# Novel Washout Filters to Enhance Simulation of Motion


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## Goals of the Washout Filter

View of moon created by virtual reality.

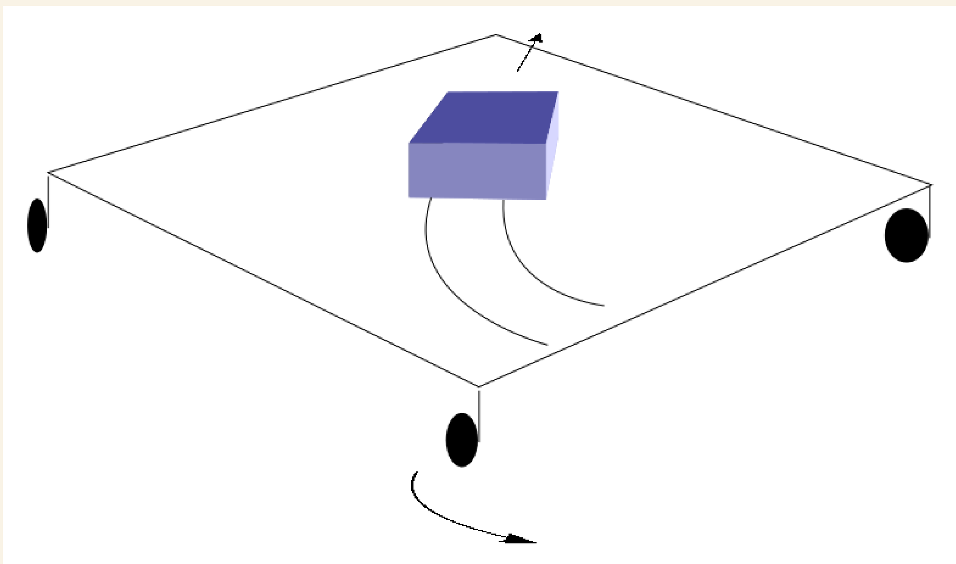
View of the physical simulator.

We are seeking a physical simulator of a vehicle driven on the surface of a celestial body. This will be added to a virtual reality simulation. We desire that the motion of the simulator be so that the acceleration forces experienced by the vestibular system[1] are similar to if the crew member were to actually drive the vehicle on the surface of the celestial body. But the simulator is constrained, first in its position in that it cannot travel far, and second in its orientation in that it must approximately face the same direction.

## Classical Washout Filter

The *classical washout filter* [2,3,4] starts with the translational acceleration and angular velocity. After appropriate filtering, these are integrated to obtain translational position and orientation for the simulator. This is effective for airplane simulators. But for simulating land based vehicles, we prefer to use a more direct washout filter, which starts with translational position and orientation of the vehicle. This direct approach will preserve any tilting.

## Our Washout Filter



In essence, this washout filter is as if one moves the surface of the celestial body, so as to counter the motion of the vehicle.

- Allow hypothetical translating the surface in any direction.
- Allow hypothetical rotating the surface about the $z$-axis (the axis going from the center of the celestial body to the vehicle).
- Do not allow any other hypothetical motions, such as tilting the surface, as this will change the perception of gravity, and will not preserve the actual tilt of the vehicle.

The motion of the simulator is the result of combining the motion of the vehicle on the surface, and the hypothetical motion of the surface, so that the net effect of this combination is that the simulator doesn't move or rotate very far from its original position. This motion should satisfy the following properties.

- The simulator should remain roughly in the same place, and should approximately face the same direction.

## Our Washout Filter — continued

- The hypothetical motion of the surface should be gentle, so that the vestibular experience of acceleration of the crew member in the simulator is similar to that were the crew member in the vehicle.

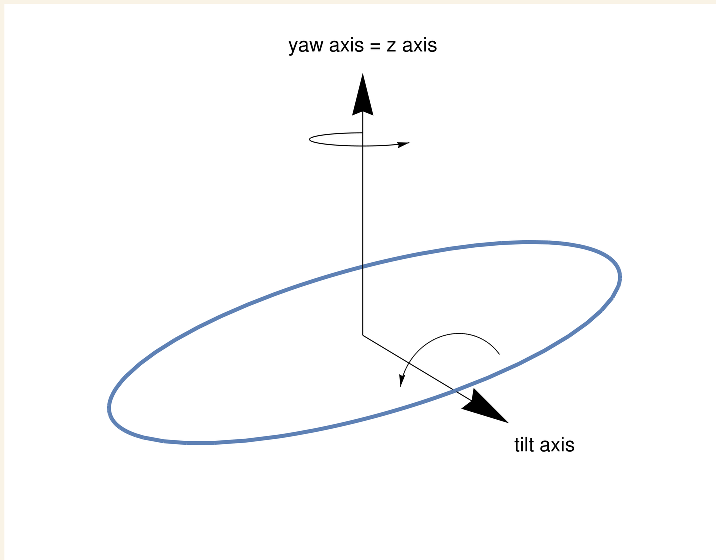
Thus the hypothetical motion of the surface is as follows:

- subtract the low pass filtered position of the vehicle, then
- apply the reverse of the low pass filtered 'yaw part' of the rotation of the vehicle.

Other additions to the washout filter include:

- Motion cueing, that is, an additional tilt to simulate the effect of low pass filtered acceleration. (Easy to implement, although perhaps hard to tune.)
- Ramping the washout filter on and off in a low jerk manner.
- Gracefully degrade performance as simulator gets close to the physical limits on the hardware and the human. (Hard to implement.)
- Human safety limits align with NASA-STD-3001.
- Vibrations at different frequencies are detected by a cascade of notch filters.

## The Tilt-Yaw Vector




Rotation $R$ is decomposed as a product of a *yaw* $Y$, that is, a rotation about the $z$-axis, and a *tilt* $T$, that is, a rotation about an axis in the $xy$-plane:

$$R = YT.$$

This decomposition is unique if $R$ isn't a $180^\circ$ rotation about an axis in the $xy$-plane.

Define the *tilt-yaw vector* as

$$\begin{aligned} &\text{tilt-yaw vector, } \boldsymbol{\xi} = [\varphi, \theta, \psi], \text{ where} \\ &\text{equivalent angle-axis of } T = [\varphi, \theta, 0], \\ &\text{equivalent angle-axis of } Y = [0, 0, \psi]. \end{aligned}$$

Advantages of this representation

- For a human on the surface of the Earth, the tilt and yaw are perceived distinctly.
- Tilt can be directly experienced because it effects how one senses the gravitational pull. The actual value of the tilt will be experienced.
- For yaw, only rate of change can be physically experienced.
- The real value of the tilt can be used in the simulator, because the vehicle is unlikely to tilt too much.
- Unlike Euler angles, the tilt-yaw vector has only one direction of singularity, and that direction is very unlikely (as it is when vehicle is upside down.)

## The Tilt-Yaw Vector — continued

- Filtering can be performed directly upon the tilt-yaw vector.
- Motion cueing can be performed by simply adding a tilt to the orientation.
- Calculation of tilt-yaw vector is easily performed using the unit quaternion representation of rotations:

$$R = YT$$

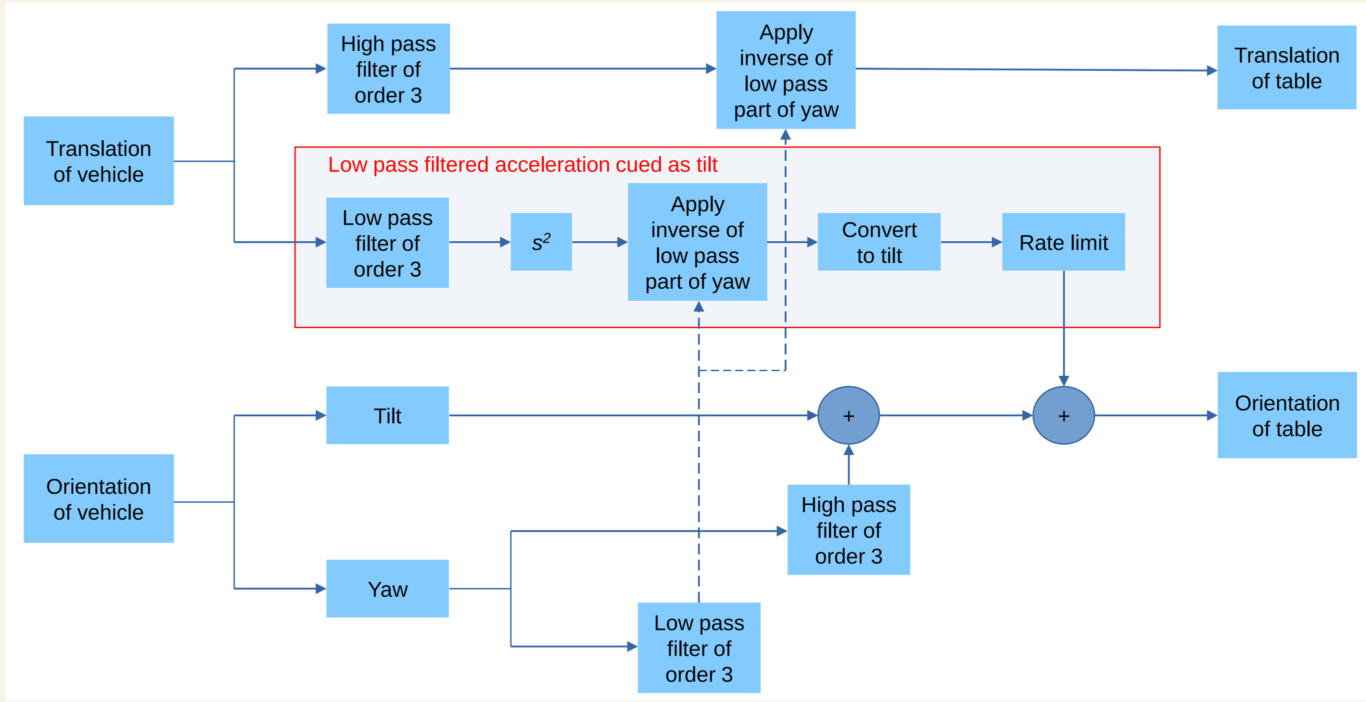
$$w_R + x_R \boldsymbol{i} + y_R \boldsymbol{j} + z_R \boldsymbol{k} = (w_Y + z_Y \boldsymbol{k})(w_T + x_T \boldsymbol{i} + y_T \boldsymbol{j})$$

$$w_T = \text{magnitude of } [w_R, z_R],$$

$$[w_Y, z_Y] = \text{unit vector of } [w_R, z_R],$$

$$\begin{bmatrix} x_T \\ y_T \end{bmatrix} = \begin{bmatrix} w_Y & z_Y \\ -z_Y & w_Y \end{bmatrix} \begin{bmatrix} x_R \\ y_R \end{bmatrix}.$$

## The Washout Filter




## Future Work and Challenges

- Pass safety standards so that we can run the simulator with a crew member. Then we can start tuning.
- Better implementations of respecting limits on hardware and software. To some extent, these requirements work against each other. For example, if the simulator is moving quickly, the software may have to decide between respecting the hardware positional limits, and the human acceleration or jerk limits.
- Adaptive methods: the literature[2,3,4] includes many methods which adapt the filters to create a more realistic experience.

## References


1. Goldberg, Jay M.; Wilson, Victor J.; Cullen, Kathleen E.; Angelaki, Dora E.; Broussard, Dianne M.; Büttner-Ennever, Jean A.; Fukushima, Kikuro & Minor, Lloyd B. (2012) The vestibular system: a sixth sense. Oxford University Press.
2. Nahon, M.A. & Reid, L.D. (1990) Simulator motion-drive algorithms: a designer's perspective. Journal of Guidance, Control and Dynamics 13(2):356-362.
3. Reid, L.D. & Nahon, M.A. (1985) Flight Simulation Motion-Base Drive Algorithms: Part 1 — Developing and Testing the Equations. University of Toronto Institute for Aerospace Studies Report 296, University of Toronto.
4. Schmidt, S.F. & Conrad, B. (1970) Motion drive signals for piloted flight simulators. (CR-1601) NASA Contractor Report.