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How to cheat in motion simulation – comparing the engineering and fun ride approach to motion cueing

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Abstract. The goal of this working paper is to discuss different motion cueing approaches. They stem either from the engineering field of building flight and driving simulators, or from the modern Virtual Reality fun rides presented in amusement parks all over the world. The principles of motion simulation are summarized together with the technical implementations of vestibular stimulation with limited degrees of freedom. A psychophysical experiment in Virtual Reality is proposed to compare different motion simulation approaches and quantify the results using high-level psychophysical methods as well as traditional evaluation methods.

1 Introduction

It is physically impossible to correctly simulate large scale ego-motion in the limited space of a laboratory. This manuscript investigates intelligent ways of cheating and trying to get around that problem. The standard approach to simulate motions (so called motion cueing) is to simulate the "relevant" cues as closely as possible, especially the acceleration of an observer.

Let us have a look at the sensor organs which are used to perceive our ego-motion in space. Visual and auditory cues enable humans to perceive their location in space on an *absolute* scale. Landmark information can be used for position fixing, triangulation, and judgments of displacements. On the other hand, the somatosensory cues, mainly proprioception and the signals from the vestibular system, code only *relative* information. For the latter, the detection of linear and angular degrees of freedom is already separated on the physiological basis and implemented in two distinct sensory organs: the otoliths and the semicircular canals, respectively. Both are part of the inner ear and project into the brain regions where the signals are probably integrated into the general knowledge of perceived self location. Due to the relative nature of the signals, piloting and path integration are susceptible to accumulation errors over time. Since the vestibular organ responds to accelerations the questions remains: What are the *relevant* accelerations that are integrated into the perceived ego-location and ego-motion?

Unfortunately, there is no general solution to the motion simulation problem. It is simply physically impossible to simulate the proper accelerations and velocities without moving the observer in the corresponding way. There is just no simulated acceleration without exactly matching the physical acceleration. Is this the final answer to the motion simulation problem?

Yes and no. There is just no way around physics. But fortunately (for our purpose), humans cannot perceive accelerations and velocities perfectly and without systematic errors. And this is where the tricky business of motion simulation starts. We can use those imperfections of the human sensory and perceptual systems to cheat intelligently. Detecting and measuring those imperfections is the realm of psychophysics, and beyond the scope of this paper. See Goldstein (1996) for an overview on psychophysical methods in general and Bülthoff and van Veen (2001), von der Heyde and Bülthoff (2000), Péruch and Gaunet (1998) for modern approaches to extend psychophysical methods to spatial cognition using Virtual Reality technology. In the remainder of this paper, we will give a brief overview on the principles of motion simulation and how they are implemented in existing motion simulation setups. Different approaches are discussed, and an experiment is proposed to disambiguate between the perceptual and cognitive effects of the various approaches.

1.1 Linear movements

In principle, velocity cannot be directly perceived by relative cues alone, like those from the vestibular system. For such a system, flying in space with some constant velocity is not different from sitting in a chair. This is the fundamental feature of an inertial system. However, changing the velocity is perceived as acceleration, or force acting on the human body.

For the case of constant linear acceleration, a substitute for the real situation is simple. Since the amplitude of the acceleration is not very well perceived by humans, one can tilt the subject backwards and use the gravity vector as a replacement for correct resulting force from gravity and forward acceleration. In this case, leaning backwards is therefore not perceived differently from being constantly accelerated forwards (see Loose, Probst, and Wist (1996) for a discussion).

Changing the acceleration, however, from 1.0g to 1.1g is easily perceived unless the change is very slow and smooth (i.e., below detection threshold). Here, the jerk component (change of acceleration) is critical, since changing from an upright position to a tilted one is only possible by a rotation. The rotation consists of an initial rotational acceleration and a final rotational deceleration, which can be perceived by the vestibular system (see below). The perception of a rotation can destroy the simple simulation described above for the case of constant linear acceleration.

1.2 Rotational movements

Unfortunately, there is no easy way of cheating for rotations. Hence, many motion simulations try to avoid the problem by avoiding quick and large rotations altogether. In general, rotations are perceived by the canal system for all three rotational degrees of freedom. However, rotations around the earth-vertical gravitational force vector (yaw) are different from rotations perpendicular to it (pitch and roll[1], see Fig 4). For the latter, the otoliths contribute with the detection of the gravitational direction (see the discussion of linear accelerations above). Whereas the yaw rotation is perceived by the otoliths only due to the centrifugal force of the rotation acting on the organs, which are located in the inner ear (off center in the head). In the upright position at least one of the two otolith systems is outside the rotational axis.

Spinning with a constant velocity can not, however, be very well detected by the vestibular system when sitting still on a rotating chair. Tilting the head will effect the rotational axis and exert a change in force on the canal system. This can not be simulated without the correct physical rotations. Whether this signal is used for spatial orientation is questionable, since humans easily get sick in this situation anyway.

Smaller yaw rotations should correctly be performed in a simulation, since psychophysical measurements have shown that they can be sensed in terms of turned angle (turning amplitude) and also turn velocity on relative and subjective scales. Comparisons between two sequential movements are possible and allow order judgments of turned angle even over a longer period of time (von der Heyde, Riecke, Cunningham, & Bülthoff, 2000).

The only convincing way of simulating larger turns is an initial yaw rotation above threshold and a back-motion below threshold. For roll and pitch, the static (otolithic) cues cannot be modified easily due to the ambiguity of linear accelerations and changes in gravitational direction. In real life, the ambiguity is resolved by using the dynamical properties of the vestibular and other sensory signals (most importantly, vision).

[1] In this manuscript we refer to the coordinate system as follows: The X-axis runs in the direction of the observers positive forward movements, with roll being defined as turns around this axis. The Y-axis correspond to a left movement and defines also the pitch axis. The Z-axis is going upwards completing the right hand coordinate system and defining the yaw rotational axis.

1.3 Summary of vestibular motion perception

In sum, there is no good way of cheating the vestibular system in order to match the physical properties of both linear and rotational movements. Either linear accelerations and velocities are treated wrong, or the rotational degrees of freedom can not be implemented satisfactorily, or both.

Summary of most commonly used “tricks”:

- Moving the observer below detection threshold to gain additional simulation space.
- Trading the gravity vector for an acceleration. This makes use of the fact that the we cannot distinguish well between, e.g., an absolute constant acceleration of 1.0g or 1.1g.
- Masking not-to-be-detected motions by noise (i.e., vibrations and jitter).
- Guiding the attention of the observer away from the imperfections of the motion simulation, e.g., by involving the observer in a difficult task, providing attention-capturing visual and auditory cues etc. Results from change blindness and inattentional blindness studies provide insights on how to do that.

2 Technical implementations of motion simulators involving vestibular stimulations

In this section, motion simulators are introduced which “simulate” motions by replacing the actual correct physical motion through motions that are within the limited movement range of the motion simulator. Rotating chairs and large-scale plotter-like implementations of the real physical motion are excluded from the scope of this manuscript, as they do not *simulate* a motion, but actually *execute* it correctly. For typical motion simulators the space available is limited. Most commonly, all six degrees of freedom are limited in the magnitudes, velocities and accelerations which can be performed. Different systems reduce the available degrees of freedom to a subset of the complete set of all six (X, Y, Z, roll, pitch, yaw)

Figure 1: The typical Stewart motion simulation enabling movements in all six degrees of freedom. See von der Heyde (2001, Appendix B) for additional details of the computer system and the hardware.

In order to implement different degrees of freedom, actuators are typically used to move the observer. The physical arrangement of the actuators determine the degrees of freedom (DOF) that can be simulated. The general principle of a Stewart platform is commonly used to implement all six degrees of freedom in a simulation (Fichter, 1986). A *base* is connected to the *platform* by six actuators which can change in length. A typical arrangement of these actuators can be seen in Fig. 1. Variants of this platform substitute single degrees of freedom by movable joints. Fig. 2 shows an example for a system which can only perform X, Z, roll and pitch movements. Reducing the available degrees of freedom further limits the possible motions to movements in the XY-plane or single rotational axes (like the one in Fig. 3 or a simple swivel chair from the office).

2.1 What can be simulated?

How are motion cues simulated in a standard six DOF simulator? We will discuss here two typical motion simulations for flight and driving.

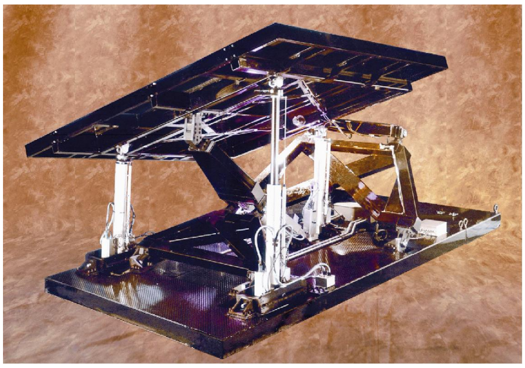

Figure 2: A possible solution in limiting the movements to four degrees of freedom. Only X, Z, roll and pitch changes can be performed.

Figure 3: Low cost solutions sometimes have only two axes. For simple flight simulations, however, it might be sufficient to simulate only roll and pitch when some other sources of vibrations are provided. In this example, two pneumatic cylinders drive roll and pitch motions, and vibrations are realized via a subwoofer below the seat.

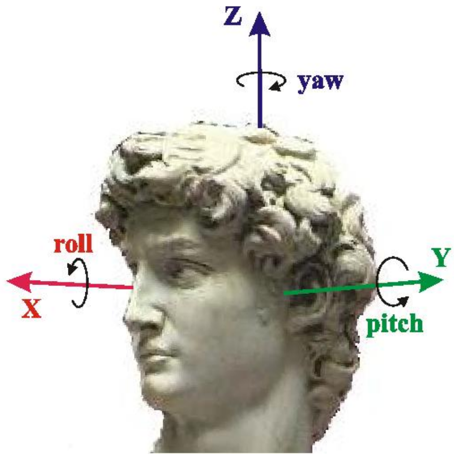

Figure 4: The coordinate system we use.

2.1.1 Traditional flight simulators

Typical movements in flight simulations are limited to takeoff, landing, and the relatively straight flight part in between. For takeoff and landing, pitch is the most important cue and is easily simulated. The straight section in a flight (constant forward velocity) is limited to small accelerations indicating turbulences, which are again easy to implement.

Heading changes (curves) are the impossible part in the simulation. In a normal flight, the plane would perform a roll movement first and then pitch in the local coordinate system. Therefore there is no significant yaw acceleration for the pilots, but a net yaw change over ground. Leaving the curve is the same maneuver in the reverse order: Stop the pitch and unroll. During the curve, the resulting force vector points downwards in plane coordinates. Contrary, the movement prior to that state was a movement away from the upright position (roll) clearly perceivable to the otoliths. The simulation can not leave this tilted position without performing a rotation in the opposite direction, but the acting forces of a real plane would require exactly this.

Consequently, there is no possibility to properly simulate the correct accelerations which result from a real flown curve. Unless the maneuvers are performed below threshold, i.e. for slow speed, a conflict between canal and otolith signals from missing centrifugal force will result.

2.1.2 Traditional driving simulators

As already discussed above, the simulation without changes of velocity (e.g. highway driving without lane changing) are easy to implement. Due to the lack of changes, the gravity vector trick can be used even for small accelerations and moderate braking maneuvers. The more complex case, including sudden changes in velocity, is typically simulated unrealistically and a possible reason for motion sickness observed in those simulators. The gravity vector trick would require perceivable rotations which are not compensated for by the visual simulation. Some experts argue that this mismatch between the two sensory cues enhances motion sickness (see, e.g., Viirre, 1996). Applying little jerks (linear kicks) improve the simulation, but do not solve the general problem.

Driving through a curve results in a combination of centrifugal force and actual yaw rotation. The resulting force from gravity and centrifugal force points toward the outside of a curve. Following this force, the vehicle tilts in reality to the outside, too. This results in a roll rotation for the vehicle, but a different roll amplitude would be required for substituting the centrifugal/gravity combination with just the gravity force. Hence, "realistic" car simulators tilt the observer outwards in curves, but do not match the required roll rotation. The heading changes during curve-driving, however, are often not performed to the appropriate amplitude, but simulated using initial kicks for the yaw rotation onset.

2.1.3 Fun rides

Is the motion simulation approach described above (we call it the "engineering approach") the only solution to the cheating problem? Of cause not, and that is why fun rides do it their own way.

The simple and intuitive description of fun rides is the following: Whether you fly or drive, lean inwards in curves! One could compare this approach with riding a motor bike or actual flying, but driving a four wheel vehicle behaves differently in real life.

2.2 Summary of real and simulated movements

As we have seen, motion simulation has to cheat in some ways. How "successful" the individual implementation is depends on the goals. Both approaches ("engineering" and "fun ride") have their limitations and different goals. For driving, the fun ride approach is certainly less realistic. However, millions of spectators per year in amusement parks cannot be wrong. Mainly, they want to have fun, but without getting sick - and they rarely do (less than 1‰, compared to 10 to 70% for some commercial engineered simulators. *Now who is right? Nobody!* It just depends on what your goal is. Our goal is to *understand*. Hence, we'll end this manuscript with a proposal for an experiment that could shed some light on the main question raised in this paper: Given a specific goal to pursue, what is the most intelligent and elegant way of cheating in motion simulation?

3 Conclusions and experiment proposal

From the above, we see that there are several ways of "cheating" in motion simulation. For the sake of simplicity, we reduce them here to the "engineering approach" and the "fun ride approach":

- The engineering approach typically simulates accelerations at least qualitatively correct, i.e. in the same direction as in the real world.
- The fun ride approach, on the other side, is more aimed for maximizing the fun of a ride while reducing motion sickness to an absolute minimum.

In the remainder of this manuscript, we propose an experiment to compare the different motion simulation approaches and quantify the results using high-level psychophysical methods as well as other traditional evaluation methods.

We hereby pursue the following goals and questions:

- Why do different motion simulations do it the way they do it? That is, can we quantify the advantages and disadvantages of the different motion simulation approaches?
  - How can we measure fun? Which approach increases the fun aspect?
  - Which approach leads to the better spatial representation and orientation? How can we quantify this?
  - Is the intended (i.e., simulated) motion trajectory better perceived with one of the approaches?
- How should we simulate motions when our goal is the correct perception of self orientation, and hence a better spatial orientation?
- Can the above goal be approached by letting subjects adjust their own motion simulation?

3.1 Methods

3.1.1 Visualization

A computer-generated 3D model of the Tübingen market place (see Fig. 5) is presented on a curved projection screen, mounted on top of a Stewart platform (see Fig. 6). The physical field of view (FOV) is 84 $\times$ 63 degrees and is identical to the simulated FOV.

3.1.2 Motion simulation

Subjects are seated on a six DOF Stewart motion platform (see Fig. 1). Translations of the platform are kept to a minimum. Visually simulated yaw and pitch movements are displayed 1:1 as corresponding yaw and pitch movements of the platform. The relation between visually simulated and physically executed roll movements are systematically varied to investigate their respective importance for spatial representations and the fun aspect.

3.1.3 Task and experimental paradigm

Subjects are passively driven in a roller-coaster-like manner over the Tübingen market place.

(a) View from Haaggasse

(b) View from Kronenstraße

(c) View from Hirschgasse

(d) View from Marktgasse

Figure 5: Four different view onto the Tübingen market place.

Figure 6: The projection screen in the Motion-Lab is mounted onto a six DOF motion platform. The simulated graphics is displayed as one channel with a field of view of 84 $\times$ 63 degrees.

However, the "rails" of the roller coaster are invisible, such that subjects cannot predict their future path. Their task is to point ("shoot") at targets (most likely monsters) that are located at fixed positions in the environment and learned beforehand. Targets are announced by a computer-generated voice via headphones. The subjects' task is to shoot at the targets "as quickly and accurately as possible". Between trials (rides), subjects get feedback about their "hit rate".

Independent variables For different, randomized rides through the market place (lasting up to 1 minute), the curve simulation is varied systematically. The relation between visual roll rotation and physical (platform) roll rotation are varied systematically among the following conditions:

- Leaning into the curves (i.e., left roll for left turn). This is the typical fun ride simulation.
- Leaning out of the curves (i.e., right roll for left turn). This is the typical engineering approach, simulating the centrifugal force by a corresponding roll rotation.
- No physical roll rotation at all, as a baseline condition.
- Display roll rotation as they were manually adjusted by other subjects in a pre-experiment.

Dependent variables Dependent variables for the shooting task include response time, pointing accuracy and pointing variability. Riecke, von der Heyde, and Bülthoff (2001) have demonstrated that speeded pointing is a viable method for quantifying spatial updating and the quality of the spatial representation of the surround after simulated or real motions through space.

Between rides, subjects are asked to rate the "fun aspect" and the "realism" of that ride.

3.1.4 Trajectories

The paths that are to be followed consist of random combinations of curves (10, 20, and 30 degree turns) and straight parts in between. The shooting tasks are always during the straight paths.

Each path starts at a street facing the market place, at high altitude, with an downward segment to gain speed. (just like in a roller coaster).

Each path ends with an upward segment during which the subject has to rate the fun and realism of that ride. A turn to face the market place brings them to the starting position for the next ride.

3.2 Hypotheses

We expect the fun ride approach to yield higher fun ratings, but lower ratings on realism.

However, spatial updating and the quality of spatial representation and orientation is expected to be superior for the engineering approach.

The no-roll condition should yield the worst results on all measures.

We do not have any clear predictions for the self-adjusted condition. Ideally, it would combine the advantages of the different approaches.

Any different outcome would question the foundations of motion simulation as we know it, and could lead to improved algorithms for motion simulation, tailored for the specific goal of the application.

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