large wave, which is expected to cause an unacceptable acceleration, is approaching [3]. This way of sailing is called active throttle control. The difficulty with this approach is that the operator has to see the wave, perform an estimation based on intuition/experience and reduce speed several seconds before the wave is encountered to allow the vessel to slow down significantly and reduce the severity of impact. This active throttle control was the inspiration for a mitigation measure called proactive thrust control, which was extensively researched at Delft University of Technology by van Deyzen [3] and Rijkens [2]. In their solution the system can be divided into three subsystems: (1) A wave measurement / prediction system, (2) A computational model that calculates the response of the ship to the predicted wave field in real-time for different speeds and (3) A control system, which automatically adjusts the propeller speed when required. Although this work is a valuable source of inspiration and proved that accelerations could be reduced using proactive thrust control, current (radar) technology has not been shown to be able to observe waves from a small fast-moving ship.

Another possible approach, used in this paper, is to adjust the ship speed according to the sea state that is encountered. The FRISC sails in conditions up to sea state 5, which is equal to 4 m significant wave height. In the VCZSK [5] (Voorschrift Commando Zeestrijdkrachten) a ’responsible’ ship speed table for the critical sea states (3-5) is provided. Application of the table has three drawbacks. First of all, the table does not discriminate between different waveheight- waveperiod combinations nor does it consider the sailing direction with respect to the waves. Secondly, it requires the operator to estimate the wave characteristics. Finally, operators need to remember and use the table correctly in the heat of the moment, which is not ideal. In this paper the drawbacks of the described table are countered by using onboard sensors to estimate the wave characteristics and by using haptic shared control to communicate the advised maximum ship speed.

Summarizing, the aim of this study is to investigate the effects of providing a haptic speed advice on the excessive accelerations encountered. Thus, the research question reads:

”To what extend can haptic feedback on the lever assist the operators of small fast ships in mitigating the excessive vertical accelerations due to wave slamming?”

It was hypothesized that when sailing with the haptic assistance the operator would experience less excessive accelerations compared to manual sailing. Because the operator currently almost fully relies on visual information the effect of reduced visibility when applying shared control is also investigated. Each condition was assessed with respect to three categories of measures: Performance, Safety and Workload.

4. THE EXPERIMENT

4.1. Participants

Twenty-four participants (4 female) between the ages of 22 and 57 (M=26.9, SD = 7.5) volunteered in a human-in-the-loop ship simulator experiment. More than half of the participants claimed to have significant experience on the water (sailing or motor boat). However, only 3 participants were in possession of a navigation license.

4.2. Apparatus

The haptic ship simulator setup was designed and built at Delft University of Technology. The setup as originally described by Hoeckx et al [1] was extended with the Fast Ship Simulator (FSSS) model from the E-Dolphin software developed by MARIN. The layout of the setup is shown in Fig. 2. The full setup consists of the following elements:

- Ship simulator - The FSSS as part of the MARIN E-Dolphin software was developed with the aim to perform training runs of potentially difficult and dynamic situations that are difficult to perform in real life. The high fidelity in the hydrodynamic behaviour of the simulated vessel is required because most risk factors are related to complex non-linear hydrodynamic ship behavior such as slamming, planing, broaching, ship-ship interactions, etc. The model used for the forces in the planning condition is based on slender body theory (2.5D). This method is an extended method of Zarnick’s strip theory [11], later extended to small fast vessels by Keuning [4], in which the hull is divided up into a number of segments for which the sum of the forces is calculated separately after which all of the forces are summed up to arrive at the total force acting on the hull. The simulated wave field follows a JONSWAP distribution. The behaviour of the model was validated using the measured ship response to regular waves. The final model used was E-Dolphin 5.2, which was modified to send the acceleration information directly over NMEA (National Maritime Electronics Association) protocol.
- Haptic levers - The haptic levers are custom-made by the Delft Haptics Lab by using the two 1 Degree of Freedom (DoF) levers from the Gemini (2014) project [18]. These levers are mounted to rotational discs such that they resembled 2 DoF azimuth thrusters. Both DoF’s are connected via steel cable capstan mechanisms to separate Maxon motors. This connection allows for efficient force translation with zero noticeable slip. In this paper only a single degree of freedom is used, while the azimuting direction is fixed.

- Operator - The operator controls the vessel using the visual and auditory information provided on the screen and the tactile and proprioceptive feedback from the haptic functionalities provided in the levers.
- Real-time processor - The Bachmann real-time processor has multiple functions. First of all it runs the haptic algorithm, which is constructed in MATLAB Simulink before it is compiled. Secondly, it acts as a bidirectional interface between the haptic algorithm and the FSSS. That means that it decodes the NMEA messages coming from the FSSS to variables that can be used in the haptic algorithm. It encodes outputs of the haptic algorithm to NMEA messages that are sent to the FSSS. The haptic algorithm runs at 1kHz to ensure haptic fidelity and prevent any noticeable delays. The ship simulator is connected to the real-time processor via an Ethernet connection, which sends and receives the NMEA sentences using UDP protocol. Finally, the real-time processor gets input from the motor encoders that are mounted on the lever actuators and controls the PWM motor drives.
- Control computer - A control computer is used to adjust the settings on the real-time processor via a custom made Graphic User Interface (GUI) using MATLAB-Simulink. The powerful graphics card of this computer is also used to run the visualization model of the simulator computer.

All systems are connected together via Ethernet cables and a network switch.

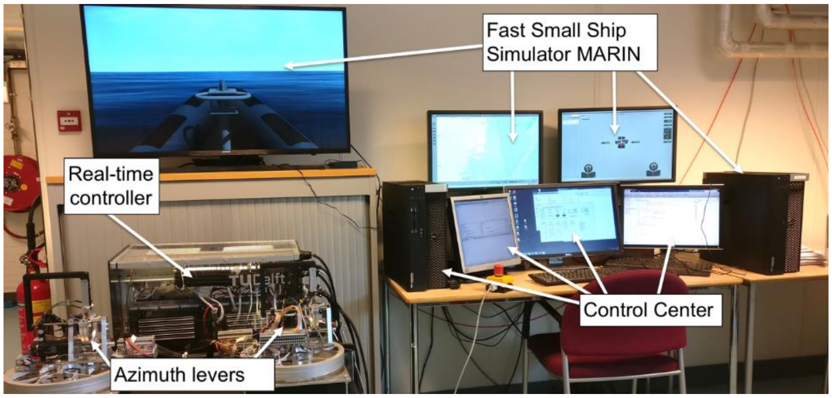

Figure 2 The haptic demonstrator setup.

4.3. The haptic algorithm

The haptic algorithm as shown in Fig. 5 consists of five modules: 1. Sea state estimation, 2. The Rayleigh database, 3. The speed RPM relation, 4. RPM to lever position and 5. Haptic force. First, the average wave height is estimated based on the heave displacement of the vessel. After that the safe speed corresponding to that average wave height is determined from the Rayleigh database using the user-defined probability of exceedance and acceleration threshold. Then this safe speed is translated to a setpoint RPM. This setpoint RPM is translated to setpoint lever position. Finally, this setpoint lever position is communicated to the helmsman using the haptic levers. In the following sections a detailed description of the construction of the haptic algorithm is provided.

1.) For the estimation of the sea state parameters the heave response of the vessel is used. For each sea state the interval between the boundaries of the response motion are defined. Then the peaks in the response motion are averaged and this average value is compared to the different intervals. In this way the actual sea state is dynamically estimated. As a result the estimated sea state changes if the average heave response value changes significantly. An update rate of this estimation is defined because a dynamic sea state estimation is required to generate a dynamic speed advice. For this update rate a moving time window of 30 seconds is used.

2.) A safe sailing speed is found using a predetermined relation between the sea state and the vessel responses. The method developed is based on a stochastic approach that uses a database of response history. This database is constructed using the simulated vessel responses to different wave conditions and at different speeds. Knowing that the FRISC will operate in sea states ranging from 0 to 5, only these sea states will be investigated. Taking a wave scatter diagram that is typical to the northern part of the North Sea the most relevant wave heights and periods can be found for that region. The largest vertical accelerations occur in short steep waves as was found by Keuning [4] and, therefore, these short steep waves are of most importance. From a wave scatter diagram of the northern part of the North Sea the following wave height and period relations were chosen to be covered by the model [1] :

- Hs = 1 m, Tp = 7 sec.
- Hs = 1.5 m, Tp = 7 sec.
- Hs = 2 m, Tp = 7 sec.

A Rayleigh plot is constructed for each combination of wave height and period considered. The Rayleigh plot is used as a tool to estimate the probability that the wave height will exceed a certain level. Assuming that the wave height is sufficiently narrow banded and normally distributed the wave crests and troughs follow a Rayleigh distribution as was found by Longuet-Higgens [12]. If a linear relation between the wave height and vessel response is assumed, it follows that the accelerations also approximate the Rayleigh distribution. The nonlinear behaviour will show up as deviations from the Rayleigh line. The simulated vessel responses to the sea states given above are measured for speeds ranging from 10 to 40 kts. For each speed and each sea state a recording of the vessel motions (velocities and accelerations) of 50 minutes (around 3000 wave encounters) was taken. For the current model this was deemed good enough statistics. In the resulting Rayleigh plot a user defined threshold acceleration and a probability of exceedance (PoE) can be set. Using the work of Keuning and Walree [7] who found that the crew of small fast rescue craft tolerated vertical accelerations up to 13 m/s^2 at the wheelhouse and 25 m/s^2 at the bow a threshold was defined. It has to be noted that the threshold acceleration is very much dependent on the crew and mission, therefore this threshold is made adjustable. However, for the experiment the threshold is fixed at using the values above. The operator is able to select a PoE of this threshold between 10^{-1} and 10^{-6}. For the experiment the PoE is fixed at 0.001. The probability that acceleration x_n exceeds threshold value α is shown in Eq. (1).

$$P(x_n > \alpha) = \exp\left(\frac{-\alpha^2}{2\sigma_x^2}\right) \quad (1)$$

where:

- x_n is the acceleration signal.
- α is the acceleration threshold.
- σ_x is the standard deviation of the acceleration signal x_n.

$$\alpha = \sigma_x\sqrt{-2\ln\big(P(x_n > \alpha)\big)} \quad (2)$$

Rewriting Eq. (1) to Eq. (2) makes using the Rayleigh plot more straightforward because linear lines of constant speed through the measured data can be drawn as can be shown in Fig. 4. At the crossing of the red lines in Fig. 4, which signify the acceleration threshold and PoE, the resulting advice speed is found using quadratic interpolation.

3.) The speed advice is translated to a setpoint RPM using a look-up table that is constructed using the FSSS simulator.
4.) The setpoint RPM is translated to a lever angle setpoint using another look-up table.
5.) The haptic force F_c, which is felt when the lever position exceeds the advised position, is modelled as a virtual spring with spring stiffness K_s. In Fig. 6 this force is illustrated showing the advice lever position X_{Adv} and the boundaries between which the advice can vary. The light coloured area indicates the current position of the force field. The dark coloured area indicates the maximum advices position, after which the force is felt.
Note that although not explicitly shown in Fig. 5, besides the force F_c an additional artificial damping force is implemented such that the user feels some mechanical resistance when changing the lever position, as is normal for maritime control levers and which is necessary to prevent the lever from changing position due to ship vibrations and shocks.

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[1] Gathering statistically significant response data for each sea state at multiple speeds is time consuming. Therefore, a limited number of sea state conditions is used to provide a proof of principle of this way of providing speed advice.

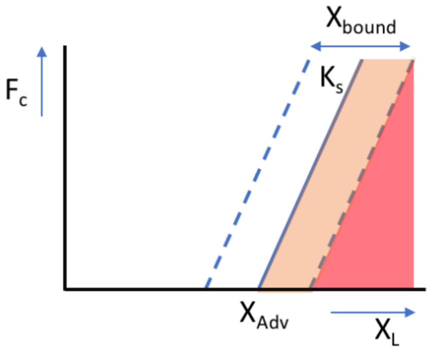


Figure 3: A schematic visualization of the haptic force algorithm showing that the virtual spring force with spring constant K_s is only generated once the lever position (X_L) reaches the advised maximum position (X_{Adv}).

4.4. Environmental conditions

All participants sailed four conditions (Manual day, Shared control day, Manual night and Shared control night) in a marked strip of deep water. These conditions are shown in Fig. 3. The track is 4 nm in length and because only the effect of head waves is considered an autopilot was used to fix the heading. A significant wave height of 2 m and a peak period of 7 seconds was chosen for the experiment to provide the participant with a challenging but realistic wave field. When starting each run a wave field comprised of (pseudo-) random components, with desired significant wave height and peak period, was generated. The randomness of the wave field ensures that the participants cannot adopt a position dependent control strategy. The length of the run is chosen such that for an average speed of 22 kts an equal number of wave groups is encountered, which makes the average wave conditions for all participants relatively equal. Before starting the experiment, the participants got one full run of manual control to familiarize themselves with the dynamics of the vessel and the wave conditions.

A drawback of this experiment is that the participants could not feel the (excessive) acceleration because during the experiment they are standing on solid ground. To partly replace this missing motion cue, a vibration signal was provided by the levers every time an excessive acceleration occurred.

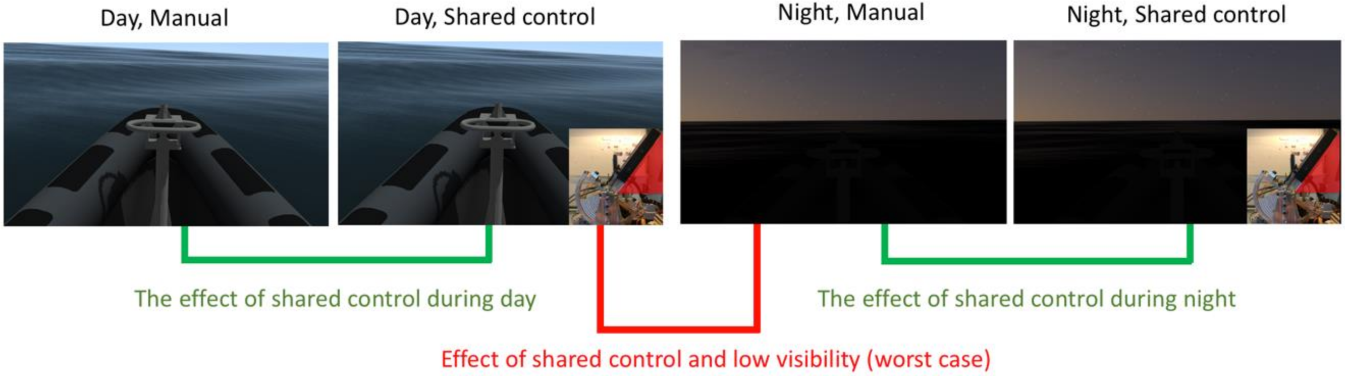


Figure 4 The four conditions: Manual day, Shared control day, Manual night and Shared control night shown respectively as well as the pairwise comparisons considered in this research.

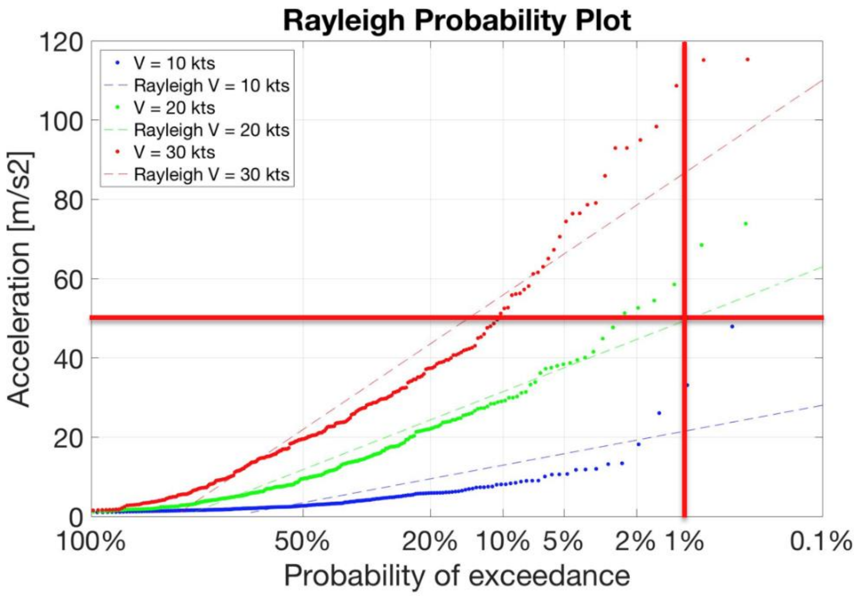


Figure 4: An example of the one of the Rayleigh plots used in the database showing the probability of exceedance of an acceleration level at different speeds.

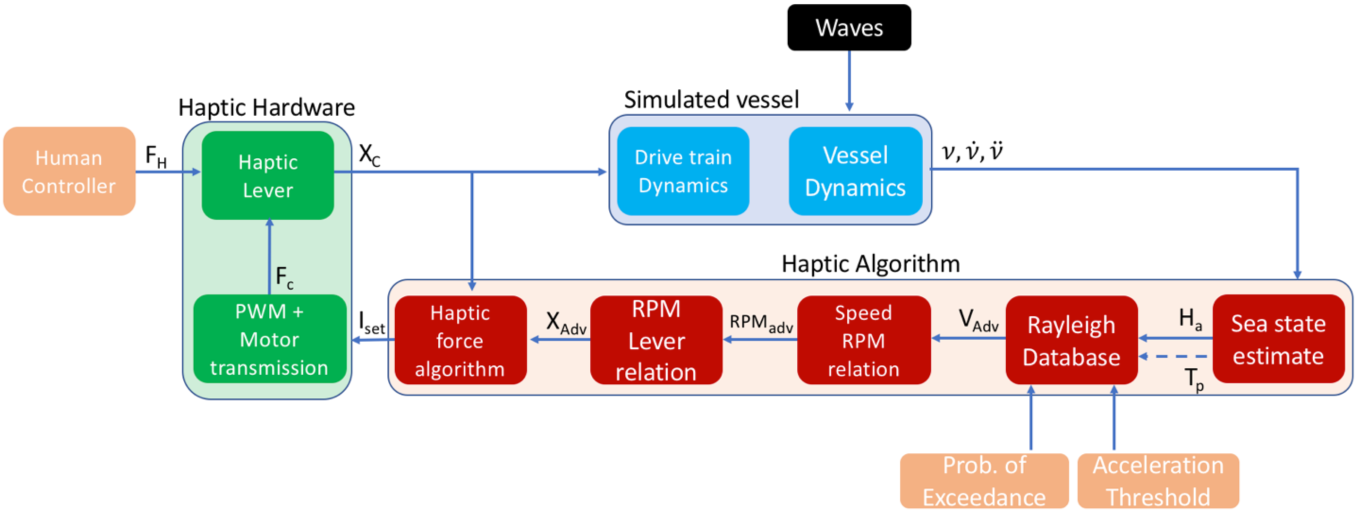


Figure 5: A block diagram showing the human controller acting on the haptic hardware, which controls the simulated vessel and the haptic algorithm used to provide a haptic speed advice.

4.5. Experimental design

Before the experiment commenced all participants were asked to read and sign an informed consent form, explaining the purpose, instructions, procedures and agreements of the study. A fully counterbalanced within-subject design was used to mitigate the learning effects. The participants were asked to maintain a firm grip on both levers. The negative RPM direction of levers was blocked to maintain realistic control strategy behaviour. In reality reversing propeller speed when moving forward at relatively high speed will cause the engines to shut down. Participants were informed about the availability of the speed advice and warning vibrations. No advice on operating strategy was given. The participants were asked to complete the trial as fast as possible while aiming to minimize the number of excessive accelerations. After each trial the completion time and number of excessive accelerations were marked on the whiteboard. In order to motivate the participants a score of a (fictive) experienced operator was set as the first score. After each trial the participants were asked to fill out a NASA Task Load Index form (NASA-TLX) [13] to assess the experienced workload. The NASA-TLX had an extra item to assess the simulator sickness on a scale of 1 to 6 (1= not experiencing any nausea, no sign of symptoms, 2= arising symptoms, 3= slightly nauseous, 4= nauseous, 5= very nauseous, retching, 6= vomiting). Because it is the first time that a human-in-the-loop experiment is conducted with the haptic ship simulator this item was added to avoid any issues. If a response of 4 or higher would be given the experiment would be stopped. Fortunately, none of the participants experienced any kind of nausea during the trials. In total the experiment including the training and NASA- TLX took approximately 45 minutes

4.6. Dependent measures

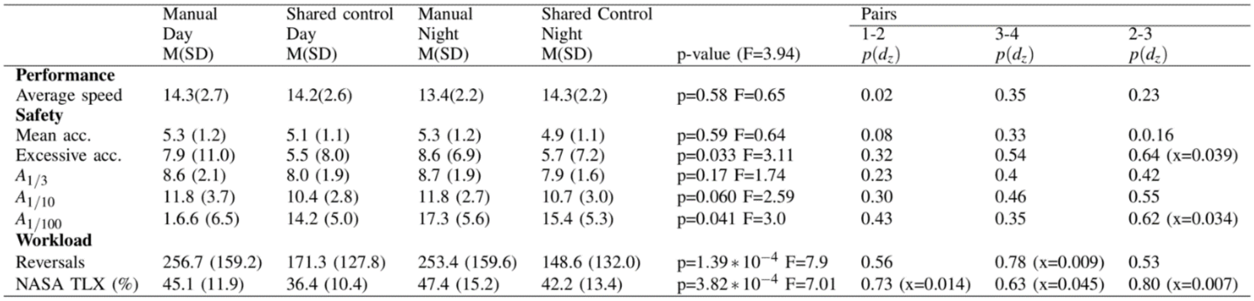
The data was measured at a frequency of 1kHz, starting from when the vessel crossed the starting line until the finish was reached. The vessel had some time to accelerate before the starting line and no deceleration at the finish was needed. However, it was found that in many cases the haptic algorithm was not completely initialized when the starting line was crossed. Therefore, it was decided to discard the first 10% of the track for every participant. The dependent measures were categorized into the three aspects "*performance*", "*safety*" and "*effort*".

Performance

To assess the performance of the participants the average speed over the trial is used. Average speed was taken because in literature on the mitigation of excessive accelerations [2],[3] the difference in average speed is used as a measure of performance.

TABLE I

MEANS (M), STANDARD DEVIATIONS (SD), EFFECT SIZES (d_z), AND RESULTS OF THE REPEATED MEASURES ANOVA (F, P) PER DEPENDENT MEASURE.



	Manual Day M(SD)	Shared control Day M(SD)	Manual Night M(SD)	Shared Control Night M(SD)	p-value (F=3.94)	Pairs 1-2 $p(d_z)$	3-4 $p(d_z)$	2-3 $p(d_z)$
Performance								
Average speed	14.3(2.7)	14.2(2.6)	13.4(2.2)	14.3(2.2)	p=0.58 F=0.65	0.02	0.35	0.23
Safety								
Mean acc.	5.3 (1.2)	5.1 (1.1)	5.3 (1.2)	4.9 (1.1)	p=0.59 F=0.64	0.08	0.33	0.0.16
Excessive acc.	7.9 (11.0)	5.5 (8.0)	8.6 (6.9)	5.7 (7.2)	p=0.033 F=3.11	0.32	0.54	0.64 (x=0.039)
$A_{1/3}$	8.6 (2.1)	8.0 (1.9)	8.7 (1.9)	7.9 (1.6)	p=0.17 F=1.74	0.23	0.4	0.42
$A_{1/10}$	11.8 (3.7)	10.4 (2.8)	11.8 (2.7)	10.7 (3.0)	p=0.060 F=2.59	0.30	0.46	0.55
$A_{1/100}$	1.6.6 (6.5)	14.2 (5.0)	17.3 (5.6)	15.4 (5.3)	p=0.041 F=3.0	0.43	0.35	0.62 (x=0.034)
Workload								
Reversals	256.7 (159.2)	171.3 (127.8)	253.4 (159.6)	148.6 (132.0)	$p=1.39*10^{-4}$ F=7.9	0.56	0.78 (x=0.009)	0.53
NASA TLX (%)	45.1 (11.9)	36.4 (10.4)	47.4 (15.2)	42.2 (13.4)	$p=3.82*10^{-4}$ F=7.01	0.73 (x=0.014)	0.63 (x=0.045)	0.80 (x=0.007)

Safety

The aspect "*safety*" is quantified in multiple ways:

Mean acceleration level [m/s^2]: The means are used to investigate the change of operator behaviour when using shared control, because the advice is only generated when the system assumes the vessel is on the boundary of the threshold acceleration level. The means will indicate if the acceleration levels are increasing on average.

Excessive accelerations [-]: The number of excessive accelerations is counted and compared because the shared control system was designed to mitigate these. If the participants would perfectly follow the shared control advice on average an excessive acceleration is encountered every 1000 waves, given a PoE setting of 0.001.

The significant acceleration levels ($A_{1/3}$, $A_{1/10}$, $A_{1/100}$) are used to gain insight in the distribution and the change in distribution of the acceleration levels. It is deemed important to investigate whether and how this changes when implementing shared control.

- $A_{1/3}$ [m/s^2]: the one third highest accelerations or significant accelerations. This metric is related to the significant wave height and therefore deemed interesting.
- $A_{1/10}$ [m/s^2]: the one tenth highest accelerations.
- $A_{1/100}$ [m/s^2]: the one hundredth highest accelerations. This metric gives an insight on the distribution of the acceleration in the tail of the spectrum.

Workload

The aspect "*workload*" is quantified in two ways:

Throttle reversals: The number of times the participant reverses the direction of the throttle with a magnitude greater than 2 degrees [15]. From literature it is known that shared control generally decreases the workload when compared to manual control. However, without respiratory or EEG measurements an alternative objective metric for workload needs to be found. Johanson et al. [16] found that when looking at user input on the system, the number of reversals and the reversal rate give an indication of the workload experienced by the participants. A reversal is signified by a significant change in the movement direction of the lever. To make sure the reversal is an intended movement and not subjected to sensory noise a minimum difference between peaks is used. The number of reversals is determined by only counting the reversals if the value between the calculating local minima and maxima of the throttle angle signal were greater than 2 degrees.

NASA TLX (%): At the end of every trial the participants were asked to grade their workload on a 21-points scale for six categories: Mental Demand, Physical Demand, Performance, Effort and Frustration. Each question was scaled from very low to very high with the exception of Performance, which was scaled from perfect to failure. The total workload was calculated by taking the mean of the percentages.

4.7. Statistical analysis

The 24 participants each completed 4 conditions resulting in a 24x4 matrix of each dependent measure. Not all dependent measures were found to be normally distributed and therefore the matrix was rank transformed according to Conover and Iman [17]. This rank transformation rewrites all scores to a scale of 1 to n (where n is the number of scores) to account for possible violation of the normality assumption that comes with using parametric tests. A repeated measures ANOVA with the four conditions as within-subject factor was used to analyse the matrix consisting of numbers between 1 and 96. For the three pairwise comparisons that were deemed relevant Bonferroni corrections were applied. To determine the effect sizes (d_z) Eq. (3) was used, where the μ_{x-y} is the mean of the difference and σ_{x-y} is the standard deviation of this difference. Spearman rank-order correlation coefficients were used to assess the associations between the dependent measures.

$$d_z = \frac{|\mu_{x-y}|}{\sigma_{x-y}} \quad (3)$$

5. RESULTS

For all dependent measures the means, standard deviations, the results of the repeated measured ANOVA and the pairwise comparisons are provided in Table I. No recordings were made during the training run and near the end of the training run an example of the speed advice was introduced. Furthermore, the experimental results of two participants were excluded from further analysis after it was found that during some trial these participants experienced 10 times more excessive accelerations than average. Fig. 11 shows the throttle angle, speed and accelerations for a typical participant over the 4 trials.

- Performance - Table I shows the results of the statistical analysis. No significant difference was found between the average speed with manual control compared to shared control.

- Safety - The mean acceleration level does not show a significant difference between the different conditions.

The number of excessive accelerations was found to vary significantly between the conditions. The effect size during night time was found to be medium and a significant effect (p=0.039) was found when comparing the shared control day to the manual night (best/worst scenario comparison).

For the $A_{1/3}$ no significant effect of shared control was found. The $A_{1/10}$ accelerations also do not show a significant effect of shared control. In the manual case the $A_{1/10}$ are about 10% higher on average.

In the tail of the acceleration distribution ($A_{1/100}$) a significant effect is shown when comparing the different conditions. When comparing the best/worst case again a significant effect (p=0.034) was found. In general, when approaching the tail of the acceleration distribution the effect sizes are observed to be growing for the different comparisons.

- Workload - The number of participant reversals shows a significant difference between the conditions. Where on average a reversal difference during day time between the shared control and the manual condition of 33% was found during night time it was 42%. The reversals for each condition are shown in Fig. 8.

The NASA-TLX questionnaire results indicate higher reported workload for the manual condition compared to the shared control conditions. For the pairwise day time comparison a significant difference between the conditions was found (p=0.014). For the night time comparison this was also found to be significantly different (p=0.045). The strongest effect was found when comparing the best/worst case scenarios (p=0.007). The results of the NASA-TLX are shown in Fig. 10.

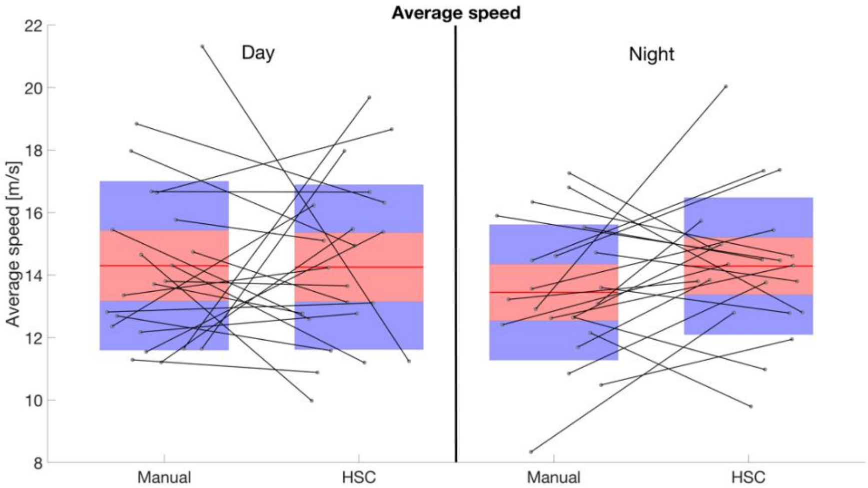


Figure 6: The average speed showing the groups of raw data, the mean (redline), the SEM (pink square) and the 95% confidence interval (blue square) for each of the four conditions. The lines show the difference for the same person due to different conditions.

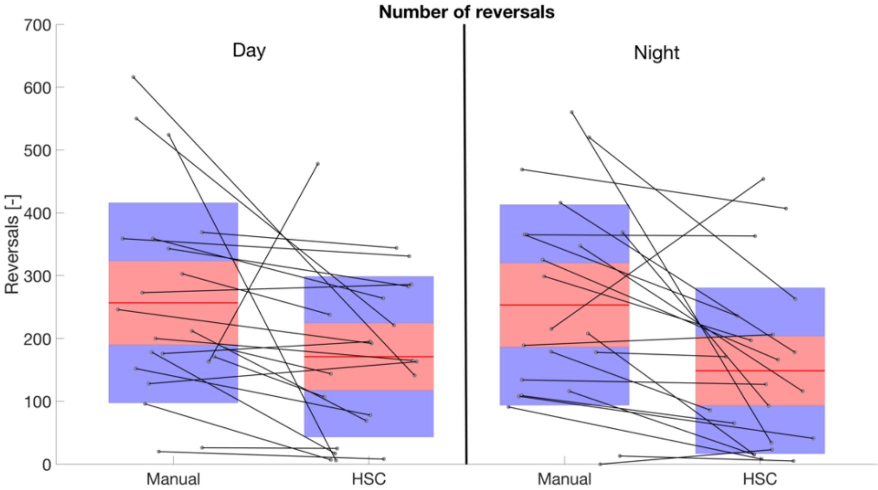


Figure 7: The number of reversals showing the groups of raw data, the mean (red line), the SEM (pink square) and the 95% confidence interval (blue square) for each of the four conditions. The lines show the difference for the same person due to different conditions

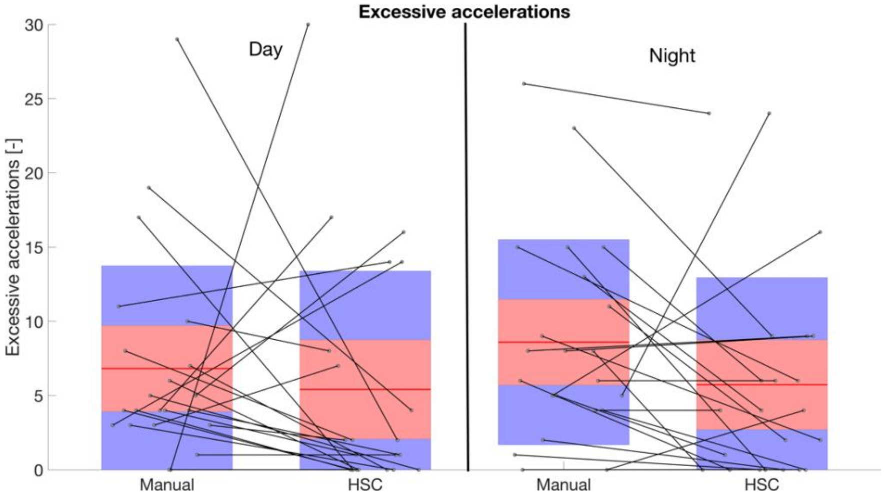


Figure 8: The number of excessive accelerations showing the groups of raw data, the mean (red line), the SEM (pink square) and the 95% confidence interval (blue square) for each of the four conditions. The lines show the difference for the same person due to different conditions.

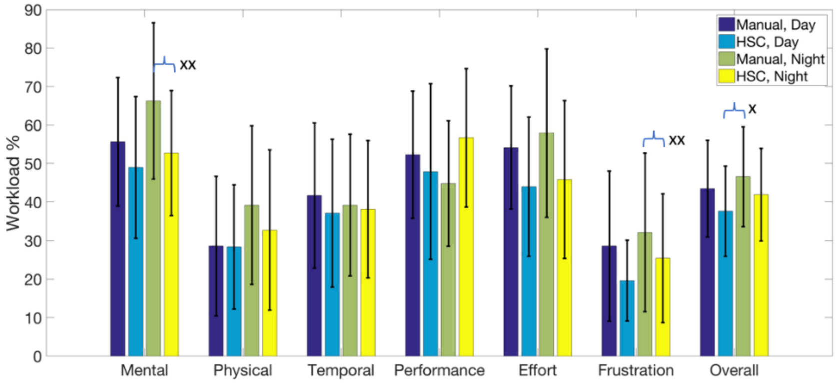
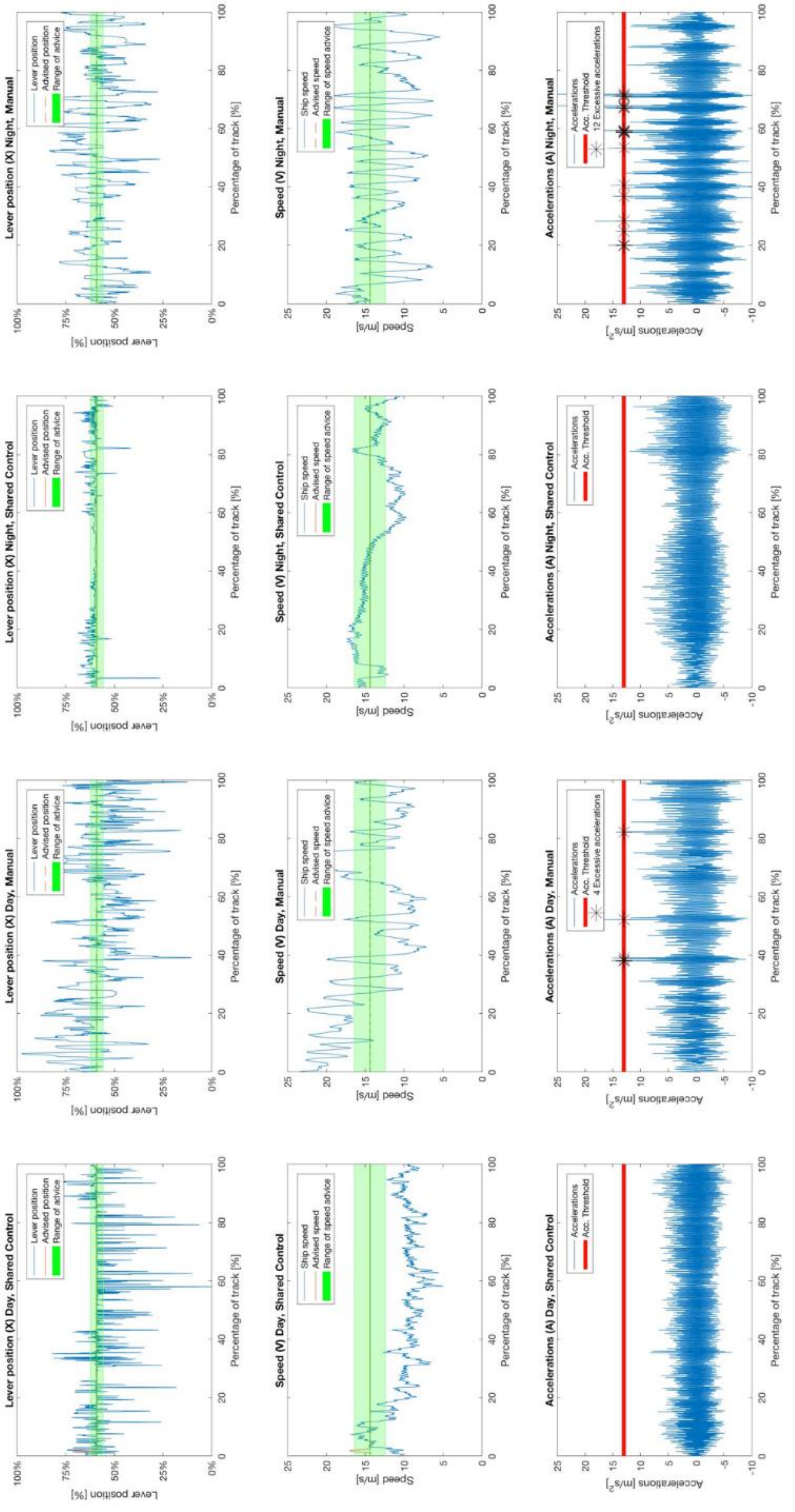


Figure 9 The results and the standard deviation of the NASA-TLX for all participants with x: p=0.01, xx: p=0.001.



Lever position (X) Night, Manual
Speed (V) Night, Manual
Accelerations (A) Night, Manual
Lever position (X) Night, Shared Control
Speed (V) Night, Shared Control
Accelerations (A) Night, Shared Control
Lever position (X) Day, Manual
Speed (V) Day, Manual
Accelerations (A) Day, Manual
Lever position (X) Day, Shared Control
Speed (V) Day, Shared Control
Accelerations (A) Day, Shared Control
Lever position
Advised position
Range of advice
Ship speed
Advised speed
Range of speed advice
Accelerations
Acc. Threshold
12 Excessive accelerations
4 Excessive accelerations
Lever position [%]
Speed [m/s]
Accelerations [m/s²]
Percentage of track [%]
100%
75%
50%
25%
0%
25
20
15
10
5
0
-5
-10
20
40
60
80
100

Figure 10 The most important metrics lever angle (X), ship speed (V) and vertical acceleration (A) for a typical participant over the four trials.

6. DISCUSSION

A human-in-the-loop experiment was conducted to investigate the effect of haptic shared control compared to manual control when sailing in waves, on the operators average speed, vertical acceleration levels, reported workload and lever reversals. The 24 participants considered in the within-subject design experiment sailed a 4nm track in head waves in both good and poor visibility conditions.

The application of shared control in the experiment showed a reduction in both the reported workload (NASA-TLX), 20% in day and 10% in night, and the measured workload (reversals), 33% in day and 42% in night. This could prove to be beneficial in reality, especially since FRISC operations can take multiple hours and it is likely that during those hours concentration reduces.

The fact that there was no significant difference between manual and shared control in terms average speed and number of reversals could be attributed to the large differences between individual subjects. For example Fig. 9 shows the lines comparing individual performance and shows that 16 out of 22 tend to experience less excessive accelerations using haptic shared control during the day condition. In the night condition this number increases to 17 out of 22. However, for a few participants the lines go up, which indicates a different strategy, namely taking more risks by repeatedly overruling the haptic speed advice. For the average speed this effect is not observed, which indicates that taking more risk in the form of excessive accelerations does not always translate in a higher average speed. Furthermore, the results in Fig. 9 do show a significant reduction of the number of excessive accelerations between manual night and haptic shared control day. This indicates that haptic shared control does influence the number of excessive accelerations, however, the effect size is low and thus only observable for the most extreme condition comparison (i.e. low visibility for manual and high visibility and haptic assistance). An increase in the number of participants could increase the statistical significance between the different runs.

Fig. 8 shows that the number of reversals for most participants decreases when using haptic shared control compared to manual control. However, (as shown in Table 1) only during night time a significant effect was found. The results from the NASA-TLX indicated that the participants experienced less control workload when using the shared control system compared to manual control. This reduction of both the measured and the reported workload corresponds to the expectations based on literature [6] on application of haptic shared control in other domains.

A. Effect of experimental design choices

When preparing the experiment choices and simplifications needed to be made due to constraints in available time and resources. In this section the impact of these simplifications on the outcome of the experiment are discussed.

Simulator setup: From literature it is known that the operators tend to react after a (excessive) vertical acceleration is felt [4]. The lack of this motion cue in the current experimental setup could have had an effect on the results. The vibration that was implemented on the levers when an excessive acceleration was encountered is much more easily dismissed than a full body vibration. Using the FSSS motion platform at MARIN together with the haptic levers could lead to different results. However, the aim of the experiment to investigate the effect of applying haptic shared control when sailing in waves and if valuable insights could be gained using the current simplified setup it would be beneficial compared to an expensive motion platform.

Participants: For the experiment 24 conveniently sampled participants were selected from among the students and staff of Delft University of Technology. After analysing the raw data two participants were excluded from further analysis. Of the remaining participants only two were in possession of a navigation license. The lack of sailing experience and the relatively small size of the group could have affected the outcome of the experiment. However, if experienced FRISC operators would have been selected for the current setup, the lack of motion cues and the presence of a navigator could have interfered with the operators' strong internal model gained from experience. This could have also had a significant impact on the results.

Wave field: Although the wave characteristics in terms of peak period and significant wave height are similar for every participant and despite the length of each run, it can happen that some participants encounter somewhat more long and shallow waves rather than steep high waves. In some cases this could have led to a more difficult wave environment.

Sea state estimator: The sea state estimation was kept simple and only looked at the heave motion of the ship. The pitch motion of the vessel could also be included in the estimation to estimate the wave steepness next to the wave height and perhaps base the sea state estimation on this combination. Experiments will need to show the usefulness of this combined method. For the future it would be worthwhile to investigate the potential of using more advanced sensors (such as radar or cameras) and signal processing techniques.

Warnings: To partly replace the missing motion cue a vibration signal was implemented on the lever when an excessive acceleration occurred. It could have happened that the vibration is easily dismissed or that the signal did not carry enough information about the severity and the duration of the acceleration signal. Therefore, if the vibration would be made dependent on the severity and/or the duration of the excessive acceleration it could give the operator more information and potentially influence behaviour.

Order effects: When looking at the order effects for number of excessive accelerations it was found that a substantial decrease in the number of excessive accelerations occurs when the participants become more experienced. This indicates that in this study the participants were not fully trained when the experiment commenced. The large number of excessive accelerations of some participants could potentially be explained by the fact that participants did not get feedback on their performance during the training-run before the experiment commenced. For future experiments a longer training run could also help to further mitigate the learning effects.

Headwaves: In the experiment is was chosen to sail in head waves because this is generally considered to be the most limiting condition. However, an often voiced argument, especially from the persons with sailing experience and a navigation license, was that the inability to steer the ship did not feel natural. What experienced operators tend to do is to maintain an angle of attack with respect to the approaching wave of about 30º. This leads to a zigzag sailing pattern in which the chance of excessive vertical accelerations due to wave slamming is decreased. The reason to set the simulated ship to autopilot is to have similar conditions for every participant and make the experiment less sensitive to operator experience. In an experiment with experienced (FRISC) operators and a more realistic simulation environment it could be useful to have also manoeuvring capabilities.

7. CONCLUSION

We hypothesized that when sailing with haptic assistance the operator would encounter less excessive accelerations compared to manual sailing. Contrary to our hypothesis, shared control did not have a significant impact on excessive accelerations, although it did reduce measured and reported workload. However, a significant decrease in the reported workload and in the number of reversals was found when shared control was used. Furthermore, for 16 out of 22 participants the number of excessive accelerations experienced was reduced when sailing with shared control. The lack of a significance in the decrease of the number of excessive accelerations can be partly explained by an observed difference in control strategy.

This study is the first to consider human-in-the-loop experiments for reducing the vertical accelerations of small fast vessels. Furthermore, it was the first time the current haptic ship simulator setup was used to perform experiments. These first steps yielded valuable insights on what metrics to select and how to apply human-in-the-loop experiments for maritime applications. Further research is needed to expand the way operator response is measured and how best to apply shared control within the maritime domain.

8. RECOMMENDATIONS

In this section some recommendations for future work are given. These recommendations are split up into improvements of the experiment and steps required to implement haptic assistance in the FRISCs.
The recommendations for improvement of the experiment are:
Connect to motion base platform: Firstly, it is recommended to connect the existing haptic controls setup to the FSSS simulator with motion base platform, which is currently based at MARIN. The participants are expected to behave and perform in a much more realistic way when they really feel the effect of wave encounters.
Test with trained/experienced operators: Measuring the response of the persons that are the end user of this technology will be valuable. Also their feedback on how the system functions and what could be improved can be very useful. In this way the model can be tuned using the experience of the operators. Testing with experienced operators is expected to be most beneficial when the simulation environment most closely resembles real life operations.
Maneuvering: In the improved experiment it is recommended to allow the operator to manoeuvre as would also be done in reality. This will further improve the operators' sense of immersion.

For actual onboard implementation, the robustness and reliability of the levers is a key aspect. A version of the haptic handles that is compact but powerful enough to provide meaningful force feedback to the operator even when wearing protective gear and in a high vibration environment could prove to be a challenge.
During further development of haptic assistance for the FRISCs it should continuously be kept in mind that the subtlety of the generated haptic forces should be in balance with the environment in which the levers are used

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