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A Cybernetic Analysis of Biodynamic Effects in Touchscreen Operation in Turbulence

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This paper describes a human-in-the-loop experiment performed in TU Delft's SIMONA Research Simulator to explicitly investigate the effects of biodynamic feedthrough (BDFT) on the execution of a two-dimensional touchscreen waypoint dragging task in turbulence. In the experiment, 16 participants performed the same task in a stationary simulator and whilst being perturbed in either surge, sway, or heave directions by the same motion disturbance signal. In addition, the effect of screen location on biodynamic effects was tested by considering two touchscreen display positions, i.e., representative for the Primary Flight Display (PFD) and the Control Display Unit (CDU), respectively. The collected results show significantly more issues with loss of screen contact for the PFD display, due to the extended arm position when operating this display. Despite the fact that small biodynamic effects are also found for off-axis disturbances, the results clearly show that issues with BDFT predominantly occur when motion disturbances are aligned with the touchscreen control input direction. Due to the use of a multisine motion disturbance signal in the experiment, explicit BDFT detection and identification was possible with spectral methods. For the conditions where sufficient BDFT was detected to allow for modeling the BDFT dynamics, a second-order BDFT model was proposed and found to explain at least 70% of the BDFT input components. With consistent BDFT model parameter estimates between conditions, this approach shows clear merit for quantitative analysis of biodynamic effects on touchscreen operation and potentially even for BDFT mitigation through model-based input cancellation.

Nomenclature

A	Sinusoid amplitude, [deg]	s	Laplace operator
b_{BDFT}	BDFT damping coefficient, [kg/sec]	t_{loss}	TSC loss of contact duration, [sec]
e_x	Error from target in horizontal direction, [deg]	t	time, [sec]
e_y	Error from target in vertical direction, [deg]	T_m	measurement time, [sec]
f_{dx}	Disturbance forcing function (surge), [deg]	u_x	finger position, horizontal direction, [deg]
f_{dy}	Disturbance forcing function (sway), [deg]	u_y	finger position, vertical direction, [deg]
f_{dz}	Disturbance forcing function (heave), [deg]	σ_e^2	Variance of the error signal, [deg ²]
f_{tx}	Horizontal target forcing function, [deg]	σ_u^2	Variance of the input signal, [deg ²]
f_{ty}	Vertical target forcing function, [deg]	ω	sinusoid frequency, [rad/sec]
$g_{d,t}$	Fade-in function, [-]		
G_{BDFT}	BDFT gain, [-]		
H_{BDFT}	Measured BDFT dynamics, [-]		
H_{NM}	Neuromuscular dynamics, [-]		
$\hat{H}_{BDFT}$	Estimated BDFT dynamics, [-]		
i_r	Run number, [-]		
k	Sinusoid index, [-]		
k_{BDFT}	BDFT stiffness, [kg/sec ²]		
m_{BDFT}	BDFT mass, [kg]		
n_{loss}	TSC loss of contact instances, [-]		
$n_{d,t}$	Sinusoid frequency integer factor, [-]		

Abbreviations

BDFT	BioDynamic FeedThrough
CDU	Command Display Unit
GA	Genetic Algorithm
PFD	Primary Flight Display
RMS	Root Mean Square
SIMONA	SIimulation, MOtion and NAvigation Institute
SRS	SIMONA Research Simulator
TSC	Touch Screen Controller

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I. Introduction

Although some examples of the implementations of touch screen controllers (TSCs) on the flightdeck exist,^{1,2} a number of unsolved challenges still stand in the way of large scale implementation of TSCs in the cockpit. From an interface design perspective, the direct manipulation offered by touchscreens has shown to be capable of improving certain in-flight tasks,³ while perhaps being less suitable as a replacement for hardware input devices in others.⁴ Another critical challenge comes from using TSCs as input devices in a possibly highly dynamic and turbulent environment as an aircraft.⁵⁻⁷ Resulting loss of finger contact with the screen and involuntary inputs due to biodynamic feedthrough (BDFT) may significantly complicate any task that is to be performed on a touch-sensitive cockpit display.

The effects of multiple variables, including display location, turbulence frequency and vibration levels on BDFT and its resulting impact on the use of TSCs in dynamic environments have been investigated in previous research.³⁻¹¹ Mitigation of the effects of BDFT, however, currently only takes place in the form of passive support systems, such as arm- or hand-rests. Mitigation of BDFT using noise signal cancellation was proposed in literature,¹² but it requires a good model of the BDFT. Efforts to build such a model for the use of touchscreens in a turbulent environment have not been found in existing literature.

This paper describes the results of a human-in-the-loop experiment, conducted in the SIMONA Research Simulator (SRS) at Delft University of Technology, aimed to gain understanding of the influence of BDFT on performing a ‘dragging’ task (e.g., waypoint repositioning) on a touch sensitive cockpit display. Participants in the experiment performed a two-dimensional pursuit tracking task on a touchscreen display, while being perturbed by fore-aft (surge), lateral (sway), or vertical (heave) motion disturbances in different experimental conditions. Furthermore, these motion conditions were tested with two different touchscreen positions and orientations in the cockpit, representative for the Primary Flight Display (PFD) and the Control Display Unit (CDU). This allows for observation of the sensitivity to BDFT whilst the finger is in contact with the TSC. The motion disturbance spectrum was identical in all axes to allow for direct comparison. Furthermore, the spectrum approximated a realistic (low-pass) turbulence signal similar to those used in previous investigations.¹³⁻¹⁶ The use of independent multisine (visual) target and motion disturbance signals enable direct quantitative measurements of BDFT effects, by comparing the Power Spectral Densities (PSDs) of the touchscreen input data over the different experiment conditions. In turn, these measurements allowed for development of a model that describes the effects of BDFT when performing a continuous dragging task.

This paper is structured as follows. Section II and Section III provide the details of the considered touchscreen control task and the experiment methods, respectively. The results of the experiment are presented in Section IV. The paper ends with a discussion and the main conclusions.

II. Control Task

II.A. Task

A target-following disturbance-rejection experiment was performed to measure the effects of biodynamic feedthrough when performing a continuous dragging task on a TSC. The diagram of the experiment control task is depicted in Fig. 1. The human controller’s task was to minimize both horizontal and vertical tracking errors, e_x and e_y , respectively. The errors were defined as the difference between the output of target functions (f_{t_x} and f_{t_y}), and the input positions of the finger, u_x and u_y .

Figure 1. Block diagram representation of the two-dimensional touchscreen tracking task.

The screen position of the target was determined directly by the output of the target forcing functions and depicted with a white triangle, see Fig. 2. The current input position of the finger was also shown with the semi-transparent

magenta circle shown in Fig. 2. The white horizontal and vertical lines always moved with the target, to prevent that its location could not be determined due to visual obstruction by the participant's hand.

Whilst performing the control task, subjects were either exposed to one of three motion conditions (pure surge, pure sway, pure heave) or to no motion disturbance (baseline condition), Fig. 3. The disturbance signal was identical for all motion directions and directly determined by the output of the disturbance forcing function $f_{d,x,y,z}$. The presence of this disturbance forcing function allowed for identification of the controller's biodynamic feedthrough dynamics, H_{BDFT} . Inputs that were made on the TSC did not influence the motion disturbance $f_{d,x,y,z}$, as both were de-coupled.

Figure 2. Experiment display.

Figure 3. Motion disturbance directions in the experiment.

II.B. Forcing Functions

The aim of this research is to both *detect* and *model* BDFT for a continuous dragging task under varying motion conditions. In order to do this, use was made of fully deterministic target and motion disturbance signals, with sines at unique and known frequencies, amplitudes and phases. Although this approach yields signals that appear random in the time domain, it is easy to separate and analyze the different components in the frequency domain. The example PSDs in Fig. 4 show the power and frequency locations of target and disturbance components that were used in the experiment. These sum-of-sines signals were defined by Eq. (1):

$$f_{d,t}(t) = \sum_{k=1}^{N_{d,t}} A_{d,t}[k] \sin(\omega_{d,t}[k]t + \phi_{d,t}[k]) = \sum_{k=1}^{N_{d,t}} A_{d,t}[k] \sin(n_{d,t}[k]\omega_m t + \phi_{d,t}[k]) \quad (1)$$

In Eq. (1), $A_{d,t}[k]$, $\omega_{d,t}[k]$, and $\phi_{d,t}[k]$ indicate the amplitude, frequency and phase of the k^{th} sine in f_d or f_t , respectively, where subscripts d and t are used to distinguish between the disturbance and target forcing functions. Primes $n_{d,t}$ were used as integer multiple of the measurement time base frequency, $\omega_m = 2\pi/T_m = 0.0767$ rad/s, to obtain a frequency for that particular wave. For this experiment, a measurement time of $T_m = 81.92$ s was used. A cresting technique was used such to set the phases to prevent any large peaks in the time domain.^{17,18}

For the target signals in both horizontal and vertical directions (f_{t_x} and f_{t_y} , respectively), the sum-of-sines signals consisted of three sines, each with different amplitudes, frequencies, and phases. The amplitudes were scaled such that the standard deviation of the signal was 13 cm in horizontal direction, and 9.75 cm in vertical direction. This ensured that the entire surface of the TSC was used. With only three low frequency sines, the 'randomness' in the time domain signal was questionable. To maintain signal characteristics that resembled a smooth dragging task whilst preventing signal recognition by the participant, the target signal was either displayed normally, mirrored over the horizontal axis, mirrored over the vertical axis, or mirrored over both axes.

The target forcing functions f_{t_x} and f_{t_y} were obtained using Eq. (1) with properties of the second and third columns in Table 1,

Figure 4. Power Spectral Densities of the forcing functions.

respectively. To prevent nonzero starting values a fade-in function was applied, indicated in Eq. (2). This fade-in function was multiplied with the forcing function from equation Eq. (1).

$$g_{d,t}(t) = 1 - \frac{1}{2} \cos\left(\frac{\pi t}{t_{fade}}\right) \quad (2)$$

The position (i.e., x, y, z) signal for the motion disturbances f_d was obtained in a similar way. This sum-of-sines signal consisted of ten sines. The selected primes have been used in a number of earlier experiments,^{13,14,16} ensuring that the frequencies in the disturbance signal covered a wide frequency range of human control at regular intervals on a logarithmic scale. Due to the higher number of sines present in this signal, recognition of the disturbance signal by the participant was not likely. This prevented the need to invert the signal, resulting in an identical motion disturbance signal for all runs.

The motion disturbance signal f_d is defined by Eq. (1) with properties from the first column in Table 1. This resulted in a position signal for the motion disturbance. As described in Section III.A.1, however, the SRS requires acceleration inputs to the motion controller and a fade-in on the motion signal. Differentiating a faded position signal twice to obtain acceleration inputs for the hexapod simulator would yield motion commands that drift the simulator to the edge of its motion bounds due to a nonzero mean. Using Eqs. (1) and (2) in combination with the chain rule as in Eq. (3), the matching acceleration signal was calculated to prevent such drift and to include the fade-in.

$$f''_{d_{x,y,z}}(t) = f_d(t) \cdot g''_d(t) + 2 \cdot g'_d(t) \cdot f'_d(t) + f''_d(t) \cdot g_d(t) \quad (3)$$

Table 1. Target and disturbance forcing function properties.

k	Disturbance, f_d				Target, f_{t_x}				Target, f_{t_y}			
	n_d	ω_d rad s ⁻¹	A_d m	ϕ_d rad	n_{t_x}	ω_{t_x} rad s ⁻¹	A_{t_x} m	ϕ_{t_x} rad	n_{t_y}	ω_{t_y} rad s ⁻¹	A_{t_y} m	ϕ_{t_y} rad
1	5	0.3835	$1.067 \cdot 10^{-1}$	-0.269	3	0.230	0.646	1.445	2	0.153	0.894	0.308
2	11	0.8437	$8.069 \cdot 10^{-2}$	4.016	7	0.537	0.784	0.000	13	0.997	1.562	-0.431
3	23	1.7641	$4.019 \cdot 10^{-2}$	-0.806	19	1.457	1.406	-1.825	17	1.304	1.866	-1.591
4	37	2.8379	$2.048 \cdot 10^{-2}$	4.938								
5	51	3.9117	$1.246 \cdot 10^{-2}$	5.442								
6	71	5.4456	$7.568 \cdot 10^{-3}$	2.274								
7	101	7.7466	$4.735 \cdot 10^{-3}$	1.636								
8	137	10.5078	$3.424 \cdot 10^{-3}$	2.973								
9	171	13.1155	$2.856 \cdot 10^{-3}$	3.429								
10	226	17.3340	$2.416 \cdot 10^{-3}$	3.486								

II.C. BDFT Model

For the BDFT analysis in this paper, the inputs that participants make on the TSC during the experiment are recorded and converted to the frequency domain. If power of the disturbance feeds through onto the input signals, peaks are observed in the PSDs of TSC input signals u_x and u_y . Fig. 5 shows an example PSD of the vertical TSC input u_y . Target signal power is clearly observed at frequencies corresponding with the sinusoid frequencies of the vertical target f_{t_y} . Furthermore, the presence of power at f_d frequencies suggests that BDFT is present for this particular condition.

Presence of disturbance power at frequencies of the motion disturbance in the input signal, however, does in itself not quantify the extent to which BDFT takes place at these frequencies. After all, a large motion disturbance power at a certain frequency is almost guaranteed to cause a large input power for that specific frequency in the TSC input signal. Instead, the ratio between the disturbance power to which the participant is exposed and the power observed in the TSC input is used as the BDFT frequency response function (FRF) estimate, Eq. (4).¹² The FRF $H_{BDFT}(j\omega_d)$ provides a nonparametric estimate of the BDFT response at the ten disturbance frequencies ω_d .

$$H_{BDFT}(j\omega_d) = \frac{S_{f_d, u_{x,y}}(j\omega_d)}{S_{f_d, f_d}(j\omega_d)} \quad (4)$$

Fig. 6 shows an example of the BDFT dynamics that were estimated from our experiment data. Red asterisks indicate the estimated BDFT FRF. Based on the shape of the FRF, a second-order transfer function with additional

Figure 5. Example PSD of experiment TSC input.

Figure 6. Estimated BDFT frequency response and model fit.

gain, see Eq. (5), was used to model these dynamics. Fig. 6 shows a typical fit of this model with dashed blue lines. An additional delay term was considered, to better capture the phase lag at the higher frequencies, but was found to be difficult to estimate reliably due to the low magnitude of the FRF at these high frequencies.

$$\hat{H}_{BDFT}(s) = G_{BDFT} \cdot \frac{1}{m_{BDFT} \cdot s^2 + b_{BDFT} \cdot s + k_{BDFT}} \quad (5)$$

The BDFT model is a mass-spring-damper system as can be verified from Eq. (5), in which G_{BDFT} corresponds with the BDFT model gain, m_{BDFT} with mass, b_{BDFT} with damping, k_{BDFT} with stiffness. To subsequently estimate these BDFT model parameters for fitting the model (dashed blue line in Fig. 6), the time-domain parameter estimation routine of Ref. 19 was used.

III. Experiment

To measure the effects of BDFT when performing continuous dragging tasks in the presence of motion disturbances, the task as described in Section II was conducted. This section provides details of the experimental setup: the experimental conditions, the apparatus, the considered dependent measures, and the methods used to analyze the obtained data. The section concludes with the hypotheses.

III.A. Method

III.A.1. Apparatus

The experiment was conducted in the SIMONA Research Simulator (SRS), located in the Faculty of Aerospace Engineering at Delft University of Technology. The SRS is equipped with a hydraulic motion system, capable of providing motion cues in six degrees-of-freedom. Time delays of the motion system for all degrees of freedom are in the order of 20 msec.²⁰ Stroosma et al.²¹ provide more information. Participants did not have influence on the motion cues they received, but instead received motion disturbances defined by the forcing functions. Participants were seated at the left side of the pedestal, from where two TSCs were to be controlled. The vertical TSC, referred to as ‘PFD’, was a 15-inch Iiyama ProLite TF1534MC-B1X. The screen was tilted from the vertical plane with an angle of 18° (Fig. 8). The second TSC, a 23-inch Dell P2314Tt, was horizontally mounted on the pedestal and is referred to as ‘CDU’, see Fig. 9. The published response times of both screens were 8 ms.^{22,23} Markers on the floor of the simulator ensured a fixed seating position for participants with respect to the TSCs. Although

Figure 7. SIMONA Research Simulator.

participants were restrained using a five-point safety harness during the experiment, there was freedom to lean forward and backward. With respect to the center of the seat lumbar support, the PFD TSC was located approximately 75 cm in front of the reference point, while the CDU TSC was located approximately 25 cm in front, and 40 cm right of the reference point.

The experiment display was 30 cm wide and 22.5 cm high. For the PFD, these dimensions covered the whole screen. On the (bigger) CDU screen, the experiment display only covered the top-left corner such that the same physical interface dimensions were maintained for both screens. An impression of the total setup can be observed in Fig. 10. Anti-static electronics touchscreen gloves were used by the participants at all times throughout the experiment (EN338 performance level 2242, NEN-EN-IEC 61340-5-1 ESD rated).²⁴

Figure 8. Control of the PFD.

Figure 9. Control of the CDU.

Figure 10. Cockpit setup.

III.A.2. Experimental Conditions

Participants were exposed to four different motion disturbance scenarios during the experiment: heave, sway, surge and a baseline condition without motion disturbance. Furthermore, two TSC locations were used for the experiment; one at the Primary Flight Display (PFD) location, the other at a location comparable to the Control Display Unit (CDU). This results in a total of eight experimental conditions. With 64 runs, this resulted in a eight repetitions per condition. To avoid target pattern recognition, the target was either displayed normally, mirrored over the horizontal axis, mirrored over the vertical axis, or mirrored over both axes.

III.A.3. Participants

Sixteen participants performed the experiment, of which fifteen were male and one female. All participants were right-handed and had experience with TSCs. The age of this group was recorded ($M = 28.7$ years, $SD = 10.8$ years), as well as the overall body length ($M = 182.0$ cm, $SD = 6.9$ cm) and mass ($M = 76.7$ kg, $SD = 12.7$ kg). All participants were fit to conduct an experiment in the SRS whilst being subjected to motion disturbances.

III.A.4. Procedures

Participants received a written briefing prior to the experiment with an explanation of the control task and the procedures. This briefing was covered again, in a sit-down briefing with the experimenter, directly prior to the experiment. After signing a consent form, a safety briefing of the simulator was given prior to adjusting the seat to a predefined position. Participants wore noise-cancelling over-the-ear headphones, with additional masking sounds representing aircraft engine noise to prevent distraction from sound coming from the SRS pistons. A two-way radio communications link was present during the experiment. The main cabin lights were dimmed, but two reading lights were turned on to alleviate strain on the eyes whilst preventing visual distractions. Participants were instructed to wear a touchscreen glove (as specified in Section III.A.1) to ensure smooth continuous finger inputs and to limit strain on the controller's finger. Furthermore, the target was only touched with the index finger. The participants were prevented from supporting their hand on the screen, as multiple touch inputs resulted in a rejected measurement.

Participants were instructed to continuously try to improve their performance, which was done by verbally indicating the sum of their root mean square (RMS) scores of both the the horizontal and vertical screen inputs after each run. A lower score indicated a better performance for a particular run. Before starting each run, participants were asked if they were ready. If desired, they could take a small break whilst remaining seated in the SRS. The total experiment

consisted of 64 runs lasting 90 seconds each. After 32 runs, a larger break of approximately 20 minutes was given in which participants left the SRS. In total, the experiment lasted 2.5 hours per participant.

III.A.5. Dependent measures

In order to gain insight in the effect of biodynamic feedthrough during TSC dragging tasks, touchscreen inputs were recorded. From these recorded inputs, a number of dependent measures were calculated:

- *Loss of Screen Contact.* The loss of contact count n_{loss} is the number of samples for which no inputs were registered due to finger loss of contact with the TSC. The loss of contact time t_{loss} indicates the matching total time period during which no inputs were registered.
- *Tracking Performance.* To assess the performance of the participants, variances of both the horizontal ($\sigma_{e_x}^2$) and vertical ($\sigma_{e_y}^2$) error signals were determined, from which contributions of the target disturbances (f_{t_x} and f_{t_y}), motion disturbance frequency (f_d) and remnant (n) were calculated as measures of performance.
- *BDFT Model Estimate.* First, to assess whether BDFT occurred for the recorded data, the variances of both the horizontal ($\sigma_{u,x}^2$) and vertical ($\sigma_{u,y}^2$) control signals were determined, from which contributions of the motion disturbance frequency (f_d) were calculated. If the feedthrough of f_d into u_x and u_y was sufficiently strong, the BDFT model of Eq. (5) was fit to the data. This resulted in four additional dependent measures: the BDFT gain G_{BDFT} , BDFT mass m_{BDFT} , BDFT damping b_{BDFT} , and BDFT stiffness k_{BDFT} . These variables were determined per participant for each condition, and for both the horizontal and vertical input signals.

III.A.6. Data Analysis

Controllers performed 64 runs during the experiment, of which the first half was treated as training. The final thirty runs were used for the data analysis. The horizontal and vertical input over each screen were separately logged at 100 Hz. Each analysis was performed for both the horizontal and vertical input signals separately. In this paper, all dependent measures are presented with box plots, over the dataset consisting of sixteen participants.

To investigate the effects of motion disturbances on the ability for participants to maintain in contact with the TSC throughout each run, input signals were checked for missing inputs. Loss of contact was registered when at least ten consecutive samples (i.e., 0.1 seconds) were detected with a zero derivative for both the horizontal and vertical input signals. Both the number of times that contact loss occurred, and the sum of the duration of contact loss, were recorded for each run. Normality checks indicated that non-parametric testing methods had to be used for statistic analysis. Friedman's ANOVA was therefore used, after which follow-up tests were performed using Wilcoxon tests.²⁵

To obtain a quantitative measure for the control performance of the participant, the TSC input error was determined. This error was determined for each direction by simply subtracting the target signal for each corresponding direction with the TSC input signals, as can be derived from Fig. 1. The variance was directly determined from this error signal, which served as measure for performance of the participants. With the total error variance obtained, it was possible to account parts of the total error variance to the known disturbances as the frequencies of those components were known.²⁶ This allowed to identify participant's sources of tracking error.

To detect whether motion disturbance signals actually fed through the participant's body to the TSC device, the Power Spectral Densities (PSDs) of the input data were determined subsequently. Since the motion disturbance signals were fully deterministic with power at known frequencies (Fig. 4), inputs signals on the TSC devices were expected to contain power at these same frequencies if sufficient BDFT occurred. PSDs were determined using the half-sided Fast Fourier Transform (FFT) of the output signals u_x and u_y , and their complex conjugate. These FFTs were calculated per individual run, after which all FFTs belonging to a certain condition were averaged. An averaged FFT was used to obtain the PSD. Presence of disturbance signals frequencies in these PSDs could subsequently be quantified, as power at the disturbance frequencies could be expressed as a percentage of the total power in the PSD.

If sufficient power from the motion disturbance signal was available in the control signal, an estimate for the biodynamic feedthrough dynamics was determined using Eq. (4) at the disturbance frequencies. To obtain an estimate for a full BDFT model ($\hat{H}_{BDFT}$), the BDFT model's parameters were estimated using both the genetic algorithm and steepest-descent optimization steps of the time-domain parameter estimation procedure of Ref. 19.

III.B. Hypotheses

The following hypotheses were formulated for the current experiment based on earlier findings and a literature search:

H1: *Loss of contact between the TSC and the finger will significantly increase with motion disturbances present compared to the baseline condition.*

Applying constant pressure to ensure smooth dragging and preventing accidental touches with finger are only some of the fine skills needed to operate a TSC. Effects of vibration, of which neuromuscular interference and BDFT are only two examples,²⁷ can interfere with these skills causing longer task completion time and reduced accuracy.^{5,8-11} Reduced sense of pressure and inertia of participant's limbs are expected to cause loss of contact with the TSC.

H2: *The target signals are more accurately tracked on the PFD than on the CDU.*

A known disadvantage of the use of TSCs is parallax,²⁸ which causes participants to perceive a different target location as a result of the viewing position if the participant is not directly in front of the screen. For the two tested display positions and orientations, parallax issues are expected to be worse for the CDU TSC.

H3: *Effects of BDFT will cause larger errors with the use of the PFD in comparison to the CDU.*

Since BDFT can be mitigated by providing passive support systems,^{12,27} it is expected that the combination of lack of support and increased inertia of the operator's stretched-out arm for this case leads to increased BDFT when using the PFD.

H4: *Effects of BDFT are strongest when motion disturbances act in the direction of TSC control inputs.*

TSC inputs along either screen axes are expected to be most perturbed by motion disturbances in the same axis. Earlier research also reported the largest touch errors in the direction of applied motion disturbance.⁹

IV. Results

This section presents the results of the experiment based on the input signals of sixteen participants. Results for the CDU tasks are presented in blue, whereas results for the PFD conditions are presented in red.

IV.A. Input Loss

Fig. 11 shows the input loss data, and indicates to which extent participants were able to keep their finger on the TSC for the duration of the experiment. Table 2 presents the corresponding statistical analysis results. The number of instances that this 'contact loss' occurred is shown in Fig. 11a, while Fig. 11b shows the total time contact with the TSC was lost.

Friedman's ANOVA, with Wilcoxon Signed-ranks post-hoc tests were used to determine whether loss of contact count and duration increased with motion disturbance conditions, when compared to the baseline. These tests reveal that, indeed, significant differences were found between both the input loss count (n_{loss}) and input loss duration (t_{loss}) during the baseline condition and the disturbance conditions when using the CDU (blue boxplots), with most significant effects for the heave disturbance (Z). This matches expectations, as the screen moves 'away' from the hand, whilst the participant's limbs lag behind the movement due to inertia (Fig. 9).

Using the same logic it can be reasoned that for the PFD, input loss count and duration would be highest for the forward (surge) motion disturbance (X). Results in Fig. 11a (red boxplots) show that this, indeed, is true. Friedman's ANOVA, with Wilcoxon Signed-ranks post-hoc tests, however, reveal that no statistical significant differences exist between the baseline and motion conditions. This can be explained by the fact that participants already lost contact with the PFD during the baseline condition without motion, on average 0.5 times per run.

An additional finding from these results is that in general, the number of times that participants lost contact with the TSC was increased whilst using the PFD, as compared to the CDU under same motion conditions. Although no hypothesis was developed for this phenomenon, a post-hoc Wilcoxon signed-ranks test between the two TSCs during baseline (NM) condition was performed to check for significance, which proved to be highly significant. It could be hypothesized that the passive support provided by the CDU helps the participant in maintaining contact with the screen. Such support is not given by the PFD, as the forward pointing arm has the freedom to move around.

IV.B. Tracking Performance

Variance of the error signal was used as quantitative measure for the performance of the participant. Results of this analysis are given in Figure 12, in which higher values indicate worse tracking performance. Once again, blue boxplots represent results for the CDU, whereas PFD results are given by red boxplots.

Figure 11. TSC input loss, count and duration.

Table 2. Friedman 's ANOVA with Bonferroni-corrected Wilcoxon Signed-ranks test results (sig^b) for input loss parameters, where ** is highly significant ($p < .00143$), * significant ($.00143 \leq p < .0072$) and – not significant ($p > .0072$). Results indicated at sig. are without Bonferroni correction, where ** is highly significant ($p < .01$), * significant ($.01 \leq p < .05$) and – not significant ($p > .05$)

Compared conditions		Dependent measures							
		Count				Duration			
Friedman χ^2 (7)		46.309, $p < .001$				27.872, $p < .001$			
Wilcoxon $\alpha = .0072$		z	r	sig^b .	sig.	z	r	sig^b .	sig.
CDU (NM)	x CDU (X)	-2.025	-.506	–	*	-2.192	-.548	–	*
CDU (NM)	x CDU (Y)	-2.825	-.706	*	**	-2.981	-.745	*	**
CDU (NM)	x CDU (Z)	-3.213	-.803	**	**	-3.180	-.795	**	**
PFD (NM)	x PFD (X)	-2.135	-.533	–	*	-1.448	-.362	–	–
PFD (NM)	x PFD (Y)	-1.450	-.362	–	–	-0.682	-.170	–	–
PFD (NM)	x PFD (Z)	-1.821	-.455	–	–	-1.422	-.355	–	–
CDU (NM)	x PFD (NM)	-3.319	-.830	**	**	-3.235	-.809	**	**

Figure 12. Variance of the horizontal and vertical input errors.

Table 3. Friedman 's ANOVA with Bonferroni-corrected Wilcoxon Signed-ranks test results error variance $\sigma_{e_x}^2$ and $\sigma_{e_y}^2$, where ** is highly significant ($p < .0025$), * significant ($.0025 \leq p < .0125$) and – not significant ($p > .0125$).

Compared conditions	Dependent measures						
	$\sigma_{e_x}^2$			$\sigma_{e_y}^2$			
Friedman $\chi^2(7)$	95.583, $p < .001$			91.729, $p < .001$			
Wilcoxon $\alpha = .0125$	z	r	sig.	z	r	sig.	
CDU (NM) x PFD (NM)	-3.102	-.775	**	-3.361	-.840	**	
CDU (X) x PFD (X)	-1.086	-.272	–	-2.999	-.750	*	
CDU (Y) x PFD (Y)	-2.172	-.543	–	-0.052	-.013	–	
CDU (Z) x PFD (Z)	-2.275	-.569	–	-3.206	-.802	**	

From Fig. 12a, in which the error variance was converted from (deg^2) to physical screen input error variance (mm^2) for easier interpretation, it becomes evident that sway (Y) motion disturbances cause the largest errors for both the CDU and PFD displays when looking at horizontal inputs. This corresponds with findings in earlier research stating that feedthrough of disturbance motions are largest when acting in the same plane as the control inputs,⁹ as horizontal inputs on the CDU correspond with the sway motion direction (Fig. 9).

Results for the vertical input in Fig. 12b support these findings as well, as surge (X) disturbances cause the error to be largest when using the CDU. Indeed, forward (surge) motion aligns with the vertical screen input of the CDU. The results show that when using the PFD too, surge leads to largest errors in the vertical input direction. This can be explained by the fact that the PFD was tilted by 18° from the vertical plane, as described in Section III.A.1 (Fig. 8). Accelerations in the negative X direction (surge) will cause the finger to slide upward, causing vertical offset from the target.

Friedman 's ANOVA followed up by Wilcoxon Signed-ranks tests (Table 3) reveal that, both for the vertical and horizontal input directions, a highly significant difference between input error exists when using the CDU and the PFD for the baseline (NM) condition. The use of the CDU leads in both cases to more error.

The following subsections cover the error variance components of the disturbance signal f_d , targets f_{t_x} and f_{t_y} and the remaining remnant n , in order to determine sources of error.

IV.B.1. Tracking performance: Horizontal Target

The f_{t_x} components of the total variance of the horizontal and vertical error signal ($\sigma_{e_x, f_{t_x}}^2$ and $\sigma_{e_y, f_{t_x}}^2$, respectively) are given in Fig. 13 as percentage of the total variance. For each motion disturbance, the target component was most strongly present in the error variance when using the CDU display when compared to the PFD. This difference was found to be highly significant (Table 4).

Note that f_{t_x} components are mainly observed in the horizontal input error e_x as expected. However, components of the horizontal target signal f_{t_x} are also detected in the vertical input error, which can be explained by mechanical coupling of participant's arm. The participant is unable to steer perfectly in a single axis, causing horizontal target

Figure 13. Horizontal Target components in the variance of error signals e_x and e_y .

Table 4. Friedman 's ANOVA with Bonferroni-corrected Wilcoxon Signed-ranks test results for horizontal target components in $\sigma^2_{e_x}$ and $\sigma^2_{e_y}$, where ** is highly significant ($p < .0025$), * significant ($.0025 \leq p < .0125$) and – not significant ($p > .0125$).

Compared conditions	Dependent measures						
	$\sigma^2_{e_x, f_{t,x}} / \sigma^2_{e_x}$			$\sigma^2_{e_y, f_{t,x}} / \sigma^2_{e_y}$			
Friedman $\chi^2(7)$	95.583, $p < .001$			31.125, $p < .001$			
Wilcoxon $\alpha = .0125$		z	r	sig.	z	r	sig.
CDU (NM) x PFD (NM)	-3.464	-	.866	**	-2.896	-.724	*
CDU (X) x PFD (X)	-3.464	-	.866	**	-.672	-.168	–
CDU (Y) x PFD (Y)	-3.464	-	.866	**	-.569	-.142	–
CDU (Z) x PFD (Z)	-3.464	-	.866	**	-.569	-.142	–

frequencies to appear in vertical inputs.¹⁶ Another reason for detection could be noise that is located at frequencies of the target component f_{t_x} .

IV.B.2. Tracking performance: Vertical Target

The f_{t_y} components of the total variance of the horizontal and vertical error signal ($\sigma^2_{e_x, f_{t_y}}$ and $\sigma^2_{e_y, f_{t_y}}$, respectively) are given in Fig. 14 as a percentage of the total variance. Similar to what was observed with the horizontal target components, vertical target components were most present in the error variance when using the CDU display. This difference between the CDU and PFD displays was again highly significant for the baseline (NM), sway (Y) and heave (Z) conditions (Table 5), and significant for surge (X).

Note that this time, f_{t_y} components are mainly observed in the vertical input error e_y as expected. However, f_{t_y} components are also observed in the horizontal input direction for reasons noted in Section IV.B.1.

IV.B.3. Tracking performance: Motion Disturbance

The f_d components in the total variance of both the horizontal and vertical error signal ($\sigma^2_{e_x, f_d}$ and $\sigma^2_{e_y, f_d}$, respectively), are given in Fig. 6 as a percentage of the total variance. Little power is observed during the NM condition for both input directions, which is easily explained by the fact that no motion disturbance power was present. The components visible simply originate from noise at the f_d frequencies.

For the horizontal input direction, Fig. 6a, it can be observed that largest components of $\sigma^2_{e_x, f_d}$ are measured during sway (Y), followed by surge (X). With sway (Y) acting in the same direction as the horizontal TSC input for both the CDU and PFD screens, large values components were to be expected. However, for both displays it can be seen that forward surge (X) motion also influences horizontal screen input. During heave (Z), f_d only contributes minimally.

For the vertical input direction, Fig. 6b, it can be observed that the largest components of $\sigma^2_{e_y, f_d}$ are measured during surge (X) for both screens, and heave (Z) for the PFD. According to hypothesis H4, this can be explained by the fact that the motion disturbance acts in the same direction as the screen input. This might be less intuitive for the

Figure 14. Vertical Target components in the variance of error signals e_x and e_y .

Table 5. Friedman's ANOVA with Bonferroni-corrected Wilcoxon Signed-ranks test results for vertical target components in $\sigma^2_{e_x}$ and $\sigma^2_{e_y}$, where ** is highly significant ($p < .0025$), * significant ($.0025 \leq p < .0125$) and – not significant ($p > .0125$).

Compared conditions		Dependent measures					
		$\sigma^2_{e_x, f_{t_y}} / \sigma^2_{e_x}$			$\sigma^2_{e_y, f_{t_y}} / \sigma^2_{e_y}$		
Friedman $\chi^2(7)$		20.375, $p = .005$			94.104, $p < .001$		
Wilcoxon $\alpha = .0125$		z	r	sig.	z	r	sig.
CDU (NM)	x PFD (NM)	-.414	-.104	–	-3.516	-.879	**
CDU (X)	x PFD (X)	-.621	-.155	–	-2.637	-.659	*
CDU (Y)	x PFD (Y)	-.724	-.181	–	-3.258	-.815	**
CDU (Z)	x PFD (Z)	-1.086	-.272	–	-3.516	-.879	**

Table 6. Motion Disturbance components in the variance of error signals e_x and e_y .

Table 7. Friedman's ANOVA with Bonferroni-corrected Wilcoxon Signed-ranks test results for motion disturbance components in $\sigma^2_{e_x}$ and $\sigma^2_{e_y}$, where ** is highly significant ($p < .0025$), * significant ($.0025 \leq p < .0125$) and – not significant ($p > .0125$).

Compared conditions		Dependent measures					
		$\sigma^2_{e_x, f_d} / \sigma^2_{e_x}$			$\sigma^2_{e_y, f_d} / \sigma^2_{e_y}$		
Friedman $\chi^2(7)$		98.521, $p < .001$			99.167, $p < .001$		
Wilcoxon $\alpha = .0125$		z	r	sig.	z	r	sig.
CDU (NM)	x PFD (NM)	-1.965	-.491	–	-1.810	-.453	–
CDU (X)	x PFD (X)	-3.309	-.827	**	-3.206	-.802	**
CDU (Y)	x PFD (Y)	-1.655	-.414	–	-0.827	-.207	–
CDU (Z)	x PFD (Z)	-3.516	-.879	**	-3.413	-.853	**

forward (surge, X) disturbance in case of the PFD, but remember that this particular screen was tilted slightly causing the finger to slide up and down with forward and backward disturbance motions.

IV.B.4. Tracking performance: Remnant

Power at frequencies that is not accounted for are referred to as remnant, and may include effects ranging from simulator motion dynamics to non-linearities in participant control behavior. The remnant components in the horizontal error signal are given in Fig. 15a, whereas remnant for the vertical error signal are given in Fig. 15b, both expressed as percentage of $\sigma_{e_x}^2$ and $\sigma_{e_y}^2$ respectively. Both for the horizontal and vertical directions, it can be observed that the use of PFD leads to higher remnant components when compared to the use of the CDU for the same motion disturbance. This indicates that participants have more trouble operating the PFD for reasons other than target or disturbance frequencies. Examples may include physical effects such as nonlinear neuromuscular effects or fatigue. This difference is highly significant for the baseline condition and significant for surge (X) and heave (Z) in the horizontal direction. For the vertical direction, the difference is highly significant for the baseline (NM), surge (X) and sway (Y) conditions.

Figure 15. Remnant components in the variance of error signals e_x and e_y .

Table 8. Friedman's ANOVA with Bonferroni-corrected Wilcoxon Signed-ranks test results for remnant components in $\sigma_{e_x}^2$ and $\sigma_{e_y}^2$, where ** is highly significant ($p < .0025$), * significant ($.0025 \leq p < .0125$) and – not significant ($p > .0125$).

Compared conditions		Dependent measures					
		$\sigma_{e_{x,n}}^2 / \sigma_{e_x}^2$			$\sigma_{e_{y,n}}^2 / \sigma_{e_y}^2$		
Friedman $\chi^2(7)$		57.188, $p < .001$			57.208, $p < .001$		
Wilcoxon $\alpha = .0125$		z	r	sig.	z	r	sig.
CDU (NM)	x PFD (NM)	-3.464	-.866	**	-3.516	-.879	**
CDU (X)	x PFD (X)	-2.999	-.750	*	-3.309	-.827	**
CDU (Y)	x PFD (Y)	-.982	-.246	–	-3.154	-.789	**
CDU (Z)	x PFD (Z)	-2.844	-.711	*	-1.396	-.349	–

IV.C. Disturbance Feedthrough

Fig. 16 shows the PSDs for both the horizontal and vertical TSC input signals u_x and u_y for the surge, sway and heave motion conditions, averaged over all participants. If BDFT occurs, peaks should be observed at frequency locations of the motion disturbance f_d . Subsequently, the extent to which the motion disturbance frequencies are present in the TSC input signal can be calculated by quantification of the presence of σ_{u,f_d}^2 components in σ_u^2 . Fig. 17 shows to what extent the disturbance signal contributes to the TSC input signals u_x and u_y , as percentage of the total TSC input signal variance. As is clear from Fig. 17, these percentages are generally very low as most energy in the input signals originates from the target signals. Fig. 18 shows an example of an input signal with separated motion component to illustrate this. Note that results for the baseline condition are omitted for the upcoming sections as no BDFT can occur without motion.

Figure 16. Power Spectral Densities of the TSC inputs.

Figure 17. Motion disturbance components in the variance of input signals u_x and u_y .

Table 9. Friedman's ANOVA with Wilcoxon Signed-ranks test results for disturbance components in $\sigma^2_{u_x}$ and $\sigma^2_{u_y}$, where ** is highly significant ($p < .0033$), * significant ($.0033 \leq p < .0167$) and – not significant ($p > .0167$).

Compared conditions		Dependent measures					
		$\sigma^2_{u_{x,d}} / \sigma^2_{u_x}$			$\sigma^2_{u_{y,d}} / \sigma^2_{u_y}$		
Friedman χ^2 (7)		93.063, $p < .001$			89.938, $p < .001$		
Wilcoxon $\alpha = .0125$		z	r	sig.	z	r	sig.
CDU (X)	x PFD (X)	-2.223	-.556	–	-3.361	-.840	**
CDU (Y)	x PFD (Y)	-1.965	-.491	–	-2.017	-.504	–
CDU (Z)	x PFD (Z)	-0.982	-.246	–	-2.534	-.634	*

Figure 18. Example timetrace of input signal, with separate motion disturbance feedthrough component.

Fig. 16a to Fig. 16c show the PSDs of the horizontal input on the CDU screen during surge, sway and heave, respectively. Although all figures show at least some presence of power at the disturbance frequencies (indicated by red stars), strongest responses are observed when sway disturbances are present. Responses to f_d for the surge and heave conditions contain barely more power than noise at other frequencies. This corresponds with the findings in Fig. 17a, where f_d components are only significantly present for sway (Y) when using the CDU.

Fig. 16d to Fig. 16f show the PSDs of the vertical input on the CDU screen during surge, sway and heave, respectively. Strongest responses to disturbance motions are observed when the motion acts in the forward direction (surge). Responses to sway and heave are minimal. This is confirmed by the data in Fig. 17b, where surge (X) is the only disturbance with significant feedthrough when using the CDU.

Fig. 16g to Fig. 16i show the PSDs of the horizontal input on the PFD screen under varying disturbances. Strong responses are observed when the motion acts in both the forward (surge) and lateral (sway) directions, although the sway response is significantly stronger. This also follows from Fig. 17a, where the red boxplots representing the PFD results shows strong responses to sway (Y) and less (but still significantly) strong response during surge.

Finally, Fig. 16j to Fig. 16l show the PSDs of the vertical input on the PFD screen during surge, sway and heave, respectively. The largest contributions are observed when the motion acts in both the forward (surge) and vertical (heave) direction. The effect of sway is negligible. Fig. 17a confirms these findings, where the red boxplots representing PFD results are showing strong response to both surge (X) and heave (Z).

For the vertical input direction, a significant difference between the PFD and CDU was found during the heave (Z) disturbance. A highly significant difference was observed between the two input methods for surge (X). Significant differences for the horizontal input direction between both screens were not found, for any disturbance.

IV.D. Biodynamic Feedthrough Dynamics

IV.D.1. BDFT Detection

Section II.C elaborated on how the BDFT dynamics were measured and modeled. In order to determine a reliable BDFT response, however, sufficient motion disturbance power should be observed in the input signals u_x and u_y as the BDFT response would otherwise be based on noise.¹²

Fig. 19a shows a representative example of identified BDFT response of horizontal input on the PFD during surge (forward) disturbance for a single participant. Red bars indicate the spread over the four BDFT responses that were identified from four runs for a single condition. The four responses obtained were initially fitted using a Genetic

Algorithm (GA), after which the results were refined using a Gauss-Newton estimation to obtain four sets of model parameters. The averaged model, thus composed with the average of these parameters, is indicated with the blue line. The Variance Accounted For, a measure described in Section IV.D.2 which is used to estimate the accuracy of the estimated model, showed that model estimates with an average accuracy of 70% could be made when at least 0.5% of the horizontal input variance $\sigma_{u_x}^2$ was composed of feedthrough from f_d .

Fig. 19b on the other hand shows a representative example of identified BDFT response of horizontal input on the CDU during surge (forward) disturbance for a single participant. From Table 10 it can be seen that the horizontal input variance $\sigma_{u_x}^2$ is only composed of 0.3% feedthrough from f_d . This also follows from Fig. 16a, where power at the f_d frequencies barely exceeds noise levels. This causes BDFT measurements with a wide spread, which makes estimation of the BDFT model unreliable.

In general it was observed that at least 0.5% of the input variance σ_u^2 needed to be composed of feedthrough from f_d , before reliable BDFT measurements and estimates could be made. It is for this reason that BDFT estimations were performed only for conditions in which σ_{u,f_d}^2 exceeded 0.5%.

Table 10. Strength of f_d components in $\sigma_{u_x,y}^2$ and BDFT detection result.

TSC	Input Direction	Disturbance	$\sigma_{u,f_d}^2 / \sigma_u^2$ ·100 [%]	Possibility of Accurate BDFT Estimation
CDU	Horizontal	Surge (X)	0.3	✗
CDU	Horizontal	Sway (Y)	1.4	✓
CDU	Horizontal	Heave (Z)	0.3	✗
CDU	Vertical	Surge (X)	2.5	✓
CDU	Vertical	Sway (Y)	0.4	✗
CDU	Vertical	Heave (Z)	0.4	✗
PFD	Horizontal	Surge (X)	0.5	✓
PFD	Horizontal	Sway (Y)	1.8	✓
PFD	Horizontal	Heave (Z)	0.2	✗
PFD	Vertical	Surge (X)	1.3	✓
PFD	Vertical	Sway (Y)	0.2	✗
PFD	Vertical	Heave (Z)	0.8	✓

Figure 19. BDFT Model Estimation Examples.

IV.D.2. BDFT Model Validation using VAF

Although the model proposed in Section II.C modeled the example BDFT dynamics in Fig. 6 reasonably well, it is possible that each condition with different motion disturbance has to be modeled by a different BDFT model. After all, BDFT is a complex mechanism that involves many variables.^{12,27} Its results might not be easily captured by a single model with varying parameters. To evaluate whether the model proposed in Section II.C can be used for all conditions in this experiment, the model is validated using Variance Accounted For (VAF). The VAF describes the extent to which the motion disturbance components in the touchscreen input signals $u_{x,fd}$ and $u_{y,fd}$ can be accounted for by the model and is expressed as a percentage.

Fig. 20 shows the VAF results for all conditions, for both horizontal and vertical inputs, where the values have been averaged over all participants. The conditions for which the disturbance feedthrough was determined to be too weak, as determined in Section IV.D.1, have been presented with a grey background. One can clearly observe that a good model cannot be determined if there is not enough feedthrough of motion disturbances to the TSC, as all gray columns contain boxplots with low VAFs. For the remainder of the conditions, a mean VAF of 70% or higher was obtained. This indicates that the model as suggested in Section II.C is capable of modeling BDFT accurately for especially the conditions with notable BDFT.

IV.D.3. Parameter estimation: G_{BDFT}

The first row of Fig. 21 shows results of the BDFT model gain (G_{BDFT}). Note that the figures for both the horizontal (Fig. 21a) and vertical (Fig. 21b) control signals also show the unreliable estimation results for the BDFT gain as explained in Section IV.D.1. These results are indicated with a grey background and, as can be verified from Fig. 21, their values are generally low when compared to the gains of conditions that are accurately describing BDFT.

Fig. 21a indicates a notable difference between the gains of surge (X) and sway (Y) for the PFD. A possible explanation is that BDFT mainly acts in the direction of the control input. Therefore, less BDFT is present in the horizontal input of the PFD when a forward disturbance (surge, X) is present. For both the PFD and the CDU, the sway (Y) motion is in plane with the horizontal control inputs. For the same sway disturbance, the PFD gain is slightly larger when compared to the gain of the CDU. This matches expectations, as increased limb inertia and reduced arm support will increase effects of BDFT.

Figure 20. Average VAF of the BDFT Model Estimation.

Fig. 21b shows that the BDFT gains for surge (X) and heave (Z) are comparable with those for vertical inputs on the PFD. Note, however, that the spread for heave is large, which may be caused by the low feedthrough into the input signal, resulting in less accurate estimations. Comparing the CDU and PFD G_{BDFT} values for surge (X), it can be seen that the CDU gain is clearly higher. This is expected, as forward disturbance (surge) acts in the same plane as the vertical inputs over the CDU. As the PFD is tilted, the same effect occurs to a limited degree, as explained in Section III.A.1 (Fig. 8). Acceleration toward the forward direction (surge) might cause the finger to slide upward, causing vertical offset from the target.

IV.D.4. Parameter estimation: m_{BDFT}

The second row of Fig. 21 shows results of the BDFT model's mass parameter (m_{BDFT}) estimation. Again, unreliable estimation results for BDFT frequency are indicated with a grey background. These values for m_{BDFT} have a huge spread, which can be attributed to the fact that the GA and MLE algorithms were fitting models to noise. The figures do not show the entire spread of these values in order to visualize m_{BDFT} values that have been estimated accurately.

Looking at the horizontal inputs in Fig. 21c during sway (Y), m_{BDFT} parameters are comparable for the CDU and PFD with values around 1.5 kg. Note that BDFT consists of many variables and this mass figure should therefore be seen as a system equivalent mass rather than just the typical mass of an arm. When the PFD is compared between the surge (X) and sway (Y) motion conditions it can be seen that m_{BDFT} is slightly, but not significantly, larger for sway.

For the vertical inputs in Fig. 21d with surge (X) disturbance motion, an increase of approximately 30% is observed for m_{BDFT} parameters when using the CDU, when compared to use of the PFD. When the PFD values for m_{BDFT} are compared between the surge (X) and heave (Z) conditions, one can see that these values are approximately 50% higher for heave (Z).

IV.D.5. Parameter estimation: b_{BDFT}

The third row of Fig. 21 shows results of the BDFT model's damping parameter (b_{BDFT}) estimation. Again, unreliable results are indicated with a grey background. Larger spreads and increased numbers of outliers for these conditions indicate that, indeed, the GA and MLE algorithms could not determine consistent parameter estimates.

For the horizontal inputs in Fig. 21e, no significant differences can be observed for values of b_{BDFT} over surge (X) and sway (Y) using the PFD. Furthermore, no significant differences were found between CDU and PFD values of b_{BDFT} during sway (Y). The results for vertical inputs in Fig. 21f indicate slightly higher values of b_{BDFT} during heave (Z) than during surge (X) when using the PFD, but this difference is not significant. Pairwise comparisons of the CDU and PFD for surge (X) show no statistical relevant differences.

(a) BDFT model estimation of G_{BDFT} , horizontal input

(b) BDFT model estimation of G_{BDFT} , vertical input

(c) BDFT model estimation of m_{BDFT} , horizontal input

(d) BDFT model estimation of m_{BDFT} , vertical input

(e) BDFT model estimation of b_{BDFT} , horizontal input

(f) BDFT model estimation of b_{BDFT} , vertical input

(g) BDFT model estimation of k_{BDFT} , horizontal input

(h) BDFT model estimation of k_{BDFT} , vertical input

Figure 21. BDFT model parameter estimation results.

IV.D.6. Parameter estimation: k_{BDFT}

The final row of Fig. 21 shows results of the BDFT model's stiffness parameter (k_{BDFT}) estimation. For the horizontal inputs in Fig. 21g, results show that use of the PFD during surge (X) results in 20% higher stiffness coefficients when compared to the use of the PFD during sway (Y). Although these differences are not significant, they can be attributed to the fact that participants' arms were supported by the PFD during surge (X), which allows the participant to increase arm stiffness. This support lacks during sway (Y), as the arm is moved left and right due to effects of BDFT. No significant differences were found between CDU and PFD values of k_{BDFT} during sway (Y).

The results for vertical inputs in Fig. 21f show similar values of k_{BDFT} during surge (X) and heave (Z) for use of the PFD. Comparing the CDU with the PFD for surge (X), it can be seen that stiffness values with the use of PFD are approximately 20% higher. This too, can likely be explained by the added support of the PFD during forward (surge, X) disturbance. The CDU does not offer such support during surge.

V. Discussion

In this paper, a cybernetic approach was used to analyze data from a human-in-the-loop experiment, aimed to gain understanding on the influence of BDFT on performing a waypoint dragging task on a touch-sensitive cockpit display. Participants in the experiment performed a two-dimensional pursuit tracking task on a TSC, either without motion or while being perturbed by fore-aft (surge), lateral (sway), or vertical (heave) motion disturbances. In addition, two different TSCs, located at typical PFD and CDU cockpit positions, were tested.

Data were first analyzed for loss of contact between the TSC and participants' fingers. Our **Hypothesis H1** stated that loss of contact between the TSCs and finger would significantly increase in the presence of motion disturbances. The obtained results showed that, indeed, loss of contact count increased from an average of 0.09 counts per run during the no motion condition to 0.56 counts during motion disturbances for the CDU, and from 0.75 to 1.32, respectively, for the PFD. This increase was highly significant for the CDU when comparing the baseline (NM) with heave (Z) conditions, both for contact loss count and contact loss duration. For sway (Y) too, significant effects were found when compared to the baseline condition on the CDU. For surge (X), results were not significant due to a large Bonferroni correction. For the PFD, however, no significant differences were found between the baseline (NM) and motion conditions. One can conclude that TSC contact loss depends on more variables than motion disturbance alone. Hypothesis H1, therefore, only holds partially.

An additional finding from the input loss analysis was that the number of times that participant lost contact with the TSC was increased when the PFD was used when compared to the CDU under the same motion conditions. This suggests that it is easier for participants to apply a consistent control strategy on a system that supports the human finger (i.e., CDU), rather than on a system where the participant is required to hold his or her arm suspended in the air (i.e., PFD). This is also consistent with the finding that PFD contact loss already occurred for an average of 0.5 times per run when no motion disturbance was present.

After analyzing data for loss of contact, performance was measured using the variance of the error signal σ_e^2 . Due to the known frequency locations of the target signals, it was possible to determine to what extent these signal contributed to the total error variance σ_e^2 . On average, around 30% of the error variances is inherently explained by the target signals. **H2** hypothesized that target signals are more accurately tracked on the PFD than on the CDU as a result of parallax, a known problem with the use of TSCs.²⁸ Pairwise comparison between the two TSCs for each disturbance condition showed highly significant differences for target component present in error signals. Participants were in all cases able to track the target more accurately on the PFD, suggesting that hypothesis H2 holds. However, it has to be noted that participants observed a slightly higher delay with the use of the CDU compared to the PFD, i.e., the magenta position indicator 'lagged' behind the actual finger position. Such errors would produce higher components of target error in the error variance, invalidating results. Although specifications of both TSCs show the same response rate (8 ms), it might be possible that touch registration time differs. Quantification of this registration time was, however, outside the scope of this research, but is planned for future research. Hypothesis H2 thus holds conditionally and it is recommended to repeat the comparison between the two TSC locations with a single touchscreen brand and type for final confirmation.

Similarly, it can be determined to what extent f_d components contribute to the total error variance σ_e^2 . **H3** hypothesized that effects of BDFT will cause larger control errors with the use of the PFD in comparison to the CDU. If this hypothesis holds, larger components of σ_{exfd}^2 should be observed for the PFD than for the CDU. Since sway (Y) is critical for the horizontal inputs at both TSCs, that condition will be used for comparison. It was shown that for sway (Y), indeed, use of the PFD resulted in higher components (15% on average) of σ_{exfd}^2 than the CDU. This difference,

however, is not significant (Table 7). The total variance of the error $\sigma_{e_x}^2$ in general, did not show significantly higher values for the PFD than the CDU during sway (Y) disturbance. Therefore, it cannot be concluded that control errors are larger when using the PFD in comparison to the CDU in general, and thus Hypothesis H3 is rejected. Note, however, that increased remnant components in the error variance for the PFD with respect to the CDU do suggest that the PFD is more susceptible to errors that cannot be attributed to either target or disturbance frequencies.

H4 hypothesized that effects of BDFT manifest predominantly when motion disturbances act in the direction of TSC control inputs. For the CDU, this means that sway (Y) was expected to show the most feedthrough for horizontal inputs, and surge (X) for vertical inputs. This was visually confirmed in the PSDs (Fig. 16b and Fig. 16d, respectively). Furthermore Fig. 17 showed that for the CDU, the f_d component in $\sigma_{u_x}^2$ was highest during sway (Y) disturbance whereas the f_d component in $\sigma_{u_y}^2$ was highest during the surge (X) condition. If the hypothesis were to hold, sway (Y) should generate the most feedthrough for the horizontal PFD inputs, whereas both surge (X) and heave (Z) should generate most feedthrough for the vertical PFD inputs, due to the fact that the screen was tilted. Indeed, the PSD in Fig. 16h visually confirm that most feedthrough in the horizontal direction of the PFD occurred during sway (Y). Analysis of the disturbance variance components also confirmed that sway (Y) causes most feedthrough. For the vertical inputs on the PFD the PSDs showed strong feedthrough for both the surge (X) and heave (Z) conditions as expected. This was confirmed by the f_d components in $\sigma_{u_y}^2$, showing strongest feedthrough for surge (X) (1.32% $\sigma_{u_y, f_{d_x}}^2$), and less strong, but still significant (0.76% $\sigma_{u_y, f_{d_z}}^2$) for heave (Z) (Fig. 17b). As the results therefore corresponded fully with the hypothesis, it can be concluded that Hypothesis H4 holds.

Overall, despite collecting data from 16 participants, the current results are still somewhat lacking in statistical power. Therefore, it is recommended that parts of this experiment are repeated with an increased number of participants. This would allow for more accurate analysis and modeling of the BDFT for conditions in which the TSC inputs were out-of-plane with the motion disturbance. With the increased accuracy, research could be performed on the dependencies of the model parameters on varying factors including pilot seating position and display location. Pairwise comparisons between different conditions often hinted at a difference, but could not be statistically proven. The input loss for the PFD during the baseline and motion conditions is only one example. Results are expected to be more statistical significant with an increased participant pool. This especially holds when multiple pairwise comparisons are made, due to the Bonferroni correction.

The final recommendation is to increase the realism of the task. This experiment aimed to observe and model BDFT for varying frequencies using a single, continuous way-point dragging task lasting 90 seconds, which simplified analysis of the results in the frequency domain. To improve realism, shorter dragging tasks should be performed by dragging a waypoint to a stationary target. Realism can furthermore be increased by adapting the turbulence profile such, that it better matches with real-world turbulence as experienced in the cockpit of a commercial airliner.

As TSCs allow for higher information density²⁹ and increased situation awareness,³⁰ the increased use of TSC devices in the cockpit environment is a given fact. One of the main disadvantage of such integration comes from the dynamic environment in which these systems are used.⁴ Mitigation of resulting BDFT through model-based signal cancellation has shown to be effective if the BDFT model is adapted to the human operator and the control task.¹² A foundation for such a model that could be implemented on touchscreen driver software is provided in this research.

VI. Conclusions

For quantitative analysis of the effects of BDFT that occur when pilots perform a way point dragging task on a TSC located in a turbulent cockpit, this paper adopted a cybernetic approach focused on a two-dimensional pursuit touchscreen tracking task. In a flight simulator experiment, TSC locations comparable to CDU and FMS positions were evaluated during pure surge (X), pure sway (Y), pure heave (Z) and baseline (fixed-base) conditions. The obtained results show a highly significant increase in loss of contact with the screen, especially for the CDU display, when heave (Z) disturbances are present. Furthermore, highly significant differences between the PFD and CDU regarding finger loss of contact during the baseline (NM) condition reveal that participants have less trouble providing continuous inputs onto a touchscreen installed at the CDU position. Task performance results, based on the variances of the horizontal and vertical tracking errors and their target, disturbance, and remnant components indicated that the effects of BDFT mainly manifest themselves when motion disturbances act in the direction of TSC control inputs. However, explicit analysis of the motion disturbance components the tracking errors revealed no significant differences in the effects of BDFT for the different TSC locations. Finally, a simple second-order mass-spring-damper BDFT model was identified from estimated frequency responses and its four parameters, estimated through model fitting, were used to further quantify the BDFT dynamics. It was found that only with sufficiently strong feedthrough of motion signals reliable BDFT modeling was possible, which was the case for six out of twelve experiment conditions. The

fitted BDFT models were found to model at least 70% of the measured BDFT signal components, which shows clear potential for possible future software-based mitigation of BDFT through model-based signal cancellation.

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