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Adaptive Motion Cueing Algorithm Based on Fuzzy Logic Using Online Dexterity and Direction Monitoring

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***Abstract*— Motion cueing algorithm (MCA) is used to reproduce the realistic driving motion feeling for the user of the virtual vehicle using linear acceleration and angular velocity motion signals while respecting the physical constrains of the simulation-based motion platform. Classical washout filter is the most common and commercial type of the MCA because of easy tuning, short processing time and simplicity. The classical washout filter is a conservative method in using workspace because of the worst-case scenario tuning technique. Also, the existing adaptive washout filter based on time-varying cut-off frequency does not consider the dexterity of the motion platform as considering this factor leads to use the high acceleration areas of the platform workspace. In this paper, an adaptive washout filter is designed and developed based on time-varying cut-off frequency using dexterity and direction monitoring factors to use the available high acceleration areas of the platform for better generation of the high-frequency part of the motion signal. The proposed adaptive washout filter is composed of three fuzzy logic units for each mode including longitudinal, lateral, yaw and heave and each unit has two inputs including motion sensation error between the real vehicle driver and user of the motion platform and the weight of the end-effector which is a parameter based on dexterity and current position of the end-effector. Each fuzzy logic unit has also one output which is the selected cut-off frequency of the related washout filter. The proposed adaptive washout filter uses the high dexterous areas of the workspace because it considers the dexterity of the motion platform in calculation of the end-effector weight as the second input of the fuzzy logic units. The proposed adaptive washout filter is validated in MATLAB/Simulink programming language and the experimental results indicate that the proposed adaptive washout filter performed better than existing adaptive and classical washout filters in terms of motion sensation error between the driver of real vehicle and the user of motion platform as well as usage of the platform workspace.**

***Index Terms*—adaptive motion cueing algorithm, fuzzy logic controller, simulation-based motion platform, performance index.**

I. Introduction

THE simulation-based motion platform (SBMP) are useful research tool for studying the safety of roads, testing new developed vehicles, and training the users of vehicles [1-3]. Due to the constraints of the platform's workspace, the motion signals from a real vehicle cannot be utilized straight in the SBMP [4-7]. The motion cueing algorithm (MCA) is utilized to reproduce motion signals of a real vehicle for the SBMP while respecting the SBMP boundaries [8, 9]. The significant drawback of the MCA is motion sickness caused by the limitations of the SBMP [10].

Schmidt and Conrad [11] introduced the first MCA known as classical washout filter. The human vestibular system [12-14] senses the motion by detecting the special force and the angular velocity of the SBMP via the otolith organs and semicircle canals, respectively. Classical washout filters have drawbacks such as constant parameters, adjustment at worst-case scenario tunning, and disregard for the model of human vestibular. Recently, researchers work on genetic algorithm and swarm intelligence to optimize the tuning problem of the classical washout filter [15-17]. This leads to generating wrong motion cues, and higher motion sensed error between the real vehicle and SBMP users.

Due to the shortcomings of the existing classical washout filter, adaptive washout filter was introduced by Parrish et al. [18] for a flight SBMP. In order to eliminate the wrong motion cues, Ariel and Sivan [19] used an adaptive washout filter in real-time utilizing of the human vestibular model. Later, researchers focused more on the adaptive washout filter because of its flexibility and better performance [20, 21]. Later, the adaptive washout filters using fuzzy logic have been developed to address the issues of the existing classical and adaptive washout filters [22-26]. The fuzzy based-adaptive washout filters can be divided in two groups including time-varying cut-off frequency and motion compensator unit. The first adaptive washout filter based on fuzzy logic was proposed by Song et al. [22] to change the classical washout filter fixed parameters in accordance with the margins of the workspace and various situations of driving scenarios. Asadi et al. [23, 24] modified the previous fuzzy based-adaptive washout filter [22] for changing the cut-off frequencies by considering the model of human vestibular and sensation error to enhance the motion fidelity for the SBMP user. Qazani et al. [27] improved, Asadi proposed work [23, 24], with consideration of SBMP's limitations along passive and active joints coordinate system rather than end-effector coordinate system. Later, Asadi et al. [25, 26] developed another generation of adaptive washout

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filter based on fuzzy logic-based motion compensator units while considering the workspace limitations as well as motion sensed motion error between the real driver of vehicle and the SBMP user to generate motion correction signals when required. Qazani et al. [28] improved, Asadi proposed work [25, 26], with consideration of active joints limitations instead of end-effector's limitations. Moreover, Qazani et al. [29] used the concept of motion compensation generator unit to vary the SBMP's neutral position for increasing the linear workspace limitation of the SBMP. However, the recent proposed adaptive washout filters [18-29] are able to reduce the sensed motion error between the driver of the real vehicle and the SBMP user, they are not able to monitor the online dexterity. The area of the platform workspace with ability of higher linear acceleration generation can be achieved via monitoring the dexterity in order to regenerate the highly efficient high frequency motion signal for the user of the SBMP.

It is useful to use the areas of the workspace with higher performance availability. Performance analysis is one of the critical topics for researchers since the generation of manipulators to evaluate the motion platform capability. Dexterity is a value between 0-1 which shows the areas of the workspace with higher accessible linear acceleration for the end-effector using the less actuator effort [30]. Paul and Stevenson [31] introduced the dexterity measurement. Yoshikawa [32] defined the square root of the Jacobin matrix to find the manipulability of the robots. Pedrammehr et al. [33-35] and Qazani et al. [36, 37] used the dexterity value in order to evaluate the performance of the parallel SBMPs such as Stewart, Hexarot and Gantry-tau manipulators [38-40]. In Fig. 1.a-b, the Steward platform workspace with the most massive inscribed cubic box is shown in isometric- and top-view, respectively. The boundary of this cubic cox is utilized as a maximum value of excursion in *x*-, *y*- and *z*-axis.

In this study, the fuzzy logic units are designed and developed while considering the dexterity and motion sensation error as inputs of the fuzzy units in order to generate the appropriate cut-off frequencies for the washout filters. The dexterity is employed to assess the motion platform performance and use the higher acceleration available areas of the platform workspace. Also, the direction detector is proposed in this study for better usage of actuator acceleration limitations. In addition, the SBMP is a Steward platform with ±30-centimetre linear displacement in *x*-axis, ±15-centimetre in the *y*-axis and ±2-centimetre in the *z*-axis. The end-effector is capable of moving 15 degrees around *x*- and *y*-axis and 20 degrees around *z*-axis while located in the neutral position.

The methodology of the developed adaptive washout filter using fuzzy logic is described in Section II. Modeling the SBMP SimMechanic, that is implemented in MATLAB/Simulink programming language by considering classical, previous adaptive and developed adaptive washout filters are presented in Section III. Moreover, this section provides and discusses the results for those of other washout filters and developed adaptive washout filter. The concluding remarks are presented in Section IV.

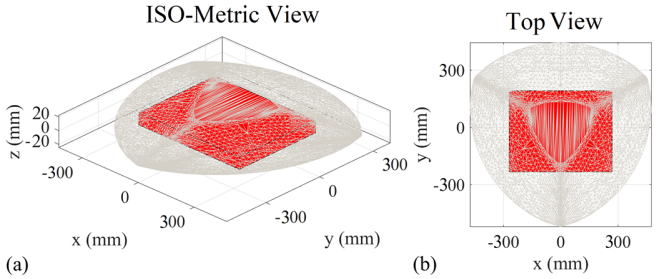


Fig. 1. The most massive inscribed cubic box inside the Steward platform workspace: (a) ISO-Metric View; (b) Top View.

II. Methodology

Zadeh [41] introduced the fuzzy logic theory, and it has been developed in control systems. Fuzzy theory based models are one of the powerful methods for the stochastic behaviour-based system and changeable inputs [42, 43]. Fuzzy is highly applicable for systems when the input-output relation is not identified [42]. The classical washout filter is composed of washout filters using fixed parameters, including cut-off frequency and damping ratio, which are adjusted regarding the worst-case scenarios. Table I shows different fixed parameters of the classical washout filter along four modes. The cut-off frequencies of the proposed adaptive washout filters are adjusted based on the dexterity of the end-effector in addition to sensed motion error between the driver of real vehicle and SBMP user to overcome the disadvantage of insufficient use of manipulator workspace and reducing the human sensation error, respectively. Therefore, in this paper, fuzzy theory is used to maximize the motion fidelity of the driving SBMP.

The developed adaptive washout filter structure based on dexterity and motion sensation error is demonstrated in Fig. 2. In this project, the control block for varying cut-off frequency in high- and low-pass filters has two signals that are considered as input. These signals will be discussed in Section III.C.

A. Human Vestibular Model

Human vestibular model is the part of the human perception system, and it is the fast sensor to sense the motion signal. Otolith limbs and semicircle canals, that form the human vestibular model, cause a sense of linear acceleration and angular velocity, respectively. The organs of the otolith feel the special force by decreasing the gravity from the linear acceleration as follows:

$$\mathbf{S_F} = \mathbf{a} - \mathbf{g} \tag{1}$$

where $\mathbf{S_F}$, $\mathbf{a}$ and $\mathbf{g}$ indicate special force, linear acceleration and gravity, respectively. By considering $\mathbf{R}$ as a seat's rotation matrix, the sensed linear acceleration in the coordinate system at the centre of the seat is calculated as [12]:

$$\mathbf{S_F} = \mathbf{a} - \mathbf{R}(\alpha,\beta,\gamma)\mathbf{g} = \begin{bmatrix} a_x - g\sin\beta \\ a_y - g\sin\alpha\sin\beta \\ a_z - g\cos\alpha\cos\beta \end{bmatrix} \tag{2}$$

where α, β and γ displays the *roll*-, *pitch*- and *yaw*-angle of the end-effector around *x*-, *y*- and *z*-axis. In studies by Telban and Cardullo [12] and Asadi et al. [13], the transition functions of otolith limbs are reviewed and evaluated. In this paper, a transition function with the best sensed special force stimulant, $\hat{f}$, over the applied force, f, is chosen that defined as follows:

TABLE I
THE TUNING PARAMETERS OF THE CLASSICAL WASHOUT FILTER.

Index	Linear Acceleration				Angular Acceleration
	High-pass Translation		Low-pass Tilt-coordination		High-pass Rotational
	ω_n	ζ	ω_n	ζ	ω_n
Longitudinal	2.75	2.00	4.50	1.00	2.00
Lateral	2.75	2.00	4.50	1.00	2.00
Heave	4.25	2.00	-	-	-
Yaw	-	-	-	-	2.5

$$\frac{\hat{f}}{f} = \frac{\tau_a s+1}{(\tau_L s+1)(\tau_S s+1)} \quad (3)$$

where τ_L, τ_s and τ_a are long time fixed, the short time fixed of the otolith limbs and neural processing term lead operator and, $\tau_L = 5.3$ seconds in the *x*-axis, $\tau_L = 5.33$ seconds in *y*- and *z*-axis, $\tau_s = 0.016$ seconds and $\tau_a = 13.2$ seconds in three directions. The semicircle system transfer function to calculate the sensed angular velocity, $\hat{\omega}$, based on applied angular velocity, ω, is as [12, 14]:

$$\frac{\hat{\omega}}{\omega} = \left(\frac{\tau_1 \tau_b s^2}{(1+\tau_1 s)(1+\tau_b s)}\right) \quad (4)$$

where τ_1 and τ_b are a long time fixed and adaption time fixed, and $\tau_1 = 5.3$ seconds in the *x*-axis, $\tau_1 = 6.1$ seconds in the *y*-axis, $\tau_1 = 10.2$ seconds in the *z*-axis, and $\tau_b = 30$ seconds in three directions

B. *Dexterity Analysis*

The usage of the higher acceleration available area of the platform workspace is the main concept of this study in order to regenerate high-fidelity linear acceleration signal. Nevertheless, the Steward platform is limited because of passive joints rotation and leg length limitations [4]. It can stop motion during the simulation if one of the joints moves to the boundaries. Normally, the simulators' engineers imagine the SBMP workspace as a cube space with fixed values and imitations in *x*-, *y*-, and *z*-axis as linear motion, and *roll*-, *pitch*-, and *yaw*-angle as angular motion. It leads to losing the high-performance area of workspace for every parallel and serial manipulator. Furthermore, the maximum angular motion of the manipulator depends on the central position of the end-effector [4]. For instance, the angular motion will be maximum when the end-effector is in its neutral position. If the manipulator is closer to the workspace boundaries, the angular motion will be reduced, consequently. Then, this simplified assumption is not worthwhile anymore. In this study, dexterity is used as a new technique in the MCA domain to monitor the end-effector dexterity. It is used as one of the fuzzy block inputs to change the value of cut-off frequency to generate suitable SBMP's motion according to the current SBMP's situation. The dexterity of the Stewart manipulator calculated as follows [7]:

$$d = \frac{1}{\|\mathbf{J}\|\|\mathbf{J}^{-1}\|} \quad (5)$$

where **J** is a Steward platform Jacobin matrix that defines the relation between legs and the end-effector velocity. It can be found based on the inverse kinematic problem of the manipulator [44]. The **J** norm is defined as:

$$\|\mathbf{J}\| = \sqrt{\text{trace}\left(\left(\frac{1}{2}\right)\mathbf{J}\mathbf{J}^T\right)} \quad (6)$$

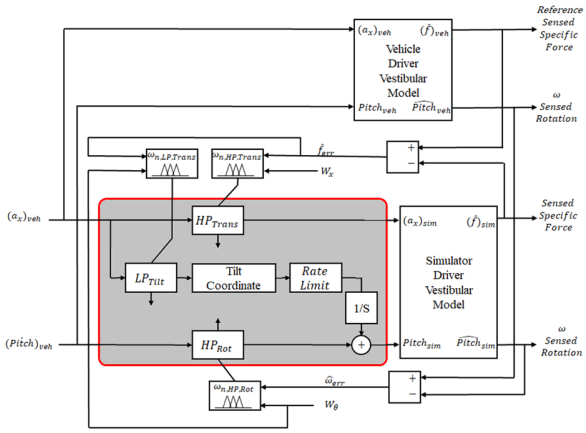


Fig. 2. The longitudinal structure of developed adaptive washout filter.

There are multiple reasons to decrease the dexterity. Singularity is the important crucial cause of the dramatic decrease in the dexterity. The developed adaptive washout filter never moves to the singular point. The fuzzy units do not let the dexterity to reach zero which means the singular position. It changes the inputs to enhance the dexterity and avoid the motion platform to reach the singularity. Also, it should be noted that, a slight reduction of dexterity has two hints for the SBMP. Firstly, it might be close to the platform workspace boundaries because of prismatic joints limitations. Secondly, if this happens while the platform of the Steward platform is well within the workspace boundaries, it proves the platform orientation near the end of the rotational limitations.

Unfortunately, the dexterity is a scalar parameter that makes this value useless for implementing the 6-DoF of the manipulator. The weight parameters of the end-effector have been defined to show the share of every DoF for every configuration of the manipulator as follows:

$$W_{x,y,z}^{\text{Initial}} = \frac{\Delta x,\Delta y,\Delta z}{\sqrt{\Delta x^2+\Delta y^2+\Delta z^2}} \quad (7.a)$$

$$W_{\alpha,\beta,\gamma}^{\text{Initial}} = \frac{\Delta \alpha,\Delta \beta,\Delta \gamma}{\sqrt{\Delta \alpha^2+\Delta \beta^2+\Delta \gamma^2}} \quad (7.b)$$

where Δx, Δy and Δz are the end-effector linear displacements along *x*-, *y*- and *z*-axis. Also, $\Delta \alpha$, $\Delta \beta$ and $\Delta \gamma$ are the angular displacements of the end-effector along *x*-, *y*- and *z*-axis. Eq. (7a-b) is the initial displacement weights of the end-effector without implementing the dexterity. The final displacement weights of the end-effector are defined by multiplication of the Eq. (7a-b) to the dexterity d as follows:

$$W_{x,y,z} = d.W_{x,y,z}^{Initial} \quad (8.a)$$

$$W_{\alpha,\beta,\gamma} = d.W_{\alpha,\beta,\gamma}^{\text{Initial}} \quad (8.b)$$

C. *Fuzzy Logic Control Unit*

In this study, Mamdani fuzzy blocks and membership functions are selected to decrease sensed special force. As the MCA inputs are nonlinear and unpredictable motion signals, the usage of the Mamdani-type fuzzy gives the better results compared with Sugeno-type fuzzy [45]. The proposed fuzzy-based controller receives two inputs and generates one output. The first fuzzy logic controller input is the weight parameter relates to the dexterity parameter, and the second input is the sensed motion error between the driver of real vehicle and the SBMP user. The output of the fuzzy logic controller is the cut-

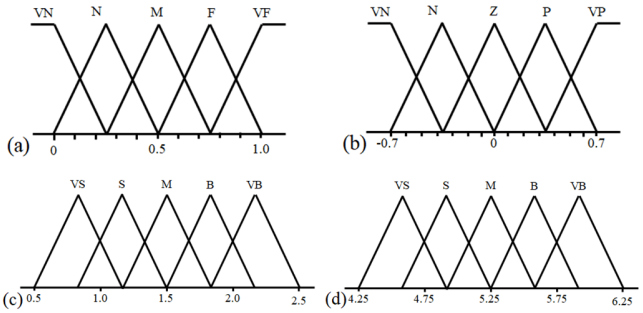


Fig. 3. The memberships function of: (a) Input weight factor; (b) input sensed special force error; (c) output translational; (d) output rotational.

off frequency of the washout filters. The input weight parameter of the dexterity is partitioned into five membership functions such as very near (VN), near (N), middle (M), far (F) and very far (VF) (Fig. 3.a). Also, the membership function of the sensed motion error between the driver of real vehicle and SBMP user is categorized as five sensation categories such as very negative (VN), negative (N), zero (Z), positive (P) and very positive (VP) (Fig. 3.b). The system of human vestibular cannot precisely determine motion quantities; then this hypothesis is worthwhile. The membership function of the frequency outputs changing units is shown in Fig. 3.c-d which varies between 0.5 to 2.5 rad/sec for high-pass filter and between 4.25 to 6.25 for the low-pass filter. They consist of five membership functions such as very small (VS), small (S), medium (M), big (B) and very big (VB). The triangular membership functions are chosen as the inputs and outputs of the fuzzy module to achieve light computational load. It should be noted that the centroid defuzzification method is used in this study which is the most popular method in MATLAB fuzzy Toolbox.

Fuzzy rules of the algorithm are defined to defeat the weakness of fixed parameters and help the Steward platform to make more efficient use of workspace for different driving scenarios. Fig. 4.a-b demonstrate fuzzy logic rules for high- and low-pass filters of translational and tilt coordination channels, respectively. It is obvious that the rules of a low-pass filter are inverse of the high-pass filter. If the manipulator is near to its neutral position with decreasing the high-pass frequency and raising the low-pass frequency improves the feeling of better motion in the workspace.

D. Direction Detector Unit

The direction detector has been proposed for adaptive washout filter for the first time in this study. Fig. 5a shows the structure of the direction detector unit. The direction detector unit is utilized to extract the directional motion of the end-effector (positive or negative side) by saving the previous signal $\mathbf{u_2}$ and comparing the sign of the last and current signal $\mathbf{u_1}$ with the end-effector position. If the input signal sign and the end-effector position are the same, it proves that the manipulator is approaching the boundary. Otherwise, it is escaping from it. For instance, the manipulator is on the positive direction of the *x*-axis, and the input signal is positive, the manipulator moves towards the positive side of the *x*-axis to get close to the boundary. Then, the final weight factor of the end-effector, which is found in Eq. (8.a-b) should be updated for the same sign on the signal and end-effector position as follows:

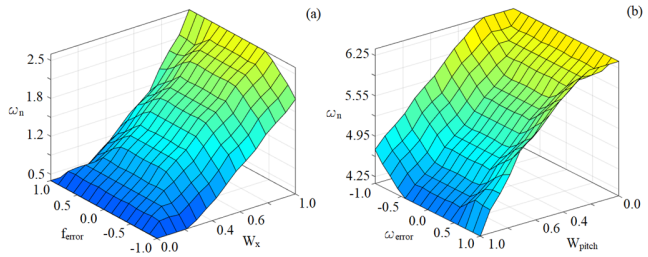


Fig. 4. The surface plot of the fuzzy logic rules for: (a) high-pass filter; (b) low-pass filter.

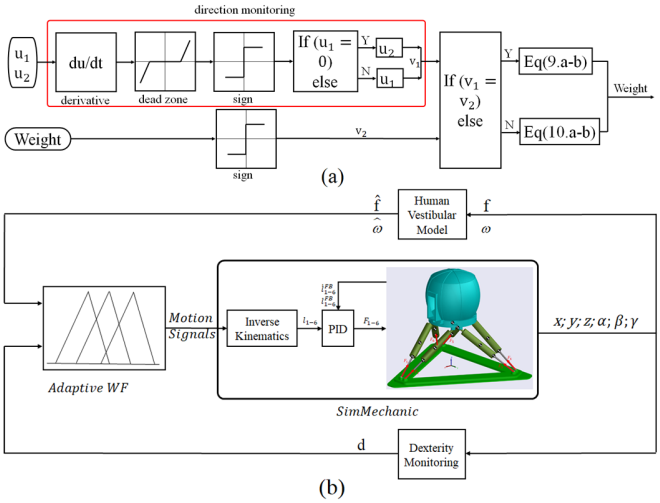


Fig. 5. The schematic structure of: (a) Direction detector unit; (b) Simulink model of the developed adaptive washout filter.

$$W_{x,y,z} = \frac{W_{x,y,z}}{2} + 0.5 \quad (9.a)$$

$$W_{\alpha,\beta,\gamma} = \frac{W_{\alpha,\beta,\gamma}}{2} + 0.5 \quad (9.b)$$

The 0.5 value is added to the weight coefficient because the manipulator will escape from going to the boundary and have more space to exploit. Also, if the sign of the input signal and the position of the upper platform position is reversed, the weight factor should be updated as below:

$$W_{x,y,z} = \frac{W_{x,y,z}}{2} \quad (10.a)$$

$$W_{\alpha,\beta,\gamma} = \frac{W_{\alpha,\beta,\gamma}}{2} \quad (10.b)$$

Then, if the Steward platform is near to the workspace limitations and the signal commands to get away the boundary, there is no need to reduce the cut-off frequency with using this technique. It produces a better motion signal with low sensed motion error. Also, this assumption can lead to better usage of the actuator speed limit to have the best motion sensation during the simulations.

III. Results and Discussions

This section is provided in two subsection which is used to verify the model using MATLAB software, validate the developed adaptive washout filter with classical and pervious adaptive washout filters developed by Schmidt and Conrad [11] and Asadi et al. [23], respectively.

A. *Verification*

In experiments, the Simulink model of the Steward platform using washout filters has been designed and developed (Fig. 5.b). Initially, the Rigs of Rods (RoR) soft body physics engine is utilized to simulate the vehicle environment (version 0.39.5) (http://www.rigsofrods.com). Then, the outputs of RoR are considered as input for the Simulink file. Then, motion signals are produced in the MCA blocks. The inputs of the developed adaptive fuzzy-based washout filter are dexterity and special sensation force error and sensed angular velocity error by the model block of human vestibular for both of the real vehicle driver and the user of the SBMP.

The regenerated motion signals are imported to the Steward platform SimMechanic model block. This block consists of leg trajectory, PID controller, Steward platform and performance analysis sub-blocks. Besides, there is a plant sub-block of the Steward platform that is modelled in SimMechanic of MATLAB software. The outputs of detectors import to the performance analysis subplot to calculate the dexterity. This sub-block also monitors the limitations of SBMP's legs and passive joints. The special sensation force and angular sensation velocity are modelled using the transition function of the otolith limbs and semicircle canal.

B. *Validation*

Figure 6.a-b shows the motion signals that are input of the Simulink file for 25 seconds. The vehicle starts moving at 1.51 seconds of the scenario and stops moving at 24 seconds of driving. The linear acceleration and angular velocity in three directions are shown in Fig. 6.a-b. The scale factor is 0.23 for linear acceleration signals and 1 for angular velocity signals to keep the platform inside the linear and angular limitation and allow MCAs to improve signal production. The scale factor should be the same for classical, previous adaptive and developed adaptive washout filters to reach the fair comparison of MCAs [46, 47].

Recorded driving scenario results in the RoR for the classical, previous and developed adaptive washout filters are listed in Table II. Root mean square error (RMSE) presents the sensed motion error between the real vehicle driver and the Steward platform user. The reported results show that the error of sensed motion using the proposed method is less than other methods due to the consideration of the human vestibular model as well as the wise usage of platform's workspace. Another section of Table II displays the correlation coefficient (CC) to demonstrate the shape similarity of the SBMP user sensed motion and the real vehicle driver motion sensation. CC is introduced in MCA by Asadi et al. [48, 49] and it can vary between 0 to 1 while 1 shows the highest fidelity regeneration of the motion signals compared with the driver of the real vehicle.

Fig. 7.a-c displays the sensed angular velocity for the driver of real vehicle and the user of the SBMP using the classical, previous adaptive and developed adaptive washout filters in the *x*-, *y*- and *z* direction. The sensed angular velocity between the driver of real vehicle and the user of the SBMP is much more dependable with lower wrong motion cues using the developed adaptive washout filter compared with pervious and classical washout filters based on Fig. 7.a-c. Also, the error of sensed

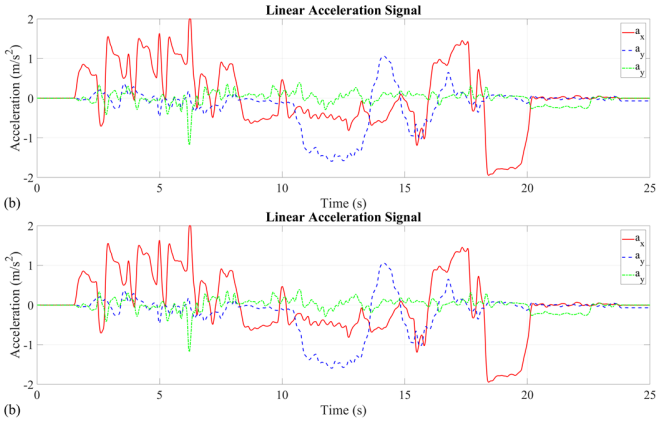


Fig. 6. The reference signal (real vehicle motions): (a) linear acceleration; (b) angular velocity.

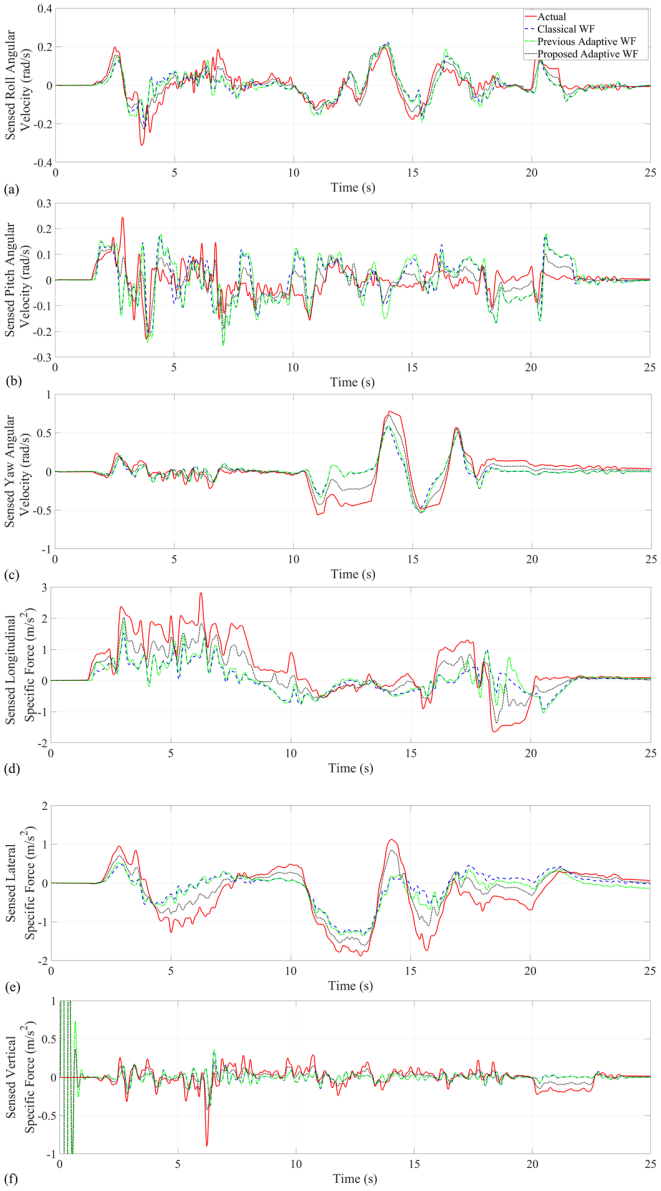


Fig. 7. The sensed angular velocity and sensed special force between the real vehicle driver and the SBMP user using classical, previous adaptive and developed adaptive washout filters along: (a) *roll*-angle; (b) *pitch*-angle; (c) *yaw*-angle; (d) *x*-axis; (e) *y*-axis; (e) *z*-axis.

TABLE II
THE RESULT OF THE CLASSICAL, PREVIOUS ADAPTIVE AND DEVELOPED ADAPTIVE WASHOUT FILTERS.

Index	RMSE			CC		
	CL WF	PRE WF	PRO WF	CL WF	PRE WF	PRO WF
SSF_x	1.2496 (m/s^2)	0.9613 (m/s^2)	0.7209 (m/s^2)	0.5663	0.7403	0.8743
SSF_y	1.3892 (m/s^2)	0.8957 (m/s^2)	0.6921 (m/s^2)	0.5426	0.7325	0.8634
SSF_z	0.1284 (m/s^2)	0.0856 (m/s^2)	0.0695 (m/s^2)	0.0095	0.0152	0.0187
SAV_x	7.4876 (deg/s)	7.6475 (deg/s)	6.4799 (deg/s)	0.4184	0.5272	0.7925
SAV_y	7.8657 (deg/s)	7.7585 (deg/s)	6.3658 (deg/s)	0.3986	0.5103	0.7648
SAV_z	5.2387 (deg/s)	4.9825 (deg/s)	4.2857 (deg/s)	0.3421	0.4448	0.5128

RMSE: Root Mean Square Error; CC: Correlation Coefficient; CL WF: Classical washout filter; PRE WF: Previous adaptive washout filter; PRO: Developed adaptive washout filter; SSF: Sensed special force; SAV: Sensed angular velocity;

angular velocity is under the human sensed angular threshold unit because, the tilt coordination channel does not generate the signals beyond the tilt rate limit. There is no significant difference between the values of sensed angular velocity error. However, the developed adaptive washout filter reduces the error of sensed angular velocity between the driver of real vehicle and the user of the SBMP 13.45%, 19.06% and 18.13% compared with classical washout filter along *x*-, *y*- and *z*-axis. Moreover, the developed adaptive washout filter decreases the error of sensed angular velocity between the driver of real vehicle and the user of the SBMP 15.26%, 17.95% and 13.98% compared with previous adaptive washout filter along *x*-, *y*- and *z*-axis. Fig. 7.d-f demonstrates the sensed special force of the driver of real vehicle and the user of the SBMP using the classical, previous adaptive and developed adaptive washout filters in the *x*-, *y*- and *z*-direction. The developed adaptive washout filter is able to accurately pursue the reference signal shape. The CC of the sensed special force using the developed adaptive washout filter increases 42.30%, 50.17% and 45.87% compared with classical washout filter along *x*-, *y*- and *z*-direction, correspondingly. In addition, the developed adaptive washout filter increases the sensed special force 25.00%, 22.73% and 18.80% compared with previous adaptive washout filter along *x*-, *y*- and *z*-direction, correspondingly. The maximum value of the sensed special force error for longitudinal movement is lower than 1.2 m/s^2 through the developed method, while it is 1.8 and 2 m/s^2 for the previous adaptive and classical washout filters, respectively.

Fig. 8.a-f shows the SBMP linear and angular displacement of the end-effector in *x*-, *y*- and *z*-axis, respectively, using classical, previous adaptive and developed adaptive washout filters. The Steward platform with developed adaptive washout filter moves more than classical washout filter due to the structure of proposed adaptive washout filter. The cut-off frequency of the high-pass filter is flexible based on the end-effector configuration in the proposed adaptive washout filter. Then, it can decrease the high-pass filter and use the larger workspace compared with classical washout filter. The proposed method changes the cut-off frequency to compensate motion sensation error by taking the online performance analysis of the platform into account. It should be noted that the

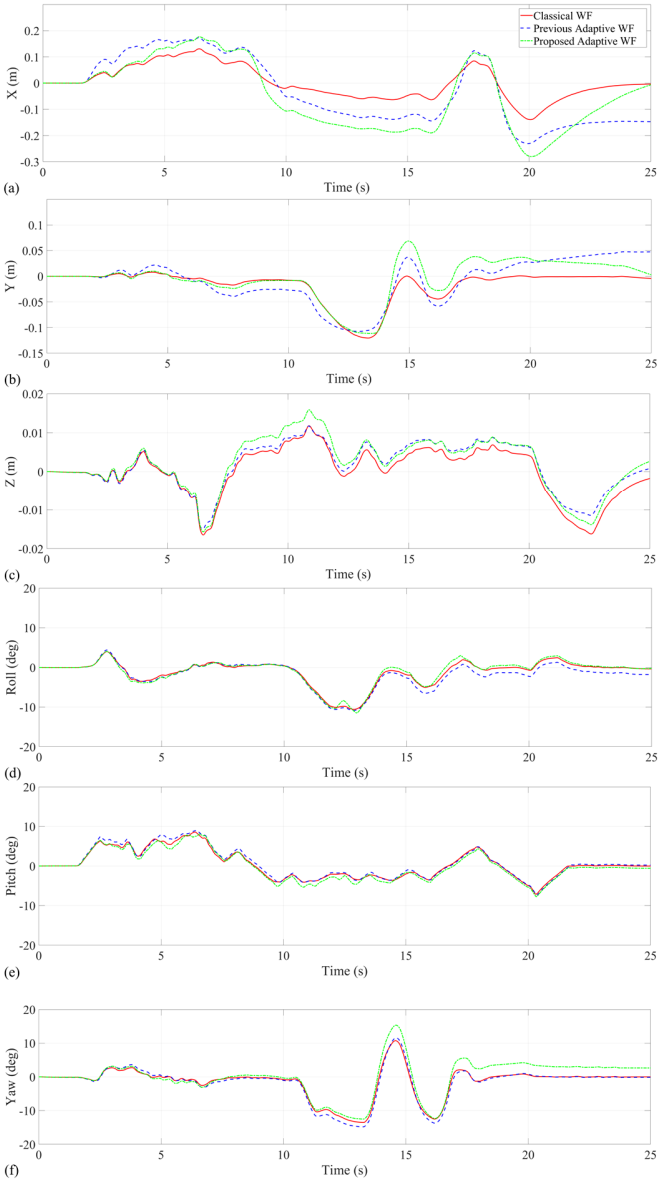


Fig. 8. Linear and angular displacement of SBMP using classical, previous adaptive and developed adaptive washout filters along: (a) x direction; (b) y direction; (c) z direction; (d) *roll*-angle; (e) *pitch*-angle; (f) *yaw*-angle.

chance of reaching the physical limitation is a bit higher for the proposed washout filter compared to classical washout filter. Also, compared to the previous adaptive washout filter, the risk of achieving physical limitation is either less or equal. It is due to the cubic box supposition of the workspace in this method.

Fig. 9 shows the variation of the dexterity as a performance analysis of the Steward platform. Our proposed adaptive washout filter's dexterity is close to the classical washout filter that has been adjusted based on the worst-case scenario. The previous adaptive washout filter has a slight dexterity reduction that shows the higher risk of reaching to the manipulator limitations or singularity. The dexterity of the previous adaptive washout filter at t=13.01 second is 0.6372, while the dexterity of the proposed adaptive washout filter is 0.7238. It leads to better performance and higher motion fidelity as it is shown in Fig. 7.

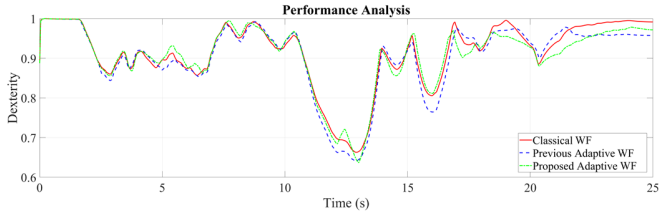


Fig. 9. Performance analysis of the SBMP using classical, previous and developed adaptive fuzzy logic-based washout filters.

Finally, the parking motion scenario (sudden accelerations or deaccelerations) is implemented to the SBMP in order to show the relatability and repeatability of the proposed adaptive washout filter over the classical and pervious adaptive washout filters. Fig. 10.a presents the sensed special force for the driver of real vehicle and the user of the SBMP using the classical, previous adaptive and developed adaptive washout filters along longitudinal mode. The shape similarity of the sensed special force between the driver of real vehicle and the user of the SBMP using developed adaptive washout filter is 0.9837, while it is 0.8651 and 0.6502 using previous adaptive and classical washout filter. It proves the better generation of the motion cues using the developed adaptive washout filter with higher fidelity over the previous adaptive and classical washout filters. Moreover, the RMSE of the sensed special force between the driver of real vehicle and the user of the SBMP using developed adaptive, previous adaptive and classical washout filters are 0.2728, 0.1762 and 0.0660 m/s^2. It proves the regenerations of the less false motion cues using the developed adaptive washout filter contrasted with the classical and previous adaptive washout filters. Also, Fig. 10.b shows the linear motion of the end-effector along *x*-axis using three investigated methods. As it is obvious, the developed adaptive washout filter is able to utilize the SBMP's workspace more wisely compared with classical and previous adaptive washout filters.

IV. Conclusions

In this paper, an adaptive washout filter based on time-varying cut-off frequency using fuzzy logic units is developed for a typical Stewart platform in order to use higher dexterous parts of the workspace. The classical washout filter is a commercial type of MCA because of simplicity, but it has some disadvantages including fixed parameters, conservative motions, and lack of considering human perception model in the design which reduces motion fidelity of the platform. Also, the previous adaptive washout filter [23] with consideration of the sensed motion error between the driver of real vehicle and SBMP user as well as the end-effector limitations is not able to use the higher dexterous part of the workspace. The developed adaptive washout filter uses the sensed motion error between the driver of real vehicle and SBMP user and the dexterity value to vary the cut-off frequency of the washout filters. The dexterity of the end-effector is monitored in this study to use the area of the platform workspace with ability of generating higher linear acceleration signals. The performance analysis factor is used as a physical limitation parameter of the SBMP for the first time in the MCA domain to use the workspace of platform efficiently via better regeneration of the high frequency motion signal. Moreover, the direction detector has been used for the first time in designing adaptive washout filter to update the value of the weight parameter (which is a parameter based on dexterity and current position of the end-effector) to use the maximum speed of the actuator. It helps to feel a better sensation of the movement in the SBMP. The Stewart platform is implemented using Simulink in MATLAB programming language. The experimental results showed that the proposed adaptive washout filter reduced the sensed motion error between the driver of real vehicle and the SBMP user compared to the classic washout filter with fixed parameters and even the previous adaptive washout filter. Moreover, the reported results also showed an improvement in term of sensed shape following factor. As a future study, the robust adaptive fuzzy [50] with implementation of the external disturbances and strict-feedback can be employed. Also, the idea of using neural network [51-56] and supervised learning methods can be used to design the high efficient MCA using the regenerated results of the proposed adaptive washout filter with low computational load and more efficiency.

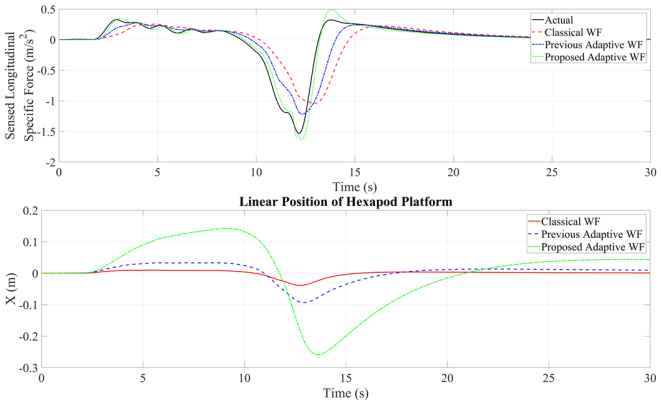


Fig. 10. (a): The sensed special force between the real vehicle driver and the SBMP user using classical, previous adaptive and developed adaptive washout filters along *x*-axis; (b): Linear displacement of SBMP using classical, previous adaptive and developed adaptive washout filters along *x*-direction.

References

[1] M. R. C. Qazani, H. Asadi, S. Khoo, and S. Nahavandi, "A Linear Time-Varying Model Predictive Control-Based Motion Cueing Algorithm for Hexapod Simulation-Based Motion Platform," *IEEE Transactions on Systems, Man, and Cybernetics: Systems,* 2019.

[2] H. Asadi, S. Mohamed, C. P. Lim, and S. Nahavandi, "Robust optimal motion cueing algorithm based on the linear quadratic regulator method and a genetic algorithm," *IEEE Transactions on Systems, Man, and Cybernetics: Systems,* vol. 47, no. 2, pp. 238-254, 2016.

[3] M. R. C. Qazani, H. Asadi, and S. Nahavandi, "A decoupled linear model predictive control-based motion cueing algorithm for simulation-based motion platform with limitted workspace," in *2019 IEEE International Conference on Industrial Technology (ICIT)*, 2019: IEEE, pp. 35-41.

[4] J.-P. Merlet, *Parallel robots*. Springer Science & Business Media, 2006.

[5] M. R. C. Qazani, H. Asadi, and S. Nahavandi, "High-fidelity hexarot simulation-based motion platform using fuzzy incremental controller and model predictive control-based motion cueing algorithm," *IEEE Systems Journal,* 2019.

[6] S. Pedrammehr, M. R. C. Qazani, H. Asadi, and S. Nahavandi, "Control System Development of a Hexarot-Based High-G Centrifugal Simulator," in *ICIT*, 2019, pp. 78-83.

[7] J.-P. Merlet, "Jacobian, manipulability, condition number, and accuracy of parallel robots," *Journal of Mechanical Design,* vol. 128, no. 1, pp. 199-206, 2006.

[8] S. Casas, C. Portalés, J. Gimeno, and M. Fernández, "Simulation of parallel mechanisms for motion cueing generation in vehicle simulators using AM-FM bi-modulated signals," *Mechatronics,* vol. 53, pp. 251-261, 2018.

[9] M. R. C. Qazani, H. Asadi, and S. Nahavandi, "A Motion Cueing Algorithm Based on Model Predictive Control Using Terminal Conditions in Urban Driving Scenario," *IEEE Systems Journal,* 2020.

[10] J. Iskander *et al.*, "From car sickness to autonomous car sickness: A review," *Transportation research part F: traffic psychology and behaviour,* vol. 62, pp. 716-726, 2019.

[11] S. Schmidt and B. Conrad, "The calculation of motion drive signals for piloted flight simulators," *Palo Alto, CA, USA: NASA,* 1969.

[12] R. J. Telban and F. M. Cardullo, "Motion cueing algorithm development: Human-centered linear and nonlinear approaches," *NASA TechReport CR-2005-213747,* 2005.

[13] H. Asadi, S. Mohamed, C. P. Lim, and S. Nahavandi, "A review on otolith models in human perception," *Behavioural brain research,* vol. 309, pp. 67-76, 2016.

[14] H. Asadi, S. Mohamed, C. P. Lim, S. Nahavandi, and E. Nalivaiko, "Semicircular canal modeling in human perception," *Reviews in the Neurosciences,* vol. 28, no. 5, pp. 537-549, 2017.

[15] S. Casas, C. Portalés, P. Morillo, and M. Fernández, "A particle swarm approach for tuning washout algorithms in vehicle simulators," *Applied Soft Computing,* vol. 68, pp. 125-135, 2018.

[16] H. Asadi, S. Mohamed, K. Nelson, S. Nahavandi, and D. R. Zadeh, "Human perception-based washout filtering using genetic algorithm," in *International Conference on Neural Information Processing*, 2015: Springer, pp. 401-411.

[17] H. Asadi, S. Mohamed, K. Nelson, S. Nahavandi, and M. Oladazimi, "An optimal washout filter based on genetic algorithm compensators for improving simulator driver perception," in *DSC 2015: Proceedings of the Driving Simulation Conference & Exhibition*, 2015: Max Planck Institute for the Advancement of Science, pp. 1-10.

[18] R. V. Parrish, J. E. Dieudonne, and D. J. Martin Jr, "Coordinated adaptive washout for motion simulators," *Journal of aircraft,* vol. 12, no. 1, pp. 44-50, 1975.

[19] D. Ariel and R. Sivan, "False cue reduction in moving flight simulators," *IEEE Transactions on Systems, Man, and Cybernetics,* no. 4, pp. 665-671, 1984.

[20] L. REID and M. NAHON, "Response of airline pilots to variations in flight simulator motion algorithms," *Journal of Aircraft,* vol. 25, no. 7, pp. 639-646, 1988.

[21] L. Nehaoua, H. Arioui, S. Espie, and H. Mohellebi, "Motion cueing algorithms for small driving simulator," in *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*, 2006: IEEE, pp. 3189-3194.

[22] J.-B. Song, U.-J. Jung, and H.-D. Ko, "Washout algorithm with fuzzy-based tuning for a motion simulator," *Journal of Mechanical Science and Technology,* vol. 17, no. 2, pp. 221-229, 2003.

[23] H. Asadi, A. Mohammadi, S. Mohamed, D. R. Zadeh, and S. Nahavandi, "Adaptive washout algorithm based fuzzy tuning for improving human perception," in *International Conference on Neural Information Processing*, 2014: Springer, pp. 483-492.

[24] H. Asadi, A. Mohammadi, S. Mohamed, and S. Nahavandi, "Adaptive translational cueing motion algorithm using fuzzy based tilt coordination," in *International Conference on Neural Information Processing*, 2014: Springer, pp. 474-482.

[25] H. Asadi, S. Mohamed, and S. Nahavandi, "Incorporating human perception with the motion washout filter using fuzzy logic control," *IEEE/ASME Transactions on Mechatronics,* vol. 20, no. 6, pp. 3276-3284, 2015.

[26] H. Asadi, C. P. Lim, S. Mohamed, D. Nahavandi, and S. Nahavandi, "Increasing motion fidelity in driving simulators using a fuzzy-based washout filter," *IEEE Transactions on Intelligent Vehicles,* vol. 4, no. 2, pp. 298-308, 2019.

[27] M. R. C. Qazani, H. Asadi, T. Bellmann, S. Mohamed, C. P. Lim, and S. Nahavandi, "Adaptive Washout Filter Based on Fuzzy Logic for a Motion Simulation Platform with Consideration of Joints Limitations," *IEEE Transactions on Vehicular Technology,* 2020.

[28] M. R. C. Qazani, H. Asadi, T. Bellmann, S. Perdrammehr, S. Mohamed, and S. Nahavandi, "A New Fuzzy Logic Based Adaptive Motion Cueing Algorithm Using Parallel Simulation-Based Motion Platform," in *2020 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)*, 2020: IEEE, pp. 1-8.

[29] M. R. C. Qazani, H. Asadi, S. Mohamed, and S. Nahavandi, "Prepositioning of a Land Vehicle Simulation-Based Motion Platform Using Fuzzy Logic and Neural Network," *IEEE Transactions on Vehicular Technology,* vol. 69, no. 10, pp. 10446-10456, 2020.

[30] K. Gupta and B. Roth, "Design considerations for manipulator workspace," *Journal of Mechanical Design,* vol. 104, no. 4, pp. 704-711, 1982.

[31] R. P. Paul and C. N. Stevenson, "Kinematics of robot wrists," *The International journal of robotics research,* vol. 2, no. 1, pp. 31-38, 1983.

[32] T. Yoshikawa, "Manipulability of robotic mechanisms," *The international journal of Robotics Research,* vol. 4, no. 2, pp. 3-9, 1985.

[33] S. Pedrammehr, M. R. C. Qazani, H. Asadi, and S. Nahavandi, "Control system development of a hexarotbased high-G centrifugal simulator," in *The 20th IEEE International Conference on Industrial Technology IEEE-ICIT 2019*, 2019.

[34] S. Pedrammehr, M. R. C. Qazani, H. Asadi, and S. Nahavandi, "Manipulability Analysis of Gantry-Tau parallel manipulator," in *ACRA 2019: Proceedings of the Australasian Conference on Robotics and Automation*, 2019: [Australian Robotics & Automation Association], pp. 1-7.

[35] S. Pedrammehr, M. R. C. Qazani, H. Asadi, and S. Nahavandi, "Kinematic Manipulability Analysis of Hexarot Simulators," in *ICIT*, 2019, pp. 133-138.

[36] M. R. C. Qazani, S. Pedrammehr, H. Abdi, and S. Nahavandi, "Performance evaluation and calibration of gantry-tau parallel mechanism," *Iranian Journal of Science and Technology, Transactions of Mechanical Engineering,* pp. 1-15, 2019.

[37] M. R. C. Qazani, H. Asadi, S. Pedrammehr, and S. Nahavandi, "Performance analysis and dexterity monitoring of hexapod-based simulator," in *2018 4th International Conference on Control, Automation and Robotics (ICCAR)*, 2018: IEEE, pp. 226-231.

[38] M. R. C. Qazani, H. Asadi, and S. Nahavandi, "A new gantry-tau-based mechanism using spherical wrist and model predictive control-based motion cueing algorithm," *Robotica,* vol. 38, no. 8, pp. 1359-1380, 2020.

[39] M. J. Tajaril, S. Pedrammehr, M. R. C. Qazani, and M. J. Nategh, "The effects of joint clearance on the kinematic error of the hexapod tables," in *2017 5th RSI International Conference on Robotics and Mechatronics (ICRoM)*, 2017: IEEE, pp. 39-44.

[40] M. R. C. Qazani, V. Mohammadi, H. Asadi, S. Mohamed, and S. Nahavandi, "Development of Gantry-Tau-3R Mechanism Using a Neuro PID Controller," in *ACRA 2019: Proceedings of the Australasian Conference on Robotics and Automation*, 2019: [Australian Robotics & Automation Association], pp. 1-8.

[41] L. A. Zadeh, *Fuzzy logic: advanced concepts and structures*. IEEE Educational Activities Department, 1992.

[42] J.-B. Song, U.-J. Jung, and H.-D. Ko, "Washout algorithm with fuzzy-based tuning for a motion simulator," *KSME international journal,* vol. 17, no. 2, pp. 221-229, 2003.

[43] H. Asadi, S. H. A. Kaboli, A. Mohammadi, and M. Oladazimi, "Fuzzy-control-based five-step Li-ion battery charger by using AC impedance technique," in *Fourth international conference on machine vision (ICMV 2011): machine vision, image processing, and pattern analysis*, 2012, vol. 8349: International Society for Optics and Photonics, p. 834939.

[44] M. R. C. Qazani, H. Asadi, S. Mohamed, and S. Nahavandi, "An Inverse Kinematic-based Model Predictive Motion Cueing Algorithm for a 6-DoF Gantry-Tau Mechanism," in *ACRA 2019: Proceedings of the Australasian Conference on Robotics and Automation*, 2019: [Australian Robotics & Automation Association], pp. 1-9.

[45] H. Ying, Y. Ding, S. Li, and S. Shao, "Comparison of necessary conditions for typical Takagi-Sugeno and Mamdani fuzzy systems as universal approximators," *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans,* vol. 29, no. 5, pp. 508-514, 1999.

[46] H. Asadi, C. P. Lim, A. Mohammadi, S. Mohamed, S. Nahavandi, and L. Shanmugam, "A genetic algorithm–based nonlinear scaling method for optimal motion cueing algorithm in driving simulator," *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering,* vol. 232, no. 8, pp. 1025-1038, 2018.

[47] H. Asadi *et al*., "A Model Predictive Control-based Motion Cueing Algorithm using an optimized Nonlinear Scaling for Driving Simulators," in *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, 2019: IEEE, pp. 1245-1250.

[48] H. Asadi, "Human perception-based washout filtering," Deakin University, 2015.

[49] H. Asadi, S. Mohamed, K. Nelson, and S. Nahavandi, "A linear quadratic optimal motion cueing algorithm based on human perception," in *ACRA 2014: Proceedings of Australasian Conference on Robotics and Automation*, 2014: Australian Robotics and Automation Association, pp. 1-9.

[50] K. Sun, Q. Jianbin, H. R. Karimi, and Y. Fu, "Event-triggered robust fuzzy adaptive finite-time control of nonlinear systems with prescribed performance," *IEEE Transactions on Fuzzy Systems,* 2020.

[51] K. Sun, J. Qiu, H. R. Karimi, and H. Gao, "A novel finite-time control for nonstrict feedback saturated nonlinear systems with tracking error constraint," *IEEE Transactions on Systems, Man, and Cybernetics: Systems,* 2019.

[52] H. D. Kabir, A. Khosravi, S. Nahavandi, and A. Kavousi-Fard, "Partial adversarial training for neural network-based uncertainty quantification," *IEEE Transactions on Emerging Topics in Computational Intelligence,* 2019.

[53] H. D. Kabir, A. Khosravi, M. A. Hosen, and S. Nahavandi, "Neural network-based uncertainty quantification: A survey of methodologies and applications," *IEEE access,* vol. 6, pp. 36218-36234, 2018.

[54] S. M. J. Jalali, M. Karimi, A. Khosravi, and S. Nahavandi, "An efficient neuroevolution approach for heart disease detection," in *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, 2019: IEEE, pp. 3771-3776.

[55] S. M. J. Jalali, A. Khosravi, P. M. Kebria, R. Hedjam, and S. Nahavandi, "Autonomous robot navigation system using the evolutionary multi-verse optimizer algorithm," in *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, 2019: IEEE, pp. 1221-1226.

[56] H. D. Kabir, A. Khosravi, S. Nahavandi, and D. Srinivasan, "Neural Network Training for Uncertainty Quantification Over Time-Range," *IEEE Transactions on Emerging Topics in Computational Intelligence,* 2020.



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