A Survey of State-of-the-art Motion Platform Technology and Motion Cueing Algorithms

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Abstract

The history of moving-based flight simulators begins much earlier than that of driving simulators. Since the seventies of the last century, the commonly used motion system design for flight simulation is a conventional 6-DOF (degree of freedom) hexapod. The first driving simulators with more than thee DOF were based on this kind of motion platform technology as well. However, high demands to platform envelopes due to fast and complex driving dynamics resulted in a huge diversity in motion system design. In particular since the beginning of the 21st century more and more driving simulators with different kinds of motion systems appeared. Associated with the new designs and the challenge to present a realistic driving impression, motion cueing strategies had to be adapted as well. Furthermore, an increasing number of human-related factors influence the process of developing and tuning motion cueing algorithms (e.g. subjective ratings, motion perception research).

It is still an open question which motion platform design suits the demands of a realistic driving simulation best. This presentation will give a survey of currently used motion systems and recent improvements of motion cueing algorithms.

Motion Platform Technology

Early moving flight simulators like the Antoinette training simulator at Airbus in Toulouse were built at the beginning of the 20th century [1]. A central invention for the evolution of motion systems was the construction of a hexapod platform by Gough. Kappel was the first who used this platform as a base for training simulators during the 60s and early 70s. A famous article published in 1966 by Stewart [2] made this kind of platform more popular and it became the standard for flight training simulators. Meanwhile, the first driving simulator with a 3-DOF motion system was operated by Volkswagen [3]. Afterwards it took a long time until the next motion simulators appeared in 1984: a 1-DOF simulator (y-sled) at the IKK (now IFAS) [4] and a 4 DOF system developed at VTI [3]. In 1985 the first driving simulator with a 6-DOF hexapod motion system was started to be operated by Daimler Benz [3]. A few more 4-DOF simulators appeared (Mazda [3] and Trygg Hansa [5]) and the Daimler Simulator was extended with a linear sled [6] before several 6-DOF hexapods were built between 1994 and 2001 (Ford 1994 [7], JARI 1996 [8], BMW 1998/99 [9], Renault 1999 [10], Nissan 1999 [11], IZVW 1999 [12], IFAS 2001 [4], Ford renewed 2001 [13]). In 2002 the Trygg Hansa Simulator was rebuilt at VTI [5] before the high fidelity simulator NADS-1 started operation at the University of Iowa [14]. This simulator consists of a hexapod on a turntable mounted on a big xy-sled and is still the driving simulator with the biggest motion envelope in the world.

In the beginning of the 21st century more and more systems were renewed (BMW 2003 [15]) with modern technology or extended (IFAS 2004 [4] [16], VTI III 2004 [17]). A truck simulator at TU Munich [18], operated since 2004, and a driving simulator with a huge dome (as most simulators have since the beginning of the new century) at KATECH University [19], completed in 2005, are both equipped with a standard hexapod motion system. In these and the following years a remarkable number of new or combined high fidelity system designs were chosen for motion platforms to counter the high demands of fast and complex driving dynamics: Two xy-sled/hexapod simulators (ULTIMATE at Renault 2004 [20], LADS at Leeds University 2006 [21]), an “inverted” hexapod with the cabin mounted below the platform (SimCar at DLR 2005 [22]), an industrial robot arm used as a driving simulator (RoboCoaster at MPI 2007 [23]) and a completely different design consisting of a linear sled, a centrifuge, a 3-DOF gimple and a heave motion system (DESDEMONA at TNO 2007 [24]).

Motion Cueing Algorithms

The term "motion cueing" describes the presentation of visual, acoustic, vestibular and haptic information (cues) with the aim to resemble real movements in virtual environments. However, in many cases it is especially used to express the introduction of haptic cues. In the literature, different names can be found addressing the same kind of algorithm: Motion Cueing Algorithm (MCA), Motion Drive Algorithm (MDA) or Washout Algorithm (WA).

The three classic algorithms, the Classical Washout (commonly used), the Optimal Control, and the Coordinated Adaptive Algorithms are intensively discussed by Nahon and Reid [25]. The Classical MCA bears advantages when it comes to the adjustment of parameters and the structural transparency of the concept. Each parameter that is used has a clear physical meaning. The whole concept is mathematically and computationally simple and easy to implement. On the other hand, only linear filters are used and the parameters have to be tuned on the base of a worst case assumption. Therefore, in normal driving conditions, only part of the platform capacities is used. The other two algorithms are very similar to this basic one. The main difference within the Optimal Control approach is that the filter parameters are obtained in advance through a linear quadratic optimization process, for which the structure and a cost functional have to be given. The great difference in the Coordinated Adaptive Algorithm is that some coefficients in the transfer functions are varied systematically according to an online optimization result. Both have some important advantages (e.g. use of a model of the human vestibular system during the optimization or more realistic behavior of the simulator for non-worst-case situations, respectively) but are afflicted with a loss of parameter transparency, which makes their tuning difficult.

Thus the classical approach is still the base for many algorithms with small changes in single elements of the algorithm. For example there is a nonlinear filter introduced by Renault to counter unwanted washout effects [26], a structure with adaptive high-pass filter parameters, used at the UTIAS simulator [27] or frequency-dependant scaling functions, developed by researchers from Nihon University [28]. One way to get rid of the worst-case-tuning problem related to the Classical Washout is to switch parameters according to the driving situation. This kind of parameter variation is implemented within the Intelligent Adaptive MDA used for the NADS-1 simulator [29] and the Time Variant MCA, which will be introduced to the SimCar simulator at DLR in the near future [30]. A completely different control strategy is followed with the lane position based MDA where the lateral position on the road is used directly to introduce a big part of the lateral acceleration [31]. This algorithm is mainly suitable for highway driving.

Due to the big variations in new simulator designs, a lot of simulator-specific algorithms were developed to take full advantage of the respective motion capabilities. The Model Predictive Control based MCA developed for the ULTIMATE simulator at Renault uses MPC techniques to avoid time delays and to follow the given accelerations as long as possible with a 1:1 scaling [32]. This is especially important for any kind of driving dynamic related studies. Though this algorithm is not only usable for combined hexapod/xy-sled simulators it exposes its advantages the best with this kind of motion systems. To use all DOF of the NADS-1 simulator a special extended MDA for redundant DOF was created [33]. The designs of the DESDEMONA (TNO) and RoboCoaster (MPI) simulators demanded complete new algorithms. The Spherical Washout Filter was therefore developed at TNO to make use of the special abilities of their simulator [34] and MPI is using a Robot Arm Control Algorithm [35]. While DESDEMONA provides completely new possibilities for certain maneuvers (e.g. curve driving) the motion envelope of the RoboCoaster facilitates for example special motion perception experiments bearing valuable information for developing and tuning improved motion cueing algorithms.

Besides the choice of MCA, the tuning of the related algorithm parameters is the second important issue, as demonstrated by Grant et al. [31]. A lot of different methods have been tested to solve this task. For an offline tuning, Human Control Models can be used. The best known Pilot Control Model was developed by Hosman et al. [36]. It combines weighting and transfer functions for the central visual system and the central nervous system. Another approach uses a Motion Perception Model to minimize the pilot sensation error (between simulator and aircraft) by varying MCA parameters (e. g. cost function weights) [37]. Both tuning methods are strongly dependant on the validity of the human behavior or human motion perception models, respectively. Schroeder developed a more general method to optimize the motion cues of a moving-based simulator using empirical data, based upon the Sinacori fidelity criteria (evaluation of the level of motion fidelity, related to the MCA characteristics) [38]. This method analyzes the restrictions of simulator motion capabilities related to certain maneuvers with respect to the trade-off between the filter gains and break-frequencies. It does not result in a fixed parameter set for the used algorithm; nevertheless it provides guidance in MCA parameter choice. Thus it is especially useful for choosing initial parameters and reducing the ranges for possible parameter values before the start of an online parameter tuning using human-in-the-loop methods.

For online tuning (that is tuning of the parameters while operating the real system) there are two possible ways: Either the parameters of the algorithm are varied online based on the driver's comments on current settings or a comparison of given parameter sets (or algorithms) via subjective ratings takes place. Grant and Reid concluded that due to the lack of evaluated integrated perception models mathematical approaches can not accomplish a final tuning of MCA parameters [39]. To shorten the tuning process they developed an expert system which guides the driver (pilot) to a subjectively optimal tuning [40]. Others reported as well differences in obtained parameter sets when doing a subjective online tuning [30] [41]. The online comparison is done in many studies (e.g. [31], [42]) and has the advantage that once a pre-tuned parameter set (or algorithm) was rated as realistic and superior to other attempts it can then be used for the given kind of driving maneuver or scenario. Thus a tuning phase at the beginning of each experiment can be avoided. Additionally, for inter-subject driving data comparison it has the advantage that a possible influence of different tunings on driver performance can be avoided.

Motion Cueing Issues

Taking the motion envelope of the used motion platform as a given constraint to optimal motion cueing there are still many variable factors. The choice of the cueing algorithm and the tuning method has a big influence as well as the accuracy of the used driving dynamics model and the overall visualization and simulator characteristics (e.g. communication delay time, field-of-view, resolution, etc.). Thus the main question regarding the choice of these factors still has to consider the reason for the use of a moving-based simulator: What do I want to use the simulator for? What application do I have in mind? The best choices for a driving dynamic experiment and a driver behavior study are probably different.

Additionally there is always a trade-off between opposing factors. Do I want an algorithm which adapts to either driving task or motion platform restraints or should it be a linear, homogenous motion cueing? Is a simple, transparent and hence good tunable algorithm sufficient for my application or do more complex and variable algorithms provide essential advantages? Do I want to reduce a certain perception error by respective parameter changes on the cost of rising another one (e.g. tilt rate false cue vs. motion lag error)? Can I compare driver performance when introducing different motion cues due to subjectively tuned parameters or is a comparable rating of motion cue realism sufficient?

New revelations and developments in the area of human perception and human factor research may answer some of these questions in the future. Still there will be the need to analyze the given task and to weight all advantages and disadvantages of certain motion cueing influencing factors.

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