New technologies & applications in the Desdemona simulator

Mark Wentink, Bruno Grácio, Eric Groen, Philippus Feenstra, Wim Bles

TNO Defense, Safety and Security, Soesteberg, The Netherlands

Abstract

The technologically advanced motion base of the Desdemona research simulator at TNO in the Netherlands provides a completely new approach to motion cueing in flight simulation, as compared to the conventional hexapod design. In addition, for Network Enabled Capabilities, the simulator is incorporated in a networked environment that comprises of three fixed-base F16 cockpits and Desdemona with the fourth cockpit. Our paper gives an overview of motion cueing solutions and applications for Desdemona in flight simulation.

Desdemona has a centrifuge design motion platform with the unique capability to simultaneously move the cabin horizontally over the radius (8 meter diameter) and vertically in heave (2 meter stroke). In addition the gimbaled cabin has unlimited rotation around any arbitrary axis in space. This motion layout supports interesting new solutions to motion cueing that enable simulation and training of flight manoeuvres that are difficult, if not impossible, to simulate in conventional hexapod flight simulators. The solutions could typically apply to:

- **Upset recovery simulation. Desdemona can simulate typical G-loads of up to 3G in combination with large attitude changes.**
- **Sustained acceleration cueing. The capability to simulate both onset cues (Desdemona has 6 degrees-of-freedom) and sustained cues, facilitates solutions that combine Dynamic Flight Simulation with hexapod-cueing.**
- **Helicopter simulation. The 8 meter linear track can be used to accurately simulate onset cues during hovering.**

In this paper we will elaborate on new solutions for motion cueing in Desdemona and address the potential benefits in simulator training. An example is given of a motion cueing filter that correctly deals with coordinated roll manoeuvres (in turns) and uncoordinated rolls (aileron roll), something a hexapod flight simulator with classical motion cueing cannot do. This type of motion cueing filter could be used in a simulation of upset recovery with large bank angles or fighter aircraft maneuvering.

1 Introduction

1.1 Background

In co-operation with TNO Human Factors, AMST Systemtechnik developed an advanced simulator motion system based on a 6 Degrees-of-Freedom (DoFs) centrifuge design. The simulator cabin is suspended in a freely rotating gimbal system (3 DoFs, >360°) which, as a whole, can move vertically along a heave axis (1 DoF, ±1m) and horizontally along a linear arm (1 DoF, ±4m).

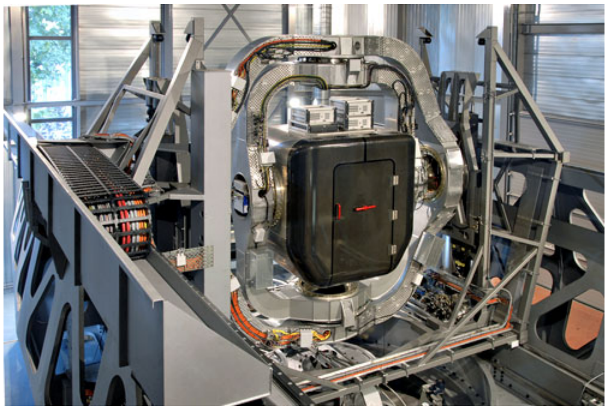

Figure 1: Desdemona Simulator.

To provide sustained centripetal acceleration (1 DoF, 0-3g), the linear arm can spin around a central yaw axis. Unique about Desdemona's 6 DoFs motion capabilities is that it can combine onset cueing along the x, y and z-axis (like a hexapod simulator) with sustained acceleration cueing up to 3g (like a Dynamic Flight Simulator). In addition, unusual attitudes and large attitude changes can be simulated one-to-one. Desdemona was developed as a spatial disorientation training and research simulator with applications in flight simulation, driving simulation and astronaut training. TNO develops the motion cueing algorithms for Desdemona.

In our simulator research the human is central, and our facilities were designed to develop Human Centered Simulation solutions for research and training purposes. Desdemona serves this purpose as well. Typical research areas for TNO, where human behavior in a moving environment is critical and that require a human centered research approach, are:

- Motion simulation and cueing
- Driving (simulation) research
- Flight (simulation) research
- Motion perception
- Mission simulation
- Space physiology

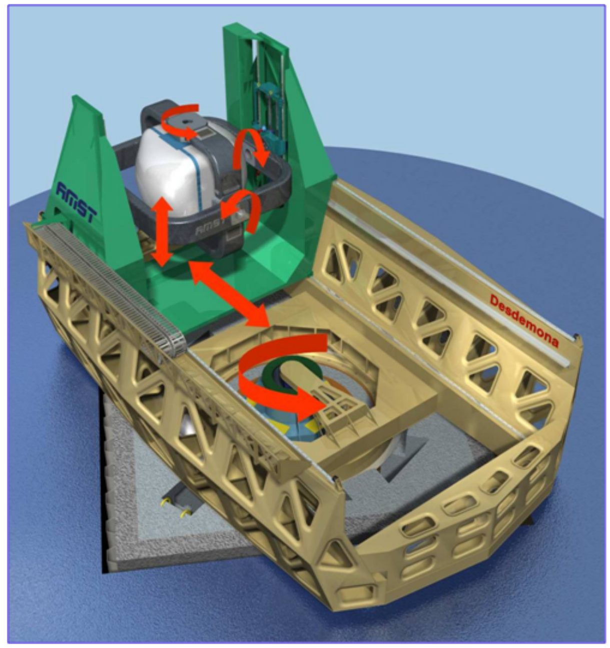

Figure 2: Desdemona simulator with discriminated DoF.

- Motion comfort

1.2 Goal

This paper points out the benefits of new technologies in motion simulation introduced by the Desdemona motion platform, as compared to standard hexapod design. Especially with regard to the simulation of specific maneuvres such as higher G-loads, and large coordinated and uncoordinated roll maneuvers. In a hexapod simulator all six pods have to act in parallel to move the cabin. It will be made clear that some of the typical limitations of the parallel kinematic design of a hexapod motion platform, such as coupling between rotations and translations, are overcome by the serial kinematic design of the Desdemona platform.

	ψ_{centr}	R	H	ϕ_{cab}	θ_{cab}	ψ_{cab}
Max. Position	>360[°]	±4[m]	±1[m]	>360[°]	>360[°]	>360[°]
Max. Velocity	155[°]	3.2[m/s]	2[m/s]	180[°/s]	180[°/s]	180[°/s]
Max. Acceleration	45[°]	4.9[m/s^2]	4.9[m/s^2]	90[°/s^2]	90[°/s^2]	90[°/s^2]

Table 1: Desdemona technical specifications.

2 Conventional hexapod motion platform

2.1 Parallel design

Almost all simulators in operation today are based on a hexapod design, also known as Stewart platform [1]. The six pods translate synchronously in order to move the simulator platform in a certain direction. It is a parallel kinematic design. Typical advantages of such a design are relatively high payload and high stiffness (and bandwidth). Disadvantages are the limited motion space (especially in rotation), and motion coupling in all directions. All motion is coupled, since the pods all have to translate simultaneously irrespective of the direction or type of motion. In simulators the motion of the pods (and thus the cabin) is usually commanded by a motion cueing filter that transforms modelled aircraft motion into confined simulator motion. The typical layout of the motion cueing filter and its drawbacks are discussed next.

2.2 Motion cueing

Figure 3 shows the layout of a typical motion cueing filter already described by Conrad et al. [2] in 1973. Almost all motion cueing filters that are implemented on full flight simulators today are based on this classical design. The filter basically consists of four channels that, together, transform aircraft motion into simulator motion cues. Conrad et al. based their design on four important conjectures:

1. The pilot vestibular system senses aircraft specific forces and angular rates.
2. Motion cueing should render specific forces and angular rates, rather than related variables such as velocity and position of the aircraft.
3. When rendering motion cues, it is desirable to preserve certain physical relations between motion cues (e.g. in coordinated flight the specific forces in the simulator should preferably compensate for the gravity components due to rotation, just as in the real aircraft).
4. Linear time invariant washout is desirable because it allows the pilots to judge different cases by comparing relative changes in cues.

In the classical washout filter aircraft onset-cues (high-frequency) are simulated by shortly translating or rotating the motion platform, after which the translational and rotational motion is gradually washed-out until the simulator cab returned to its neutral position again. Sustained cues such as the take-off acceleration are simulated by tilting the cabin slowly backwards with respect to gravity. The occurring gravity component can not be distinguished from inertial acceleration. (Einstein's Equivalence Principle). These principals can be modelled mathematically by four motion channels in the washout filter:

1. High-pass filter channel that filters aircraft specific forces such that only onset cues are simulated in this channel (resulting in limited displacements).
2. High-pass filter channel that generates rotational onset cues (resulting in limited rota-

tions).

3. Tilt coordination channel that simulates sustained specific forces, that were not already simulated in the high-pass channel, by tilting the cabin with respect to gravity.

4. Gravity coordination channel to compensate for the rotations build up in the rotational channel. The resulting gravity component is compensated by linear acceleration of the simulator in case of coordinated flight.

In practise, the gravity compensation channel is usually left out of the implemented filter, since it uses up too much motion space. Small rotations from the rotational high-pass onset channel already require considerable translation of the motion platform to equalise the gravity component. However, lately, substantial evidence has been published that shows the importance of correct specific force cues on pilot perception and control behavior [3]. To compensate the false specific forces due to rotations in the rotational channel it is required to implement at least a similar structure as the Gravity coordination channel (4). The Lm^2 filter [4] is an example of a recent motion cueing filter that introduces Gravity coordination again.

2.3 Applications

Motion cues generated by a classical motion cueing filter are typically short onset cues and low-frequent sustained forces that build up slowly in the simulator due to the $3^{\underline{o}}/\mathrm{s}$ tilt rate limit normally used in the tilt coordination channel (3 in Figure 3).

Simulation of military aircraft manoeuvres with the classical motion cueing filter is rather difficult due to their fast dynamics. However this motion cueing filter is adequate for commercial flight simulators since commercial aircraft motion is typically composed of low-frequency rotations [5]. Classical washout is widely used since it is easy to implement, is composed of linear filters and the tuning of the algorithm is transparent [6]. Typical manoeuvres performed by commercial simulators include take-off manoeuvres, turn-entry manoeuvres and throttle pulse manoeuvres; which are also used for motion filter evaluation [7, 8, 5]. Classical motion cueing filters are also used in car simulation, but in this case, the simulator configuration is often more complex.

2.4 Shortcomings

Types of motion cue errors [9]:

1. False cues
2. Scaling or missing cues
3. Phase errors

Experience has shown that false cues are the most destructive cueing errors from a perceived fidelity point-of-view [9]. Classical washout filter contains several false cues that are inherent to its design. Examples are:

- Limiting that occurs near the simulator motion envelope limits. This event creates a deceleration of the simulator cabin that is inexistent in the aircraft.

- Position washout, since the simulator cabin needs to return to neutral after an onset cue. If the washout is not performed, the simulator could not have enough motion space to perform the next cue.

- Tilt coordination, since it is an artefact used to obtain sustained cues of specific force's. The extra angular motions that are used to tilt the motion platform generate false cues. Abrupt changes in the specific force also tend to generate false cues because the simulator cannot cope with those due to the rate limiter. The rate limiter is used to guarantee that the angular rates induced by tilt coordination are below the human threshold.

Classical washout motion filters have to be tuned for the worst case scenario because the algorithm contains fixed parameters. This makes that the

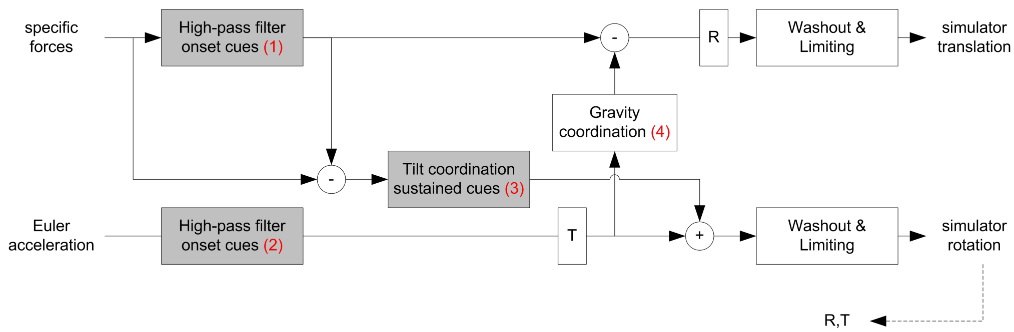

Figure 3: Typical layout of (classical) motion cueing filter for flight simulation.

motion envelope is not used in a efficient way. The linear properties of this algorithm are also a disadvantage since they do not take into account the nonlinearities of the human motion perception system [6].

3 Desdemona motion platform

3.1 Serial design

The Desdemona motion platform is based on a serial kinematic design. The DoF form a cascaded system beginning with centrifuge yaw followed by radial and heave motion, then the roll gimbal, then yaw and finally pitch. Each of these DoF can be moved independent of the others, for example, to simulate aircraft pitch only the pitch axis is moved. Even more so, (large) attitude changes of the simulator cabin are completely decoupled from linear motion of the cabin. In contrast to conventional hexapod systems, where rotational motion is simulated at the cost of motion space for translational motion.

Desdemona's centrifuge axis (the first DoF) allows for continuous G-loads up to 3g.

The serial design of the gimbals in which the cabin is suspended allows for continuous rotation ($>360^\circ$) around any arbitrary axis in space. Large (uncoordinated) aircraft attitude changes can be simulated.

3.2 Motion cueing

The serial motion layout of the Desdemona simulator requires a different motion cueing algorithm that fully employs the advanced possibilities such as continuous rotations and G-forces through centrifugation. For lateral motion cues, a new algorithm was developed that can both simulate uncoordinated and coordinated roll-manoeuvres (in combination with higher G-forces).

Figure 4 shows an overview of the basic principle of the Desdemona lateral motion filter. Onset cueing is left out for simplicity. The filter consists of a feedback controller on lateral specific force using the simulator roll angle as controlled variable (1,4), plus a roll rate feed-forward channel (3). In the specific force feedback loop the calculated specific force in the simulator cabin is compared to the required specific force coming from the aircraft model, the difference is compensated for by tilting the cabin in roll (2). The so-called Jacobian feedback structure used in the motion filter is a well known solution in controlling a serial robotic arm. If the magnitude of the aircraft specific force is larger than 1g, then Desdemona's centrifuge axis can be used to increase the G-load in the simulator (e.g. 2g in a coordinated 60º turn).

Aircraft roll rate is directly injected in the feedback loop at (3). If aircraft roll is coordinated and thus accompanied by zero lateral specific force, the specific force feedback loop will try to 'washout' the roll rate and roll angle of the simulator

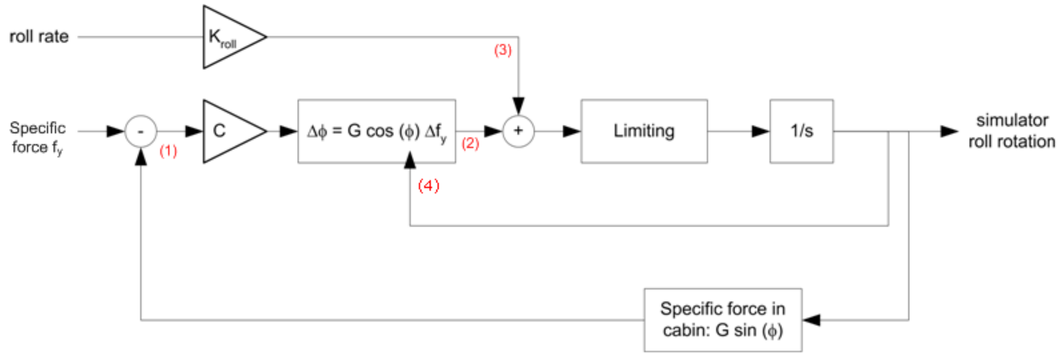

Figure 4: Desdemona lateral motion filter.

cabin so that the specific force in the cabin becomes zero again. In this case only the roll onset is simulated, any sustained roll will be diminished in the feedback loop. In case of an aileron roll where the lateral specific force is not zero or a manoeuvre with a large side-slip angle, the simulator roll angle will not wash-out in the feedback loop. Instead, the roll angle will increase to follow the aircraft lateral specific force in the simulator. The cabin will even rotate over 360º if the aircraft does so too. Both coordinated and uncoordinated lateral manoeuvres are simulated by the same motion cueing filter.

3.3 Motion Cueing evaluation

The figures below show two applications of the Desdemona motion cueing solution in lateral manoeuvres that involve roll and/or lateral specific force. In both cases we assume the aircraft sharply rolls towards a 45º bank angle. The roll acceleration of the aircraft is modelled as a simple first order response to a stepwise control input on the steering column. The roll acceleration response is shown in Figures 5 and 7 as a dotted line. The resulting aircraft bank angle is shown as well, eventually the aircraft banks 45º.

The first manoeuvre is correctly coordinated, the aircraft enters a turn and the lateral specific force in the aircraft is zero (the dinner trays stay where they are!). In the second manoeuvre, despite the roll of the aircraft, the aircraft does not go into a coordinated turn, the flight path of the aircraft is less curved or even straight ahead. The second manoeuvre resembles an aileron roll or a manoeuvre with substantial side-slip. Dinner trays slide of the tables due to a significant lateral specific force of about 0.7g caused by gravity.

In both examples the roll gain in the Desdemona motion cueing filter is set to 0.5 and the specific force gain is set 1.

In the first manoeuvre (Figures 6 and 8), the Desdemona motion cueing filter correctly simulates the roll acceleration onset when the pilot suddenly moves the steering column to the left. In order to reduce the lateral specific force that builds up in the simulator (due to the roll angle), the roll acceleration is quickly washed-out by the specific force feedback loop. Since the aircraft manoeuvre is coordinated, the lateral specific force is zero in the aircraft. Due to the feedback loop the lateral specific force in the simulator does not exceed 0.3m/s^2.

In the second simulated manoeuvre (Figures 7 and 8), the lateral specific force in the aircraft increases with the bank angle of the aircraft. The manoeuvre is uncoordinated. Again the roll onsets are correctly cued in the simulator. Instead of returning to an upright position, the simulator cabin now rolls to the same bank angle as that in the actual aircraft, being 45º. The gimbals of Desdemona allow for unlimited rotation, therefore the cabin orientation can also follow complete aileron rolls of 360º if necessary.

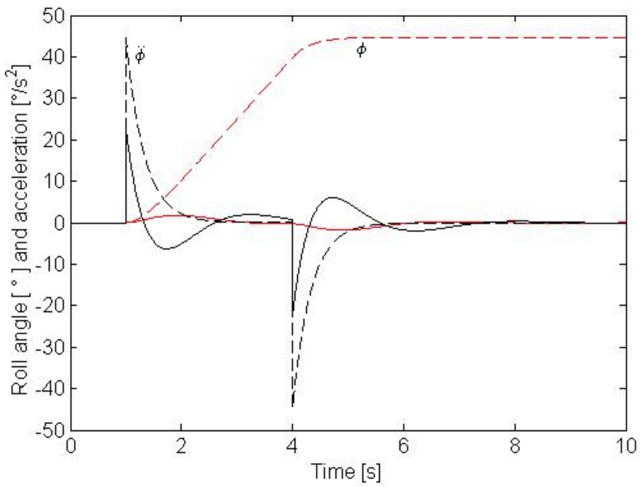

Figure 5: Roll angle (in red) and roll acceleration (in black) in the aircraft (dotted) and in the simulator (solid) during a coordinated roll manoeuvre. Remember that the roll scaling is 0.5.

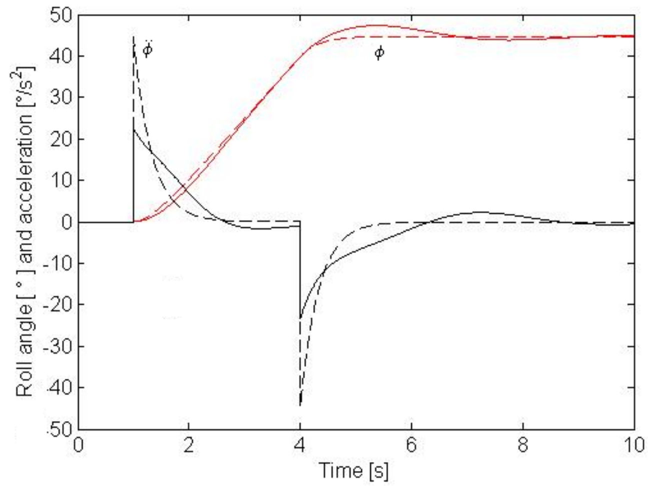

Figure 7: Roll angle (in red) and roll acceleration (in black) in the aircraft (dotted) and in the simulator (solid) during an uncoordinated roll manoeuvre.

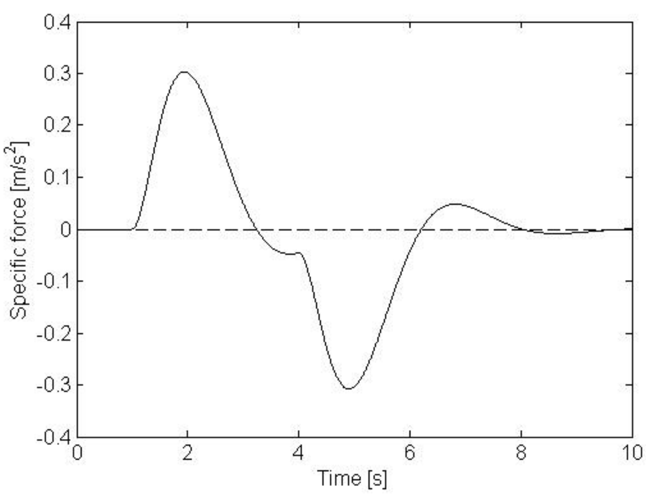

Figure 6: Lateral specific force in the aircraft (dotted) and in the simulator (solid) during a coordinated roll manoeuvre.

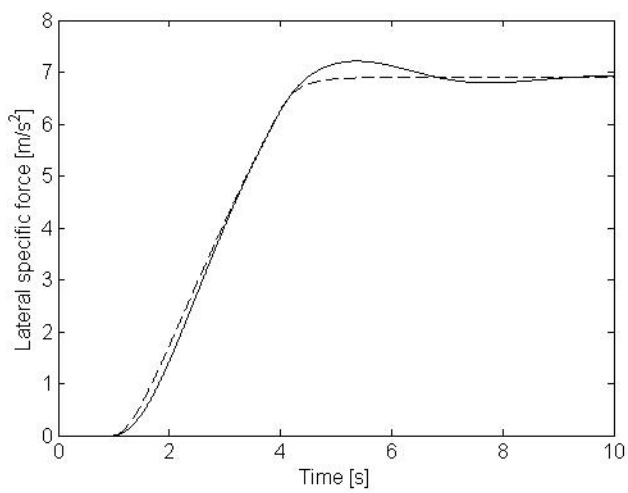

Figure 8: Lateral specific force in the aircraft (dotted) and in the simulator (solid) during an uncoordinated roll manoeuvre.

3.4 Applications

Because of the kinematic design of Desdemona, we believe that we can enlarge the motion space of the simulation, when compared with hexapods. This was illustrated already for the different roll manoeuvres. Elaborating on this approach we believe that upset recovery simulation involving large pitch and roll angles as well as sustained G-loading of up to 3g is also possible.

Helicopter simulators often use a hexapod motion base. With Desdemona more manoeuvres can be simulated adequately, such as the landing under brownout conditions. This is possible because of the extended motion envelope of Desdemona, e. g., the large track can eliminate the false cues due to position washout.

For driving simulation Desdemona also offers some advantages for manoeuvres such as curve driving [10, 11, 12], lane changes (large track length) and roll-over manoeuvres.

4 Conclusions

Desdemona is a new type of motion platform based on a serial kinematic design. Compared to the parallel kinematic design of conventional hexapod platforms, Desdemona can combine limited linear motion in any arbitrary direction with sustained centrifugal acceleration and unlimited rotations. Although Desdemona was originally designed for pilot-in-the-loop disorientation training, the simulation goals include motion cueing research, flight simulation, driving simulation and the specification of future moving base simulators.

This paper described a motion filter that handles coordinated and uncoordinated roll manoeuvres simultaneously. This means that both manoeuvres can be performed during a simulator run, without trade-off. The kinematic design of Desdemona allows the implementation of this motion cueing algorithm. It would be more difficult to implement this cueing solution in a conventional hexapod design, because of the high roll angles involved. The new cueing solution used in Desdemona guarantees that the specific force in the cabin is felt realistic due to the lateral specific force feedback loop (1 in Figure 4). This is important since specific force plays a major role in pilot orientation. This solution is suitable for military aircraft since these aircraft are able to perform both roll manoeuvres.

We believe that Desdemona is a major asset regarding upset recovery training [13]. Desdemona kinematic design would permit simulating typical upset situations, like large angular displacements on pitch and/or roll. This new motion cueing algorithm in conjunction with other inhouse solutions would allow the pilot to correctly recover from upset situations. In this context, correctly means that pilots would experience almost the same motion cues as in the real aircraft.

References

[1] D. Stewart, "A platform with six-degrees-of-freedom," in *Proceedings of the Institute of Mechanical Engineers*, vol. 180, no. 5, 1965, pp. 371–386.

[2] B. Conrad, S. F. Schmidt, and J. G. Douvillier, "Washout circuit design for multi-degrees-of-freedom moving base simulators." in *Visual and Motion Simulation Conference*, no. 73-929. Palo Alto, California: AIAA, September 1973.

[3] P. R. Grant, B. Yam, R. Hosman, and J. A. Schroeder, "Effect of simulator motion on pilot behaviour and perception," *Journal of Aircraft*, vol. 43, no. 6, pp. 1914–1924, November-December 2006.

[4] F. V. Biervliet, "Introducing a new approach to motion: Lm^2," patent pending: PCT/EP2006/009841.

[5] N. A. Pouliot, C. M. Gosselin, and M. A. Nahon, "Motion simulation capabilities of three-degree-of-freedom flight simulators," *Journal of Aircraft*, vol. 35, no. 1, pp. 9–17, January-February 1998.

[6] M. A. Nahon and L. D. Reid, "Simulator motion-drive algorithms: A designer's perspective," *Journal of Guidance, Control and Dynamics*, vol. 13, no. 2, pp. 356–362, March-April 1990.

[7] M. Idan, M. A. Nahon, and D. Sahar, "A comparison of classical and robust flight simulator motion control," in *Modeling and Simulation Technologies Conference and Exhibit*, no. 98-4366. Boston, MA: AIAA, August 1998.

[8] M. Idan and M. A. Nahon, "Off-line comparison and robust flight simulator motion control," *Journal of Guidance, Control and Dynamics*, vol. 22, no. 5, pp. 702–709, September-October 1999.

[9] P. R. Grant and L. D. Reid, "Motion washout filter tuning: Rules and requirements," *Journal of Aircraft*, vol. 34, no. 2, pp. 145–151, March-April 1997.

[10] P. Feenstra, M. Wentink, Z. C. Roza, and W. Bles, "Desdemona, an alternative moving base design for driving simulation," in *DSC 2007 North America*, Iowa City, September 2007.

[11] A. R. Valente Pais, M. Wentink, M. Mulder, and M. M. van Paassen, "A study on cueing strategies for curve driving in desdemona," in *Modeling and Simulation Technologies Conference and Exhibit*, no. 07-6473. Hilton Head, South Carolina: AIAA, August 2007.

[12] M. Wentink, A. R. Valente Pais, M. Mayrhofer, P. Feenstra, and W. Bles, "First curve driving experiments in the desdemona simulator," in *DSC 2008 Europe*, Monaco, January-February 2008, pp. 135–146.

[13] *Airplane Upset Recovery Training Aid*, Revision 1 ed., August 2004.