To Move or Not to Move? Analyzing Motion Cueing by Means of Massive Simulations

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To Move or Not to Move? Analyzing Motion Cueing by Means of Massive Simulations

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***Abstract*—Motion platforms and motion cueing algorithms (MCA) have been included in Virtual Reality applications for several decades. They are necessary to provide suitable inertial cues in vehicle simulators. However, the great number of operational constraints that these motion platforms and algorithms suffer, namely, physical limited space, elevated costs, absence of sufficient power, difficulty of tuning and lack of standardized assessment methods, have hindered their widespread use. This work tries to give clues about open questions in the field, such as: How important is MCA tuning? How much does size and latency/power matter? Can absence of motion be better than poor motion cueing? What are the key factors that should be addressed to enhance motion cueing? Although absolute certain answers cannot be given, this paper tries to clarify these issues by performing massive experiments with simulated motion platforms of different type, size and power. Ideally, subjective experiments would have been preferred. However, the use of simulated devices allows comparing many different motion platforms. In this paper, forty of these devices are simulated and compared with objective indicators in order to measure their relative performance using the classical MCA, something that would require an unreasonable amount of effort with real users and real devices. The obtained results show that MCA tuning is of the utmost importance in motion cueing. They also suggest that high power can usually compensate for lack of size and that a 6-DOF motion platform slightly improves the performance of a 3-DOF motion platform.**

***Index Terms*—Analysis, massive simulation, motion cueing; motion platform; vehicle simulation; Virtual Reality, washout algorithms.**

I. INTRODUCTION

MOTION platforms are robotic mechanisms that can be used, among several other applications, to provide motion cueing in vehicle simulators [1]. The algorithms designed to control how these devices are used and synchronized with the rest of simulator's perceptual cues are called Motion Cueing Algorithms (MCA), Motion Drive Algorithms (MDA) or, sometimes, *washout algorithms/filters* [2]. Motion platforms have been used in Virtual Reality (VR) applications at least since the 1950s [3, 4] and most of the proposed MCA date back to the 1970s and 1980s [5, 6].

However, it is still unclear how to optimally simulate self-motion using motion cueing devices, despite the fact that self-motion simulation is considered an essential part of many commercial flight and driving simulators [7]. Interestingly enough, this has not avoided that motion cueing generation be required for simulation certification in many areas [8, 9]. Current simulation standards consider that motion cueing is mandatory for vehicle simulators under regulation.

Nevertheless, not all vehicle simulators include self-motion generation. Some of them are restricted to audio-visual perceptual cues. This apparent contradiction can be explained by a series of convergent factors. First, some users experience severe motion sickness [10] when self-motion cues are included in simulators. Second, motion platforms are usually unaffordable devices that are not easy to design, build and control. In addition, the field lacks a standard mechanism to assess whether perceptual motion cues are properly generated. In fact, the most common MCA is still the classical algorithm, which was proposed in 1969 [11]. This apparent lack of progress prompts engineers and researchers to raise questions about the evolution of motion cueing in VR systems.

On the one hand, it seems clear that the physical features of the robotic motion platform could have a decisive influence in the result. In this regard, the amount of reachable workspace (physical size or space) and the power of the actuators can significantly enhance or degrade the users' perceptual experience. It is well known that motion platforms introduce delays in the simulation and usually downscale the rendered movements so that the motion platforms' limits are not reached. According to Sinacori's nomenclature [12], time delays cause *phase distortion* whereas gain reduction causes *magnitude distortion*. This reduces both the physical, perceptual and behavioral validity of the simulator [13] and should be minimized to the extent possible, since physical constraints hamper its complete elimination. However, several questions remain unclear, such as: Is power more important that size? Can a small/weak device be worse than no device at all? What is the influence of the number of degrees of freedom (DOF) of the robotic device? Is it a key factor or just an enhancement? On the other hand, given the lack of standardized assessment methods, the tuning of MCA turns into a complex task. This raises several questions too: How much influence does have proper tuning in the final result? Can poorly tuned MCA be

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worse than no motion?

Ideally, these questions would be answered by performing experiments with several motion platforms – with different features - and real users. This would require to design and build as many devices as possible, in order to test their performance with the same users. However, this approach is almost unfeasible since most research teams are unable to construct or even house dozens of robotic mechanisms.

For this reason, this work tries to provide answers to the previous questions by means of simulated motion platforms. To that end, a total of twenty 6-DOF and twenty 3-DOF motion platforms with different combinations of size and power are tested using the classical washout and compared with objective indicators that measure the generated motion cues. The objective measures that have been chosen have been previously assessed to be correlated with the subjective perception of self-motion. Nonetheless, it is important to emphasize that absolute certain answers cannot be given; yet, the performed experiments would provide sufficient evidence to give clear patterns, trends or clues and open new avenues for research in motion cueing.

The rest of the paper is organized in the following way. Section 2 reviews related works about motion cueing. Section 3 describes the materials and methods utilized to perform the experiments. Section 4 deals with the presentation of results. In section 5, these results are discussed. Finally, section 6 outlines the future work and shows the conclusions of the paper.

II. RELATED WORK

The first MCA are attributed to the National Aeronautics and Space Administration (NASA) engineers [11, 14, 15]. The work of Schmidt and Conrad was later revised and studied in depth by Reid and Nahon at the University of Toronto Institute for Aerospace Studies (UTIAS) [16-18]. This algorithm has come to be known as the classical algorithm or classical washout. Parrish et al. proposed a modified version of the classical washout [19, 20] that is known as the adaptive algorithm. Not long after, optimal control theory was applied to the motion cueing problem leading to the optimal algorithm [21, 22]. Since then, most of the vehicle simulators have used one of these three algorithms or slightly modified versions of them. Only recently, Dagdelen et al. proposed an MCA based on model-base predictive control [23], which has received some attention lately [24-27]. Although many other algorithms have been proposed, the classical algorithm is still the most common, due to its effectivity, simplicity and to the fact that no proper consensus has been reached as to what is the best way to generate motion cues.

One of the reasons for this ambiguity is that, differently from other research areas, motion cueing lacks of a standardized – universally accepted – appraisal methods. Although the field seems to walk towards objective assessment methods [28-33], there is still much work to do. Nevertheless, these recent objective assessment approaches have allowed to study the problem of tuning MCA in a systematic way. One of the earliest studies about MCA tuning was conducted by Grant at UTIAS [34, 35], who proposed an expert system to help tune washout filters [36] without using objective assessment measurements. Automatic tuning systems have been proposed only recently [37-41]. However, subjective evaluation and tuning is still present in many works [42-44], although a combination of both methods is also a possibility [45-47] and seems to be the preferred method.

The first MCA were designed for aircraft and the 6-DOF Stewart-Gough hexapod [48] was generally adopted as a *de facto* standard for flight simulation. Thus, almost all of the earlier works on motion cueing were designed for 6-DOF parallel manipulators, which is still, undoubtedly, the most common setup. Yet, recently, there has been a renewed interest in low-cost simulators that could be used instead of more expensive 6-DOF designs. 2-DOF [49-51] and 3-DOF [52, 53] motion-based simulators have been recently proposed and setup to provide inertial cues in different vehicle simulators. 4-DOF [54] or 5-DOF [55, 56] systems have received much less attention. 5-DOF systems have similar complexity and relatively low advantages over the 6-DOF designs in terms of cost. 1-DOF vehicle simulators are not commonly used. In addition, 8-DOF setups [57, 58] and serial designs [59] have also been proposed as a way to overcome some of the problems that parallel manipulators create, although these proposals are not focused on cost reduction.

Some researchers have asked several of the questions tackled in this paper and some others, performing experiments in order to provide answers with sufficient scientific evidence. Several researchers have compared different MCA for the same vehicle or simulator. Most of them compare classical, adaptive and optimal algorithms [60-62]. Others extend the comparison to different algorithms [25, 63, 64]. However, no clear outcomes can be derived about this issue since different researchers have obtained different results.

Other researchers have tried to establish if motion-based simulators provide sufficient perceptual or training advantages over fixed-based (motionless) simulators [44, 60, 65]. The general answer is that motion-based simulators are preferred over fixed-base setups, with some exceptions [66]. However, these works do not try to analyze the conditions under which motion-based simulators are preferred over motionless simulators. The most common outcome of these papers is “users prefer the motion-based simulator”. It is important to emphasize that motion-based simulators can be significantly enhanced or degraded by many factors, and therefore, a single motion vs no-motion comparison provides little information.

Some other researchers have studied the influence of MCA tuning and filter setting in the resulting motion cueing [2, 45, 46, 60, 67]. However, most of these studies are limited to some set of parameters or test-candidate filters, giving little room for extracting deep conclusions.

Some studies focus on latency and time delays, whereas the effect of motion platform size/workspace on motion cueing has received less attention, probably because of the burden of building several physical devices to perform such a comparison if simulation techniques are not applied. Most studies on time delays try to establish a maximum limit for simulator delays (not only about motion, also about visual delays [68]) so that pilot control behavior, performance and training transference are properly achieved [69, 70].

Yet, to the best of our knowledge, the use of massive simulation to explore several simultaneous features of motion cueing has not been proposed. The most similar work to the research proposed here is [28], where virtual (simulated) motion platforms are utilized to perform the comparison of several 3-DOF architectures with respect to the reference Stewart-Gough 6-DOF hexapod. The study concludes that the 6-DOF architecture marginally improves some 3-DOF designs, the latter being much cheaper. However, our approach is different, since several other factors are being considered other than the motion platform design (size, power/latency, tuning), the number of simulated devices is much higher and the tuning procedure and the motion assessment is different.

III. MATERIALS AND METHODS

A. *Kinematic Description of the Motion Platforms*

Two different types of motion platform are used throughout this work: a 6-DOF and a 3-DOF motion platform. The 6-DOF mechanism is a Stewart-like device with six rotational motors instead of the traditional prismatic actuators of the Stewart-Gough hexapod. It features a 6-RSS (rotational, spherical, spherical) parallel manipulator. As most parallel designs, it offers high stiffness, accuracy, speed, and payload handling, but limits the simultaneous rendering of large DOF displacements. This type of device is widely used in vehicle simulation. The use of rotational actuators makes it more affordable since electrical rotational motors are widely available. Fig. 1 shows the design of a rotational Stewart-Gough 6-DOF parallel manipulator.

The 3-DOF motion platform is a heave-pitch-roll parallel robot equipped with three rotational motors, as shown in Fig. 2. It features a 3-RSSUP (rotational, spherical, spherical, universal, prismatic) parallel mechanism. Despite having only three DOF, this design is able to generate perceptual motion cues up to five of the six possible DOF: three by physical motion, plus two simulated DOF making use of the tilt-coordination technique [13, 71], which takes advantage of the somatogravic illusion [72]. Although this mechanism needs more joints per DOF than the Stewart design and the universal prismatic link of the motion base – used to avoid uncontrolled yaw – is rather complex to fabricate, this design requires only three actuators instead of six. Thereby, the economic cost of the vehicle simulator is significantly reduced, since a 3-DOF device is nearly two times cheaper than a 6-DOF one, assuming similar sizes, payloads and actuators' power. For this reason, this design represents a reasonable trade-off between cost and performance.

Despite having only two designs, they can be constructed in several sizes depending on the lengths of the different legs and the locations of the actuators. For this work, both designs (6-DOF and 3-DOF) have been (virtually) instantiated in four different sizes, which are named S, M, L and XL. It is important to emphasize that these different designs are not shaped just performing a simple scale of a base model. They have different legs and locations of the actuators so that their translational and rotational capabilities change in increasing order of magnitude. However, only the kinematic properties of the devices do matter in this study, not the particular building elements. Table 1 and Table 2 list the kinematic properties of this eight different motion platforms (four with 6-DOF and four with 3-DOF). It is worth noting that these ranges represent the reachable workspace of each isolated channel/DOF, when the rest are set to zero. The combination of several channels leads to potential severe reductions of the simultaneous reachable workspace. However, this kind of non-linear dependency is not easy to depict. As both tables show, the motion platforms labelled with S provide short linear and rotational displacements, whereas the ones labelled with XL have a large reachable workspace. This latter motion device would be hard to actually bring about due to the physical size of its building blocks and because mechanical joints have actual limits that constrain their operation.

TABLE I
KINEMATIC WORKSPACES (SIZES) OF THE EACH OF THE FOUR 6-DOF MOTION PLATFORMS (MP)

MP	*Surge (m)*	*Sway (m)*	*Heave (m)*
S	[-0.14, 0.10]	[-0.11, 0.11]	[-0.054, 0.058]
M	[-0.40, 0.34]	[-0.35, 0.35]	[-0.22, 0.25]
L	[-0.85, 0.87]	[-0.81, 0.81]	[-0.53, 0.64]
XL	[-1.53, 1.98]	[-1.64, 1.64]	[-0.95, 1.22]
MP	*Yaw (°)*	*Pitch (°)*	*Roll(°)*
S	[-16.32, 16.32]	[-8.60, 7.81]	[-8.88, 8.88]
M	[-34.68, 34.68]	[-25.46, 20.30]	[-23.04, 23.04]
L	[-56.68, 56.68]	[-46.13, 35.81]	[-39.35, 39.35]
XL	[-84.14, 84.14]	[-70.76, 76.28]	[-59.50, 59.50]

TABLE II
KINEMATIC WORKSPACES (SIZES) OF THE EACH OF THE FOUR 3-DOF MOTION PLATFORMS (MP)

MP	*Heave (m)*	*Pitch (°)*	*Roll (°)*
S	[-0.045, 0.055]	[-7.29, 5.97]	[-6.88, 6.88]
M	[-0.19, 0.21]	[-21.63, 18.90]	[-21.98, 21.98]
L	[-0.45, 0.55]	[-38.84, 31.51]	[-37.40, 37.40]
XL	[-0.90, 1.10]	[-63.39, 50.87]	[-68.08, 68.08]

B. *Simulation Method*

Since motion cueing deals with perception, the evaluation of MCA has been traditionally performed with subjective experiments using questionnaires about pilot/drivers opinions. However, if a comprehensive test with many different motion platforms and setups is desired, as in the case of this work, the use of real devices with real users, although preferable, would be almost impossible. In addition, in recent years, objective motion cueing evaluation has raised attention as a great deal of advantages can be obtained performing objective measures, namely, repeatability, universality, easier tuning and fair comparisons.

For this reason, this work proposes to analyze the behavior of several motion platforms of different size and power using objective indicators that try to measure the operation of MCA. In addition, the use of objective measurements allows using simulation techniques, so that simulated motion platforms can be used instead of the actual ones. The use of simulation provides countless advantages, namely: (i) there is no need to actually build the devices saving time, energy and money; (ii) the type and features of the mechanisms can be changed with relatively little effort; (iii) tests can be performed faster than with users and even faster than real-time; (iv) potential risks and accidents are avoided; (v) ideal or unfeasible devices can be tested to give clues about the limits of the underlying technology.

The objective evaluation performed throughout this work is achieved by comparing, on a signal-by-signal basis, the expected motion of the vehicle with the actual motion experienced by the user in the simulator (over the motion platform). The expected/reference motion is calculated by the physics module of the vehicle simulator. Thereby, it is easy to obtain. The motion performed by the robotic mechanism can be measured using inertial or optical tracking systems, like [73]. However, if the motion platform is virtual (it is a simulated one) this information is even easier to obtain as it can be queried directly to the virtual motion platform. The proposed comparison analyses both specific force and angular velocity, which are the inputs of the human vestibular system responsible for motion perception [74]. Therefore, six signals, (F_x, F_y, F_z, ω_x, ω_y, ω_z), representing the specific force and angular velocity in all three dimensions, respectively, are compared with their respective reference/expected signals. The comparison scheme replicates exactly the one used in [38].

There are several ways to compare signals. In the case of motion cueing, these motion fidelity indicators try to measure either (or both) magnitude distortion or phase distortion. Some objective indicators have been proposed to analyze motion cueing [28, 33, 41]. This work uses the objective motion cueing indicators depicted in [32] since they have shown some correlation with the perception of users and they can be used for automatic MCA tuning, which will be advantageous to find the best possible motion fidelity for each of the configurations/motion platforms compared. The following indicators are used in this paper: Normalized Average Absolute Difference (NAAD), Normalized Pearson Correlation (NPC) and Estimated Delay (ED). The first one is sensitive to magnitude distortion whereas the other two are sensitive to phase distortion. All these indicators are designed so that the optimal value is one (perfect unscaled undistorted motion), and the higher the value, the worst is the generated motion with respect to the expected one. For a detailed explanation of the objective indicators, readers can consult [32].

As aforementioned, the proposed experiments are based on simulated/virtual motion platforms. This work uses the Newtonian-Lagrangian physics-based simulation method explained in [75] with some adaptations for the goals defined in this paper. The virtual motion platform shown in [75] simulates the dynamics of the building blocks (joints, legs, actuators, etc.) of a robotic mechanism. It uses NVidia PhysX v2.8.3 [76] as the physics simulation library [77]. This virtual motion platform is capable of representing the kinematic or dynamic behavior of a real motion platform, and therefore, it is suitable for testing motion cueing algorithms.

As the authors do not want to restrict the study to a particular configuration (masses, inertias, motor gear ratios, etc.) of the motion devices, a small modification of the virtual motion platform is proposed: in order to simulate the same mechanism (design + size) but with different dynamic properties, a transport delay and a second order low pass filter have been added to each of the inputs of the virtual motion platform. The low pass filter has a variable cut-off frequency with constant gain and damping set to unity. In addition, *Nx_bf_kinematic* flag has been set to the actors of the simulated scene representing the motion platform elements. Thereby, by changing the transport delay and the cut-off frequency of the filter, the effect of latency and power loss can be simulated. This leads to several simulated motion platforms, as seen in Table 3. This approach has several advantages: (i) the different mechanisms are clearly sorted in decreasing order of power; (ii) any motion platform with dynamic properties that are similar to those listed in Table 3 would be represented by these simulated devices; (iii) it eases the task of changing the experiments.

Once a motion platform and an objective indicator are chosen, the final step is to tune the MCA so that the value of the objective indicator obtained with the robotic mechanism is the best that can be possibly achieved. Tuning MCA is often a difficult task. However, having objective indicators, the problem can be turned into an optimization problem, which can be solved by using heuristic search methods in a large but fitted parameter-space. This work utilizes a genetic algorithm (GA) to find the best values for the parameters of the washout algorithm. The tuning scheme reproduces and uses the method explained in [38], which readers can consult for further details that lay out of the goals of this paper.

Since there are different designs (6-DOF and 3-DOF) and each of these architectures can be built in different sizes while combining different power properties, the resulting simulation portfolio reaches a total of forty simulated motion platforms (four sizes, five dynamic configurations, and two different designs). For each of these devices, a comprehensive GA-based tuning search, trying to establish how good it may be for motion cueing, is performed. This kind of analysis can only be done by means of massive simulations with computers, showing the clear advantages that simulation techniques can offer in this field.

TABLE III
DYNAMIC FEATURES OF THE 3-DOF AND 6-DOF MOTION PLATFORMS

Motion Platform	*Power*	*Transport delay (s)*	*Cut-off frequency (Hz)*
Ideal	∞	0	-
1	high	0.1	3
2	medium	0.4	1
3	low	1	0.5
4	very low	2	0.125

C. *Experiments*

The experiments here described are designed to study how motion cueing varies with different robotic mechanisms and conditions, studying the influence of power/latency, size, type of motion platform, tuning, etc. The classical washout is used through this work as it is the most common MCA and its parameters are relatively easy to understand. *Live for Speed* (LFS) driving simulator is utilized as physics module for the vehicle simulator. One lap to the *Blackwood* track, driving with a *BMW FB02* car, is measured. To avoid variations due to human driving skills, the driving session is recorded with the automatic pilot on. The computer used to run the simulations (first the driving simulator and then the virtual motion platform with the tuning/optimization algorithm) is a PC with an Intel Core i7-3770 @ 3.4 GHz, with 10 GB of RAM and a Windows 10 x64 operating system.

For each motion platform, the heuristic GA-based search is applied twice: first to identify the best possible setup for each device with the classical washout, and later to identify the worst possible setup with the same algorithm. The search time for the GA is set to 2,000 seconds, which is enough time to find a proper set of values for the parameters of the MCA. However, the parameters themselves are not important. Therefore, only the resulting motion fidelity objective indicators are stored. For both motion platforms, the UTIAS classical washout implementation is utilized and the number, type and allowed ranges for the values of the MCA parameters are depicted in Table 4. A detailed description of the meaning and effect of the parameters is explained in [32]. Since the 3-DOF motion platform has less channels to tune, this work proposes to tune 14 parameters for the 3-DOF case and 18 parameters for the 6-DOF device. The parameters of the classical washout not shown in Table 4 were set to unity.

TABLE IV
VARIABLE PARAMETERS IN THE OBJECTIVE MCA TUNING

Module-parameter	*3-DOF range*	*6-DOF range*
TA–x scale	[0-2]	[0-2]
TA–y scale	[0-2]	[0-2]
TA–z scale	[0-2]	[0-2]
THPF–x cut-off (Hz)	-	[0-10]
THPF–y cut-off (Hz)	-	[0-10]
THPF–z cut-off (Hz)	[0-10]	[0-10]
TLPF–x cut-off (Hz)	[0-10]	[0-10]
TLPF–y cut-off (Hz)	[0-10]	[0-10]
TC–x tilt limit (◦)	[0-20]	[0-20]
TC-y tilt limit (◦)	[0-20]	[0-20]
RL-x rate limit (◦/s)	[0-10]	[0-10]
RL-y rate limit (◦/s)	[0-10]	[0-10]
RA–x scale	[0-2]	[0-2]
RA–y scale	[0-2]	[0-2]
RA–z scale	-	[0-2]
RHPF–yaw cut-off (Hz)	-	[0-10]
RHPF–pitch cut-off (Hz)	[0-10]	[0-10]
RHPF–roll cut-off (Hz)	[0-10]	[0-10]

Note: TA = translational amplifier; THPF = translational high-pass filter; TLPF = translational low-pass filter; RHPF = rotational high-pass filter; TC = tilt coordination; RL = rate limiter; RA = rotational amplifier.

Three different experiments are conducted, referred to as A, B and C. In Experiment A, the NPC indicator is utilized. This objective metric is the one that obtained the best correlation with respect to the subjective opinions in [32]. However, it is only sensitive to phase distortion. Therefore, in order to account not only for phase distortion but also for magnitude distortion, Experiment B uses a multiplicative combination of NAAD and NPC, whereas Experiment C employs a multiplicative combination of NAAD and ED. In all cases, the no-motion scenario was included in the experiments, in order to compare the motion fidelity results obtained with each device with respect to a ground-fixed simulator, giving a total of 42 values for each motion platform. To avoid improper figures, since the optimization methods are heuristic, results are averaged from ten tests.

IV. RESULTS

A. *Results of Experiment A*

Tables 5 and 6 show the results of Experiment A for the 6-DOF motion platform, where the optimal value for the indicator is one, as explained above. Experiment A.1, depicted in Table 5, reflects the search for the best values for the parameters of the MCA. Experiment A.2, shown in Table 6, reflects the opposite situation (worst possible values). This latter experiment is much less significant than the former, since the desire of the simulator designer is to tune MCA for good motion cueing. Similarly, Tables 7 and 8 show the results of Experiment A for the 3-DOF parallel mechanism. Fig. 3 and Fig. 4 offer additional graphical details. They correspond with the data in Tables 5 and 7 (best possible tuning).

TABLE V
RESULTS FOR EXPERIMENT A.1 (BEST VALUES) FOR THE 6-DOF

		Motion Platform					
		Ideal	*1*	*2*	*3*	*4*	*No Motion*
Size	*S*	1.2134	1.2398	1.3010	1.3374	1.4233	1.5000
	M	1.2121	1.2294	1.2614	1.3312	1.3902	1.5000
	L	1.2047	1.2109	1.2429	1.3257	1.3781	1.5000
	XL	1.1879	1.2084	1.2548	1.3302	1.3667	1.5000

TABLE VI
RESULTS FOR EXPERIMENT A.2 (WORST VALUES) FOR THE 6-DOF

		Motion Platform					
		Ideal	*1*	*2*	*3*	*4*	*No Motion*
Size	S	1.8073	1.7643	1.8835	1.7724	1.8942	1.5000
	M	1.6197	1.6755	1.7916	1.8079	1.9022	1.5000
	L	1.7257	1.7139	1.7404	1.7752	1.9202	1.5000
	XL	1.6582	1.8283	1.8768	1.7845	1.9399	1.5000

TABLE VII
RESULTS FOR EXPERIMENT A.1 (BEST VALUES) FOR THE 3-DOF

		Motion Platform					
		Ideal	*1*	*2*	*3*	*4*	*No Motion*
Size	*S*	1.2114	1.2697	1.3162	1.3389	1.4399	1.5000
	M	1.2036	1.2622	1.3153	1.3371	1.4194	1.5000
	L	1.1946	1.2453	1.3052	1.3260	1.4201	1.5000
	XL	1.1906	1.2525	1.3024	1.3262	1.4303	1.5000

TABLE VIII
RESULTS FOR EXPERIMENT A.2 (WORST VALUES) FOR THE 3-DOF

		Motion Platform					
		Ideal	*1*	*2*	*3*	*4*	*No Motion*
Size	*S*	1.7843	1.8628	1.8290	1.8527	1.9282	1.5000
	M	1.8961	1.7417	1.8748	1.8173	1.9148	1.5000
	L	1.7988	1.8316	1.7797	1.7990	1.9146	1.5000
	XL	1.8709	1.8290	1.7797	1.8076	1.9105	1.5000

Results show that tuning makes a big difference, since a poorly tuned classical washout provides bad indicators even for the ideal motion platform, as depicted in Tables 6 and 8. Another key factor is latency, which degrades the performance of motion cueing when it is too high. Size seems to have a much less important effect than power. For ideal devices (zero latency mechanisms), a pattern can be identified that suggests that increasing size, there is also an increase in motion fidelity. However, although some devices show also this behavior, not all motion platforms show this pattern clearly. In addition, the improvement obtained increasing size is not always significant, especially in the 3-DOF case. An increase in power seems to be much more effective. Results also show that the 6-DOF design provides results that are only slightly better than those of the 3-DOF motion platforms are. With ideal devices, the difference is marginal. However, with less powerful mechanisms the difference is bigger. Regarding the motion vs no-motion question, this test, surprisingly suggests that motion is preferred even for slow and small motion platforms. Worst values are all above the no-motion threshold (1.5) and seem to deteriorate with the latency of the device. Size does not have a significant impact in Experiment A.2.

B. *Results of Experiment B*

Tables 9-12 show the results of Experiment B. Fig. 5 and Fig. 6 offer additional graphical details of Experiment B.1 for both motion platforms.

TABLE IX
Results for Experiment B.1 (best values) for the 6-DOF

		Motion Platform					
		Ideal	*1*	*2*	*3*	*4*	*No Motion*
Size	*S*	1.4245	1.4797	1.4697	1.5483	1.6514	1.7648
	M	1.4160	1.4485	1.4638	1.5361	1.5888	1.7648
	L	1.4064	1.4433	1.4474	1.5486	1.6021	1.7648
	XL	1.3867	1.3956	1.4746	1.5474	1.6067	1.7648

TABLE X
Results for Experiment B.2 (worst values) for the 6-DOF

		Motion Platform					
		Ideal	*1*	*2*	*3*	*4*	*No Motion*
Size	*S*	2.3673	2.3071	2.0720	2.2597	2.3126	1.7648
	M	2.3038	2.2529	2.2273	2.1477	2.2777	1.7648
	L	2.2157	2.0939	2.1338	2.2256	2.3230	1.7648
	XL	2.3301	2.0092	1.9963	2.2223	2.3518	1.7648

TABLE XI
Results for Experiment B.1 (best values) for the 3-DOF

		Motion Platform					
		Ideal	*1*	*2*	*3*	*4*	*No Motion*
Size	*S*	1.4277	1.4615	1.5244	1.5514	1.7012	1.7648
	M	1.4156	1.4604	1.5214	1.5616	1.6773	1.7648
	L	1.3875	1.4657	1.5174	1.5610	1.6657	1.7648
	XL	1.3759	1.4511	1.5086	1.5578	1.6657	1.7648

TABLE XII
Results for Experiment B.2 (worst values) for the 3-DOF

		Motion Platform					
		Ideal	*1*	*2*	*3*	*4*	*No Motion*
Size	*S*	2.3944	2.2517	2.1267	2.2324	2.3322	1.7648
	M	2.3580	2.1764	2.1888	2.2365	2.3425	1.7648
	L	2.1258	2.0687	2.2040	2.2048	2.3031	1.7648
	XL	2.0386	2.2994	1.9787	2.2134	2.3127	1.7648

Again, tuning makes a big difference. In this case, even with the best possible set of parameters, Platform 4 is close to the no-motion score for both designs (3-DOF and 6-DOF). Therefore, if proper tuning is not applied, building motion platforms with these features would probably be a waste of resources. Still, motion-based systems appear to be better than a static system. With this test, there are still differences between 6-DOF and 3-DOF architectures, in favor of the former. However, the best possible motion platform (Ideal-XL) provides slightly better results for the 3-DOF case, something that is not hold for most of the other cases. The patterns observed in Experiment A.1, regarding size and power, are also present in Experiment B.1. Latency seems to have a significant impact, whereas size is important but it seems to, somehow, have a limit. For instance, Platform 2 and Platform 3 do not show a big influence with respect to size, both for 3 and 6-DOF, whereas the ideal device does it. Worst values are again well above the result of no-motion (1.7648). However, they show a rather uniform pattern, since latency and size do not have a clear impact on the figures of Experiment B.2.

C. *Results of Experiment C*

Tables 13-16 show the results of Experiment C. Fig. 7 and Fig. 8 offer additional graphical details of Experiment C.1 for both motion platforms.

TABLE XIII
Results for Experiment C.1 (best values) for the 6-DOF

		Motion Platform					
		Ideal	*1*	*2*	*3*	*4*	*No Motion*
Size	*S*	1.2141	1.2254	1.5629	1.7181	1.7385	1.6720
	M	1.2106	1.1789	1.4196	1.3939	1.5640	1.6720
	L	1.1924	1.2152	1.4494	1.3694	1.5554	1.6720
	XL	1.1846	1.2321	1.3780	1.2998	1.5402	1.6720

TABLE XIV
Results for Experiment C.2 (worst values) for the 6-DOF

		Motion Platform					
		Ideal	*1*	*2*	*3*	*4*	*No Motion*
Size	*S*	4.3295	4.5368	4.5904	4.6548	4.7133	1.6720
	M	4.5204	4.6000	4.6434	4.6605	4.7015	1.6720
	L	4.6377	4.4945	4.4211	4.6904	4.7481	1.6720
	XL	4.6403	4.4841	4.6982	4.6813	4.7601	1.6720

TABLE XV
RESULTS FOR EXPERIMENT C.1 (BEST VALUES) FOR THE 3-DOF

		Motion Platform					
		Ideal	*1*	*2*	*3*	*4*	*No Motion*
Size	*S*	1.2257	1.4418	1.8621	2.0317	2.0489	1.6720
	M	1.2031	1.3372	1.6440	1.7192	1.8551	1.6720
	L	1.2052	1.3296	1.5624	1.7780	1.8616	1.6720
	XL	1.1913	1.3293	1.6120	1.7471	1.9546	1.6720

TABLE XVI
RESULTS FOR EXPERIMENT C.2 (WORST VALUES) FOR THE 3-DOF

		Motion Platform					
		Ideal	*1*	*2*	*3*	*4*	*No Motion*
Size	*S*	4.3885	4.5707	4.6459	4.6985	4.7178	1.6720
	M	4.1828	4.2422	4.6550	4.7065	4.7185	1.6720
	L	4.6419	4.5763	4.5810	4.6641	4.6643	1.6720
	XL	4.4186	4.6236	4.6621	4.5940	4.7872	1.6720

The results of Experiment C.1 are a little different from the ones of Experiment A.1 and Experiment B.1. Small devices (S) get significantly poorer results than the rest. In addition, the difference between the 6-DOF motion platform and the 3-DOF device is larger than in previous tests. In fact, Platform 3 and Platform 4 get results that are worse than no-motion, even the XL versions, for the 3-DOF case. The effect of latency and tuning is similar to those observed in Experiment A.1 and Experiment B.1. Regarding Experiment C.2, worst values are well above the no-motion threshold (1.672). They also show a tendency to worsen with latency (for both designs), whereas size does not seem to play a factor.

V. DISCUSION

Results clearly show that MCA tuning is one of the main factors for proper motion cueing. In fact, in some cases, it is necessary to optimally tune the MCA to get decent objective indicators. Moreover, we have to take into account that, in these experiments, the working ranges for the parameters were set to reasonable values. Therefore, what these experiments consider bad tuning could not be as bad as they could really get. This reflects that it is not enough to design good algorithms and build powerful, large devices if the algorithms that control them are poorly tuned. Even worse, this could be a total waste of resources. Although this seems intuitive, not all authors have acknowledged this problem and some works present results about motion cueing without showing that the algorithms have been optimally tuned, or at least a significant effort has been set in the tuning process. In fact, some works do not even mention this problem, when it is a very important one. On the one hand, if tuning is done subjectively, it would be difficult to get closer to the optimal value since the procedure can be hardly automated. Thereby, the results shown in this paper reflect the best-case scenario. On the other hand, if tuning is performed objectively, it might not be comfortable for every user, and thus subjective-based adjustments could be necessary. If so, how can we be sure that the MCA is at its best version? Therefore, it is urgent that the MCA tuning and the MCA assessment problems be systematized so that a proper standard solution is accepted.

Latency (or power) seems also to play a very important role in motion cueing. This should be no surprise, as the goal of any motion platform is to provide motion that is synchronized with the visual motion. This is hardly ever accomplished. However, the effect of latency seems to be much more important than the effect of increasing/decreasing size. Let us not forget that increasing the size of real motion platforms causes an immediate rise in mass and rotational inertias, reducing the power/mass ratio, which increases latency. Therefore, an increase in size requires a corresponding increase in power to maintain latency. According to the results, it is best to increase power while maintaining a decent size.

In addition, the work presented here tries to frame a limit for this technology by means of simulating ideal devices. In the experiments performed, the ideal motion platforms performed far from the perfect motion fidelity result, even the biggest ones. Moreover, a decrease in power (or equivalently an increase in latency) provides a significant decrease in the objective motion indicators. Thereby, building a motion platform with slow motion can be deemed as a bad idea, even if it is huge. Unfortunately, marketing reasons could make simulators' designers fall into the temptation of including motion cueing with slow or weak devices (to cut costs but show off that the vehicle simulator is motion-based). According to the experiments, this is something that should be avoided, since it is very doubtful that high-latency devices can provide motion cueing that is noticeable better than no motion.

In this regard, with the results of the experiments, the motion vs no-motion question cannot be answered in terms of yes/no responses. Some experiments suggest that motion is better whereas others suggest otherwise, at least if the motion platforms are not similar to the ideal one. However, it is worth noting that the objective indicators play a significant role in the results of this comparison, since they are designed assuming that the actual motion is going to be correlated with the expected one. NPC, for instance, does not penalize much the absence of motion while it penalizes inverse correlated motion. It is, thus, possible that the optimization algorithm (GA) tunes the MCA to perform small movements (or even to avoid motion) in the case of slow motion platforms (Platform 3 and Platform 4). This could explain why the values obtained for Experiment A.1 and Experiment B.1, in the case of high-latency devices, are similar to the no-motion situation. In addition, motion sickness would probably arise in human subjects with Platform 3 and Platform 4, and therefore, a simple yes/no answer makes little sense. Analyzing patterns, however, some answers can be provided and it can be said that there is not enough evidence to support motion-based simulators over no-motion in the following cases: (i) tuning is not optimally performed; (ii) latency is too high regardless of size; (iii) size is too small (as seen in Experiment C.1). Therefore, our experiments suggest that investing resources in a motion platform should only be done if researchers are sure that it would be better than not doing it. Therefore, the answer to our initial question is that motion-based simulators are not necessarily always better than fixed-based simulators, and it can be speculated that only a fraction of the motion-based simulators are significantly effective, for several factors (bad tuning, high latency, small size, etc.).

Size seems to have some importance in motion cueing, because in most cases, an increase in size provides an increase in motion fidelity. This is especially true when changing from size S to M in Experiment C.1. This suggests to advice against the design of very small devices. However, the role of size might have been overestimated, since not all the results point in the same direction. In any case, it seems clear that powerful devices benefit from an increase in size. It can be argued that the effect of size in some platforms is small because motion cueing could be already ruined by other factors, namely absence of power. It can also be argued that the XL devices used in the experiments are not really huge. They could have been larger, but it is worth noting that, whereas the rotational movements of a vehicle could, in some cases, be undistortedly (1:1 scale) reproduced by motion platforms with large rotational DOF because these movements usually have limits, translational movements, on the contrary, are often unbounded (this highly depends on the vehicle, though). For instance, the displacement of a car on the ground plane would never possibly be perfectly reproduced with a motion platform, whereas slopes, bumps and tilts may be. Thus, increasing the size of the motion platform to allow larger translational movements offers only a marginal improvement. In ground vehicles, as the one tested, this is especially true for surge and sway displacements, whereas the vertical axis (heave) is usually easier to handle. The physics of planes, helicopters or even ships is different, and thus, the situation could be different.

The experiments also suggest that the amount of improvement of the 6-DOF device with respect to the 3-DOF mechanism is small in most cases, especially for ideal devices. In Experiment A.1, since only correlation is measured, the differences are marginal. The problems with translational DOF may be one of the main reasons for the surprisingly good results of the 3-DOF device, since the hexapod offers only a small amount of surge and sway translational motion with respect to the 3-DOF device. Real vehicles have translational displacements five or six orders of magnitude larger than the motion space of vehicle simulators [31]. In addition, using the tilt coordination technique, sustainable surge and sway motion can be simulated by means of slow pitch and roll rotations in 3-DOF devices.

VI. CONCLUDING REMARKS AND FUTURE WORK

This study tries to analyze some important questions about motion cueing by performing massive simulations with objective motion fidelity indicators and virtual motion platforms, while making the study as generalized as possible. There are several conclusions that can be drawn from the experiments conducted in this work. The first conclusion is that proper tuning of MCA is of the utmost importance, since it significantly enhances or degrades the quality of the motion cueing.

Another important conclusion is that high power, and thus, low latency, can usually compensate for lack of size, as long as the simulator is correctly setup, although very small sizes could make the vehicle simulator doubtful for proper motion cueing. High latencies, as expected, significantly degrade motion cueing. Even the ideal devices (zero latency) score far from the perfect score, which shows the limitations of this technology.

Regarding the number of DOF, the 3-DOF design performed surprisingly well in the experiments. The 6-DOF, despite being better in a general case, improves the limited-DOF design only marginally in some cases. This result is consistent with the findings of [28].

Regarding the motion vs no-motion question, evidence seems to suggest some room in favor of motion, when it is properly performed. Nevertheless, the factors (low power, low size, poor tuning) leading to favor no motion are not difficult to arise, and represent a real risk for motion cueing in vehicle simulators.

As a summarizing advice, the experiments conducted in this paper suggest that, if motion cueing is needed in a vehicle simulator researchers should: (i) tune the MCA properly; (ii) neither build a motion platform that is too small, nor worry if it is not huge; (iii) invest economic resources in powerful actuators rather than in size, provided that condition (ii) is met; (iv) a 3-DOF design could be enough if cost is a problem. Finally, as a tangential conclusion, these experiments also show the power of simulation, since this kind of study would have been almost impossible without the use of computer simulations.

A substantial amount of future work can be outlined as well, although the effort necessary to complete it would also be considerable. This includes, for instance, extending this analysis to: other motion platforms (2-DOF, 4-DOF or even different architectures of 3 and 6-DOF devices like serial manipulators), other vehicles (planes, helicopters, ships, etc.), different vehicle simulators, other MCA (adaptive, optimal, MPC, etc.), or other objective indicators. For instance, a 4-DOF heave-yaw-pitch-roll design could be interesting to perform further experiments, since it may represent a good compromise between cost and performance for the design of low-cost motion cueing devices. Changing the experiments would obviously change the figures, but it would be of interest to check if the observed patterns are kept.

In addition, it is also possible to perform some experiments with users, although the extension of the tested conditions make this very difficult to setup, unless a great number of research groups are involved. Last, but not necessarily least, it would also be interesting to study the compared effect on motion cueing of other aspects of motion-based vehicle simulators often neglected, such as actuators control methods, visual-motion setups, DOF combination algorithms or mitigation strategies [78].

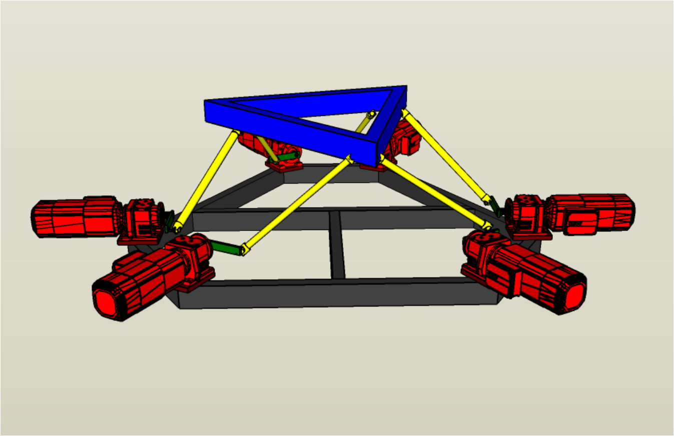

Fig. 1. CAD design of the rotational 6-DOF motion platform.

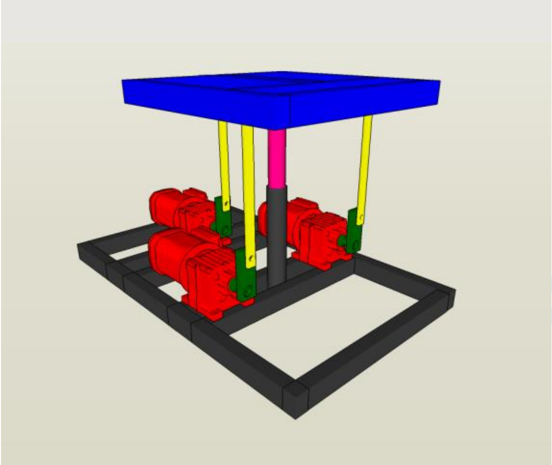

Fig. 2. CAD design of the rotational 3-DOF motion platform.

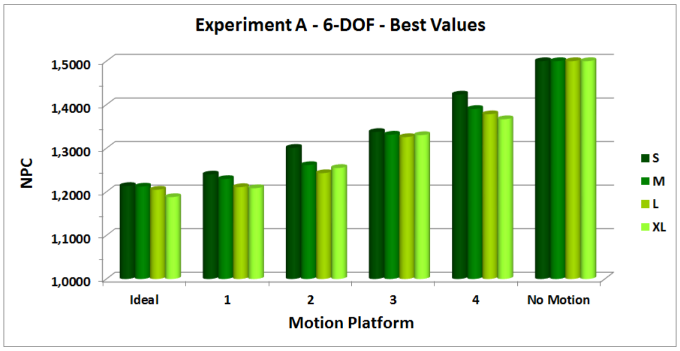

Fig. 3. Graphical results for Experiment A.1 (best values) for the 6-DOF devices.

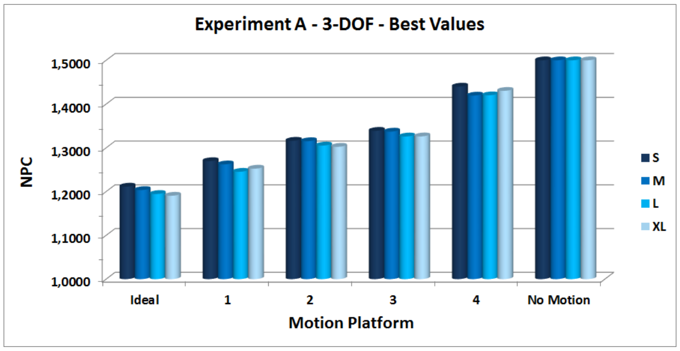

Fig. 4. Graphical results for Experiment A.1 (best values) for the 3-DOF devices.

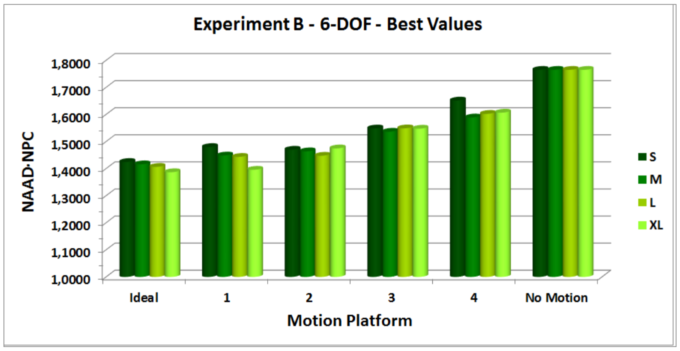

Fig. 5. Graphical results for Experiment B.1 (best values) for the 6-DOF devices.

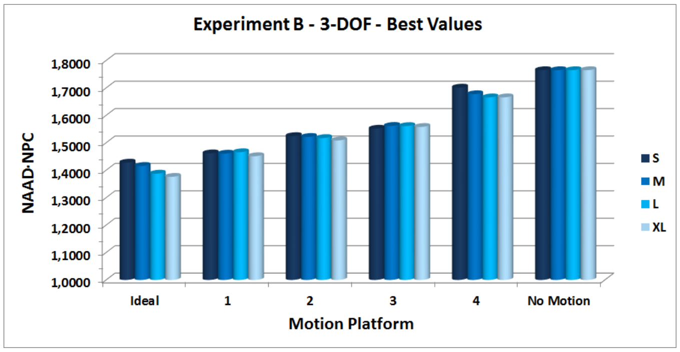

Fig. 6. Graphical results for Experiment B.1 (best values) for the 3-DOF devices.

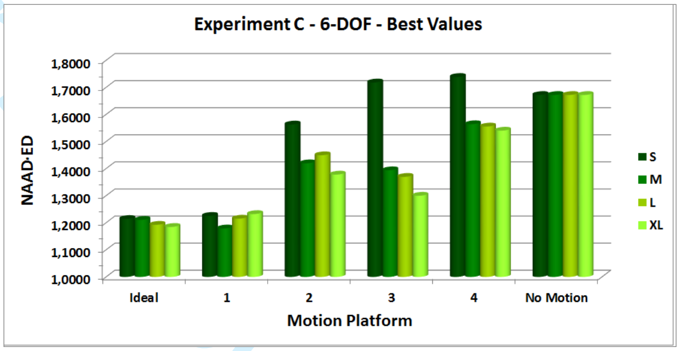

Fig. 7. Graphical results for Experiment C.1 (best values) for the 6-DOF devices.

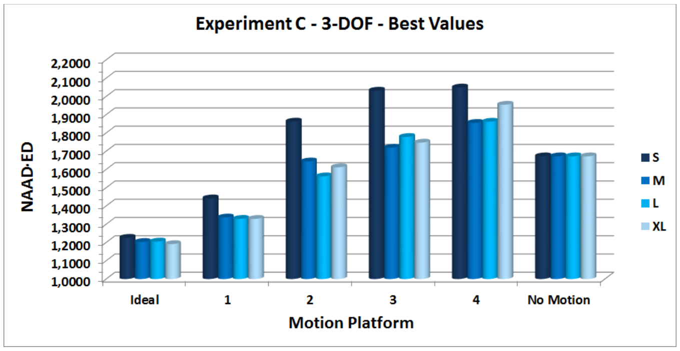

Fig. 8. Graphical results for Experiment C.1 (best values) for the 3-DOF devices.

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