On the Objective Evaluation of Motion Cueing in Vehicle Simulations

Sergio Casas-Yrurzum, Cristina Portalés-Ricart, Pedro Morillo-Tena, and Carolina Cruz-Neira, *Senior Member, IEEE*

***Abstract*— Motion-based simulators are used for a variety of applications, such as research, education, entertainment and training. In fact, motion cues are required to achieve the highest regulatory certifications in training vehicle simulators. Nonetheless, the reproduction of self-motion cues presents technological and economic limitations that are not present in the generation of audiovisual cues. For this reason, the generated motion does not generally match the expected one. Therefore, it is necessary to define means to assess the suitability/fidelity of the generated motion cues. After more than 50 years of motion-based vehicle simulation, no mechanism has been universally accepted as the standard solution for the evaluation of motion cues. This paper reviews the mechanisms for obtaining measures of motion fidelity, focusing on those based on objective methods. Since the design of the Objective Motion Cueing Test in 2006, researchers have shown a renewed interest in identifying objective methods to evaluate motion cueing, as the number of works following this approach in recent years reveals. Objective motion fidelity systems allow also performing automatic tuning of MCA by means of optimization techniques, which addresses one of the other main problems of these algorithms. Nevertheless, a universally accepted objective method to assess perceptual motion fidelity in vehicle simulators has not been proposed yet. For this reason, this review work frames and classifies the existing methods. In addition, the authors propose a series of features that an ideal evaluation method for assessing perceptual motion fidelity should include and provide future research guidelines for this complex topic.**

***Index Terms*— Motion cueing, objective evaluation, motion fidelity, motion validity, MCA, vehicle simulation, virtual reality.**

I. Introduction

VEHICLE simulation is a multimodal interactive computer-based application paradigm that is designed to reproduce the operation of real vehicles. Vehicle simulators are primarily used for research and training, the latter being their most common application. Training-oriented vehicle simulators are utilized to avoid using real vehicles in driver/pilot training. In most cases, this reduces costs and increases safety. This is especially important in flight simulation where one hour of real flight is remarkably expensive [1]. However, vehicle simulation can also be used for research, awareness raising, development, education and entertainment. Research applications include analyzing pilot behavior, the evaluation of new vehicle components, or even accident forensics.

Although the main goal of a vehicle simulator is usually to recreate the conditions under which the vehicle is piloted/driven/operated in the real world (let us use the word *operate* hereafter to account for different vehicle types), different uses imply different requirements. The reproduction of the behavior of the vehicle is accomplished by means of the generation of the different perceptual cues that are experienced by the vehicle operator when using a real vehicle. This is especially true in driver/pilot/human-in-the-loop (DIL/PIL/HIL) vehicle simulators, in which the user is in charge of operating the vehicle. Although it is possible to build vehicle simulators that are designed for other purposes, such as driving safety awareness, and do not need to simulate the actual control of the vehicle [2], HIL is, undoubtedly, the most common set-up. For this reason, vehicle simulators are often categorized as Virtual Reality (VR) applications, since the goal of the system is to create a virtual world where users believe they are operating the simulated vehicle.

The main perceptual cues that can be felt when operating a vehicle are visual, auditory and motion cues. However, whereas audiovisual cues are always included in vehicle simulators, motion cues remain controversial. In fact, they are purposely excluded in many vehicle simulators. In many vehicles, it is possible to experience other perceptual cues, such as haptic/proprioceptive cues coming from the interaction with the vehicle controls [3] that can also be important. In addition, in some vehicles, there may be others such as wind in a speedboat or in a motorcycle simulator, or heat in a tank simulator, but these special conditions are hardly generalizable and are usually addressed with customized solutions.

There are good reasons for the discussion about the convenience of including motion cues. When using a vehicle simulator, audiovisual cues can be very realistic and similar to the expected ones, if properly generated. Although not all the details can be perfectly simulated, the field of view and the visual sensation can be very compelling with current state-of-the-art visual technology (VR glasses, high-resolution displays, stereoscopic rendering, etc.). The same happens with sound. Even the dynamics of the vehicles can be

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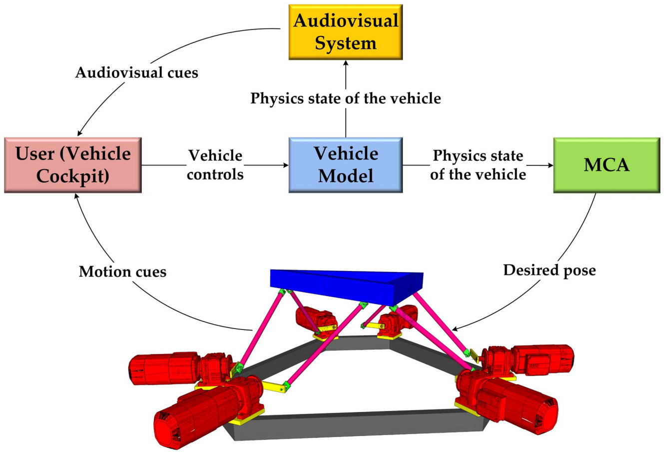

Fig. 1. Scheme of the generation of perceptual cues in vehicle simulators.

very accurately reproduced with real-time physics libraries. However, the reproduction of gravito-inertial cues that deceive the human vestibular system encounters physical problems that have no easy solution. The obvious problem is that to feel motion, the human body needs to be actually moved. Since the vehicle's motion range is typically several orders of magnitude larger than the available physical space of the simulator [4], no perfect solution can be provided for the time being. In addition, motion cueing is an expensive activity because it typically involves expensive hardware. In summary, the generation of motion cues presents technological and economic limitations that are not present in the generation of audiovisual cues [5]. These limitations will be present until science finds a way to safely deceive the human brain motion senses without actually moving the body.

Motion cues are usually generated by means of robotic mechanisms called motion platforms (Fig. 1). These devices are able to perform controlled movements on the simulator seat from which the user usually operates the vehicle. The algorithms that control these devices are called Motion Cueing Algorithms (MCA) or Motion Drive Algorithms (MDA). Many algorithms of this kind have been proposed [6]–[19] but the most referenced solution is still the Reid-Nahon implementation of the Classical Washout Algorithm [20]–[22]. There are also many different robotic designs upon which these MCA could be applied, but the 6-DOF Stewart-Gough motion platform [23] has become a *de facto* standard. Nevertheless, no motion device has unlimited motion capabilities, and the algorithms that are used for the generation of motion cues have to be designed to cope with the fact that the simulator displacements are constrained by physical limits. Therefore, MCA are typically designed with the idea of modifying the motion signals so that the generated motion is perceptually optimal while respecting the physical constraints of the motion hardware. Motion downscaling, motion filtering and the exploitation of particular perceptual illusions [24] (like the somatogravic illusion [25]–[27]) are some of the techniques employed to address these limitations.

In any case, the generated motion seldom matches (not even perceptually) the real or expected one. Therefore, it is necessary to define a way to assess and qualify the suitability of the generated motion cues. After more than 50 years of motion-based vehicle simulation, no mechanism has been universally accepted as the standard solution for the assessment and evaluation of motion cues. As motion perception is subjective, because it depends on physiological and psychological factors that are user-dependent and still partially unknown, the problem has been traditionally addressed by means of subjective evaluations. However, these kinds of evaluations could be inconsistent and do not allow to clearly compare different solutions. For these and other reasons, objective assessment mechanisms have been proposed in recent years. This has motivated the review work presented in this paper. However, this does not mean that subjective methods should be ignored, since they serve a purpose: to satisfy the vehicle operator and fine-tune the MCA for specific users.

There are only a few academic review works published about motion cueing [28]–[32], but to the best of our knowledge, this is the first literature review about the objective evaluation of motion cueing. As flight simulation has often shadowed the rest of the research on vehicle simulation, this review will deal with all sorts of vehicle simulators.

The rest of the paper is organized as follows. Section II will explain the different evaluation systems that can be used to assess motion cues. Section III reviews the objective evaluation systems that have been used in recent and past works. Section IV discusses different findings from different authors and proposes a set of features for future research in objective motion cueing. Finally, section V draws the conclusions and outlines future work.

II. Evaluation of Motion Cueing

The problem of identifying appropriate mechanisms for the assessment of simulators, and motion cueing in particular, is not new. Given its importance within the area of vehicle simulation, it has been formally studied at least since the 1970s [33]. In 1977, Sinacori presented a report to assess the motion and visual cues of a helicopter simulator [34] providing some of the foundations of the field, although some works had been published before to understand and evaluate the use of aircraft by human pilots, such as [35], [36], which could be also used for simulated aircraft. In fact, Cooper-Harper's Handling Quality Rating (HQR) remains the standard for measuring aircraft flying qualities and is a popular method to assess flight simulators. Since these early works, several researchers have studied the problem from different perspectives. However, many problems have hindered the development of a solid criterion for motion assessment, such as the disparity of vehicle simulators and their components, the different goals of different simulators and the large number of algorithms, motion platforms, types of vehicles and users. In addition, the subjective nature of the problem gives room for several interpretations. In fact, no consensus has been found about how to properly evaluate motion cueing. This is, in turn, the main reason why it is still unclear what is the best way to generate motion cues in a vehicle simulator [27].

Some researchers, such as Sinacori [34] and Schroeder [37] talk about *motion fidelity*. Some others talk about *motion validity* [38]. There are also different types of motion fidelity and validity. Therefore, it is important to clarify these concepts first. In simulation, *validity* refers to how closely the simulated results match the data collected from real life situations, whereas *fidelity* refers to the extent to which a simulator is capable of replicating the corresponding environment and experience [39]. When dealing with motion simulation, *motion validity* refers to the correctness of the generated motion, and *motion fidelity* lies in a more general, experiential or even subjective plane. However, the differences are subtle and *motion fidelity* is often used as an umbrella term [40]. Other terms, such as motion evaluation, motion incongruence, motion incoherence, motion error, motion validation, etc. refer to either motion fidelity or motion validity.

A simulator can provide *physical*(objective/engineering) *fidelity/validity* [38] if the motion cues that are expected for the simulated vehicle can be directly provided by the simulator (although this rarely occurs), *perceptual fidelity/validity* [38] when the human perception of self-motion is comparable to a real situation, *behavioral fidelity/validity* [38] when the behavior of the operator is consistent with respect to a real situation, and *functional fidelity/validity* [41] when there is fitness for purpose and the simulator accomplishes the goals it was designed for [42]. In this work, the term *motion fidelity* will be used hereafter, as most authors do.

Physical fidelity is sometimes overlooked, since, in most vehicle simulators and vehicle types, physical fidelity is unattainable. The focus is instead set on perceptual fidelity. For this reason, the terms motion fidelity and perceptual motion fidelity are often used indistinctly in different contexts as synonyms, since it is understood that the simulator must have fidelity for the human operator's subjective perception, not for the physical signals. Regarding behavioral fidelity, it is analyzed when the simulator is used to study the behavior of their users. Functional fidelity is much less generalizable with respect to the assessment since it depends on the objective of the simulator, which are often multiple. However, it is important to emphasize that a simulator without sufficient functional fidelity may be a waste of resources.

Motion fidelity is affected by many factors: the motion software, the robotic motion platform, the vehicle model or even by task-related factors. Therefore, it is not easy to analyze. For this reason, some evaluation systems only focus on one of these elements. This was especially true in the past, because civil flight simulator regulations were mainly focused, not many years ago, on assessing the motion hardware [43]. Fortunately, this is slowly changing, and there is awareness on the fact that a motion system must be evaluated in an integrated manner, since all the elements contribute and modify the resulting motion cues and their perception. As Advani rightly points out "measuring the mechanical properties only defines what the device is capable of doing, and not what it actually does" [43].

Of course, the evaluation of motion cues depends somehow on the objectives of the simulation. The discussion about the necessity of motion cueing in vehicle simulators (the long-debated "motion versus no-motion" question) has been sometimes confusing, since motion cues can be helpful for some objectives but not for others. Some studies suggest that the inclusion of motion provides valuable information for vehicle operators and help them improve their control behavior, especially for complex tasks [44], whereas other studies conclude that they do not provide significant benefits for training [45], [46]. An important body of research about the study of transfer of training can be found in the academic literature. Readers could consult, for instance, Bürki-Cohen's work [47], [48], to know more about this topic. In addition, a good discussion showing the case against and for using motion can be found in [49]. Notwithstanding, certification standards and regulation organizations have always supported and required motion cues in vehicle simulators to obtain the highest simulation certification [49]–[52], not only for aircraft [53].

In any case, it is necessary to provide mechanisms to assess if motion is properly generated. As motion cues are present in the operation of real vehicles, the only reasonable argument to exclude these perceptual cues, besides price, is an improper motion cueing generation that either hinders or has no effect on the simulator goals. Therefore, the only way to improve them is to properly assess these motion cues.

Motion evaluation can be performed in two main ways: *subjectively* or *objectively*. Subjective evaluation relies on the opinions of the vehicle operators and is based on the idea that the problem needs a perceptual solution. This is true for perceptual fidelity, but not for other measures of motion fidelity. In any case, as perceptual fidelity is often the goal of most motion-based vehicle simulators, researchers have supported their solutions on subjective evaluations. This is the most evident and natural way of appraising motion in a simulator and it is based on questionnaires/comments/ratings from the users of the simulator.

On the contrary, objective evaluation is based on identifying numerical indicators that assess the motion cues generated by the simulator. These indicators try to measure physical, behavioral, functional or even perceptual fidelity, since they can also be designed to reflect the functioning of the human perception system.

Subjective evaluation can be performed in several ways. The most common method is to assess motion after motion cues have been generated. The simulator is first used and then, the user is prompted to appraise it. This *offline subjective evaluation* is the most common method and is sometimes used to complement other evaluation forms [34], [37], [54]–[59]. It can be performed by means of subjective discrete scales [11], [41], [42], [60], subjective ratings [56], [61], [62], questionnaires [59], [63]–[65] or even by means of informal comments [13]. The alternative to offline subjective evaluation is a *continuous subjective evaluation*, where users can be continuously rating the motion cues of the simulator. This method, proposed recently [55], [58], [66]–[68] seems much more appropriate since humans can have a hard time summarizing a whole session with a simulator. In addition, it allows identifying specific problems in particular moments where *false cues* (motion cues that are unexpected or have the wrong direction [69]) or incorrect cues are generated, without hampering an overall assessment. The down side is that to assess motion continuously, some kind of manual interface is needed. Therefore, the user cannot operate the vehicle and assess motion at the same time, and pre-recorded runs should be used. It could be argued that the rating might be done in real time through voice communication but it would be certainly complicated to make a continuous rating this way.

In either case, subjective evaluation presents several problems: (i) different persons can give different results; (ii) even the same person at different times may provide different answers, so the process is likely to produce high variability; (iii) no direct link with the rendered cues is usually obtained and therefore, it is hard to identify the causes of low fidelity situations; (iv) it cannot be automated and, thus, cannot be used to improve the tuning of MCA.

Objective evaluation, on the contrary, is based on identifying motion fidelity metrics that can be calculated either by a mathematical function or by means of an algorithm. Thus, it is systematic and can be automated, with obvious benefits. For physical and behavioral fidelity, this method seems the most appropriate one. The challenge is to find a function that can be considered suitable to assess perceptual fidelity. In fact, the main reason why subjective assessments are still used is that current objective assessment methods are open to criticism due to the proposed metric not matching the real human perception.

Objective motion evaluation is performed by measuring objective data from the simulator. Depending on the objective data being analyzed, objective evaluation can be classified in *direct objective evaluation* or *indirect objective evaluation*.

Direct evaluation compares motion data from the output of the MCA (often the specific force and angular velocity experienced by the user) with the expected motion that the simulated vehicle is enjoying, either by plotting graphs [70], [71] or by calculating some kind of error measure or heuristic indicator [60], [72], [73]. Examples of direct objective evaluation can be found in [14], [62], [74]–[76]. Direct evaluation can be used to measure physical fidelity or even perceptual fidelity, if motion data is somehow manipulated to account for the effects of the human perception system. This can be called *perceptual direct objective evaluation*.

Indirect evaluation, on the contrary, is performed by analyzing other variables related to the use of the simulator, but not motion itself. This data can be related with the performance of the vehicle operator (angle of the vehicle, deviation from a reference point, time to complete a task, etc.) or with their behavior or activity (steering wheel activity, time looking at a particular display, etc.). These cases can be used to measure behavioral fidelity. It is important, however, not to measure operator's performance, activity or behavior when trying to assess perceptual motion fidelity. The fact that the behavior of the human operator is the expected one or that a task is completed correctly, does not mean that motion is perceptually correct (i.e. it is perceived as correct by the human operator with respect to the motion of the simulated vehicle).

In any case, these objective evaluation methods have the potential to solve most of the problems of subjective evaluation: it is repeatable and reliable; it may provide direct information about false motion cues and can be used to automate the tuning of MCA. The only drawback is that it is not the natural way to assess perceptual fidelity and, for this case, the objective indicators should be designed with a subjective basis. There are many possible objective indicators. Therefore, its validity should be demonstrated first.

III. Objective Evaluation of Motion Cueing

Sinacori was one of the first authors to acknowledge the need for the objective evaluation of motion cueing. Although he did not provide a heuristic or mathematical function to assess motion cues, he proposed to classify motion cues in three categories (low fidelity, medium fidelity and high fidelity) depending of the gain and phase of the generated motion with respect to the expected one [34]. His proposal is supported on the fact that most MCA are based on washout filters that use high-pass filters to modify the motion signals in order to comply with the physical limitations of motion platforms. He analyzed several motion configurations and rated them from the opinions of a helicopter pilot, correlating the opinions of the pilot with the break frequency and the gain of the washout filter used to control the motion platform. Although the idea of a *motion fidelity scale* is remarkable, the experiment needed further validation with more pilots and more configurations. Schroeder confirmed Sinacori's findings with a more detailed experiment [37]. The boundaries proposed by Schroeder (refined from the ones obtained by Sinacori) between the three fidelity levels form the *Sinacori-Schroeder criterion* (Fig. 2).

This idea, with modifications, has been reproduced in several experiments [77]–[79]. Yet simple, this criterion constitutes the foundation of some subsequent objective evaluation systems. The advantage of this modulus–phase-distortion plot is that it is easy to understand and it is a transparent means of qualifying motion fidelity among visible bounds [80]. The problem with Sinacori's proposal is that not everything in motion cueing can be explained by motion gain and phase. Besides, not all MCA are based on washout filters. Thus, gain and phase are not easy to measure if multiple DOF are combined and non-sinusoidal signals are used. In addition, the frontier between the different fidelity regions is somehow arbitrary and it only offers three different levels in the assessment.

In search for the perfect motion cueing method, optimal control theory was applied in the 80s to the motion cueing problem, leading to the Optimal Control Algorithm [10], [81]. This algorithm is based on an estimation of the perception provided on the user by the motion signals. Therefore, it needs to evaluate the perceptual motion fidelity first, in order to create a transfer function for the MCA that optimizes this perception. To do so, it uses a heuristic function based on perception models. Different implicit evaluation systems provide different variations of this algorithm, which is still used [71], [82], [83].

This idea of using a heuristic function was also used in the Adaptive Washout Algorithm [9], [13], [84], [85], a variation of the Classical Washout Algorithm. In this case, however, the function is a cost function to penalize motion that is likely to violate the physical constraints of the motion platform, although it could also include measures of motion fidelity.

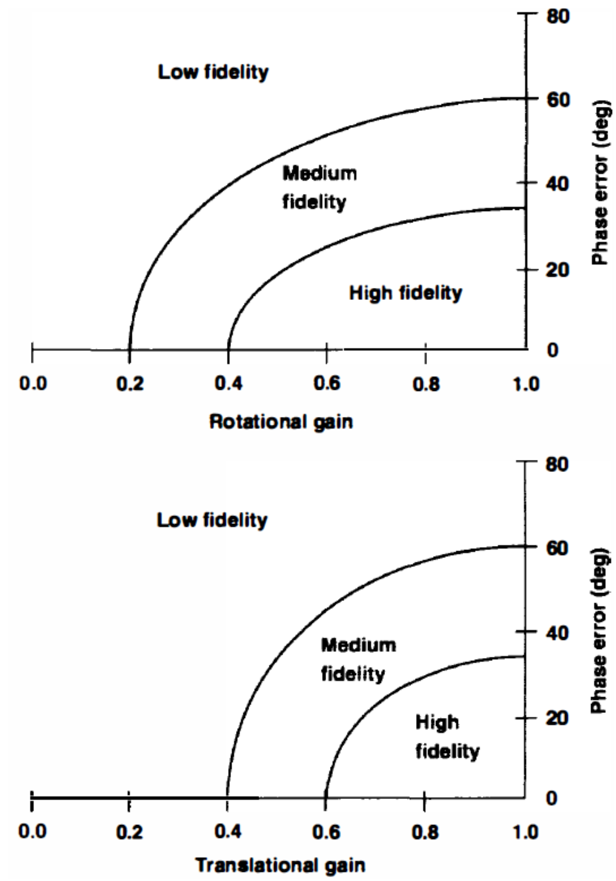

Fig. 2. Sinacori-Schroeder criterion and boundaries for the vertical axis (extracted from [49]).

Heuristic functions to evaluate motion cueing have been proposed or used also by other researchers [59], [73], [86]–[89], even for MCA that do not rely on washout filters [90]. Some are based on analyzing the motion signals or its perception [42], [60], [70], [73], [91], and some on pilot performance or control behavior [56], [57], [65], [74].

The problem of motion evaluation has always been strongly related with the problem of tuning MCA. Since these algorithms typically have several parameters that control what parts of the motion signals are eliminated to respect the physical constraints of the simulator, it is essential to find suitable values for these parameters. This is an optimization problem that needs a solid evaluation system to be solved – optimization methods are based on fitness functions that control the optimization process -. Grant studied the MCA tuning problem in the 1990s [92], [93]. He also strongly defended the need for subjective evaluation [69]. His position was based on the lack of well-developed complete perception models. In his opinion, although there were some interesting vestibular models to explain the operation of the vestibular system, the perception of motion relies in the combination of visual, vestibular and other cues. Given the lack of suitable models that account for all these factors simultaneously, a mathematical optimization based only on vestibular information is likely to fail. This, in our opinion, could explain why the Optimal Control Algorithm has not been adopted as a true optimal solution for the motion cueing problem.

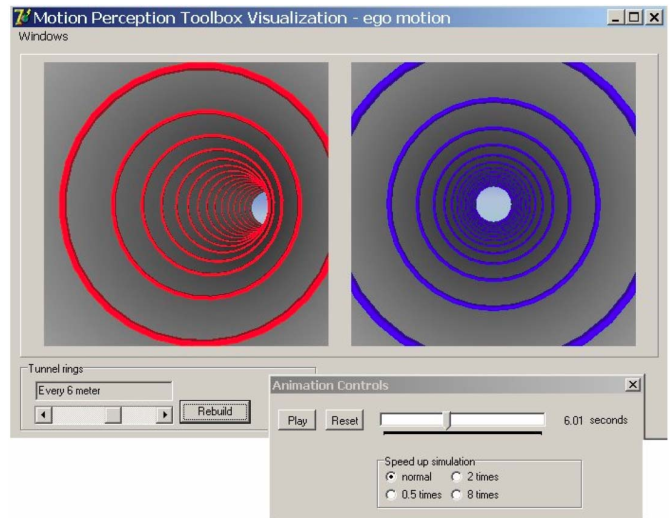

Fig. 3. MPT visualization (extracted from [99]).

Another approach to obtain measures of motion fidelity is the explicit use of perception models or pilot models (such as the ones described and compared in [94]), where the goal is to evaluate how motion could be perceived or utilized by humans for vehicle-based tasks. The most sophisticated efforts of this kind are probably the Hess criterion, proposed in 2001 and the Motion Perception Toolbox (MPT), proposed in 2006, although both methods have encountered limited success.

The Hess criterion [95] is based on the use of a structural pilot model developed with the goal of providing proprioceptive, vestibular, and visual cue modeling. Hess proposes a Handling Qualities Sensitivity Function (HQSF) to assess motion in vehicle simulators, which is based on previous works [96]–[98] but unlike these previous works includes also a measure of visual cues and focuses on multi-axis tasks. Unfortunately, the determination of this fidelity metric is complicated, since it introduces complex models (not only about the vehicle but also about human pilot behavior) and it is also difficult to interpret [80]. In addition, the method is inherently task-dependent since the pilot model is developed for a specific task.

MPT is a set of MATLAB functions that try to analyze how motion could be perceived by human operators [99]. It includes transfer functions to model visual and vestibular processing of motion information, as well as their interactions (this would somehow respond to Grant objections). Its main limitation is that it generates time histories of perception variables for both the vehicle and the simulator. It is, therefore, difficult to decide if those variables are similar enough, even though it also includes a visualization module that depicts the perceived self-motion by means of a virtual tunnel display (see Fig. 3). The perception models used in the MPT are based on consensus in the literature. However, the problem with perception models is that they are based on a variety of physiological and experimental data, and different values for their parameters, or even contradictory models have been proposed. As the designers of MPT acknowledge, the development of a universal motion perception system is not possible yet.

TABLE I
TEST MATRIX FOR THE OMCT – TESTS 1 TO 10 (ADAPTED FROM [113])

	Simulator Response Output					
Aircraft Signal Input	*Pitch*	*Roll*	*Yaw*	*Surge*	*Sway*	*Heave*
Pitch	1			2		
Roll		3			4	
Yaw			5			
Surge	7			6		
Sway		9			8	
Heave						10

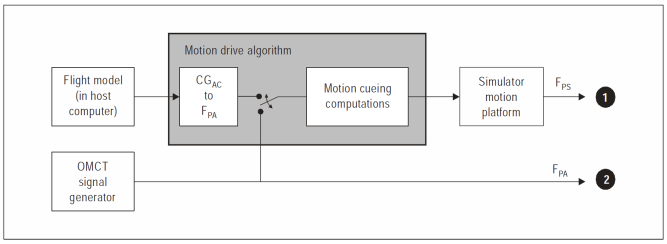

Fig. 4. OMCT working scheme (extracted from [52]).

In any case, several research works have used evaluation systems based on perception models [88], [100]–[102].

Grant's view remained for several years and few works proposed objective motion evaluation and objective MCA tuning methods during the following years. Nevertheless, the need for objective evaluation remained [4]. For this reason, researchers started to seriously consider an objective system to certify flight simulators. With this idea, ICAO pushed for a solution and its researchers designed and published the Objective Motion Cueing Test (OMCT) [43], [52], [80], [103] in 2006.

OMCT is based on the Sinacori's idea of analyzing gain and phase. Unlike Sinacori, who uses a single frequency, OMCT is applied by using a series of sinusoidal signals - from 0.1 rad/s (0.0159 Hz) to 15.849 rad/s (2.515 Hz) [52] - to each of the input channels of the MCA, in order to measure the output amplitude and phase distortion of each of these channels. The test includes both the hardware and the software elements (see Fig. 4). To account for several of the cross-channel interactions, a test matrix is defined that is used to measure both correct and possible false cues (see Table I). Since its design, several researchers have analyzed their simulators in terms of the sinusoidal-signal evaluation matrix of OMCT [75], [104], [105]. However, OMCT is a frequency-based method. Thus, it only really works for linear MCA. In addition, OMCT is a measurement procedure and it does not include a fidelity criterion to qualify the generated motion. For this reason, several researchers have recently dealt with the development of motion fidelity criteria to accompany the motion analysis of OMCT [56], [57], [105]–[109].

Although OMCT seems to be the first objective evaluation system with wide acceptance, it is a physical motion fidelity system. It is true, however, that if a simulator is physically correct (or very close to that) it should be perceptually correct. The correlation between physical fidelity and perceptual fidelity is expected to be high, and the measures over physical signals are clearly defined.

OMCT was designed for fixed-wing aircraft and was not initially conceived to be used to tune MCA. Nevertheless, the adaptation of OMCT to other vehicles (such as rotorcraft or cars) has already been proposed or studied [110], [111] and the use of OMCT to automatically tune MCA can also be explored [112], although it is important to remember that OMCT does not try to measure or account for perception and its use for tuning MCA should be limited if perceptual fidelity is the goal of this tuning.

In any case, OMCT is not the only objective method that has been proposed. In fact, in recent years several researchers have proposed different methods to evaluate MCA objectively with the purpose of using these assessment methods to improve the tuning process. Le Bouthillier [61] and Thöndel [114] seem to be the first researchers to have proposed the use of objective evaluation systems alongside optimization algorithms. Neither of these works details the process. Nevertheless, many other authors have proposed more detailed solutions based on this idea. Roza [104] adapts OMCT to provide a single fidelity measure and tune a Classical Washout. De Ridder [112] follows a similar approach, using the simplex method, which does not seem the most appropriate optimization method for this problem (it is prone to get stuck at local minima). Asadi [102], [115] uses a Genetic Algorithm (GA) to tune MCA based on a heuristic function for the objective perceptual evaluation of motion. Casas [91] also provides a GA for tuning a Classical Washout, although with heuristic mathematical indicators correlated with subjective perception but not based on perceptual models. The indicators try to measure signal correlation, scaling and delay with respect to the expected motion. Slightly modified versions of these indicators are later used in a recent work [116] in which objective motion metrics are used to compare two prediction strategies for a motion cueing algorithm based on model predictive control (MPC) [15]. Both Asadi and Casas propose also other soft computing approaches, such as Particle Swarm Optimization (PSO), to solve the tuning problem with objective evaluations [72], [87], [117]. Bilimoria [70] provides a similar approach but with a heuristic function that is not subjective-based. His major contribution is perhaps the transformation of the Sinacori diagram to the washout filter parameter space. Reardon [59] compares three tuning methods, and the one based on a quantitative (objective) evaluation approach provides the worst ratings in the HQR scale. Jones also proposes an objective evaluation method using different heuristic fitness functions that are used to tune a rotorcraft simulator [42], [60] with promising results and some correlation between the objective and subjective measures in some tasks, although he acknowledges that more work is necessary to determine whether the method is suitable for the objective tuning of motion platforms. The fitness functions used in these works are improved later by Jones in [89] providing more balance in the motion cueing characteristics during the tuning procedure, which is performed by means of a GA. Mohammadi [101] tunes the MPC algorithm using also a GA and an objective fitness function. However, this work is hard to reproduce since several of the variables (input signals, vehicle, possible motion hardware, etc.) of the experiment are not clearly specified. In addition, the authors compare the automatic tuning against a manual tuning performed by them, a comparison that does not provide much value. Another use of a GA for the MPC algorithm can be found in [118]. This approach, however, is interactive and a human score is included in the cost function, which is interesting because the user is part of the optimization process.

As can be seen, different optimization methods can be used to tune an MCA, and although the optimization method is important, it is not as important as the cost function used to assess motion. The general conclusion of this body of research is that a perfect solution for tuning an MCA still does not exist because of the inaccuracy of the objective metric itself, but the field seems to be slowly advancing towards a self-tuning of these algorithms. Indeed, although some of these research works face several practical problems and provide restricted success, the amount of research about the optimization of MCA with objective evaluation methods in the last seven years, suggests that the area is getting closer to Sinacori's vision of assessing motion cueing through automatic methods.

IV. Discussion

Although many objective evaluation systems have been proposed, none can be still considered the absolute universal solution. OMCT seems a promising method, since it is backed by a strong and professional community. However, it does not include a proper link with the subjective perception and it is difficult to interpret and translate frequency test information into a general criterion that could be related to the tasks [42]. Thus, it can only be considered a method for assessing physical motion fidelity. In any case, it could be pointed as the reference method for the evaluation of physical motion fidelity in aircraft simulators. The extension to other types of vehicles and other MCA different from the Classical Washout should still be further investigated.

Behavioral and functional motion fidelity are typically measured with customized methods, depending on the simulator tasks and goals. Thus, no reference general solution can be provided. In addition, these evaluation methods are often easy to design and implement, because in some cases, the simulator data (time, virtual vehicle position/orientation, etc.) is directly used for the behavioral or functional evaluation, and no extra effort is needed.

Regarding objective perceptual motion fidelity, none of the proposed evaluation methods has still met sufficient success. Methods based on perception models face inconsistency problems since not enough information exists about how to model the human perception system (some perception mechanisms are not completely known yet), whereas those methods based on heuristic mathematical indicators do not completely account for motion perception.

In this regard, the existing motion fidelity criteria seem to be either too simple or too complicated [80]. Simple methods often neglect that similar sized cueing errors may result in different perceptions. As pointed out in [55], "the perceived motion coherence or incoherence does not only depend on the absolute differences between motion cues, but also on the integration process of these motion cues in the human brain. For example, scaling errors are often perceived as more coherent than similar sized false cues". In addition, false cues seem to be rated more incoherent than missing cues, a situation that most objective methods do not address well.

Methods that are too complicated, however, may depend on too many parameters/variables, such as [101], or may be too difficult to set-up and interpret, such as the Hess criterion and in some cases may even miss the point of finding a criterion to decide if motion is acceptable or not.

Therefore, many unknowns remain undisclosed and researchers should focus on this promising but difficult area. In addition, even if a solid evaluation method were found, the big question, however, is where to draw the boundaries for acceptable motion cueing. Thus, a substantial amount of research is still left and objective motion fidelity assessment can be identified as the most important research body that vehicle simulators should face in the following years.

After analyzing the characteristics of the existing assessment methods and in order to provide future research guidelines for this complex topic, the authors propose a series of properties/features that an ideal evaluation method for assessing perceptual motion fidelity should include:

-***validity***: the instances that humans consider good solutions, should obtain high scores.

-***acceptability***: the instances that obtain high scores should be accepted by human users as good solutions (it is the reciprocal of the latter feature). As there is no ground truth to compare with, these two features are the most difficult to achieve. The goal is of course to represent the human perception (perceptual fidelity), but the only unquestionable ground truth is physical fidelity. If physical fidelity is achieved, perceptual fidelity should follow. However, physical fidelity is generally unattainable, and compromises should be made to obtain the highest level of perceptual fidelity, purposely ignoring the pursue of physical fidelity. One problem for accomplishing this is the avoidance of false cues. Since false cues are very hard to define mathematically, it is extremely hard to detect and avoid them.

-***repeatability***: it must offer the same values when the same experiment is repeated over time. If subjectively done, there can be intra-individual variance (low reliability) and inter-individual variance (high variability).

-***applicability***: it must be feasible and easy to apply to the extent possible. In this regard, it is best if the measure can be obtained automatically and with little or no human intervention.

-***availability***: it should be available 24 hours, 7 days a week.

-***performance***: it should be fast to calculate.

-***universality***: it should be applicable to all MCA, motion platforms types, users, vehicle types, vehicle dynamics, models and systems in general.

-***completeness***: it should include all the elements in the simulation loop (not only the motion base or only the MCA). This may even include the vehicle operator or at least a way to introduce their reactions.

-***ease of interpretation***: the resulting fidelity measure should be easy to interpret, even for non-experts in the field.

-***no interference***: the assessment procedure should not interfere in the normal use of the vehicle simulator.

-***sortability*** (i.e., usable for tuning): the measurements should be presented in a way that they can be sorted from worst to best, so that the evaluation system could be used in optimization algorithms and allow automatic tuning of MCA. This can be achieved if the evaluation provides a single value, but other options can be applied if the resulting evaluation method does not offer a single measure but can be summarized in one value.

It is evident that subjective evaluation methods cannot provide all these features. Certainly not repeatability, which would be only provided by objective methods. However, it is also hard that availability, performance and even sortability be fulfilled with subjective approaches.

Some of the works reviewed in this paper fulfill most of the requirements but none is able to provide all of them. For instance, the method proposed in [91] accomplishes all these goals, except for the second goal, which is not completely fulfilled, and the first one, which is only partially accomplished; OMCT lacks these two features, lacks ease of interpretation and also lacks universality since it is designed for washout-based MCA and aircraft; MPT [99] does not comply with the last requirement and possibly with the second one since not everybody perceives motion in the same way; the Hess criterion [95] lacks, at least, applicability and acceptability; the methods proposed in [65], [88], [110] do not comply with the sortability requirement and are not used for tuning the MCA; the assessment method used in the tuning procedure utilized by Roza and de Ridder [104], [112] lacks completeness because they use a kinematic model of the motion platform and do not evaluate its dynamics (they do that to "assess only the MDA part of the FSTD"), but provide sortability upon OMCT, a remarkable contribution because OMCT does not originally provide a single value; the works of Asadi and Mohammadi [101], [102], [115] lack complete applicability since the evaluation function has many parameters that should be tuned first; the methods proposed by Cleij and van Leeuwen [55], [58], [66], [67] lack repeatability and no interference, among other problems, because they interfere in the normal use of the vehicle simulator and are, thus, only applicable for passive simulation (when the user does not operate the vehicle); the methods that use simulated motion platforms [73], [87], [88], [91], [112] provide complete availability. On the contrary, those methods using the real hardware may not be always available.

Table II summarizes the main works reviewed in this paper. It is important to highlight that many of these works use several evaluation methods and some of the analyzed features cannot be specified for all of them. For this reason, blank cells represent missing or not applicable information. As can be seen, there are works dealing with all sorts of vehicles, simulators and algorithms, but the classical washout and the 6-DOF hexapod are the most common setup. In addition,

TABLE II

SUMMARY OF THE MOST IMPORTANT WORKS REVIEWED IN THIS PAPER REGARDING MOTION EVALUATION

Ref.	**[34]**	**[37]**	**[73]**	**[95]**
Year	**1977**	**1996**	**1998**	**2001**
First Author	**Sinacori**	**Schroeder**	**Pouliot**	**Hess**
Vehicle Type	Rotorcraft	Rotorcraft	Fixed-wing aircraft	Rotorcraft
Vehicle Tested	Helicopter	Helicopter model	Boeing 747	A model of a BO-105
Simulator	FSAA (6-DOF)	VMS (6-DOF)	6-DOF, 3-DOF	Two models: a large (similar to VMS) and a small motion system (6-DOF)
MCA	FSAA Ames Logic (a washout algorithm)	A washout algorithm	Modified CW	
Automatic Tuning	No	No	No	No
Evaluation Type	HMIPCB, OSR	GPCB, OSR	HMIM	HQSF
Ref.	**[43, 80, 103]**	**[99]**	**[65]**	**[61]**
Year	**2006-2007**	**2006**	**2011**	**2012**
First Author	**Advani**	**Wentink**	**Cossalter**	**Le Bouthillier**
Vehicle Type	Fixed-wing aircraft	Any (but focused on aircraft)	Motorcycle	Fixed-wing aircraft
Vehicle Tested		Fighter	Aprilia Mana 850	Cessna 172
Simulator		Desdemona (6-DOF)	4-DOF	3-DOF
MCA	CW	SW	A customized washout	CW
Automatic Tuning	No	No	No	Apparently yes (based on an Inertial Measurement Unit)
Evaluation Type	OMCT (proposed)	MPT	HMIPCB, SQ	OSR
Ref.	**[104]**	**[115]**	**[70]**	**[55]**
Year	**2013**	**2015**	**2015**	**2015**
First Author	**Roza**	**Asadi**	**Bilimoria**	**Cleij**
Vehicle Type	Fixed-wing aircraft	Car	Spacecraft	Car
Vehicle Tested	F-100	A theoretical driving scenario	Space shuttle	Unspecified CarSim vehicle model
Simulator	GRACE (6-DOF)		VMS (6-DOF)	CMS (8-DOF)
MCA	CW, modified CW	CW, non-linear CW	VMS-MCA	CW
Automatic Tuning	Yes	Yes	Yes	No
Evaluation Type	OMCT	HMIPM	HMIM	CSR, OSR
Ref.	**[112]**	**[59]**	**[54]**	**[74]**
Year	**2015**	**2015**	**2015**	**2015**
First Author	**de Ridder**	**Reardon**	**Venrooij**	**Zaal**
Vehicle Type	Fixed-wing aircraft	Rotorcraft	Car	Fixed-wing aircraft
Vehicle Tested	Fokker 100	UH-60A Black Hawk	Mid-size Sedan with a 160 kW engine	Commercial transport aircraft
Simulator	6-DOF	VMS (6-DOF)	CMS (8-DOF)	VMS (6-DOF)
MCA	CW, NLR MCA (similar to CW)	VMS-MCA	CW, PBMC	VMS-MCA
Automatic Tuning	Yes	Apparently yes	Yes, but not detailed	Yes

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TABLE II
(*Continued.*) SUMMARY OF THE MOST IMPORTANT WORKS REVIEWED IN THIS PAPER REGARDING MOTION EVALUATION

Evaluation Type	OMCT	HMIM, OSR, SQ	HMIPM, OSR, SQ	OMCT, HMIPCB, OSR
Ref.	**[91]**	**[88]**	**[101]**	**[89]**
Year	**2016**	**2017**	**2018**	**2018**
First Author	**Casas**	**Onur**	**Mohammadi**	**Jones**
Vehicle Type	Car	Rotorcraft	Car	Rotorcraft
Vehicle Tested	Formula 3, Formula 1			Eurocopter EC135
Simulator	6-DOF, 3-DOF	A set of hypothetical helicopter motions		AVES (6-DOF)
MCA	CW	CW	MPC	A derivative of CW
Automatic Tuning	Yes	No	Yes	Yes
Evaluation Type	HMIM	HMIPM, HMIPCB	HMIPM	HMIM

Legend (Simulator):
FSAA = Flight Simulator for Advanced Aircraft @ NASA Ames, CA, USA
GRACE = Generic Research Aircraft Cockpit Environment @ National Aerospace Laboratory (NLR), The Netherlands
***VMS* = Vertical Motion Simulator @ NASA Ames, CA, USA**
CMS = CyberMotion Simulator @ Max Plank Institute (MPI), Germany
AVES = Air Vehicle Simulator @ German Aerospace Center (DLR), Germany

Legend (MCA):
CW = Classical Washout
SW = Spherical Washout
MPC = Model-based Predictive Control
PBMC = Perception-based Motion Cueing

Legend (Evaluation):
OMCT = Objective Motion Cueing Test
HMIM = Heuristic Mathematical Indicators based on Motion
HMIPM Heuristic Mathematical Indicators based on Perception Models
HMIPCB Heuristic Mathematical Indicators based on Pilot Control Behavior
HQSF = Handling Qualities Sensitivity Function
MPT = Motion Perception Toolbox
CSR = Continuous Subjective Rating
OSR = Offline Subjective Rating
SQ = Subjective Questionnaires
GPCB = Graphs based on Pilot Control Behavior

whereas earlier works do not treat the tuning problem, it is noticeable the tendency to use objective evaluation methods also to tune MCA, in almost all recent works (since 2012).

V. CONCLUSION AND FUTURE RESEARCH AREAS

The problem of identifying appropriate mechanisms for the assessment of motion cues in vehicle simulators is not new. However, researchers and engineers have shown a renewed interest in recent years in finding objective methods to evaluate motion cueing, a trend that has motivated this review work. Fig. 5 shows a timeline of the most important research works about motion cueing and its evaluation. These and other research works have been framed and classified in this review, which proposes also a series of features that an ideal evaluation method for assessing perceptual motion fidelity should include.

From the literature reviewed, only OMCT stands out as a method with academic and industrial acceptance, since it has been applied by several authors to several case studies and it is part of the "Manual of Criteria for the Qualification of Flight Simulation Training Devices" of the ICAO. Nevertheless, OMCT can only be considered as a method to evaluate physical motion fidelity, not perceptual fidelity, it was designed for 6-DOF devices and seems to be oriented to the Classical Washout [104], as it assumes linearity. This is a logical decision, since this setup is the current standard in aircraft simulation. Future research should focus on extending or adapting this objective motion test to other vehicle types, as in [119] or [111] - which suggests that OMCT needs to

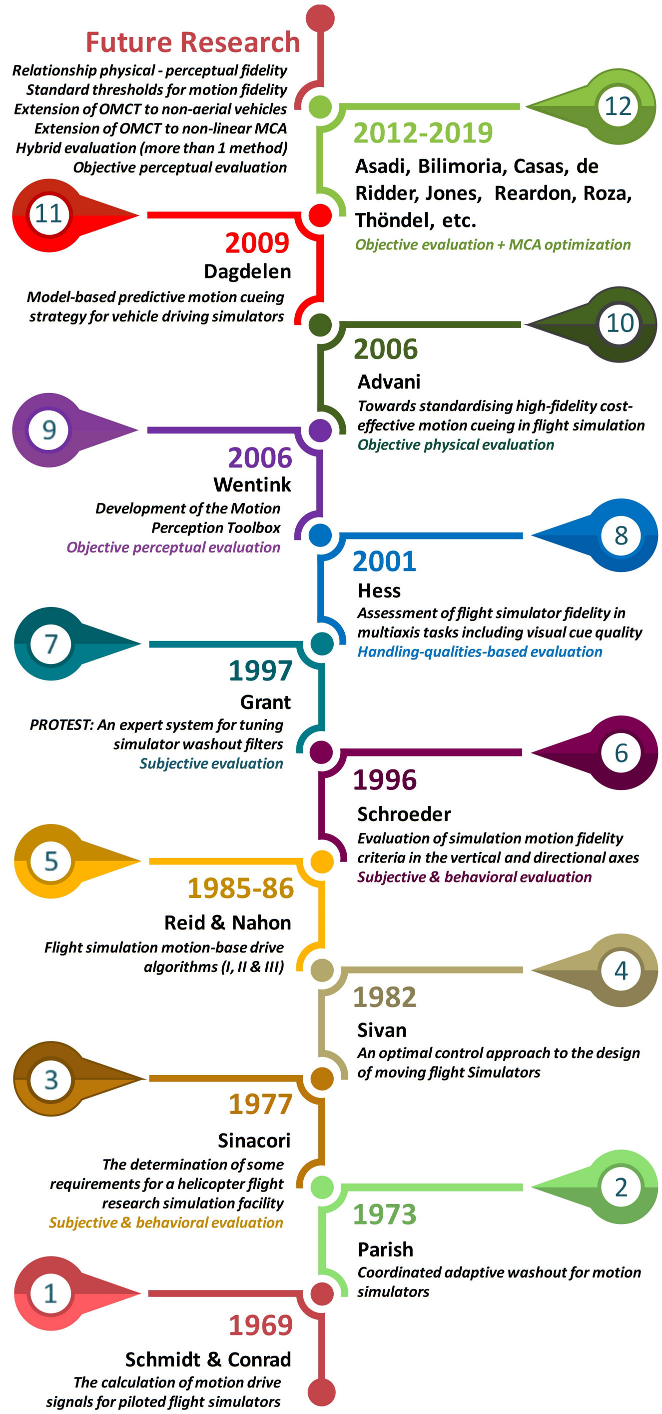

Fig. 5. Timeline of the most important works about motion cueing and its evaluation.

be improved to be used for rotorcraft, to non-linear MCA and to limited-DOF devices used in low-cost vehicle simulators. Alternatives to the OMCT, such as the recently proposed Eigenmode Distortion (EMD) analysis [120], [121], which unlike OMCT accounts for perception and includes the vehicle dynamics, are also a promising research direction.

Research should also try to quantify the amount of physical fidelity lost with limited-DOF solutions. The relationship between objective physical fidelity and perceptual fidelity is also worth investigating and represents a different way to reach objective perceptual motion fidelity. It would be also very important to define standard thresholds for motion fidelity in order to define a fidelity criterion based on OMCT [74].

Regarding perceptual motion fidelity, many researchers have started recently to apply heuristic mathematical indicators to create objective assessment methods for the evaluation of perceptual motion fidelity. The amount of research done in this area suggests that objective perceptual motion evaluation is a promising approach. Although these methods usually allow applying optimization methods and thus optimally tune MCA upon these objective measures, the success of the methodology has not been completely demonstrated with respect to human subjective opinions. Therefore, more work is necessary in this area, although some promising results have already been achieved. The problem of finding the best strategy to perform this optimization process is also worth studying [72], [87].

Some authors, such as Grant, denied many years ago, the feasibility of using an objective perceptual motion evaluation system. Others, such as Sinacori, foresaw a future in which objective indicators could be used to perceptually appraise motion. In our opinion, in the following years, research should focus on identifying a way to assess motion in a perceptually-based objective manner, or at least to introduce objective measures in the process. In fact, Sinacori advised to "create and use a motion fidelity that uses both objective and subjective data". Although this recommendation is from 1977, it seems natural that subjective and objective approaches be combined, or at least that objective methods be partially or completely based on a subjective validation, so that their perceptual fidelity can be demonstrated.

It is possible, as Roza concludes [104] that "one size doesn't fit all and that a combined method for the assessment of motion fidelity on simulators will ultimately prove to be the solution". This combined method could include objective assessments, task-related assessments, and a structured subjective rating. In any case, the problem is not solved yet, although promising results have been achieved in the last ten years - thanks to a renewed interest in the motion question -, compared with the relatively slow progress of the past. The authors believe this comprehensive review work could serve to foster and guide future research works in this field.

References

[1] A. D. Judy, "A study of flight simulation training time, aircraft training time, and pilot competence as measured by the naval standard score," Ph.D. dissertation, College Educ., Southeastern Univ., Lakeland, FL, USA, 2018.

[2] S. Casas, C. Portalés, I. García-Pereira, and M. Fernández, "On a first evaluation of romot—A robotic 3D movie theatre—For driving safety awareness," *Multimodal Technol. Interact.*, vol. 1, no. 2, pp. 1–13, 2017.

[3] J. Schroeder and P. Grant, "Pilot behavioral observations in motion flight simulation," in *Proc. AIAA Modeling Simulation Technol. Conf.*, Jun. 2012, p. 8353.

[4] R. Hosman, "Are criteria for motion cueing and time delays possible?" in *Proc. Modeling Simulation Technol. Conf. Exhibit*, Portland, OR, USA, Aug. 2012, p. 4028.

[5] S. Casas, C. Portalés, and M. Fernández, "To move or not to move?: The challenge of including believable self-motion cues in virtual reality applications–understanding motion cueing generation in virtual reality," in *Cases on Immersive Virtual Reality Techniques*. Harrisburg, PA, USA: IGI Global, 2019, pp. 124–144.

[6] S. F. Schmidt and B. Conrad, *The Calculation of Motion Drive Signals for Piloted Flight Simulators*. Palo Alto, CA, USA: NASA, 1969.

[7] S. F. Schmidt and B. Conrad, *Motion Drive Signals for Piloted Flight Simulators*. Palo Alto, CA, USA: NASA, 1970.

[8] B. Conrad and S. F. Schmidt, "A study of techniques for calculating motion drive signals for flight simulators," NASA Ames Res. Center, Moffett Field, CA, USA, Tech. Rep. 71-28, 1971.

[9] R. V. Parrish, J. E. Dieudonne, R. L. Bowles, and D. J. Martin, "Coordinated adaptive washout for motion simulators," *J. Aircr.*, vol. 12, no. 1, pp. 44–50, Jan. 1975.

[10] R. Sivan, J. Ish-Shalom, and J.-K. Huang, "An optimal control approach to the design of moving flight simulators," *IEEE Trans. Syst., Man, Cybern.*, vol. SMC-12, no. 6, pp. 818–827, Nov. 1982.

[11] L. D. Reid and M. A. Nahon, "Response of airline pilots to variations in flight simulator motion algorithms," *J. Aircr.*, vol. 25, no. 7, pp. 639–646, Jul. 1988.

[12] M. A. Nahon and L. D. Reid, "Simulator motion-drive algorithms—A designer's perspective," *J. Guid., Control, Dyn.*, vol. 13, no. 2, pp. 356–362, Mar. 1990.

[13] M. A. Nahon, L. D. Reid, and J. Kirdeikis, "Adaptive simulator motion software with supervisory control," *J. Guid., Control, Dyn.*, vol. 15, no. 2, pp. 376–383, Mar. 1992.

[14] M. Wentink, W. Bles, R. Hosman, and M. Mayrhofer, "Design & evaluation of spherical washout algorithm for Desdemona simula," in *Proc. AIAA Modeling Simulation Technol. Conf. Exhibit*, San Francisco, CA, USA, 2005, p. 6501.

[15] M. Dagdelen, G. Reymond, A. Kemeny, M. Bordier, and N. Maïzi, "Model-based predictive motion cueing strategy for vehicle driving simulators," *Control Eng. Pract.*, vol. 17, no. 9, pp. 995–1003, Sep. 2009.

[16] M. Bruschetta, F. Maran, and A. Beghi, "A fast implementation of MPC-based motion cueing algorithms for mid-size road vehicle motion simulators," *Vehicle Syst. Dyn.*, vol. 55, no. 6, pp. 802–826, Feb. 2017.

[17] M. Bruschetta, C. Cenedese, A. Beghi, and F. Maran, "A motion cueing algorithm with look-ahead and driver characterization: Application to vertical car dynamics," *IEEE Trans. Human-Mach. Syst.*, vol. 48, no. 1, pp. 6–16, Feb. 2018.

[18] 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 Trans. Intell. Vehicles*, vol. 4, no. 2, pp. 298–308, Jun. 2019.

[19] A. Sharma, M. S. Ikbal, and M. Zoppi, "Acausal approach to motion cueing," *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 1013–1020, Apr. 2019.

[20] L. D. Reid and M. A. Nahon, "Flight simulation motion-base drive algorithms: Part 1. Developing and testing equations," Univ. Toronto, Toronto, ON, Canada, UTIAS Rep. 296, 1985.

[21] L. D. Reid and M. A. Nahon, "Flight simulation motion-base drive algorithms: Part 2—Selecting the system parameters," Univ. Toronto, Toronto, ON, Canada, UTIAS Rep. 307, 1986.

[22] L. D. Reid and M. A. Nahon, "Flight simulation motion-base drive algorithms: Part 3—Pilot evaluations," Univ. Toronto, Toronto, ON, Canada, UTIAS Rep. 319, 1986.

[23] D. Stewart, "A platform with six degrees of freedom," *Proc. Inst. Mech. Eng.*, vol. 180, no. 1, pp. 371–386, 1965.

[24] P. R. MacNeilage, M. S. Banks, D. R. Berger, and H. H. Bülthoff, "A Bayesian model of the disambiguation of gravitoinertial force by visual cues," *Exp. Brain Res.*, vol. 179, no. 2, pp. 263–290, Nov. 2007.

[25] E. L. Groen and W. Bles, "How to use body tilt for the simulation of linear self motion," *J. Vestibular Res.*, vol. 14, no. 5, pp. 375–385, 2004.

[26] J. Laurens and J. Droulez, "Bayesian processing of vestibular information," *Biol. Cybern.*, vol. 96, no. 4, p. 405, Mar. 2007.

[27] D. R. Berger, J. Schulte-Pelkum, and H. H. Bülthoff, "Simulating believable forward accelerations on a Stewart motion platform," *ACM Trans. Appl. Perception*, vol. 7, no. 1, pp. 1–27, Jan. 2010.

[28] J. J. Slob, "State-of-the-art driving simulators, a literature survey," Eindhoven Univ. Technol., Eindhoven, The Netherlands, DCT Rep. 107, 2008.

[29] K. Stahl, G. Abdulsamad, K.-D. Leimbach, and Y. A. Vershinin, "State of the art and simulation of motion cueing algorithms for a six degree of freedom driving simulator," in *Proc. 17th Int. IEEE Conf. Intell. Transp. Syst. (ITSC)*, Qingdao, China, Oct. 2014, pp. 537–541.

[30] N. J. I. Garrett and M. C. Best, "Driving simulator motion cueing algorithms—A survey of the state of the art," in *Proc. 10th Int. Symp. Adv. Vehicle Control (AVEC)*, Loughborough, U.K., 2010, pp. 183–188.

[31] M. Fischer, "A survey of state-of-the-art motion platform technology and motion cueing algorithms," presented at the 2nd Motion Simulator Conf., Braunschweig, Germany, Sep. 2007.

[32] S. Casas, R. Olanda, and N. Dey, "Motion cueing algorithms: A review: Algorithms, evaluation and tuning," *Int. J. Virtual Augmented Reality*, vol. 1, no. 1, pp. 90–106, Jan. 2017.

[33] K. J. Szalai, "Motion cue and simulation fidelity aspects of the validation of a general purpose airborne simulator," NASA, Washington, DC, USA, Tech. Rep. TN D-6432, 1971.

[34] J. B. Sinacori, "The determination of some requirements for a helicopter flight research simulation facility," NASA, Moffet Field, CA, USA, Tech. Rep. NASA-CR-152066, TR-1097-1, 1977, vol. 7805.

[35] G. E. Cooper and R. P. Harper, Jr., "The use of pilot rating in the evaluation of aircraft handling qualities," Advisory Group Aerosp. Res. Develop. Neuilly-Sur-Seine, Paris, France, Tech. Rep. NASA TN D-5153, 1969.

[36] G. E. Cooper, "Understanding and interpreting pilot opinion," *Aeronaut. Eng. Rev.*, vol. 16, no. 3, pp. 47–52, Mar. 1957.

[37] J. A. Schroeder, "Evaluation of simulation motion fidelity criteria in the vertical and directional axes," *J. Amer. Helicopter Soc.*, vol. 41, no. 2, pp. 44–57, Apr. 1996.

[38] G. Reymond and A. Kemeny, "Motion cueing in the Renault driving simulator," *Vehicle Syst. Dyn., Int. J. Vehicle Mech. Mobility*, vol. 34, no. 4, pp. 249–259, Oct. 2000.

[39] D. M. Pool, "Objective evaluation of flight simulator motion cueing fidelity through a cybernetic approach," Ph.D. dissertation, Control Simul., Delft Univ., Delft, The Netherlands, 2012.

[40] D. Liu, N. D. Macchiarella, and D. A. Vincenzi, "Simulation fidelity," in *Proc. Hum. Factors Simulation Training*, 2009, pp. 61–73.

[41] P. Perfect, E. Timson, M. D. White, G. D. Padfield, R. Erdos, and A. W. Gubbels, "A rating scale for the subjective assessment of simulation fidelity," *Aeronaut. J.*, vol. 118, no. 1206, pp. 953–974, Jan. 2014.

[42] M. Jones, "Motion cueing optimisation applied to rotorcraft flight simulation," *CEAS Aeronaut. J.*, vol. 8, no. 3, pp. 523–539, Jul. 2017.

[43] S. Advani, R. Hosman, and M. Potter, "Objective motion fidelity qualification in flight training simulators," in *Proc. AIAA Modeling Simulation Technol. Conf. Exhibit*, Hilton Head, SC, USA, 2007, p. 6802.

[44] L. R. Young, "Some effects of motion cues on manual tracking," *J. Spacecraft Rockets*, vol. 4, no. 10, pp. 1300–1303, 1967.

[45] B. Waters, P. Grunzke, and P. Irish, "Preliminary investigation of motion, visual and G-seat effects in the advanced simulator for undergraduate pilot training/ASUPT," in *Proc. Amer. Inst. Aeronaut. Astronaut., Vis. Motion Simulation Conf.*, Dayton, OH, USA, 1976, p. 1976.

[46] T. H. Gray and R. R. Fuller, "Effects of simulator training and platform motion on air-to-surface weapons delivery training," Air Force Hum. Resour. Lab, Brooks AFB, TX, USA, Tech. Rep. AFHRL-TR-77-29, 1977.

[47] J. Burki-Cohen, T. H. Go, and T. Longridge, "Flight simulator fidelity considerations for total air line pilot training and evaluation," in *Proc. AIAA Modeling Simulation Technol. Conf.*, 2001, pp. 1–9, Paper AIAA-2001-4425.

[48] J. Burki-Cohen, A. Sparko, and T. Go, "Training value of a fixed-base flight simulator with a dynamic seat," in *Proc. AIAA Modeling Simulation Technol. Conf. Exhibit*, 2007, p. 6564.

[49] J. A. Schroeder, *Helicopter Flight Simulation Motion Platform Requirements*. Moffett Field, CA, USA: NASA, 1999.

[50] FAA. (2019). *National Simulator Program (NSP)*. Accessed: Dec. 1, 2019. [Online]. Available: https://www.faa.gov/about/initiatives/nsp/

[51] *Federal Aviation Administration. 14 CFR Part 60. NSP Consolidated Version*, FAA, Washington, DC, USA, 2008, vol. 73.

[52] *Manual of Criteria for the Qualification of Flight Simulation Training Devices. vol. I, - Aeroplanes*, ICAO, Montreal, ON, Canada, 3rd ed., 2009.

[53] D. N. Veritas, Ed. (2011). Standard for Certification Maritime Simulator Systems No. 2.14. DNV. [Online]. Available: https://rules.dnvgl.com/docs/pdf/DNV/stdcert/2011-01/Standard2-14.pdf

[54] J. Venrooij *et al.*, "Perception-based motion cueing: Validation in driving simulation," in *Proc. Driving Simulation Conf.*, 2015, pp. 153–161.

[55] D. Cleij, J. Venrooij, P. Pretto, D. Pool, M. Mulder, and H. Bülthoff, "Continuous rating of perceived visual-inertial motion incoherence during driving simulation," in *Proc. DSC Eur., Driving Simulation Conf. Exhib.*, 2015, pp. 191–198.

[56] P. M. T. Zaal, J. A. Schroeder, and W. W. Chung, "Objective motion cueing criteria investigation based on three flight tasks," *Aeronaut. J.*, vol. 121, no. 1236, pp. 163–190, Jan. 2017.

[57] P. Zaal, J. A. Schroeder, and W. W. Chung, "Refinement of objective motion cueing criteria based on three flight tasks," in *Proc. AIAA Modeling Simulation Technol. Conf.*, Jan. 2017, p. 1081.

[58] D. Cleij *et al.*, "Comparison between filter-and optimization-based motion cueing algorithms for driving simulation," *Transp. Res. F, Traffic Psychol. Behav.*, vol. 61, pp. 53–68, Feb. 2017.

[59] S. Reardon and S. Beard, "Evaluation of motion tuning methods on the vertical motion simulator," in *Proc. 71st Amer. Helicopter Soc. Annu. Forum*, 2015, pp. 5–7.

[60] M. Jones, "An objective method to determine the fidelity of rotorcraft motion platforms," in *Proc. AIAA Modeling Simulation Technol. Conf.*, Jan. 2017, p. 1082.

[61] J. Le Bouthillier, Y. Liang, and P. Allard, "Pilot evaluation of a low cost 3 degree-of-freedom flight simulator driven by the classical washout filter algorithm," *Online J. Comput. Sci. Technol.*, vol. 2, no. 1, pp. 102–106, 2012.

[62] S. Casas, I. Coma, J. V. Riera, and M. Fernández, "Motion-cuing algorithms: Characterization of users' perception," *Hum. Factors, J. Hum. Factors Ergonom. Soc.*, vol. 57, no. 1, pp. 144–162, 2015.

[63] M. Bruenger-Koch, S. Briest, and M. Vollrath, "Do you feel the difference? A motion assessment study," presented at the Driving Simulation Conf. Asia–Pacific, Tsukuba, Japan, 2006.

[64] M. Bruenger-Koch, "Motion parameter tuning and evaluation for the DLR automotive simulator," in *Proc. Driving Simulation Conf. North Amer. (DSC-NA)*, Orlando, FL, USA, 2005, pp. 262–270.

[65] V. Cossalter, R. Lot, M. Massaro, and R. Sartori, "Development and validation of an advanced motorcycle riding simulator," *Proc. Inst. Mech. Eng. D, J. Automobile Eng.*, vol. 225, no. 6, pp. 705–720, Feb. 2011.

[66] D. Cleij, J. Venrooij, P. Pretto, D. M. Pool, M. Mulder, and H. H. Bülthoff, "Continuous subjective rating of perceived motion incongruence during driving simulation," *IEEE Trans. Human-Mach. Syst.*, vol. 48, no. 1, pp. 17–29, Sep. 2018.

[67] T. D. van Leeuwen, D. Cleij, D. M. Pool, M. Mulder, and H. H. Bülthoff, "Time-varying perceived motion mismatch due to motion scaling in curve driving simulation," *Transp. Res. F, Traffic Psychol. Behav.*, vol. 61, pp. 84–92, Feb. 2018.

[68] F. Ellensohn, J. Venrooij, M. Schwienbacher, and D. Rixen, "Experimental evaluation of an optimization-based motion cueing algorithm," *Transp. Res. F, Traffic Psychol. Behav.*, vol. 62, pp. 115–125, Apr. 2019.

[69] P. R. Grant and L. D. Reid, "Motion washout filter tuning: Rules and requirements," *J. Aircr.*, vol. 34, no. 2, pp. 145–151, Mar. 1997.

[70] K. D. Bilimoria and S. Reardon, "Motion parameter selection for flight simulators," in *Proc. AIAA Modeling Simulation Technol. Conf.*, Jun. 2015, p. 2946.

[71] 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 Trans. Syst., Man, Cybern. Syst.*, vol. 47, no. 2, pp. 238–254, Feb. 2017.

[72] S. Casas, C. Portalés, P. Morillo, and M. Fernández, "A particle swarm approach for tuning washout algorithms in vehicle simulators," *Appl. Soft Comput.*, vol. 68, pp. 125–135, Jul. 2018.

[73] N. A. Pouliot, C. M. Gosselin, and M. A. Nahon, "Motion simulation capabilities of three-degree-of-freedom flight simulators," *J. Aircr.*, vol. 35, no. 1, pp. 9–17, Jan. 1998.

[74] P. M. T. Zaal, J. A. Schroeder, and W. W. Y. Chung, "Objective motion cueing criteria investigation based on three flight tasks," presented at the Challenges Flight Simulation, London, U.K., Jun. 2015.

[75] O. Stroosma, M. van Paassen, M. Mulder, R. J. Hosman, and S. K. Advani, "Applying the objective motion cueing test to a classical washout algorithm," in *Proc. AIAA Modeling Simulation Technol. (MST) Conf.*, Boston, MA, USA, Aug. 2013, p. 4834.

[76] B. Gouverneur, J. A. Mulder, M. M. van Paassen, O. Stroosma, and E. J. Field, "Optimisation of the SIMONA research simulator's motion filter settings for handling qualities experiments," in *Proc. AIAA Modeling Simulation Technol. Conf. Exhibit*, Austin, TX, USA, 2003, p. 5679.

[77] W. Chung, D. Robinson, J. Wong, and D. Tran, "Investigation of roll-lateral coordinated motion requirements with a conventional hexapod motion platform," in *Proc. AIAA Modeling Simulation Technol. Conf. (AIAA)*, 1998, p. 4172.

[78] J. Mikula, D. Tran, and W. W. Y. Chung, "Motion fidelity criteria for roll-lateral translational tasks," in *Proc. AIAA Modeling Simulation Technol. Conf. Exhibit*, Portland, OR, USA, 1999, p. 4329.

[79] D. M. Pool, M. Van Paassen, and M. Mulder, "Effects of motion filter gain and break frequency variations on pilot roll tracking behavior," in *Proc. AIAA Modeling Simulation Technol. Conf.*, 2013, p. 5224.

[80] S. Advani and R. Hosman, "Revising civil simulator standards—An opportunity for technological pull," in *Proc. AIAA Modeling Simulation Technol. Conf. Exhibit*, 2006, pp. 21–24.
[81] M. Kurosaki, "Optimal washout for control of a moving base simulator," in *Proc. 7th Triennial World Congr. (IFAC)*, Helsinki, Finland, vol. 2, 1978, pp. 1311–1318.
[82] D. A. Pham, S. Röttgermann, F. G. Flores, and A. Kecskeméthy, "Optimal motion cueing algorithm selection and parameter tuning for sickness-free robocoaster ride simulations," in *Mechanisms, Transmissions and Applications*. Cham, Switzerland: Springer, 2015, pp. 127–135.
[83] I. G. Salisbury and D. J. N. Limebeer, "Optimal motion cueing for race cars," *IEEE Trans. Control Syst. Technol.*, vol. 24, no. 1, pp. 200–215, Jan. 2016.
[84] R. V. Parrish, J. E. Dieudonne, R. L. Bowles, and D. J. Martin, "Coordinated adaptive washout for motion simulators," in *Proc. AIAA Vis. Motion Simulation Conf.*, Palo Alto, CA, USA, 1973, pp. 930–973.
[85] L. Nehaoua, A. Amouri, and A. H. , "Classic and adaptive washout comparison for a low cost driving simulator," in *Proc. 13th Medit. Conf. Control Autom.*, Limassol, Cyprus, 2005, pp. 586–591.
[86] S. Casas, C. Portalés, I. Coma, and M. Fernández, "Applying particle swarm optimization to the motion-cueing-algorithm tuning problem," in *Proc. Genetic Evol. Comput. Conf. Companion*, 2017, pp. 265–266.
[87] S. Casas, C. Portales, J. V. Riera, and M. Fernandez, "Heuristics for solving the parameter tuning problem in motion cueing algorithms," *Revista Iberoamericana Automática Informática Ind.*, vol. 14, no. 2, pp. 193–204, 2017.
[88] C. Onur, U. Ture, and U. Zengin, "Pilot perception and control behavior models as a tool to assess motion-cueing algorithms," in *Proc. AIAA Model. Simul. Technol. Conf.*, Jun. 2017, p. 3475.
[89] M. Jones, "Enhancing motion cueing using an optimisation technique," *Aeronaut. J.*, vol. 122, no. 1249, pp. 487–518, Feb. 2018.
[90] A. Mohammadi, "Enhancing human motion perception in model predictive motion cueing algorithm," Ph.D. dissertation, Inst. Intell. Syst. Res. Innov., Deakin Univ., Melbourne, VIC, Australia, 2018.
[91] S. Casas, I. Coma, C. Portalés, and M. Fernández, "Towards a simulation-based tuning of motion cueing algorithms," *Simul. Model. Pract. Theory*, vol. 67, pp. 137–154, Sep. 2016.
[92] P. R. Grant, "The development of a tuning paradigm for flight simulator motion drive algorithms," Ph.D. dissertation, Dept. Aerosp. Sci. Eng., Univ. Toronto, Toronto, ON, Canada, 1996.
[93] P. R. Grant and L. D. Reid, "PROTEST: An expert system for tuning simulator washout filters," *J. Aircr.*, vol. 34, no. 2, pp. 152–159, Mar. 1997.
[94] P. Grant and J. Schroeder, "Modeling pilot control behaviorfor flight simulator design and assessment," in *Proc. AIAA Modeling Simulation Technol. Conf.*, Jun. 2012, p. 8356.
[95] R. A. Hess and W. Siwakosit, "Assessment of flight simulator fidelity in multiaxis tasks including visual cue quality," *J. Aircr.*, vol. 38, no. 4, pp. 607–614, Jul. 2001.
[96] Y. Zeyada and R. A. Hess, "Modeling human pilot cue utilization with applications to simulator fidelity assessment," *J. Aircr.*, vol. 37, no. 4, pp. 588–597, Jul. 2000.
[97] R. A. Hess and T. Malsbury, "Closed-loop assessment of flight simulator fidelity," *J. Guid., Control, Dyn.*, vol. 14, no. 1, pp. 191–197, Jan. 1991.
[98] R. A. Hess, T. Malsbury, and A. Atencio, "Flight simulator fidelity assessment in a rotorcraft lateral translation maneuver," *J. Guid., Control, Dyn.*, vol. 16, no. 1, pp. 79–85, Jan. 1993.
[99] M. Wentink, J. Bos, E. Groen, and R. Hosman, "Development of the motion perception toolbox," in *Proc. AIAA Modeling Simulation Technol. Conf. Exhibit*, Keystone, CO, USA, Jun. 2006, p. 6631.
[100] M. Mayrhofer, B. Langwallner, R. Schlüsselberger, W. Bles, and M. Wentink, "An innovative optimal control approach for the next generation simulator motion platform DESDEMONA," in *AIAA Modeling Simulation Technol. Conf. Exhibit*, 2007, p. 6474.
[101] A. Mohammadi, H. Asadi, S. Mohamed, K. Nelson, and S. Nahavandi, "Optimizing model predictive control horizons using genetic algorithm for motion cueing algorithm," *Expert Syst. Appl.*, vol. 92, pp. 73–81, Feb. 2018.
[102] H. Asadi, S. Mohamed, K. Nelson, S. Nahavandi, and D. R. Zadeh, "Human perception-based washout filtering using genetic algorithm," in *Proc. Int. Conf. Neural Inf. Process.* Cham, Switzerland: Springer, 2015, pp. 401–411.
[103] S. Advani and R. Hosman, "Towards standardising high-fidelity cost-effective motion cueing in flight simulation," presented at the Roy. Aeronaut. Soc. Conf., Cutting Costs Flight Simulation Balancing Qual. Capability, London, U.K., 2006.
[104] M. Roza, R. Meiland, and J. Field, "Experiences and perspectives in using OMCT for testing and optimizing motion drive algorithms," in *Proc. AIAA Modeling Simulation Technol. (MST) Conf.*, 2013, p. 4385.
[105] R. Hosman and S. Advani, "Design and evaluation of the objective motion cueing test and criterion," *Aeronaut. J.*, vol. 120, no. 1227, pp. 873–891, May 2016.
[106] P. M. T. Zaal, J. A. Schroeder, and W. W. Chung, "Transfer of training on the vertical motion simulator," *J. Aircr.*, vol. 52, no. 6, pp. 1971–1984, Nov. 2015.
[107] P. Zaal, J. A. Schroeder, and W. W. Chung, "Objective motion cueing criteria for commercial transport simulators," in *Proc. Modeling Simulation Technol. Conf.*, Jun. 2018, p. 2935.
[108] E. van Duivenbode, E. van Oene, J. van Hoof, L. Jacobs, and D. Belleter, "Objective motion cueing Test. Development, strengths, weaknesses and possibilities," in *Proc. AIAA Scitech Forum*, Jan. 2019, p. 0177.
[109] L. Zaichik, Y. Yashin, P. Desyatnik, and Y. Arkhangelsky, "Motion cueing fidelity in upset recovery simulation," in *Proc. AIAA Scitech Forum*, Jan. 2019, p. 0711.
[110] M. Fischer, A. Seefried, and C. Seehof, "Objective motion cueing test for driving simulators," *Proc. DSC Eur.*, 2016, pp. 41–50.
[111] M. Jones, "The suitability of objective motion criteria for rotorcraft manoeuvres," in *Proc. AIAA Scitech Forum*, Jan. 2019, p. 0180.
[112] K. De Ridder and M. Roza, "Automatic optimization of motion drive algorithms using OMCT," in *Proc. AIAA Modeling Simulation Technol. Conf.*, Jan. 2015, p. 1139.
[113] R. Hosman and S. Advani, "Status of the ICAO objective motion cueing test," presented at the Flight Simulation Res., New Frontiers Conf., 2012.
[114] E. Thöndel, "Design and optimisation of a motion cueing algorithm for a truck simulator," in *Proc. Eur. Modeling Simulation Conf. (ESM)*, Essen, Germany, 2012, pp. 165–170.
[115] H. Asadi, S. Mohamed, D. Rahim Zadeh, and S. Nahavandi, "Optimisation of nonlinear motion cueing algorithm based on genetic algorithm," *Vehicle Syst. Dyn.*, vol. 53, no. 4, pp. 526–545, Feb. 2015.
[116] M. Grottoli, D. Cleij, P. Pretto, Y. Lemmens, R. Happee, and H. H. Bülthoff, "Objective evaluation of prediction strategies for optimization-based motion cueing," *Simulation*, vol. 95, no. 8, pp. 707–724, Dec. 2018.
[117] H. Asadi *et al.*, "A particle swarm optimization-based washout filter for improving simulator motion fidelity," in *Proc. IEEE Int. Conf. Syst., Man, Cybern. (SMC)*, Oct. 2016, pp. 1963–1968.
[118] A. Mohammadi, H. Asadi, S. Mohamed, K. Nelson, and S. Nahavandi, "Multiobjective and interactive genetic algorithms for weight tuning of a model predictive control-based motion cueing algorithm," *IEEE Trans. Cybern.*, vol. 49, no. 9, pp. 3471–3481, Sep. 2019.
[119] W. Dalmeijer, I. Miletović, O. Stroosma, and M. Pavel, "Extending the objective motion cueing test to measure rotorcraft simulator motion characteristics," in *Proc. 73rd Amer. Helicopter Soc. Int. Annu. Forum Technol. Display*, vol. 7, 2017, p. 6.
[120] I. Miletović *et al.*, "Eigenmode distortion as a novel criterion for motion cueing fidelity in rotorcraft flight simulation," 2018.
[121] S. Stoev, O. Stroosma, M. M. van Paassen, I. Miletovic, and M. Mulder, "Eigenmode distortion analysis for motion cueing evaluation in fixed-wing aircraft simulators," in *Proc. AIAA Scitech Forum*, Jan. 2019, p. 179.

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