Tobias Bellmann
(DLR Institute for System Dynamics and Control)

ROBOTIC FLIGHT SIMULATION COMMERCIALIZED - THE DA42 FLIGHT SIMULATOR
FOCUS TOPIC: SIMULATORS AND HARDWARE SOLUTIONS

The presented project utilizes a standard industrial robot system as motion platform for a light-airplane flight simulator with full motion support. This innovation was only possible through transfer of DLR research results, especially enabling technologies as interactive path-planning algorithms, workspace optimization and safety tests. Having access to 6 years of DLR’s continuing experience with interactive robot based motion simulators and the support of the robot manufacturer KUKA, and the aircraft company Diamond Aircraft, Grenzebach commercialized successfully the first robot based flight simulator for general aviation pilot training.

As the robot is an off-the-shelf component, mass-produced for the manufacturing industry, it is possible to cut the costs for such a simulator from 7-25 M€ to about 1 M€. This renders the simulator interesting for flight-schools with small airplanes, as it allows reducing the number of training hours in real aircraft by 75%. The availability of high-end flight simulators also improves training quality significantly. The commercial product, a full-flight simulator for the Diamond DA42 aircraft, developed during this project, has reached prototype status at the beginning of 2013 and orders for 20+ units are pending.

Olaf Stroosma
(Delft University of Technology, SIMONA)

APPLYING THE OBJECTIVE MOTION CUEING TEST TO A CLASSICAL WASHOUT ALGORITHM
FOCUS TOPIC: NEW METHODS

As part of the new ICAO 9625 simulator qualification guidelines a new method to quantify simulator motion systems has been proposed: the Objective Motion Cueing Test. This talk will feature the author’s experiences in applying this test to several motion configurations of a hexapod research flight simulator. It includes lessons learned which are hoped to assist other practitioners in performing and interpreting the OMCT.

The OMCT excites the combined motion cueing algorithm and motion base hardware in one degree of freedom and with one frequency at a time to construct a transfer function from aircraft model output to motion base response. It also defines some unwanted cross effects to be minimized, such as simulator pitch motion due to aircraft surge. By incorporating the
cueing algorithms or motion filters in the test, in addition to just the robotic characteristics of the motion system and its controller, the test provides a wider view on the pilot’s motion sensations. With today’s high quality motion hardware, the pilot’s perception is now predominantly shaped by the structure and configuration of the cueing algorithm, underlining the importance of this more integrated test.

Many motion bases in use today use a motion cueing or washout algorithm that is based on the so-called classical washout algorithm, described by Reid and Nahon. It also forms the basis for a set of algorithms running on the SIMONA Research Simulator (SRS) at the Delft University of Technology. The talk will briefly review this algorithm as it is implemented on the SRS, with a special focus on aspects that influence the results as measured by the OMCT. Some interesting aspects are: filter reference location, axis transformations, and order of filters. Although not tested in the OMCT, cross-coupling effects exist when multiple degrees of freedom are driven simultaneously.

Performing the OMCT on an actual simulator introduces the questions of how to drive the motion system, how to measure the motion base response as required by the OMCT and how to process the measured data to arrive at the OMCT metric. The talk will briefly introduce the software setup of the OMCT simulation in general and the signal generation in particular. As mentioned earlier, some parameters in the classical washout algorithm can have a significant effect on the OMCT results. An analysis of one aspect, the filter reference location, illustrates this point. It was found that performing tilt coordination rotation around the upper gimbal centroid location, as proposed by Reid and Nahon, instead of around the design eye or OMCT reference point, can alter the shape of the surge and especially pitch response considerably. Data will be presented to show how this is even the case for a relatively small offset such as the 1.20m of the SRS. It is hoped that this and other insights can help other users of OMCT better understand their results.

(Note: this will be a shortened presentation of work to be presented in a paper at the AIAA MST conference in August)

Dr.-Ing. Martin Fischer
(German Aerospace Center-DLR, Institute of Transportation Systems)
SAME, SAME – BUT DIFFERENT: CALIBRATION AND TUNING FOR VARIOUS MOCK-UP CONFIGURATIONS
FOCUS TOPIC: PERCEPTION AND HUMAN FACTORS

Only one mock-up was used in the DLR’s dynamic simulator so far - but soon there will be three different ones:
- the already existing mid-class car mock-up
- a tram mock-up and
- a modular vehicle mock-up which will be composed of a base plate and a number of cockpit and chassis modules which can be arranged in various configurations

This variety in simulator set-ups causes a number of questions, which have to be addressed:
- How can we assure that the performance of the simulator is the same for the different mock-up’s, which is equivalent to different mass distributions and head-points?
- Should we calibrate the set-up’s with respect to physical measures (i.e. certain vehicle dynamic signals) or to human motion perception?
- Are study results obtained with different hardware configurations still comparable if we alter the motion cueing parameters?

The presentation will show the latest enhancements of the DLR simulator, especially focusing on the new mock-up’s. Furthermore, some ideas on how to answer the pinpointed questions will be summarized as a starting point for discussions.
Prof. Dr. Jelte E. Bos
(TNO, Perceptual and Cognitive Systems)

PERCEIVED DISTANCE DURING OSCILLATORY LINEAR MOTION
FOCUS TOPIC: PERCEPTION AND HUMAN FACTORS

When oscillating linearly in the dark, humans perceive tilt at low frequencies and translation at high frequencies. The majority of information is available on tilt perception. We therefore asked seventeen subjects for their perceived distance between the turning points during sinusoidal lateral motion over fixed peak-to-peak distances of 1 and 2 m, both at frequencies of 0.1, 0.2 and 0.3 Hz. Larger distance resulted in larger estimates in all subjects. However, perceived distance only increased with frequency in twelve subjects, while it showed to decrease with frequency in four. One subject showed no frequency effect. We conclude that in some subjects the central nervous system uses high-pass filtering of otolith afferents, typically coding for inertial and gravitational acceleration to obtain an estimate of acceleration due to motion only, and integrates this estimate of inertial acceleration over time to get an estimate of distance. In other subjects, however, higher order cognitive processing seems to be at issue, possibly taking prior knowledge into account.

Dr. Daan Pool
(Delft University of Technology, Aerospace Engineering, Control & Simulation)

EVALUATING SIMULATOR MOTION CUEING FIDELITY BASED ON BEHAVIORAL MEASUREMENTS
FOCUS TOPIC: PERCEPTION AND HUMAN FACTORS

Finding a proper method or metric for evaluating simulator motion cueing fidelity is something that simulator manufacturers, engineers, and legislators still struggle with, even after decades of experience in ground-based simulation. From 2006 to 2012, a large research project has ran at the Control & Simulation Division at Delft University of Technology, which aimed to develop a novel objective method for the assessment of flight simulator motion fidelity. This proposed method involved the capturing of pilots’ responses to visual and (simulator) motion cues during manual tracking tasks using multimodal pilot models, to obtain quantitative measurements of pilots’ usage of motion information and increased understanding of how these different modalities interact during manual aircraft control. Furthermore, an attempt was made to quantify the behavioral discrepancies that may occur in flight simulators compared to real flight, and to relate these observed discrepancies to the choices in the presentation of simulator motion cues.

In this project, pilot tracking behavior was found to be strongly affected by degraded simulator motion fidelity. With simulator motion cues that are increasingly attenuated compared to the 1-to-1 case, pilots are seen to rely increasingly less on the presented motion information, reverting to a more visual-based control strategy. Even though these results are very important in that they show adaptation of pilot low-level control behavior to bad simulator cueing, still some work remains to be done before the conclusions from this work can be applied for true behavior-based optimization of simulator motion cueing in both aircraft and automotive simulation.

This presentation will address a number of research efforts that are currently being performed at our group to answer some of these important questions. Examples of ongoing and planned research projects investigating simulator motion fidelity that will be presented are:

1) Evaluation of the applicability of our conclusions and methodology to more operationally relevant manual control tasks, such as tracking tasks where additional cues from an out-of-the-window view are available in parallel to motion cues and discrete maneuvering tasks as performed regularly during aircraft control

2) Applying our methods to find optimal motion cueing settings for car driving simulation
3) Relating the observed changes in control behavior due to degraded motion fidelity to the results obtained from perceptual approaches to assess simulator motion fidelity, such as measured visual-vestibular coherence zones.

4) Evaluating the extent to which reduced cueing fidelity affects simulator-based pilot training and its transfer to the real aircraft, with a focus on relating the level of simulator fidelity to the development of pilots’ internal representations of manual aircraft control during simulator training.

We firmly believe that the increased understanding of human control behavior and perceptual processes during manual vehicle control that can be gained from such research is key to the development of a well-founded approach to the assessment of simulator motion cueing fidelity.

Anca Stratulat  
(PSA Peugeot-Citroën, Cognitive Sciences and Human Factors)  
Philippe Vars  
(PSA Peugeot Citroën, Driving Simulation Center)  

MOTION PERCEPTION ON DYNAMIC DRIVING SIMULATOR SHERPA²  
FOCUS TOPIC: PERCEPTION AND HUMAN FACTORS

A series of research studies on motion perception on dynamic driving simulators showed that the use of a constant gain around 0.6 is commendable [1,2]. However, we observed that on our dynamic driving simulator, SHERPA², this gain is considered as being too high, meaning that the acceleration still is overestimated. Therefore, we are using a linear gain rather than a constant gain, this gain decrease from 0.4 to 0.2 with the increase of simulated acceleration/deceleration for the current driving situations. This value was chosen empirically as a result of the observations gathered during the use of the simulator and the mechanical limits of the simulator. However, a perceptual validation of this gain value should be considered. In parallel, our studies on motion perception showed that there is a perceptual difference between acceleration and braking, and that the ratio of tilt and translation should be adapted to the level of simulated acceleration. However, these results were obtained on passive drivers (they were submitted to a predefined acceleration) [3,4], and therefore we question ourselves how the use of tilt-coordination in combination with translational motion influences the motion perception during active driving (man-in-the-loop). In order to answer to these questions, a series of experiments are considered during the next year.

Mattia Bruschetta  
(University of Padova, Department of Information Engineering)  
**A REAL TIME IMPLEMENTATION OF MPC BASED MOTION CUEING STRATEGY**  
**FOCUS TOPIC: NEW METHODS**

One of the main difficulties in the design of effective Motion Cueing (MC) algorithms is given by the complex nature of the human perception systems, since from a physiological point of view the role and priorities of stimuli of different nature to the overall perception of accelerations is not yet well known. In most dynamic simulators, motion cueing algorithms are based on the so called “classical” approach that basically consists of a sequence of filters combined in order to:

- remove low frequency components of accelerations and velocities obtained from the vehicle dynamic model;
- transfer part of the low frequency translational accelerations to the angular dynamic using a low pass filter (tilt coordination);
- limit the platform motions with a further high pass filter to keep the platform in a neutral position. This is commonly called washout action.

This simple strategy has seen a wide range of implementations over the years. However, it has some shortcomings:

- being a filtering based approach, it is not possible to guarantee stimuli consistency between the dynamic simulation environment and the real platform movements;
- it cannot explicitly handle hard constraints on the platform movements and accelerations;
- it is not possible to exploit any available information on the driver’s behavior in the future;
- the tuning of the algorithm is in general difficult, since it is not easy to give physical interpretation to most of the parameters.

Here an experimental application of a MC algorithm based on the Model Predictive Control (MPC) technique for a small size dynamic simulator is described. MPC is a model-based control methodology that allows to effectively handle limits on the working space and to exploit information on future reference signal. The idea of using MPC for MC is not new, but in these early works, the proposed solutions are not used for experimental application in real situations. Moreover, they focus on investigating the prediction capabilities rather than on taking advantage of the optimization approach of MPC. A real time implementation of an MPC based motion cueing strategy in experimental environment is described. Performance of the implemented algorithm is evaluated on the field by professional test drivers using an innovative platform. In particular, it is shown that the MPC based approach gives satisfactory performance even in the case where no prediction of future driver’s behavior are available, it allows to effectively handle the platform working area, to limit the presence of those platform movements that are typically associated to driver motion sickness, and to devise simple and intuitive tuning procedures.
Filip Van Biervliet
(AXx Acceleration Worx)

**FFS MOTION FIDELITY, A NECESSARY STEP FORWARDS**

**FOCUS TOPIC: NEW METHODS**

Loss of Control is now identified as a major aviation safety threat. Dedicated manual flight training in FFS - full flight simulators - is part of the answer. However there is a close link between pilot control strategy and motion perception. Therefore manual flight training is only effective if there is adequate motion fidelity.

There is a discrepancy at this moment between the public’s perception of the level of sophistication and performance of FFS and their actual performance. In the last 30 years, there has been very little improvement in flight simulator motion from the pilot’s perspective.

The author (age 54, aerospace engineer TUD and airline type rating instructor) developed a new and successful motion control method to improve motion fidelity. Its characteristics and effects on pilots in a normal training environment will be discussed.

The author has 30 years of in-depth field experience on existing FFS, piloting skills on a variety of large jets (15,000 hrs on B737, A330 and MD11) combined with academic flight handling knowledge.

Suzanne Nooij
(MPI for biological Cybernetics, Human perception, Cognition and Action)

**ROLL RATE THRESHOLDS IN DRIVING SIMULATION**

**FOCUS TOPIC: PERCEPTION AND HUMAN FACTORS**

Motion based driving simulators have a limited physical workspace. One method to perceptually expand their workspace is to simulate sustained linear acceleration by a combination of translation and tilt below drivers’ vestibular threshold (tilt coordination). The tuning of tilt coordination filters is often done empirically, without considering the variability of perceptual thresholds. However, previous studies have shown that the perceptual threshold for tilt derived from vestibular self-motion information alone varies when visual cues are also provided. There is also evidence that the mental load induced by complex tasks such as driving influences threshold values. Active driving simulation provides a variety of visual and vestibular cues as well as demands on attention which vary with task difficulty. It is thus important to measure perceptual thresholds for tilt in conditions that closely resemble typical driving simulation to determine how different sensory and cognitive factors contribute to drivers’ motion sensitivity. Knowing the relative contribution of these components will lead to more optimized simulated driving.

To assess these factors, we measure roll rate perception thresholds under 4 different conditions which include an active motor task, visual information and combined translational and rotational motion. In each condition, motion stimuli are adjusted according to a single-interval adaptive procedure (yes-no task) specifically designed to induce a neutral response criterion. This procedure allows for an unbiased estimate while at the same time minimizes the number of presentations. The first condition provides drivers with full visual and vestibular motion cues. They actively drive through a curve while the tilt coordination filter systematically varies the roll rate saturation level. This allows the identification of the roll rate threshold during active control of self-motion. The second condition is the same as condition 1 but drivers sit as passive observers in the simulator cabin and report tilt perception while the simulator drives them through the curve. Here, the roll rate saturation is adjusted to determine the absolute threshold in passive conditions, with multisensory (visual and vestibular) stimulation still presented. In the third condition drivers are deprived of the visual stimulus as well, to assess the effect of lateral acceleration on drivers’ roll rate detection threshold. In the fourth condition, the absolute roll rate threshold is measured removing every additional sensory cue to self-motion. Drivers report here the perception of tilt while being passively tilted in darkness. Questionnaires about motion sickness, simulation realism and cognitive workload are also collected for all drivers before, during and after each condition.
Overall, perceptual thresholds are expected to increase with task difficulty and attentional load. If so, this will allow for higher roll rates to be employed for tilt coordination without losing simulation fidelity. Results from the planned experiment will be discussed with regards to previous literature, motion simulator workspace and motion drive algorithms.

Bruno Augusto  
(Swedish National Road and Transport Research Institute)  
METHODS TO IMPROVE AND EVALUATE THE MOTION SENSATION IN DRIVING SIMULATORS

Achieving a lifelike sensation of longitudinal velocity and acceleration is a fundamental difficulty even for the most advanced driving simulators. It is also an aspect of great importance in most simulator studies. The increasing focus on driver assist systems as well as on CO2 issues, further pushes the need for realistic speed and acceleration cues, since these topics are ultimately related to driving style. The sensation of acceleration, speed and distances depends on several factors such as level of detail in the graphics, vibrations, sound, peripheral vision, strategies and control algorithms for the moving base platform etc. While some research on how humans perceive motion has been done, little is known on how much the lack of a certain cue or the addition of another one affects the driver’s behaviour in the simulator. The Memos project aims at investigating the coupling between different driving cues and the perception of longitudinal motion. More specifically, visual, audible, haptic and vestibular impressions are combined in different manners to try and identify how they influence the sensation of longitudinal translational speed and acceleration. The project is divided in three parts from which two are now complete, and the presentation at hand will discuss some of the already available preliminary results.

Jürgen Pitz  
(FKFS, University of Stuttgart, Automotive Mechatronics)  
THE NEW STUTTGART DRIVING SIMULATOR - TECHNOLOGY AND APPLICATIONS

The new Stuttgart Driving Simulator: This presentation gives an overview of the new Stuttgart Driving Simulator, which has been designed and realized in a joint effort of Stuttgart University and FKFS. The driving simulator is based on a motion system with eight axes. In terms of motion space it is currently the largest motion simulator in Europe. The simulator supports the exchange of real passenger cars and is capable to perform interactive proband studies in a highly immersive environment.

The main topics of the presentation are the setup of the Driving Simulator and the hardware-in-the-loop integration of real automotive electronic systems with an “electronic horizon” for driver assistance systems, e.g. a real-time GPS simulator on the radio frequency level. Furthermore the paper presents selected research and development tasks.

Dr. Paolo Pretto  
(MPI for biological Cybernetics, Human perception, Cognition and Action)  
PERCEPTION-BASED MOTION SIMULATION  
FOCUS TOPIC: PERCEPTION AND HUMAN FACTORS

This project aims to bring the impression of simulated motion as close to reality as possible by implementing psychophysical laws of perception into the control framework of simulators. Human motion perception models are experimentally tested in driving and flying scenarios
using our MPI CyberMotion Simulator in order to enable a new generation of highly effective motion simulators.

Decades of development in simulation technology have produced a variety of high-fidelity simulators that are capable of excellent motion rendering within wide operational ranges. Yet, very often simulator users experience dizziness and discomfort even with the most advanced motion systems. One of the main reasons for this well-known problem is the mismatch between the rendered motion and its actual perception by the simulator user.

The WABS project aims to develop control systems for motion simulators that are able to create a more realistic impression of motion by generating motion that is perceptually correct rather than physically correct. This new approach exploits the most up-to-date knowledge of human motion perception models to implement real-time, platform-independent control algorithms for a more convincing motion rendering.

Frank M. Cardullo  
(State University of NY, Binghamton)  
VECTION: WHAT IS IT AND CAN A SIMULATOR VISUAL SYSTEM INDUCE THE PHENOMENON?  
FOCUS TOPIC: NEW METHODS

Visually induced self-motion, often referred to as vection, is a phenomenon that is often observed in the real world. The famous railroad station paradox is an often quoted example. In this manifestation a person in a stationary train experiences the illusion that he/she is moving when the adjacent train begins to move. Once the person realizes that he/she has not received vestibular or somatosensory stimulation or gazes at a fixed object the illusion is destroyed and replaced with a veridical sense of homeostasis. Past research has indicated that there is latency in the onset of the vection illusion from about a second to as long as 10 seconds. Furthermore it has been found that this latency can be reduced to as little as 0.1 second if a vestibular stimulus of even a jolt in the appropriate direction. However it also has been shown that a superliminal vestibular stimulus in the wrong direction will abruptly destroy well developed vection. Until recently virtually all this research has been conducted in a laboratory and not in a flight simulator.

This presentation will review the recent literature to assess the extent to which the above questions have been answered. It will also discuss the development of a novel approach to quantitative metrics for assessing the ability of simulator visual systems to induce vection.

Johann Schwandtner  
(AMST – Systemtechnik GmbH)  
AN INNOVATIVE APPROACH FOR MOTION CUEING ON A SEVEN-AXIS MOTION SIMULATOR  
FOCUS TOPIC: NEW METHODS

Most motion based flight simulators use a conventional six degree of freedom (DoF) hexapod (Stewart platform) system for motion generation in all directions and orientations. The AMST ASD (Advanced Spatial Disorientation trainer) can also rotate without limit around its vertical centre axis, providing seven mechanical degrees of freedom for motion simulation. Motion cueing algorithms are needed to transfer aircraft forces to the limited workspace of a simulator. Most hexapod-based motion simulators still use algorithms based on the classical washout concept. This concept uses a “simple” mathematical structure (high and low pass filters as well as tilt coordination) to calculate the movement of the simulator depending on the aircraft accelerations. Although this control structure is used in many applications, two drawbacks should be noted: a) because of the concept based on linear filters, the envelope must be designed for worst case scenarios; in normal operation only part of the motion envelope is therefore used; b) there is no accounting for the perception of the pilot: primarily the perception of motion should be realistic and not necessarily the motion itself. (It is known
from perceptual studies that actual motion may not need to exactly match the motion to be simulated.)

One way to minimize the discrepancy between real and simulated motion could be implementation of efficient numerical optimization techniques. The main objective of this optimization is the minimization of the deviation of perceived pilot motion induced by the simulator compared to perceived pilot motion in the real aircraft. A second, but also important objective, is the constraint of the staying within the workspace. Such a problem is known as an optimal control problem. Mainly two methods can be found to solve optimal control problems: a) the indirect method and b) the direct method. The approach described herein uses the second method. Therefore the optimal control problem must be discretized and converted to a nonlinear programming (NLP) problem. Then efficient NLP-solvers can be used for minimizing the cost function, varying the free controls.

It is clear that mathematical optimization algorithms can be used for this problem, but both mathematical models of human motion perception as well as a kinematic model of the motion system are needed. The kinematic model of the AMST ASD is derived with a mathematical analysis package. The mathematical formulation of human motion perception is more difficult. For this aspect, knowledge gained as a partner during the SUPRA project, makes this possible. The feasibility of this approach can be confirmed and the first profiles show encouraging results.