The neuromuscular and vestibular system

A pilot needs his body to influence his environment. And this body is actuated by muscles. This means that, to understand the pilot's behavior, we need to understand how his muscles work. But next to this, a pilot also gets his input from the environment. A very important contributor to this input is the vestibular system. We will also look at how this system works.

1 The neuromuscular system

1.1 The build-up of the system

The **neuromuscular system** (NMS) consists of three parts. There are the **brain** and the **spinal cord**, which together form the **central nervous system** (CNS). This system provides inputs to the third part: the **muscles**. When the NMS is used to control an aircraft, the NMS actually becomes part of the closed-loop system dynamics.

If we know how the NMS works, we can influence the system dynamics. One way to do this is to change the NMS behavior. This can for example be done by training the pilot. Alternatively, we can adjust the **feedback system** to be better suited for the NMS. For example, the stick feedback can be programmed such that the pilot flies in a more comfortable and/or more effective way.

The way in which the NMS influences the dynamics depends on the type of aircraft. In small aircraft, the control stick is more or less directly connected to the control surfaces. For such aircraft, it is often difficult to influence the feedback system. On the other hand, in fly-by-wire aircraft, a computer is in-between the NMS and the control surfaces. With such aircraft, designers have a lot of freedom varying the feedback system.

There is a possible design problem. When applying an input, accelerations of the controlled vehicle can lead to involuntary movements of the arm/hand. For example, you can push a stick forward to accelerate forward. But because your vehicle accelerates forward, you are automatically pushed back, thus reducing the desired input. When designing a neuromuscular input system, designers should take this into account.

1.2 Feedback systems

A **force-feedback system** is a system that provides feedback to the human controller through forces. These forces inform the user of several things, like the actual machine position, the machine limitations, the machine perception and more. Next to this, force feedback can be used to encourage/discourage certain control actions, or to increase the stability of the human-machine interaction.

There are several examples of force-feedback systems.

- In **haptic feedback systems**, the user is provided feedback through the sense of touch. We can, for example, have a haptic control panel. When the human controller pushes this panel, it pushes back. The amount in which it does this is the feedback to the human controller. By using haptic control, humans get better feedback and can thus more accurately control the system.
- In **exoskeleton force feedback**, an external mechanical 'skeleton' is used. By moving, for example, his arm, the human controller provides input. The skeleton can resist these movements to a certain degree, thus providing feedback. This method of feedback allows for a multi-dimensional input, thus increasing the number of possibilities to control the system.
- In **master-slave feedback** the human controls the master machine. This machine then sends the control signals to a slave machine. This slave machine measures its environment and sends its

feedback back to the master. This feedback mechanism is very convenient when machines need to work in situations too dangerous or too big/small for humans.

1.3 The build-up of muscles

Let's take a closer look at muscles. Muscles are connected to the bones through **tendons**. Muscles are activated by **motor neurons** (α-neurons). This causes the muscles to contract, thus moving the skeleton of the human. The actual response of the muscles is measured by **sensory neurons** (γ-neurons). This data is then sent back to the brain as feedback.

Muscles are mostly made out of 'muscle fibres' called **myofibrils**. Due to the chemical structure of the myofibrils, muscles can only contract. To enable bones to move in multiple directions, **antagonistic pairs** of muscles are often present in the human body. When one of these muscles (the **flexor**) contracts, tension on the bone increases. This allows rotation in one direction. When the other muscle (the **extensor**) contracts, tension on the bone is released, enabling motion in the other direction.

The γ-neurons measure the muscle stretch and the muscle stretch velocity. These two parameters are very important, since they mainly determine the amount of force that can be generated by the muscle. If the muscle is too short, too long or moving too fast, it is not capable of generating big forces.

Next to γ-neurons, there are also **Golgi tendon organs** (GTOs). A GTO measures how much the tendon is stretched. This amount of stretch is a good indication of the muscle force. This does not directly mean that the muscle is contracted though. Muscle force can also be caused by a passive muscle stretch.

Not all the measured data is sent directly to the brain. There are also 'short-cuts' in the spinal cord. This allows for very fast reactions called **reflexes**. Reflexes enable fast and complex behavior without any conscious effort from the brain. Reflexes can be both innate or acquired through learning. An example is the **stretch reflex**: when a muscle stretches too much, this stretch is counteracted. Another example is the **GTO reflex**: when the muscle force becomes too big, the muscle is relaxed. This prevents damage to the muscle and/or the tendon.

Next to muscles, the body also has **skeletal bones**. These bones provide rigidity and inertia to the body and provide attachment sites for muscle tendons. Finally, there is the **skin**. This flexible layer provides protection of the muscles and the skeleton from the outside world.

1.4 Modeling the neuromuscular system

How can we model the muscular system? The basic idea is that we model the muscle as a simple mass-spring-damper system. The mass of the system consists of all relevant body material, like muscles, bones and skin. But the muscle isn't the only part dealing with muscle forces. These force also needs to be transmitted through the skin. We model the skin as a simple massless spring-damper system. The force caused by the whole muscle system is then given by

$$F_s(t) = M_a \ddot{x}_a(t) + B_a \dot{x}_a(t) + K_a x_a(t) + B_s \dot{x}_s(t) + K_s x_s(t), \tag{1.1}$$

where x_a denotes the musculo-skeletal deflection, while x_s denotes the skin deflection. The total deflection is thus the sum of these two deflections.

The **admittance** is defined as the ratio x_s/F_s between the hand position x_s and the force F_s. Humans can adjust the admittance. When a human needs to keep the exerted force constant, he uses a high admittance, resulting in a flexible system. On the other hand, if the human needs to keep the position constant, a low admittance is used, causing a stiff system.

There is a way to measure the admittance. First, we need to give the human controller instructions. For example, we can tell him to maintain the position or to maintain the force. We then impose a perturbation force/torque D. As a result of this, the manual controller applies a force/torque F. This results in a pedal displacement X. By measuring D, F and X, we can calculate the admittance. This admittance strongly influences the NMS dynamics. So when a manual control system is designed, the influence of the admittance on the NMS dynamics has to be taken into account.

2 The vestibular system

The **vestibular system** is a system in our inner ear. It arranges our feeling for balance and spatial orientation. The vestibular system has several subsystems, each having a specific task. We will look at these individual subsystems.

2.1 The otholith organ

The **otolith organ** (OTO) is sensitive to **specific forces**. (The specific force consists of accelerations and gravity.) It is located in both the **utricle** and the **saccule**. The utricle mainly has horizontal sensitivity, while the saccule has vertical sensitivity. The otholith organ can be seen as a membrane which deforms when specific forces are applied. The deformation of the membrane is generally modeled as

$$H(s) = \frac{1}{(\tau_{OTO} s + 1)^2}, \tag{2.1}$$

where the time constant τ_{OTO} is small (only a few milliseconds). Another way to model the otholith organ is

$$K \frac{1 + \tau_n s}{(1 + \tau_1 s)(1 + \tau_2 s)}, \tag{2.2}$$

where $K = 3.4$, $\tau_n = 1$s, $\tau_1 = 0.5$s and $\tau_2 = 0.016$s. The otholith organ measures both tonic and phasic units. **Tonic** units concern the magnitude of the acceleration, while **phasic** units concern changes in the acceleration.

2.2 Semi-circular canals

The vestibular system also has three **semi-circular canals** (SCC). (One for each direction.) These canals are filled with a fluid. When there is a rotational velocity, the fluid moves in the canals. Small hairs detect this shift. So the semi-circular canals measure angular velocities. Modeling the SCC can be done using

$$H_{SCC}(s) = \frac{1 + \tau_L s}{(1 + \tau_1 s)(1 + \tau_2 s)}, \tag{2.3}$$

where $\tau_L = 0.1097$ s, $\tau_1 = 5.924$ s and $\tau_2 = 0.005$ s. The frequency range of the SCC is from 0.1 rad/s to 10 rad/s. The output is proportional to the rotational velocity.

However, not only your vestibular system tells you that you are moving. Often your eyes tell you this too. If you move, then your environment appears to move around you. Your eyes see this and inform your brain of the motion. This perception of self-motion due to visual stimuli is called **vection**. An exception occurs when your environment moves, but you do not. In this case, your brain will get a wrong signal. This is called **retinal slip**.

The signals from your visual system and from the vestibular system are both feedback for your eyes. Using this information, the two images from both eyes are merged and missing pieces of information are filled in.

2.3 The subjective vertical

You always have a notation of your orientation. This is captured in the **subjective vertical** (SV). This is the vector of which you believe is straight down. If the SV strongly deviates from the actual vertical, then you are disoriented.

But how does the vestibular system know what the vertical is? For this, it uses both the otholith organ and the semi-circular canals. The otholith organ detects specific forces. So it is simply able to find out which direction the specific force points to. From this it can derive the direction of gravity. However, simple accelerations of the body should not be taken into account. And this is where the semi-circular canals come in. If the direction of the specific force changes, but you don't rotate, then you must be accelerating. So, based on the specific forces of the OTO and the rotational velocities indicated by the SCC, the subjective vertical is updated.

You might be wondering: don't you use visual information as well to determine the SV? In fact, you do. Let's call $\hat{\omega}_{vest}$ the rotations as indicated by the vestibular system and $\hat{\omega}_{vis}$ the rotations as indicated by the visual system. These two signals need to be merged. This is modeled according to the **visual attractor** model, which states that the processed rotations $\hat{\omega}_{total}$ are given by

$$\hat{\omega}_{total} = (\hat{\omega}_{vis} - \hat{\omega}_{vest})H_{VA}(j\omega) + \hat{\omega}_{vest}. \tag{2.4}$$

Here, the transfer function $H_{VA}(j\omega)$ is a low pass filter. So when the vestibular system and the visual system give different signals, your brain initially believes the vestibular system, but then slowly starts to believe the visual system.

Next to the visual system and the vestibular system, there is also the **proprioceptive system**. This system consists of skin pressure receptors. It measures forces exerted on the body. Based on these forces, your brain makes another estimate of your motion. And again, these signals are merged to get an output that is as meaningful as possible.

2.4 Modeling manual control

When modeling manual control, we also need to take into account how the body acquires its data. We have seen that it mainly does this through the vestibular system and the visual system. An important difference is that the vestibular system generally measures the actual orientation y, while the visual system measures the orientation difference $e = y_{ref} - y$. So, the two systems have different input signals.

It also turns out that the vestibular system is faster than the visual system. That is, it has a lead with respect to the visual system. In other words, the perception delay is lower for the vestibular system. Especially when following a target, this means that the vestibular system contributes to the inner loop, while the visual system makes up the outer loop of the human controller.