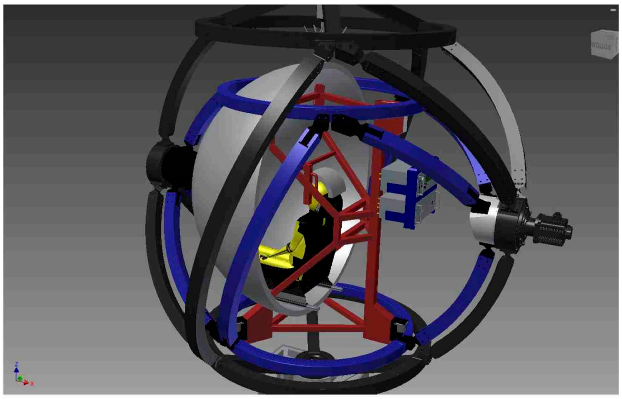
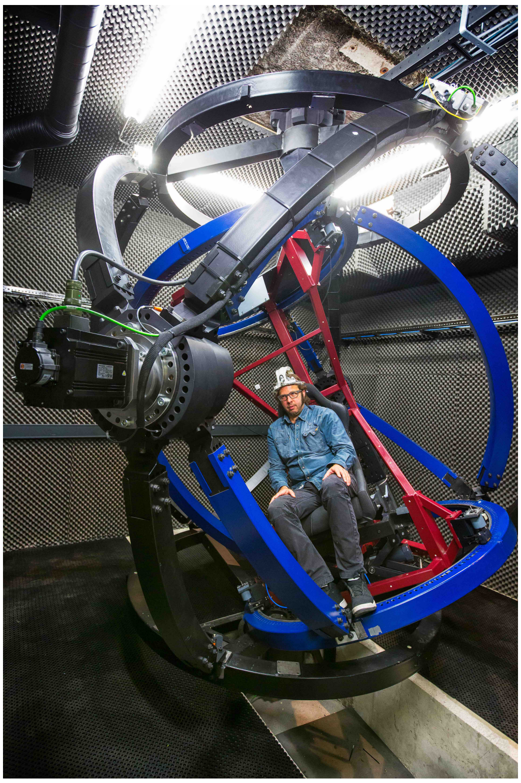
Project for master students (Experimental) Physics/ Science/CNS Tracks 2 or 4:
Systems Characterization of the Two-Axis Vestibular Stimulator

The biophysics group of John van Opstal has a newly constructed two-axis vestibular stimulator, which will be used to test the function of the human vestibular system (compensatory eye movements, spatial perception, psychometrics, brain imaging, multisensory integration, sensorimotor coordination), while subjects undergo whole-body rotations around two independent axes with different dynamic profiles.



Schematic of the vestibular chair: an earth-fixed vertical axis rotates the outer (black) sphere (horizontal canal stimulation), while the nested horizontal axis independently rotates the blue sphere. The orientation of the subject within the blue sphere (the red frame) determines vertical vestibular canals (RALP/LARP) stimulation.



In this internship (which could preferentially be carried out by two to three students) we aim to characterize the full mechanics and acoustics of the vestibular chair by systematic measurements, and modeling, of its input-output transfer functions. To that end, the following sub-projects are carried out:

1) **AXIS 1:** Transfer function of the outer sphere, with the inner sphere stationary: we apply systems theory (e.g., Van Opstal, 2016) by stimulating the sphere with Gaussian White Noise commands, and recording the actual chair movements. First verify that there is a stimulus-response relationship by recording the response of the system to many repetitions of the (frozen) GWN stimulus. Then calculate the linear impulse response function from this experiment by cross-correlation between output and input:
$$h_{OUT}(\tau) = \frac{\Phi_{yx}(\tau)}{P} \qquad (1)$$
where P is the power (variance) of the GWN, and the cross-correlation function is defined by
$$\Phi_{yx}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} y(t) \cdot x(t+\tau)\, dt \qquad (2)$$
2) Test *linearity* by predicting the responses of the chair to arbitrary input commands (different GWN patterns, pink noise, LP noise, BP noise, sinusoid stimulation, step- and ramp responses, etc.) with convolution:
$$y(t) = \int_{0}^{\infty} h(\tau) \cdot x(t-\tau)\, d\tau \qquad (3)$$

3) If the linear predictions deviate significantly and systematically from the measurements: Characterize potential nonlinear behaviour of the chair by training an artificial neural network to the GWN input, and construct the higher-order Volterra kernels from the trained network (Wray and Green, 1994):
$$\begin{aligned} y(t) = &\int_{0}^{\infty} k_1(\tau) \cdot x(t-\tau)\, d\tau \\ &+ \int_{0}^{\infty}\int_{0}^{\infty} k_2(\tau_1,\tau_2) \cdot x(t-\tau_1)x(t-\tau_2)\, d\tau_{1,2} \\ &+ \int_{0}^{\infty}\int_{0}^{\infty}\int_{0}^{\infty} k_3(\tau_1,\tau_2,\tau_3) \cdot x(t-\tau_1)x(t-\tau_2)\,x(t-\tau_3)d\tau_{1,2,3} \\ &+ \cdots \qquad (4) \end{aligned}$$

4) Predict the system's responses to the test stimuli in (2) with the nonlinear ANN approximation. Is there a significant improvement? Which nonlinearities dominate?

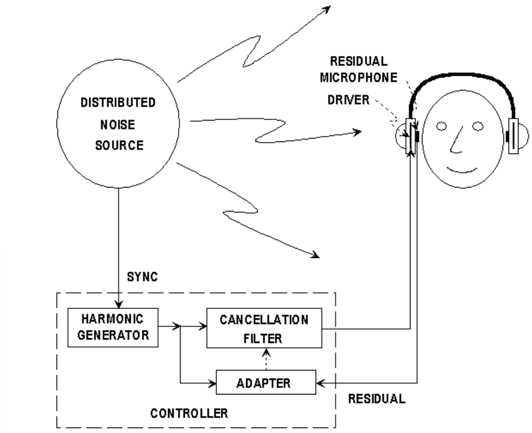
5) Test the system's (linear/nonlinear) responses by applying loads to the chair (e.g., 25 kg, 50 kg, 75 kg, 100 kg, and eventually human subjects). How does

this affect the overall transfer of the system? Characterize the Gain changes, Phase changes, or is it just a weight-dependent scaling factor/tensor?

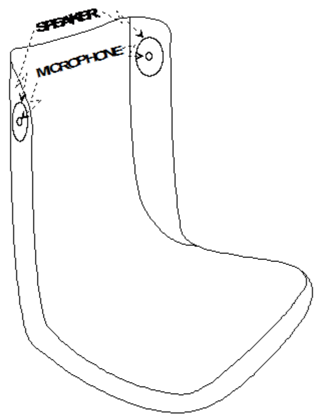
6) **AXIS 2:** Repeat 1-5 for the inner axis, with the outer axis stationary, and the chair in different orientations within the blue sphere: $\Phi = 0^o, 30^o, \ldots, 330^o$.

7) **AXIS 1+2:** Repeat 1-5 for the two axes simultaneously set in motion. Adopt a suitable coordinate system to describe the chair's movements (it's 'gaze direction') under combined rotations, and test how well the movement of the 'subject's head' can be predicted from the independent, combined, application of the single-axis measurements of 1-6.

8) **SOUND:** Characterize the motor noise from motor 1 and motor 2 under different stimulation regimes. Measure the motor noise at the position of the subject's head with a microphone. Use GWN stimulation, as well as constant rotation stimulation (outer axis only, at different velocities), and sinusoidal stimulation (both inner and outer axes, different amplitudes and frequencies). Is the noise periodic? What is the bandwidth? Can we parameterize it? Is it possible/conceivable to generate anti-noise? (active noise cancellation; see, e.g. http://doctord.dyndns.org/Pubs/POTENT.htm)



Noise-cancellation headset system.



"Silent seat" with noise cancellation around the listener's head.

9) **Challenge:** combination of chair motion with motion of a visual stimulus on the projection screen: generate a visual stimulus with the laser projection system *that remains stable in the world*, despite the complex motion of the chair by a simultaneous outer axis/inner axis movement pattern.

Preferred start: September, 2016
Supervisors: G Windau, AJ van Opstal, MM van Wanrooij, PhD student

Literature:

Wray J, Green GGR (1994): Calculation of the Volterra kernels of nonlinear dynamic systems using an artificial neural network. Biol Cybernet 71: 187-195

Van Opstal AJ (2016): The auditory system and human sound-localization behavior. Elsevier, Academic Press, NL, Chapters 3 and 4.