Angular Velocity Perception Threshold and Sense of Presence for a Three Degrees of Freedom (DOF) Driving Simulator in Virtual Environment

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Abstract

Angular velocity perception plays an important role for a better sense of presence in driving simulators. This paper deals with the angular velocity perception threshold and sense of presence.

A three degrees of freedom (DOF: roll, pitch, and heave) driving simulator, a motion tracking sensor, a driving simulation software, and self-prepared questionnaires were used.

Due to the subjective assessments, there were no significant differences between static and dynamic platform types. Eight different cases were investigated with respect to visual and inertial factors (field of view (FOV) and motion platform).

Subjective evaluations showed that there were no significant differences between static and dynamic conditions. Lower FOV, static platform, stereo vision condition has provided the best condition (best realism depending on objective-subjective measure relationship).

Introduction

Context

In driving simulation, sense of presence is a very well-known and important topic to study further on, and therefore it is required to develop systems and/or methods to increase it [1, 2].

State of the Art

Improving the realism of motion cueing is realizable by using other sensory cues, for example, visual cues. Body orientation's perception might be affected by visual cues. Due to [3, 4], visual cues had more elevated level of influences on the perceived orientation than the sensed direction of gravity named as "vection" (visually induced illusion of angular or linear self-motion). A negative correlation has resulted in vertical movement between individual vestibular threshold and vection onset latency (VOL): the lower the vestibular threshold, the longer the delay in vection [3, 5, 6] (vection onset latency and vestibular thresholds (VOL)).

The impact of vestibular stimulation with various angular accelerations and velocities on perceiving the visual motion direction was examined. Fixed accelerations resulting in diverse angular velocities and fixed angular velocities obtained at diverse accelerations were merged in 20 healthy participants. It was shown that perception thresholds significantly raised with increasing angular velocity. It has also resulted that raised acceleration had no significant influence on the perception thresholds. It was concluded that merely the achieved angular velocity was the dominant factor in the treatment of vestibular-visual interaction [7].

A study was accomplished to investigate the perceptual relationships between angular and linear perception thresholds during simultaneous rotation and translation on a curved path. Rotation thresholds augmented vaguely, however not significantly, with synchronous linear velocity magnitude. Yaw rotation perception threshold was determined as 1.45 ± 0.81 °/s (3.49 ± 1.95 °/s^2). Translation thresholds elevated significantly with raising magnitude of synchronous angular velocity. These findings suggest that aware perception might not separate estimates of linear and angular motion parameters during curved-path movement [8].

A turning cabin driving simulator was constructed and multiple projectors were used together with a 360-degree cylindrical screen to generate a display. Driver participants reported a significant less amount of simulator sickness when the simulator cabin turned around the yaw axis. The results emphasized that a much higher amount of optical flow was experienced by all drivers when the cabin was static [9].

A research was realized in order to compare different visual conditions [10]. A first experiment was composed of three DOF (roll, pitch, and heave) at computer automatic virtual environment (CAVE) as CAVE active stereo and mono visions as well as head-mounted display (HMD) vision. The stereo and mono visual cases' performances differed from each other very indistinctly. HMD experience resulted in

weaker speed perception and velocity was harder to maintain; furthermore HMD required more amount of lateral control effort to maneuver through the cones. Nevertheless, HMD yielded a higher accuracy for stopping at a predefined line. As a conclusion, subjects did not make a clear predilection for any of the visual conditions [10].

A second experiment included comparing the driving performance between the CAVE and six DOF ride motion simulator (RMS). Driving performances between the CAVE and RMS were highly similar. Driving session appeared to be more consistent between the first and second drives on the RMS comparing to the CAVE. During the curvature driving, it required more level of control by the participants to guard the trajectory. The speeds were underestimated for the both cases (CAVE and RMS). Simulator sickness measures were approximately similar between the RMS and CAVE cases. The relief-band had the role of lowering the simulator sickness symptoms between the first and second drives [10].

Simulators with motion platform systems were used to put the driver in the loop with an existence of a motion feedback from motion platforms for diverse kinds of DOFs. The type of the motion platform and its related motion envelope was a main element for the capability to satisfy specific motion cues. Algorithms for three types of motion systems with the eight DOF systems (six DOF, x and y rails), six DOF systems (roll, pitch, yaw, surge, sway, and heave), and three DOF systems (roll, pitch, and linear rail) were discussed [11].

A motion-cueing strategy used for a dynamic simulator with three DOF (roll, pitch, and yaw) to accomplish the roll, pitch, yaw, surge, and sway motions (five DOF) by using an online optimization algorithm was investigated in [12]. Furthermore, experiments were introduced to show the validity of the five DOF motion platform. By introducing the constrained optimization real-time optimal motion-cueing algorithm (ROMA), the motion control does not ensure merely a precise cue to the participant but also secures the mechanical construction of the motion platform. Tests were realized online and revealed that the proposed strategy brings much more realistic movements than the classical algorithm does for a three DOF motion platform. The proposed motion cueing is in general applicable to all motion simulators with rotational three DOF [13].

Eight low-cost non-vestibular motion-cueing systems were evaluated and compared with respect to the driver performance as the cueing system disengaged: seat belt tensioning system, vibrating steering wheel, motion seat, screeching tire sound, beeping sound, road noise, vibrating seat, and pressure seat. The results indicated that these systems were advantageous in reducing velocity and acceleration and they enhanced lane-keeping and/or stopping accuracy. The seat belt tensioning system had a particularly higher impact on driver braking performance. This system decreased driving velocity, raised stopping distance, lowered maximum deceleration, and enhanced stopping preciseness. It was deduced that low-cost non-vestibular motion cueing could be a preliminary option in order to ameliorate simulator's cabin characteristics so that it better complies with real-life driving situation [14].

"CAVE" is a multiple-face prism with images on each surface used in virtual reality (VR) environments. It has been rated as being adequate and ample as the "immersive" simulation of VR comparing to the insufficient head-mounted displays (HMDs) in that domain [15, 16, 17, 18]. Nevertheless, current HMDs are able to rival with many CAVEs [19].

A study was accomplished in order to compare the levels of presence and anxiety, fear that was visualized by using a CAVE and a head-mounted display (HMD) [20]. The experiments for the two visualization systems were realized to compare their impacts on the participants (non-phobic users). After having experienced each visualization system (HMD or CAVE), the participants were requested to complete an adapted Slater et al. questionnaire [20, 21]. Due to [20], the CAVE yielded a more elevated level of presence for users. The results depicted that the CAVE increased anxiety more than the HMD did [20].

An experimental procedure was discussed in order to evaluate the HMD Oculus and three LCD screens (ECO_2 static driving simulator) for a specific driving scenario with respect to simulation sickness. HMD Oculus caused a more elevated level of nausea, dizziness, and eyestrain than those with ECO_2 static driving simulator. In terms of headache, mental pressure, fear, and uneasiness, no significant difference was obtained between HMD Oculus and ECO_2 static driving simulator, although the mean values of those in HMD Oculus were all higher than those in ECO_2 driving simulator. Regarding the visual quality, ECO_2 static driving simulator was assessed significantly better than HMD Oculus. With regard to the immersive impression, no significant difference was found between two devices [21].

Scientific Issue

In driving simulation, there are mainly two stimuli as visual environment and motion platform of the simulator as whether it is active or passive. The reason why angular velocity has been investigated was:

- Since it is an important factor for motion perception, its relation with the sense of presence gives an idea about realism.

The questions to be investigated in this research were:

- "What is the value of angular velocity perception threshold in the driving simulation in terms of sensory stimuli?" (It refers to the angular velocity sensitivity for the feeling of immersion in driving simulators.)
- "How different the sense of presence is perceived in the driving simulation with respect to sensory stimuli?"
- "Is there any relationship between angular velocity perception threshold and the sense of presence in the driving simulation with regard to sensory stimuli?"

Plan of the Article

There are two important topics to investigate, in terms of driving simulation, which are the angular velocity threshold and sense of presence for a three DOF (roll, pitch, heave) driving simulator that emphasizes this research paper. The paper is organized as follows: Section 2 describes "methods and materials," section 3 highlights "objective measures," section 4 explains "subjective measures," section 5 deals with "results and discussion," and finally section 6 concludes this paper.

Methods and Materials

Proposed Approach

The objective of the experiments in this paper is to investigate angular velocity thresholds (thetadot$_{_pt}$, pitch velocity perception threshold; phidot$_{_pt}$, roll velocity perception threshold; and psidot$_{_pt}$, yaw velocity perception threshold), their influence on sense of presence, and the comparison of sense of presence for the $2^3 = 8$ different cases given in Table 1.

Therefore, a scenario has been established in the driving simulation software SCANeRstudio version 1.4 that enables building a specific driving incidence. The scenario is composed of traffic situation, buildings, several roundabouts, curvatures, and the environmental surroundings.

For this study, merely the sustained velocities (angular velocity, yaw velocity) were taken into account.

The term "sense of presence" refers to being or sensing more realistic in the virtual environment.

The three DOF motion system (roll, pitch, and heave), used in this paper, is composed of four electric actuators located at the four corners of the cockpit. This system has a faster response than the two DOF motion system (roll, pitch) including in the basic package (100 Hz possible vibrations). It also helps to make elevations on the vertical axis, which takes an important role to make relief feel realistically. This system is being exploited by actuators of D-BOX [22].

The performance of this three DOF motion platform is shown in Table 2.

The control of this motion platform is provided by the PC and it comes with the cockpit.

The construction is made up of aluminum profiles. It maintains a realistic cockpit altitude, identical to that of a real vehicle.

The CAVE system at Institut Image of Arts et Métiers ParisTech (modular virtual environment (MoVE); it is a device consisting of a visual immersion stereoscopic capture of the user's position) has the characteristics as given in Table 3.

The MoVE is composed of cubic shape surrounded walls with 3 m side, with four faces immersive, passive stereoscopic visualization on Infitec projectors: Projection Design F30SX+.

TABLE 1 Design of experiments.

	Inertial stimulus
	Static/dynamic
Mono/stereo visions FOV 1 (horizontal, 60°; vertical, 60°)/FOV 2 (horizontal, 220°; vertical, 90°)	

TABLE 2 The characteristics of this three DOF motion platform.

Maximum vertical acceleration	Limited to 1 g (9.81 m/s^2) through the software
Stroke of each actuator	35 mm
Maximum speed of each actuator	100 mm/s
Load capacity	455 kg
Roll (estimate)	±3.2°
Pitch (estimate)	±2.5°

TABLE 3 Characteristics of the MoVE.

Tracking system	Four infrared cameras tracking ArtTrack2
Rending system with computers	Two rendering servers: a calculator with 2x Nvidia Quadro Plex D7000 and a computer with 3x AMD FirePro V9800
Audio system	The spatial audio with a 2.1 kit
Projector system	It has a structure that consists of eight video projectors from "projectiondesign" which was acquired by "Barco." It has a resolution maximum up to 1920px1200p. Its native resolution is 1400px1050p with an aspect ratio of 4:3

Figure 1 illustrates the three DOF (with roll, pitch, and heave motion) dynamic driving simulator in a four-face CAVE system. Figure 2 shows the used classical motion-cueing algorithm from a hexapod (six DOF) motion platform [21, 23], and it was adapted to a three DOF motion platform. For the real-time head tracking feature, advanced real-time tracking (ART) device was utilized.

For each case, the angular velocity perception thresholds (roll velocity ω_x, pitch velocity ω_y, yaw velocity ω_z in °/s as objective metrics) that depend on the vehicle as well as the vestibular dynamics and the sense of presence (subjective measures through questionnaires) of the drivers are measured. Figure 3 shows the sensor XSens that is used to measure the head (vestibular related) dynamics data (attached to the headphone from right) [21, 24, 27].

The effect of "the number of faces (FOV 1, FOV 2) in CAVE system," "vision type (mono, stereo)," and "motion platform condition (static, dynamic)" is explained statistically for the driving simulation and the sense of presence for the subjects who participated in the experiments.

The mono vs. stereo vision was controlled from the projector system given in Table 3. The projectors themselves were having passive stereoscopic visualization characteristics, as of factory adjustments. In order to switch from stereo to mono vision, the passive stereoscopic visualization was inactivated during the experiments. FOV 1 (one face is on) and FOV 2 (four faces are on) properties were given in Table 1. The native resolution of the projectors as being 1400p X 1050p was used in the experiments with aspect ratio of 4:3.

Mono or stereo vision, static or dynamic platform, and FOV 1 and FOV 2 were the factors (variables) of which their effects had been investigated.

Subjects

Figure 4 also depicts statistics for driving experience of the participants in the driving experiments.

Twenty-seven subjects (25 males and 2 females) aged 32.74 ± 7.82 years old (mean ± SD) and with driving experience of 13.55 ± 8.40 years (mean ± SD) participated in the experiments.

Protocol

The subjects have driven the same scenario as given in Figure 4 on the dynamic simulator. The two-tailed Mann-Whitney U tests and the linear regression tests were achieved

FIGURE 1 Three DOF (pitch, roll, heave) dynamic driving simulator during experiments: FOV 2 on left, FOV 1 on right.

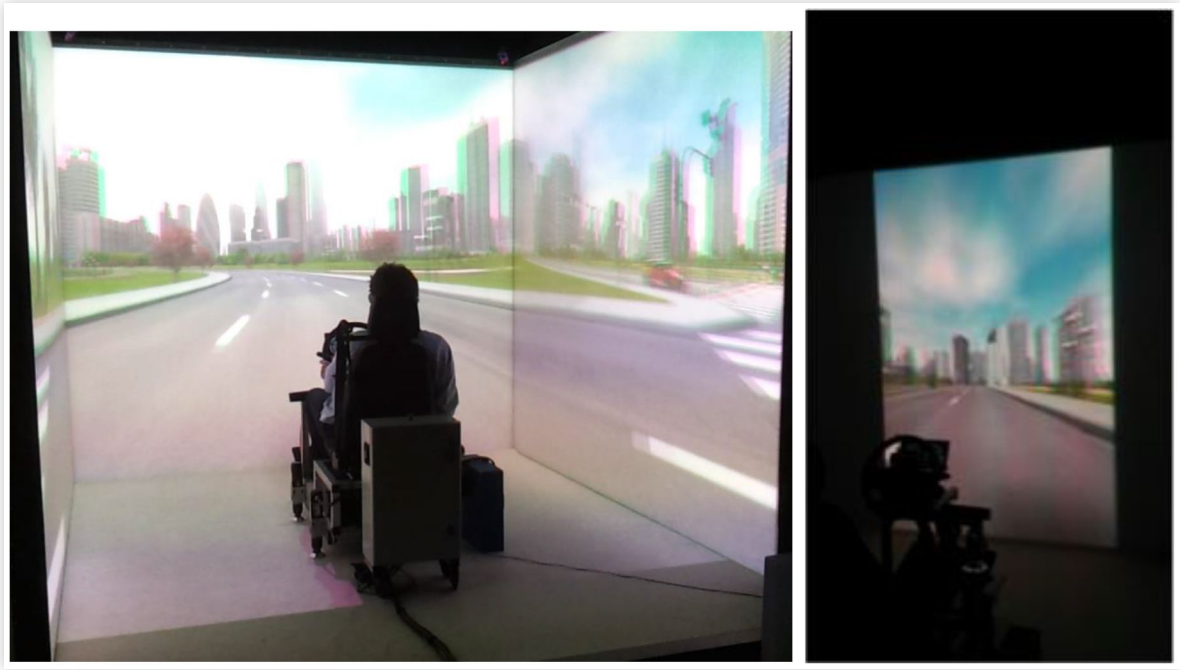
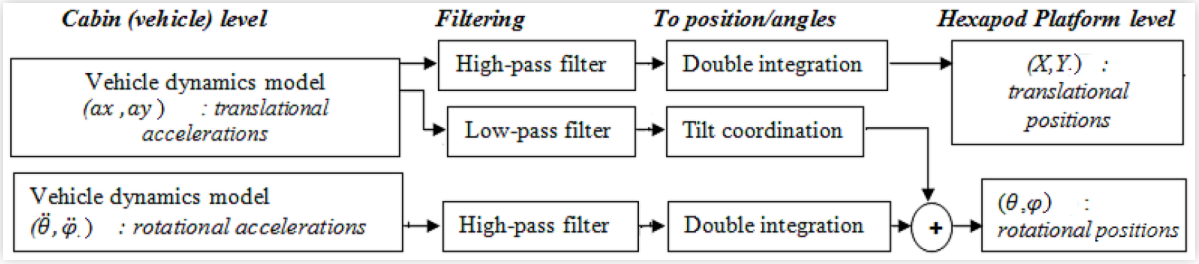


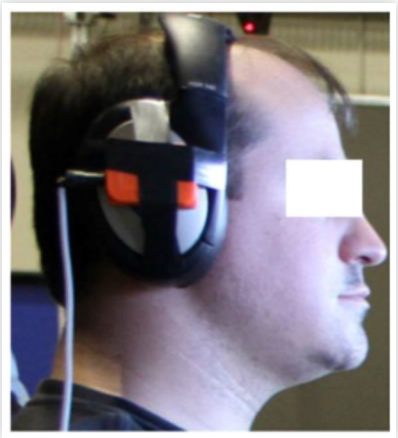
FIGURE 2 Classical motion-cueing algorithm [1, 21].



by using between subjects design. Each participant has driven the session for familiarization before the evaluation and measure sessions. The two-tailed Mann-Whitney U tests were used to evaluate the significance in difference for the subjective measures (via questionnaire), whereas the linear regression tests were applied to obtain the correlation between vehicle and head level measures for getting yaw angular velocity perception threshold and also subjective measures and head level yaw angular velocity (see Figure 6).

The vehicle velocity (km/h) profile during the driving sessions and the vehicle trajectory (m × m) are shown in Figures 4a and 4b, respectively.

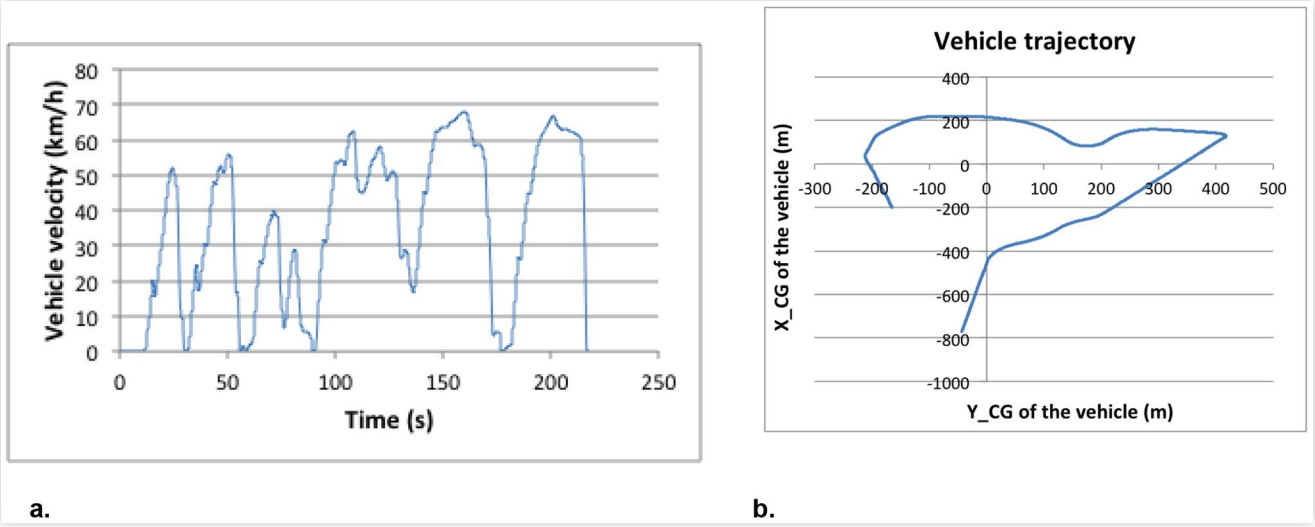
FIGURE 3 Vestibular level data acquisition [1, 21, 24, 25].



Objective Measures

The dynamics data of vehicle and head motions are all recorded in ".mat" files by using MATLAB. By constructing a Simulink model, the angular velocity data of vehicle and head (vestibular) were able to be processed. In order to evaluate the angular velocity thresholds as of pitch velocity, as of roll velocity, and as of yaw velocity thereafter to assess the self-reports for the sense of presence, curve fitting tool (centered and scaled first-degree polynomial bi-square robust with linear least squares fitting option was used) [26] and two-tailed Mann-Whitney U tests are, respectively, employed in MATLAB [27].

FIGURE 4 (a) Vehicle velocity (km/h) profile during the driving sessions and (b) vehicle CG (center of gravity) trajectory during the driving experiments.



First-degree polynomial fitting between sets of data is for predicting how associated are those two data with each other, in other words that is used to indicate the linear relationship of two sets of angular velocities in order to determine the angular velocity thresholds [26].

In order to analyze the significance in differences of the subjective ratings for the sense of presence between the mono vision and stereo vision type data, another analysis method (bilateral Mann-Whitney U test) is used in MATLAB. Mann-Whitney U test can evaluate two sets of data without condition on sample size [27].

Subjective Measures

The subjective measure is defined as conducting a questionnaire evaluation for all subjects at the end of each driving simulation phase. It was not a direct measure of the perception but instead it was the measure of reaction to the simulation. These issues are associated with the subject's self-reports on the sense of presence. Questions focus on the rating of experienced visual information, acceleration information, steering wheel feeling, braking information, etc. Table 4 lists the questions after each driving phase. The purposed questionnaire in this report has been built and modified from the following sources [23].

The participant had to report on his/her own for each of these questions with a value. This value should reflect psychophysical sense of presence during the experiment (from 1 to 10). Thereafter, these values were statistically analyzed.

TABLE 4 List of questions.

Questions	Expression of question	
Q1	Visual information	(1, very bad; 10, very well)
Q2	Acceleration information	(1, very bad; 10, very well)
Q3	Steering wheel feeling	(1, very disagreeable; 10, very agreeable)
Q4	Braking information	(1, very bad; 10, very well)
Q5	Roll motion	(1, too little; 10, too strong)
Q6	Pitch motion	(1, too little; 10, too strong)
Q7	Driving impression during straight forward	(1, very bad; 10, very well)
Q8	Driving impression during curvature	(1, very bad; 10, very well)
Q9	Entire driving impression	(1, very bad; 10, very well)

Results and Discussion

The results of this research discuss the driving simulation comparison between mono and stereo type visions, the comparison between dynamic and static platform conditions, and the comparison between FOV 1 and FOV 2 in the CAVE. The MATLAB/Simulink is used to calculate the data and present the results.

ωx, ωy, and ωz were measured from the participants' right ear levels (thetadot_vest, phidot_vest, psidot_vest) for the same driven scenario for the static and dynamic platforms via using the sensor in Figure 3 [21] during the experiments.

Figure 5 summarizes the method and the data analysis used in the paper. Angular velocities (roll velocity, pitch velocity, and yaw velocity) from the vehicle level and the head (vestibular) level were collected during the experiments. Then from MATLAB ("cftool": curve fitting toolbox) curve fitting was realized between head and vehicle angular velocity data as with centered and scaled first-degree polynomial bi-square robust with linear least squares fitting option (Table 5, Figure 6). The mean value of the fit (the magnitude as absolute value) gives the angular velocity perception threshold. If there is significant relationship between "sense of presence self-report" and "angular velocity perception threshold," it indicates that this angular velocity perception threshold is realistic.

FIGURE 5 Method and data analysis.

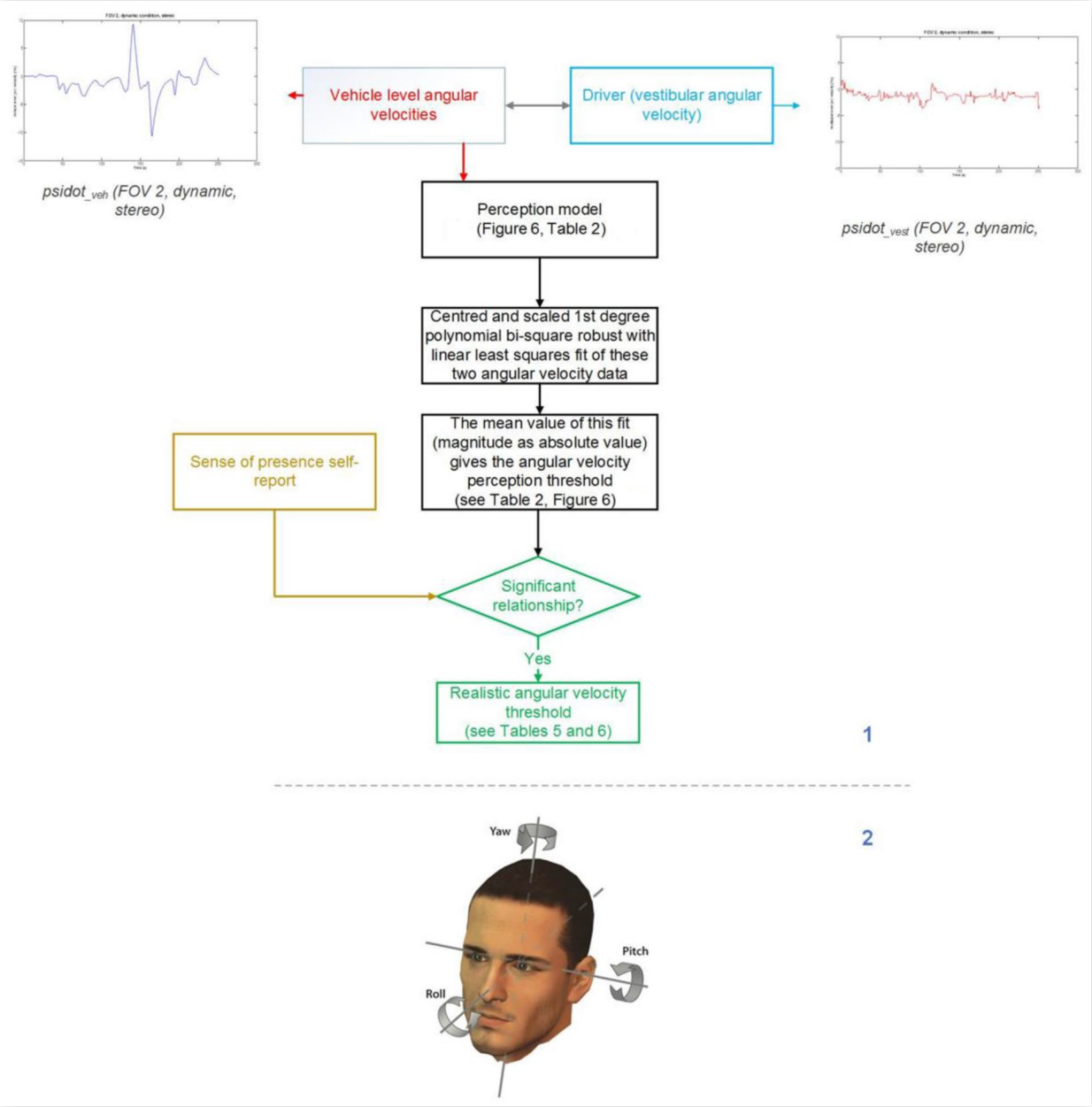


Table 5 shows the pitch, the roll, and the yaw velocity perception thresholds. The thresholds were taken into account as in absolute values. SSE, sum of squared errors; RMSE, root mean squared error; and R-square are the terms coming from the curve fitting. For more information, the sources [26, 27] can be referred.

Upper part of Figure 6 depicts the time domain measures of yaw velocity for vehicle (blue curve) and vestibular (red curve) levels. Below part of Figure 6 shows the method proposed to identify the angular (pitch, roll, and yaw) velocity perception thresholds. The head movements (vestibular cues) and the vehicle movements were taken into account. Furthermore visuo-vestibular interaction (visuo, vehicle, and vestibular, head angular velocities) was investigated in Figure 6.

In below part of Figure 6, "psidot-vest" is the vestibular level measured yaw velocity in °/s, whereas the "psidot-veh" is the vehicle level (visual cues) yaw velocity in °/s. Blue line named "fit" is the curve fitting as with centered and scaled first-degree polynomial bi-square robust with linear least squares fitting option. This fit shown with blue line in Figure 6 specifies the (yaw) angular velocity perception threshold. In Figure 6, the ordinate values of the blue line correspond to the angular velocities matching to the vehicle yaw velocities.

Subjective Analysis

Comparison of Mono Type Vision with Stereo Type Vision The subjective evaluation results have been

TABLE 5 Perception threshold for angular velocities.

		Static condition head/vehicle						Dynamic condition head/vehicle					
		Mono vision			Stereo vision			Mono vision			Stereo vision		
		ω_{x_pt}	ω_{y_pt}	ω_{z_pt}	ω_{x_pt}	ω_{y_pt}	ω_{z_pt}	ω_{x_pt}	ω_{y_pt}	ω_{z_pt}	ω_{x_pt}	ω_{y_pt}	ω_{z_pt}
FOV 1	Lower 95% confidence interval	0.3°/s	1.19°/s	1.26°/s	0.5°/s	0.91°/s	1.51°/s	0.77 °/s	1.14 °/s	1.25 °/s	0.69°/s	0.68°/s	1.55°/s
	Mean	0.31°/s	1.21°/s	1.3°/s	0.51°/s	0.93°/s	1.54°/s	0.78 °/s	1.15 °/s	1.27 °/s	0.69°/s	0.7°/s	1.57°/s
	Upper 95% confidence interval	0.33°/s	1.24°/s	1.34°/s	0.52°/s	0.95°/s	1.57°/s	0.8 °/s	1.17 °/s	1.29 °/s	0.7°/s	0.72°/s	1.59°/s
	SSE	39	85.88	205.5	14.8	60.56	123.9	17.79	42.82	67.59	13.84	88.61	79.14
	R-square	0.1557	0.8894	0.546	0.5619	0.8569	0.6369	0.5516	0.913	0.8233	0.8147	0.8192	0.8107
	RMSE	0.2316	0.3437	05317	0.1355	0.2741	0.3921	0.1571	0.2437	0.3062	0.1304	0.3299	0.3118
		Static condition head/vehicle						Dynamic condition head/vehicle					
		Mono vision			Stereo vision			Mono vision			Stereo vision		
		ω_{x_pt}	ω_{y_pt}	ω_{z_pt}	ω_{x_pt}	ω_{y_pt}	ω_{z_pt}	ω_{x_pt}	ω_{y_pt}	ω_{z_pt}	ω_{x_pt}	ω_{y_pt}	ω_{z_pt}
FOV 2	Lower 95% confidence interval	0.68°/s	0.68°/s	1.3°/s	0.28°/s	0.52°/s	1.44°/s	0.74 °/s	1.17 °/s	1.1 °/s	0.85 °/s	1.1 °/s	1.1 °/s
	Mean	0.7°/s	0.72°/s	1.36°/s	0.32°/s	0.56°/s	1.52°/s	0.76 °/s	1.19 °/s	1.15 °/s	0.86 °/s	1.12 °/s	1.14 °/s
	Upper 95% confidence interval	0.72°/s	0.75°/s	1.4°/s	0.35°/s	0.59°/s	1.61°/s	0.78 °/s	1.22 °/s	1.2 °/s	0.88 °/s	1.14 °/s	1.19 °/s
	SSE	54.81	154	340.7	112.9	102.5	668.7	95.65	93.19	425.1	42.64	60.03	366.6
	R-square	0.5712	0.65	0.5816	0.5085	0.7934	0.5352	0.4062	0.8537	0.2554	0.6104	0.8682	0.3101
	RMSE	0.2798	0.469	0.6977	0.4357	0.415	1.06	0.3389	0.3345	0.7144	0.2274	0.2697	0.6666

explained due to the self-report of the participants just after each experimental session. Table 6 indicates subjective assessments for "the sense of presence" questionnaire in the case of "FOV 2, dynamic platform."

Table 6 indicates the statistical difference analysis regarding the inertial factors (static or dynamic platform conditions). It does not show many options for multiple comparisons. The nonparametric tests in Table 6 show dual comparison from the left column to the right column (2×4). From Table 6, there were no significant differences between static and dynamic platform conditions for visual information, acceleration information, steering wheel feeling, braking information, driving impression during straight forward, driving impression during curvature, and entire driving impression. Merely, in terms of roll and pitch motion, the dynamic condition was perceived stronger than the static platform condition for the lower FOV with stereo vision. Furthermore, there were no significant differences between static and dynamic platform conditions in terms of subjective assessments for lower FOV with mono vision and for higher FOV with mono and stereo visions.

Objective-Subjective Measure Relationships Linear regression model was benefited to clarify the relationships between self-reports of the "sense of presence" (subjective measure) and the angular velocity thresholds (objective measure). The linear acceleration perception threshold was the "x1" and the self-report was the "y" for the linear regression model. MATLAB function "fitlm" [27] was used for the linear regression fitting (least squares method was chosen for the fitting).

$$\text{Linear regression model: } y \sim \text{Intercept} + x1 \ [27]$$

The linear regression model is used to explain the objective (angular velocity perception thresholds) and subjective (self-reports for sense of presence) relationships.

Table 7 gives the results for objective (angular velocity perception thresholds) and subjective (self-reports for sense of presence) relationships. According to Table 7, "yaw velocity perception threshold" is significantly related to "entire driving impression" except for higher FOV with static platform and mono vision.

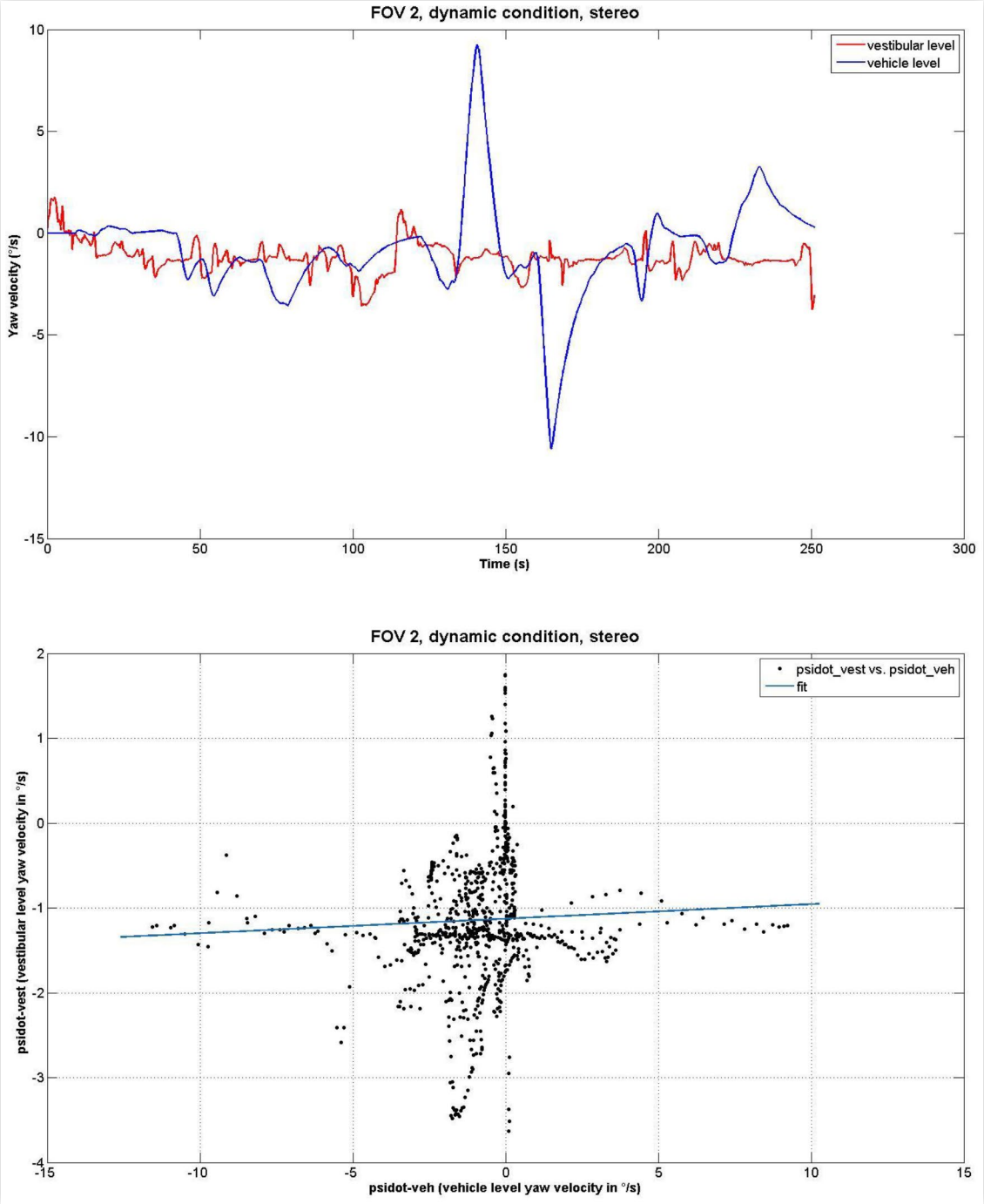
Table 8 gives the subjective weighted angular velocity perception threshold results. In Table 8, "d" refers to dynamic while "s" refers to static. Also subj (subjective), w (weighted), thetadot_pt (pitch velocity perception threshold), phidot_pt (lateral acceleration), and psidot_pt (yaw velocity perception threshold) are given in Tables 7 and 8.

Conclusion

The pitch, roll, and yaw angular velocity thresholds were discussed and how they can be identified from visuo-vestibular level angular velocities. Also, the subjective assessments were realized by using "sense of presence" questionnaires for the conditions.

As a result, it is seen that lower FOV, static platform, stereo vision condition has provided the best condition. In other words, the angular velocity (pitch, roll, and yaw velocity)

FIGURE 6 Specifying the yaw velocity perception threshold from t = 0 s (condition: FOV 2, dynamic condition, stereo).



thresholds have been significantly related to the self-report of entire driving impression for lower FOV, stereo vision at static platform condition. According to the subjective evaluations, there were no significantly difference ($p > 0.05$) between the static and the dynamic platform conditions apart from the "roll" and the "pitch" motion perception for lower FOV and stereo vision. The roll and the pitch motions were perceived stronger at the dynamic platform rather than the static platform condition at lower FOV and stereo vision. Except for higher FOV, static platform, and mono vision case, there was a significant relationship between yaw velocity perception threshold and "entire driving impression." Pitch velocity perception thresholds were significantly related with "entire driving impression" for lower FOV, static platform, stereo vision; for lower FOV, dynamic platform, stereo vision; and for higher FOV, dynamic platform, stereo vision. Roll velocity perception thresholds were significantly related with "entire driving impression" for lower FOV, static platform, stereo vision; for higher FOV, static platform, mono vision; and for higher FOV, dynamic platform, mono vision.

TABLE 6 Self-report for the sense of presence with respect to the platform condition.

	FOV 1 s_mono	FOV 1 d_mono	FOV 1 s_stereo	FOV 1 d_stereo	FOV 2 s_mono	FOV 2 d_mono	FOV 2 s_stereo	FOV 2 d_stereo
Visual information	5.33	5.00	5.38	5.33	6.33	6.33	7.06	7.43
	U(27) : p = 1 > 0.05		*U(27) : p = 0.9302 > 0.05*		*U(27): p = 1 > 0.05*		*U(27) : p = 0.4467 > 0.05*	
Acceleration information	5.33	5.00	5.69	6.39	5.00	6.67	6.29	6.43
	U(27) : p = 1 > 0.05		*U(27) : p = 0.2520 > 0.05*		*U(27) : p = 0.5 > 0.05*		*U(27) : p = 07088 > 0.05*	
Steering wheel feeling	6.00	5.33	6.19	6.83	6.33	5.67	6.71	7.00
	U(27) : p = 1 > 0.05		*U(27) : p = 0.4130 > 0.05*		*U(27) : p = 0.8 > 0.05*		*U(27) : p = 0.6754 > 0.05*	
Braking information	4.67	5.33	4.69	5.61	4.67	5.67	4.94	5.29
	U(27) : p = 0.6 > 0.05		*U(27) : p = 0.2149 > 0.05*		*U(27): p = 1 > 0.05*		*U(27) : p = 0.6456 > 0.05*	
Roll motion	4.33	5.33	4.38	5.89	4.33	6.33	5.29	5.81
	U(27) : p = 0.6 > 0.05		*U(27) : **0.0337 < 0.05***		*U(27) : p = 0.5 > 0.05*		*U(27) : p = 0.4649 > 0.05*	
Pitch motion	4.00	5.33	3.81	5.94	4.33	6.00	5.00	5.86
	U(27) : p = 0.6 > 0.05		*U(27) : **0.0012 < 0.05***		*U(27) : p = 0.7 > 0.05*		*U(27) : p = 0.2566 > 0.05*	
Driving impression during straight forward	6.00	5.67	6.25	7.22	6.00	7.00	7.00	7.90
	U(27) : p = 1 > 0.05		*U(27) : p = 0.1449 > 0.05*		*U(27) : p = 0.3 > 0.05*		*U(27) : p = 0.1314 > 0.05*	
Driving impression during curvature	4.67	6.00	5.25	6.22	5.00	7.00	6.06	6.95
	U(27) : p = 0.5 > 0.05		*U(27) : p = 0.1950 > 0.05*		*U(27) : p = 0.8 > 0.05*		*U(27) : p = 0.1286 > 0.05*	
Entire driving impression	5.00	5.67	5.81	6.39	4.67	6.67	6.41	7.05
	U(27) : p = 1 > 0.05		*U(27) : p = 0.4970 > 0.05*		*U(27) : p = 0.3 > 0.05*		*U(27) : p = 0.2453 > 0.05*	

TABLE 7 Objective and subjective measure relationships.

Entire driving impression	FOV 1 s_mono	FOV 1 d_mono	FOV 1 s_stereo	FOV 1 d_stereo	FOV 2 s_mono	FOV 2 d_mono	FOV 2 s_stereo	FOV 2 d_stereo
thetadot_pt	p-value = 0.0732 > 0.05	p-value = 0.121 > 0.05	p-value = **0 < 0.05**	p-value = **1.1e−07 < 0.05**	p-value = 0.0524 > 0.05	p-value = 0.0732 > 0.05	p-value = 0.0524 > 0.05	p-value = **0 < 0.05**
phidot_pt	p-value = 0.121 > 0.05	p-value = 1 > 0.05	p-value = **0 < 0.05**	p-value = 0.333 > 0.05	p-value = **3.21e−08 < 0.05**	p-value = **0 < 0.05**	p-value = 0.0524 > 0.05	p-value = 0.121 > 0.05
psidot_pt	p-value = **3.79e−08 < 0.05**	p-value = **3.7e−08 < 0.05**	p-value = **0 < 0.05**	p-value = **0 < 0.05**	p-value = 0.0732 > 0.05	p-value = **0 < 0.05**	p-value = **0.0216 < 0.05**	p-value = **0.0408 < 0.05**

TABLE 8 Subjective weighted angular velocity perception threshold.

	FOV 1 s_mono	FOV 1 d_mono	FOV 1 s_stereo	FOV 1 d_stereo	FOV 2 s_mono	FOV 2 d_mono	FOV 2 s_stereo	FOV 2 d_stereo
Subj_w_ thetadot_pt	-	-	0.93 × (5.81 ÷ 10) = 0.54 °/s	0.7 × (6.39÷10) = 0.45 °/s	-	-	-	1.12 × (7.05 ÷ 10) = 0.79 °/s
Subj_w_ phidot_pt	-	-	0.51 × (5.81 ÷ 10) = 0.30 °/s	-	0.7 × (4.67 ÷ 10) = 0.33 °/s	0.76 × (6.67 ÷ 10) = 0.51 °/s	-	-
Subj_w_ psidot_pt	1.3 × (5 ÷ 10) = 0.65 °/s	1.27 × (5.67 ÷ 10) = 0.72 °/s	1.54 × (5.81 ÷ 10) = 0.89 °/s	1.57 × (6.39 ÷ 10) = 1.00 °/s	-	1.15 × (6.67 ÷ 10) = 0.77 °/s	1.52 × (6.41 ÷ 10) = 0.97 °/s	1.14 × (7.05 ÷ 10) = 0.80 °/s

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Definitions/Abbreviations

FOV - Field of view

DOF - Degrees of freedom

HMD - Head-mounted display

RMS - Ride motion simulator

VOL - Vection onset latency

ROMA - Real-time optimal motion-cueing algorithm

VR - Virtual reality

ECO_2 - Ecological driving

MoVE - Modular virtual environment

ART - Advanced real-time training

SD - Standard deviation

CG - Center of gravity

Q_n - Questions; n = 1, …, 9

ω_x - Roll velocity

ω_y - Pitch velocity

ω_z - Yaw velocity

thetadot_vest - Pitch velocity measured from the participants' right ear levels

phidot_vest - Roll velocity measured from the participants' right ear levels

psidot_vest - Yaw velocity measured from the participants' right ear levels

cftool - Curve fitting toolbox of MATLAB

SSE - Sum of squared errors

RMSE - Root mean squared error

FOV1 s_mono - Field of view of horizontal 60°, vertical 60°, static platform, mono vision

FOV1 d_mono - Field of view of horizontal 60°, vertical 60°, dynamic platform, mono vision

FOV1 s_stereo - Field of view of horizontal 60°, vertical 60°, static platform, mono vision

FOV1 d_stereo - Field of view of horizontal 60°, vertical 60°, dynamic platform, stereo vision

FOV2 s_mono - Field of view of horizontal 220°, vertical 90°, static platform, mono vision

FOV2 d_mono - Field of view of horizontal 220°, vertical 90°, dynamic platform, mono vision

FOV2 s_stereo - Field of view of horizontal 220°, vertical 90°, static platform, mono vision

FOV2 d_stereo - Field of view of horizontal 220°, vertical 90°, dynamic platform, stereo vision

thetadot_pt - Pitch velocity perception threshold

phidot_pt - Roll velocity perception threshold

psidot_pt - Yaw velocity perception threshold

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