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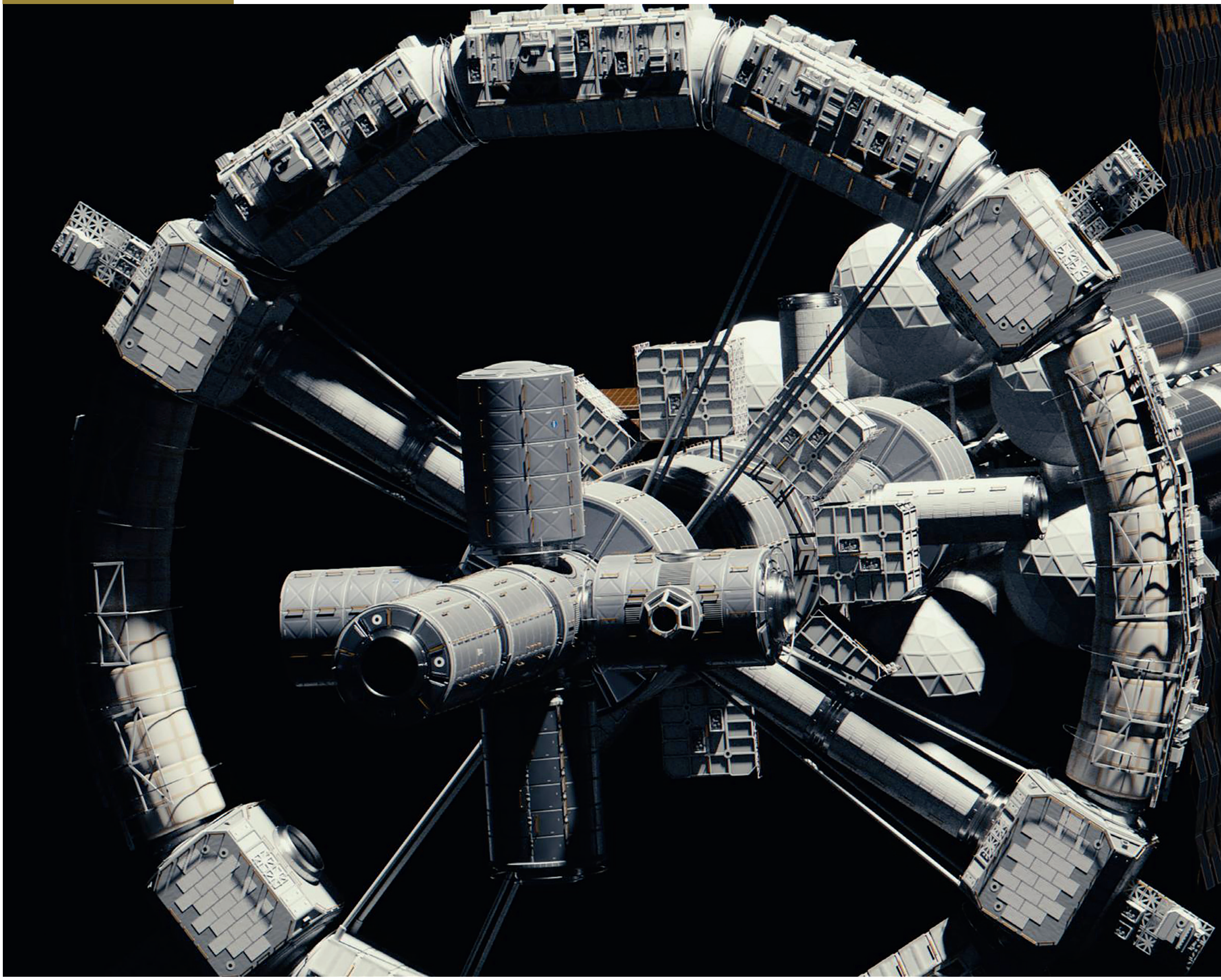

Investigation of the Coriolis effect in rotating space platforms

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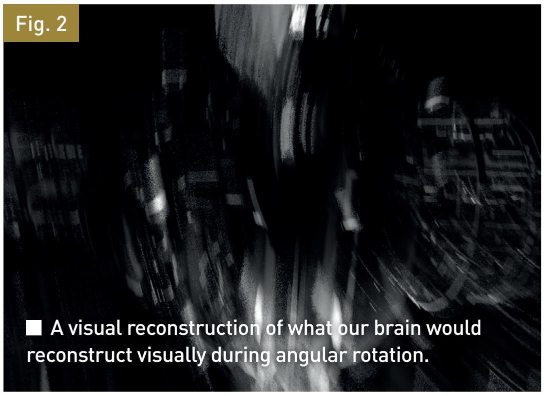
The presence of prolonged microgravity in space has long been known to have a negative impact on the human body such as deterioration of bones and muscles. Rotating space platforms have the potential to mitigate the health risks for prolonged space travel by creating an Earth-like artificial gravity environment for the habitants. In this article, Tigran Mkhoyan elaborates on his presentation in the 'Artificial Gravity' segment of October's Asgardia Space Science & Investment Congress (ASIC).

Figure 1. Artist rendering of a hypothetical rotational spacecraft.

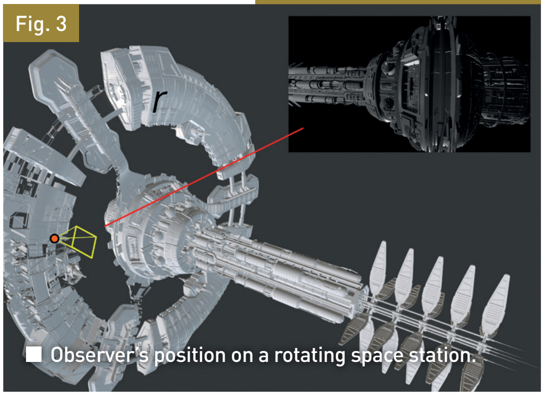
blenderartists.org/Benjee10

Fig. 2



A visual reconstruction of what our brain would reconstruct visually during angular rotation.

Fig. 3



Observer's position on a rotating space station.

Arguably, most of us interested in space travel have seen or heard about the movie *2001: A Space Odyssey* with its famous rotating spacecraft 'Discovery One'. We have passed almost two decades since 2001, yet there is no rotating space platform to be seen. Of course, there are many technical challenges in realising such a system in space. However, one important aspect is how the human vestibular system, adapted to our life on Earth responds to the rotational environment needed for sustained artificial gravity, and in particular the role of the semi-circular canals (SCC).

A problem that can arise in such an environment is a false and often nauseating sensation of rotation, the so-called Coriolis effect. The coriolis effect is induced by the rotation of the space platform, combined with the simultaneous rotation of the human's head (active Coriolis Coupling). For the 'space traveller' inside the spaceship this may result in a severely restricting environment, where any head movement outside of the rotational axis could cause a sensation of tumbling, nausea or dizziness. The solution depends on how severe the Coriolis effect is, which depends on the design of the spacecraft and its radius arm. This article sets out to investigate the effect of spacecraft design on the Coriolis effect using a human perception model.

Vestibular cross-coupling

The SCC, are in fact 'biological gyros', responsible for the perception of the angular acceleration in three axes, head-centric x, y and z. In the presence of a sustained rotational environment, any active head tilt outside of the main rotational axis would trigger a cross-coupled signal from SCC, making us believe that we are spinning and tumbling. If we were the passengers inside a spaceship with a sustained angular rotation, Figure 2 depicts roughly what our brain would reconstruct visually from such a cross-coupled impulse.

The relative orientation of the 'observer' looking outwards into the rotational axis (yellow viewpoint) is shown in Figure 3. The 'mechanical' cross-coupling initiated by a head tilt of ▯ degrees, simply arises due to the kinematic coupling as described in the bottom equation in Figure 4 (Holly 1996).

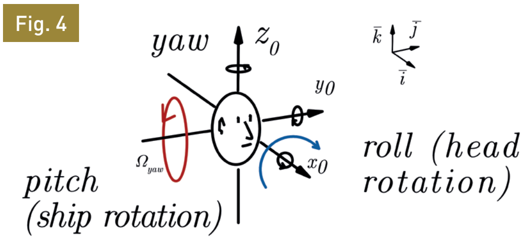
Figure 4 shows standard coordinates and unit vectors for the kinematic relationship of head motion in the presence of sustained (spacecraft) rotation. Pure rotation in roll around the head-centric x-axis, under sustained central rotation of the spaceship, propagates to the other axes (y and z) as shown by the cross-coupling terms (Coriolis cross-coupling).

We see in this set of equations that the angular acceleration and velocity are reflected in the other head-axes as cross-coupled terms. The process of this cross-coupling is illustrated in Figures 5 and 6. Here the subject initiates a head tilt inside a similar rotational environment on Earth, the human centrifuge.

Human centrifuge

The Coriolis effect is not limited to a rotational environment in space. On Earth, we can generate elevated G-levels (>1G) in human centrifuges by introducing a sustained angular rotation. While mainly used as passive G-trainers (Figure 7 left), when combined with additional degrees of freedom, centrifuge-based simulators are great for dynamic flight simulation (high G-manoeuvres, space re-entry

Fig. 4



$${}^h\alpha = \begin{bmatrix} {}^h\alpha_X \\ {}^h\alpha_Y \\ {}^h\alpha_Z \end{bmatrix} = \begin{bmatrix} \ddot{\theta} \\ \Omega\dot{\theta}\cos(\theta) + \dot{\Omega}\sin(\theta) \\ -\Omega\dot{\theta}\sin(\theta) + \dot{\Omega}\cos(\theta) \end{bmatrix}$$

Fig. 5

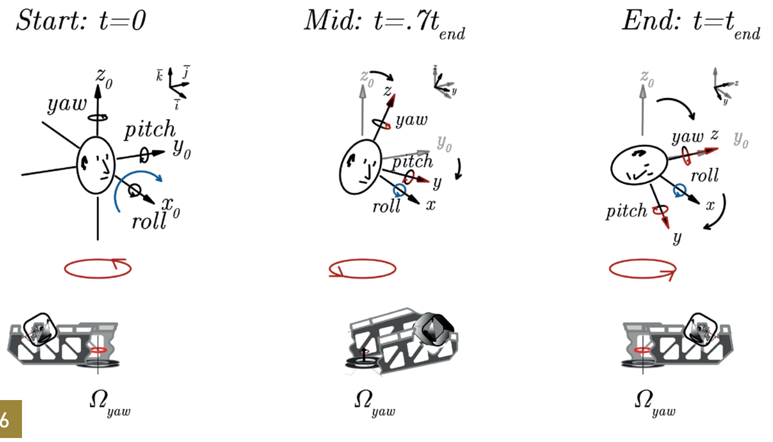


Fig. 6

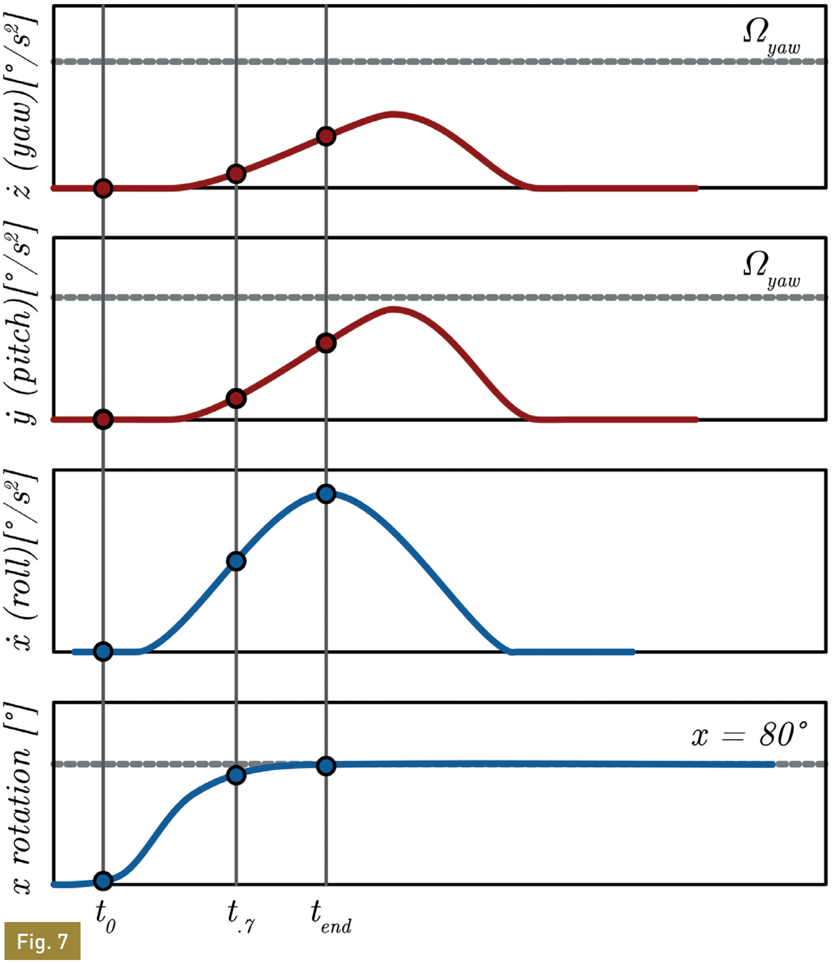
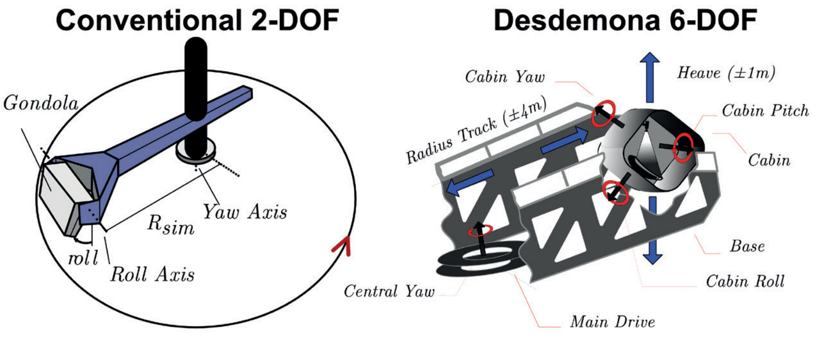


Fig. 7



etc). An example of this is the Desdemona dynamic flight simulator shown in Figure 7 (right). The main disadvantage of a human centrifuge in pilot training is the Coriolis effect experienced during the G-onsets (acceleration and deceleration of the centrifuge) and simultaneous cabin motion.

As the centrifuge spins up or down to regulate the G-level, the cabin, where the pilot is situated, needs to be swung out for correct alignment of the G-vector. This motion triggers similar impulse from the SCC as would occur if the pilot *actively* moved his/her head inside the cabin. In contrast to active Coriolis effect, the latter is referred to as the *passive* Coriolis effect.

In the previous work by Mkhoyan et al. (2019) the passive Coriolis effect (induced by cabin motion) was mitigated through a predictive dynamic motion cueing filter, based on the Coherent Alignment Method (COHAM) concept. The so-called COHAM filter introduces simultaneous lead and lag in the pitching rotation of the simulator cabin, used to align the subject with the result gravitational vector. Experiments were performed with test pilots and the COHAM motion filter was preferred over the conventional cueing in terms of nausea, sickness, dizziness and comfort. Mitigating the active Coriolis effect (induced by head motion) in a spacecraft with several passengers on board would be both impractical and most likely infeasible from the engineering perspective.

Spacecraft design

Is a rotating spacecraft feasible? What would be the Coriolis effect experienced in such a vessel? How big should the vessel be? Is it feasible to launch and assemble such a structure?

To attempt to answer these questions, better understand the severity of the Coriolis effect and how the kinematics of the rotating body affect it, we can look at a basic spacecraft design example.

Let's take a target of 1G (the nominal Earth gravity level). The resultant G-level on Earth depends on the radial acceleration, tangential acceleration and the Earth gravitational constant g. In space, in a steady-state artificial gravity environment, the contribution to the G-level on Earth depends on the radial, tangential and the Earth gravitational constant g. In space, in a steady-state artificial gravity environment, the contribution to the G-level is caused by the angular rotation, composed of the square of the angular velocity of the ship and the radius arm (see Table 1 equation 1). The parameter that directly *affects* the level of Coriolis effect perceived is the rotational velocity Ωr.

The parameter that affects the size and thus the structural weight of the spaceship is the radius r. Rewriting the equation gives us the relationship of both (see Table 1 equation [2]).

Table 1 shows a basic spacecraft design for rotational velocity and radius based on approximate launch budget and size estimations.

Assuming we would like to build and launch a spaceship the size of Discovery One, taking a very rough estimate on the size, we have a radius of r=150m and an approximate mass of 5440 tonnes. Inserting the values into equation 2, we obtain a rotation velocity of Ωr=0.26 rad/s. To launch this vessel at the approximate launch price (US$1600/kg) of Falcon Heavy (US$1600/kg), we require a budget of US$8.70 billion. Taking the maximum payload capacity of 63.2 tonnes we would require 5440t/63.2t= 87 flights.

While not impossible, the weight estimate is already conservative and carrying out that many flights, would also require an enormous effort and cost to safely assemble the structure in space. If we were to look at a more realistic design that is potentially feasible in the short term, we can try to reduce the ship radius arm by a factor of 10 (see, for example, Figure 8).

Going through the same calculation as shown in Table 1 (ship 2) we get a result that already looks more promising. Since the structural mass scales approximately by factor 100, the launch cost reduces to US$87.04 million and we can achieve it in a single flight!

What about the rotational velocity? At Ωr=0.801 rad/s this is significantly higher. Will we experience the Coriolis effect?

To investigate this the Augmented Coriolis Response Model filter (ACRM) was used. The diagram of the filter is shown in Figure 9. It is composed of the rotational kinematics (Holly 1999) and the well-known Hosman SCC model, representing the response of SCC organs to angular acceleration in a second-order filter form.

Fig. 8

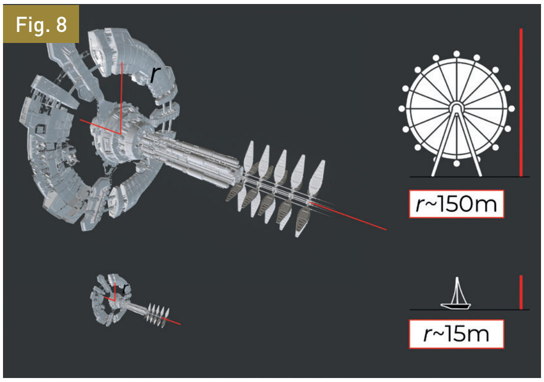


Table 1

$$R_{tr} = \sqrt{a_r + a_t + g} \quad \text{(transient)}$$

$$R_{ss} = \sqrt{a_r + \cancel{a_t} + \cancel{g}} \qquad (1)$$

$$R_{ss} = a_r = \omega_{ship}^2 r \quad \text{(steady state)}$$

Design for rotation:

$$\omega_{ship} = \sqrt{\frac{R_{ss}}{r}} \qquad (2)$$

Ship 1:
Radius r = 150 m
at launch cost 1600$/kg (Falcon 9 heavy) we have:

$$5440 \cdot 1000 \cdot 1600 = \mathbf{\$8.70\ bn}$$

$$5440[t]/63.2 = \mathbf{87\ flights}$$

$$\omega_{ship} = \sqrt{\frac{9.81}{150}} = \mathbf{0.26\ rad/s}$$

Ship 2 - more realistic:
Radius r = 15 m (structural weight factor 10^2 less)
at launch cost 1600$/kg (Falcon 9 heavy) we have:

$$5440 \cdot 1000 \cdot 1600/10^2 = \mathbf{\$87.04\ million}$$

$$5440[t]/10^2/63.2 = \mathbf{1\ flight!}$$

$$\omega_{ship} = \sqrt{\frac{9.81}{15}} = \mathbf{0.81\ rad/s}$$

The filter takes as input the centre rotation of the spacecraft and the head movements performed inside the rotating environment (spacecraft) as depicted in Figure 10. The result of the simulation for head tilts of approximately 10 degrees from the centre axis and head motion-induced Coriolis cross-coupling is shown in Figures 11 and 12.

Since the z-axis tilts into the axis of centre rotation, this combined movement of the head and the sudden inertia imposed on the preceptors in the SCC by the centre rotation, causes lagged peaks in z, y and x-axes, with the highest magnitude in the z-axis as shown in Figure 11. The pure kinematic cross-coupled angular accelerations arriving at the SCC canals are shown in the lower plot in Figure 12.

This ACRM output describes what will be 'perceived' by the second-order SCC model

Fig. 9

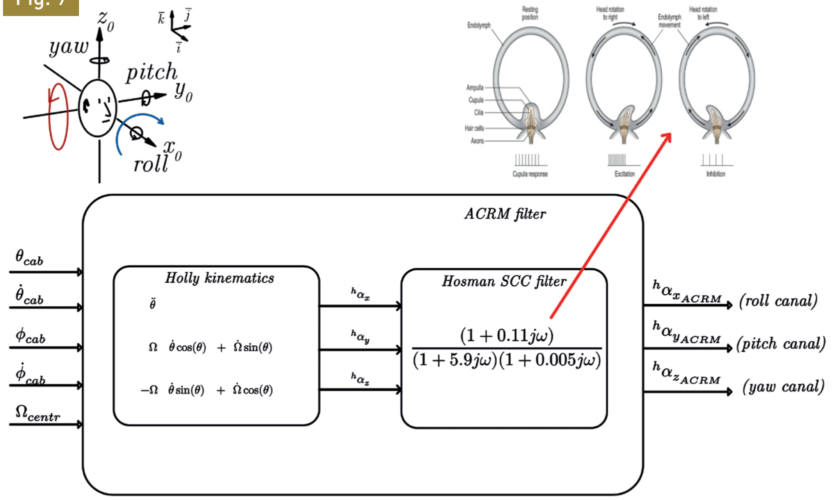


Fig. 10

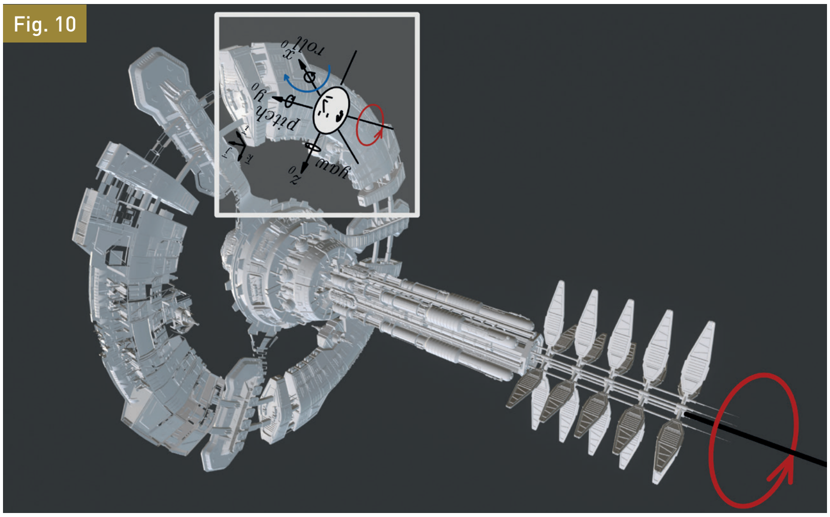


Fig. 11

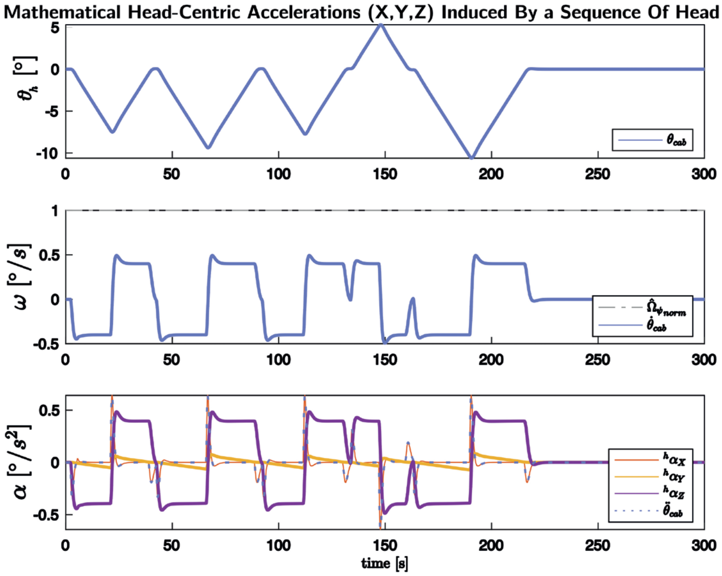

Mathematical Head-Centric Accelerations (X,Y,Z) Induced By a Sequence Of Head Tilts

Fig. 12

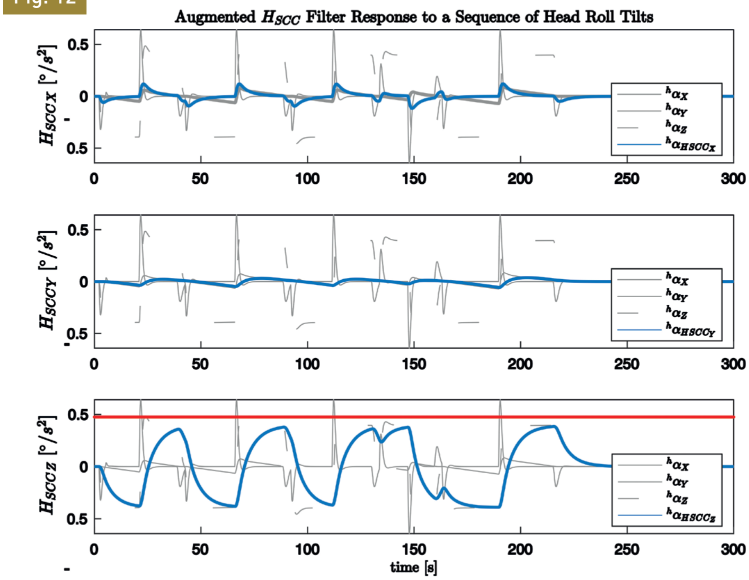
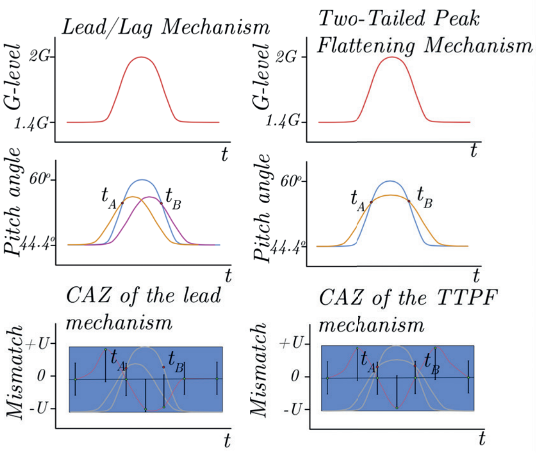

Augmented H_{SCC} Filter Response to a Sequence of Head Roll Tilts

Fig. 13



as a result of the pure kinematic coupling. We see that the impulse in the z-axis (Figure 12) is already close to the perception threshold of 0.5 deg/s^2, proposed by Groen et al. (1948). What does this mean? It means that if we assume that the 0.5 deg/s^2 is perceivable, we would start to experience the Coriolis effect at only 10-degree head tilts in a space ship of the current configuration. Of course, it is always possible to reduce the rotational velocity and increase the diameter of the ship but is there another solution?

In the Coriolis study, this was achieved by the COHAM filter and the so-called concept of two-tailed peak flattening (TTPF) as shown in Figure 13. This concept introduced a combination of a lead and lag in the cabin coordination creating a slight mismatch in the orientation, while anticipating for the pilot input. This effectively resulted in reduced kinematic (and thus perceived) cross-coupling between the centre rotation and the cabin rotations.

The response of the motion filter is shown in Figures 14 and 15. We see that the COHAM filter introduces mismatch in the gravitational vector and follows the TTPF described curve by flattening and stretching out the cabin coordination.

While the experiments showed that the COHAM motion filter had a positive impact on the experienced Coriolis effect (the subjects reported higher comfort, less dizziness and nausea), this is only a passive Coriolis solution. In this configuration, the pilot is requested not to tilt his/her head and the cabin rotations are to an extent deterministic and controllable. Achieving the same in a spacecraft without severely inhibiting the quality of life of the passengers would be both technically and ethically not feasible. Is there a way to mitigate the active Coriolis force induced by head movements? A potential method that was recommended in the study for further investigation is galvanic vestibular stimulation (GVS). This is a relatively old technique but one that has gained popularity in the simulator and gaming industry.

Figure 16 shows examples of GVS applications. Simulator industry vMotion3 platform (left) and the gaming industry, a VR device called project orpheus for PS4 (right).

The principle is based on stimulating the mastoid, at the rear of the head, and certain areas of head and neck. Doing so can either induce or potentially mitigate the perception of motion. In the first case, it is used as an augmentation on top of a VR experience often called a 4D experience. However, working in reverse fashion it could potentially be coupled to a feedback system monitoring head movements. Studies were performed to show the potential use of this in simulation and the research is gaining momentum; however, to investigate the potential use of GVS in rotational spacecraft more experiments are required.

Ambitious goal

In summary, many of us would agree that a potentially feasible and ethically responsible form of space travel is by rotational vessel. However, the realisation of such a system is quite an ambitious goal.

We will have to carefully asses the design in terms of technical feasibility but, most importantly, also ensure the quality of life in the artificial gravity environment. The Coriolis effect is one of the potential issues, for shorter arm spacecraft and needs to be investigated further. We have also seen that potentially there are ways to adapt the vestibular system by external stimuli. But the real question is, how far are we prepared to take it to reach Mars and beyond? If the desire is there we will find a way. ■

Acknowledgements

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About the author

Tigran Mkhoyan is a PhD candidate at the Faculty of Aerospace Engineering of the Delft University of Technology, Department of Aerospace Structures and Materials, and graduated from the Delft University of Technology, department Control and Operations, with the specialisation in advanced control and motion cueing for Dynamic Flight Simulation and pilot training. He is currently working on the Smart-X project, an Autonomous Smart Morphing Wing to bridge the gap between aeroelasticity and advanced control and push the advancements in aircraft technology towards a new generation of Smart aircraft.

Fig. 14

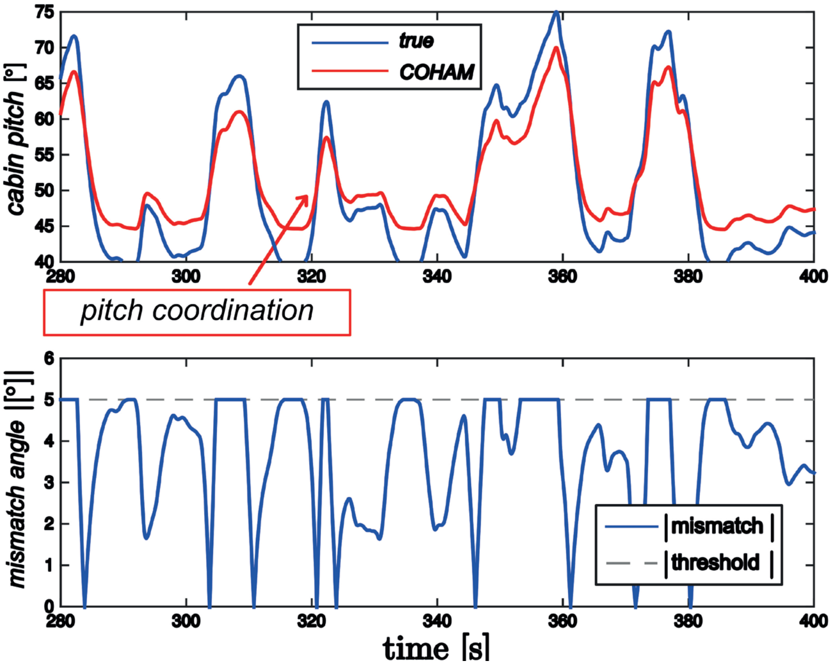


Fig. 15

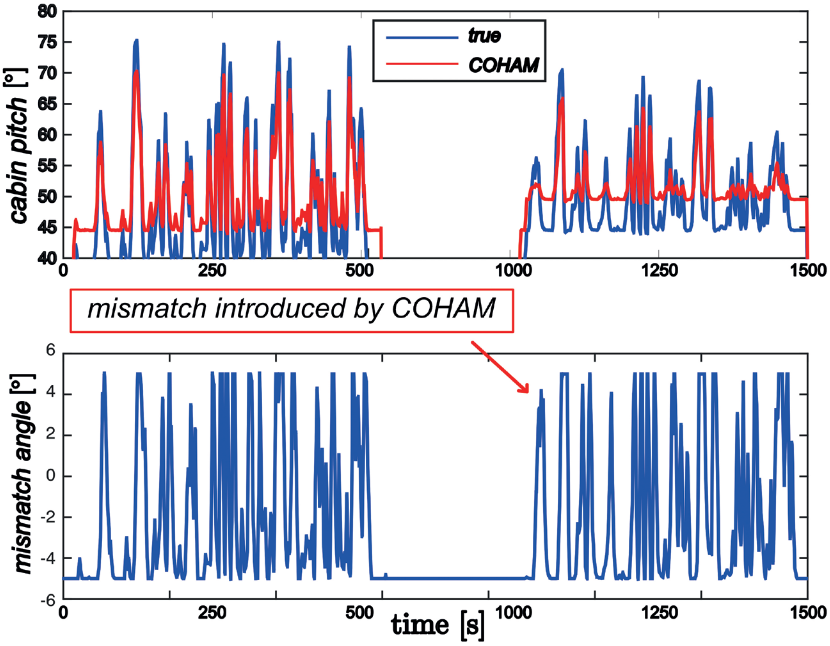
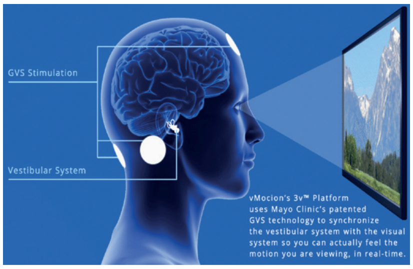


Fig. 16

vMocion 3v



vMocion's 3v™ Platform uses Mayo Clinic's patented GVS technology to synchronize the vestibular system with the visual system so you can actually feel the motion you are viewing, in real-time.

Project Morpheus PS4