SOLUTIONS - EXERCISE 2

Sensors, electric motors and Simulink

1. SENSORS FOR A FORKLIFT

For example:

2D/3D scanning. The emitted laser light is reflected from the environment and then collected again. The direction and the distance to the reflection point is recorded. A map of the environment can be constructed from the individual points.

Indoor triangulation methods. Inside the building are beacons, whose locations are known. The vehicle has a receiver/transmitter that compares its location relative to the beacons. The beacons can be for example radio transmitters or mirrors which are user with a laser scanner. Requires a map of the environment with the locations of the beacons.

Proximity sensors. To prevent severe damages in case of malfunction or other unexpected events, there must be proximity sensors to stop the motors in case of for example a collision. Mechanisms could be mechanical (built for example in bumpers) or optical that go off, when the distance is small enough.

Machine vision. Machine vision could be one way for a vehicle to figure its surveillance out. Stereo vision uses two different visual data sources to produce distance and 3D information. Another option would be structured light; the 3D-"image" is generated via comparing the changes in the light pattern when it hits the surfaces. Machine vision requires a lot of computing power and well-designed programs.

Magnetic or optical markers, such as QR codes or electric wires embedded in the floor or walls. The AGV can follow for example an electric wire in the floor with only a couple of magnetic sensors.

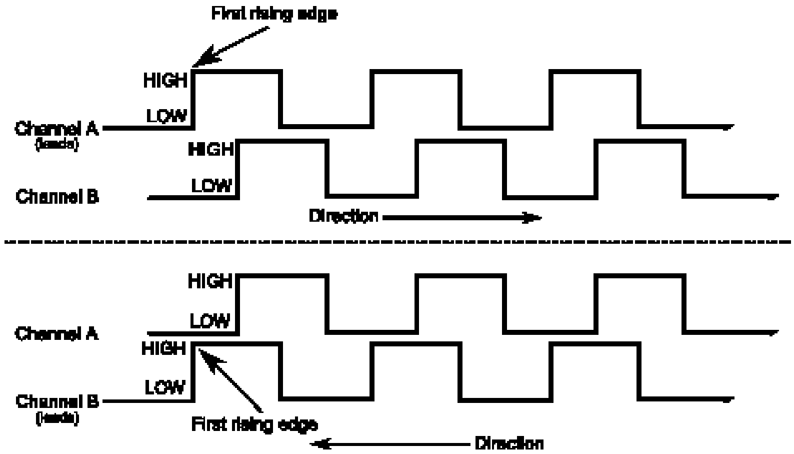
The best solution is to integrate two or more methods in one vehicle. None of the sensors is absolutely accurate and some sensors operate better in some purposes, the others in somewhere else.

2. POSITION SENSORS

Q1. Case 1. Because the pitch of the ball screw is 8 mm, the object moves linearly 8 mm when shaft of the motor rotates one revolution.

$$Required\ resolution = \frac{object\ movement/rev}{precision} = \frac{8\ mm/r}{0.02\ mm} = 400\frac{1}{r} \quad (1)$$

At least 400 positions per revolution must be detected in order to achieve the desired resolution. With a 1x encoding, i.e. when detecting only a rising **or** a falling edge from **one** encoder channel, this would mean that the code disc must have 400 slots. If the rising **and** falling edge of **one** encoder channel are detected i.e. two positions per slot are detected, then 200 slots or in the code disc would be sufficient. In these cases the other encoder channel is used for detecting the direction of rotation. With quadrature (4x) encoding i.e. when detecting both rising and falling edges from both encoder channels, 100 slots would be enough to get the required position resolution.



In this exercise there are two photodetectors which produce a 90 degree phase shifted signal from one row of slots and the edges from only one channel are detected. This means that we can detect twice the number of positions than there are slots in the code wheel. Channel B is used to detect the direction of rotation.

Therefore, we are using 2x encoding and 200 slots is enough.

b. With the conveyor belt, the object moves 2π·18.5mm per motor revolution.

$$R = \frac{2\pi \cdot 18.5\ \frac{mm}{r}}{0.02\ mm} = 5811.95\frac{1}{r} \quad (2)$$

Therefore, the measurement resolution must be at least 5812 pulses per revolution in order to achieve the desired precision. If measuring with 2x encoding, this means 2906 slots per revolution.

c. With the reduction gear, the object moves less per one revolution.

$$\frac{\frac{8}{6.3}\ mm/r}{0.02\ mm} = 63.49\frac{1}{r} \quad (3)$$

->resolution 64 edges per revolution i.e. 31.7 ppr with 2x encoding.
d.

$$R = \frac{\frac{2\pi \cdot 18.5}{6.3} \frac{mm}{r}}{0.02\, mm} = 922.53 \frac{1}{r} \tag{4}$$

->923 pulses i.e. 461,3 ppr with 2x encoding.

3. Permanent magnet DC motor modeling

Q1. In this exercise we assume, that the accelerating torque is constant. The torque is calculated using the current during acceleration and the motor torque constant. After the torque is calculated, the task is just basic dynamics.

Torque during acceleration:

$$T = K_t \cdot I \tag{5}$$

Total moment of inertia:

$$J_{tot} = J + J_2 \tag{6}$$

Acceleration:

$$\alpha = \frac{T}{J_{tot}} \tag{7}$$

Acceleration time:

$$t = \frac{\omega}{\alpha} = \frac{2\pi \cdot n}{60 \cdot \alpha} \tag{8}$$

Q2. Reduced moment of inertia

Inertia of the mass on the conveyor belt pulley can be thought as a point at the radius of the pulley:

$$J_{mass} = mr^2. \tag{9}$$

The final inertia on the motor shaft is reduced with the gear:

$$J = \frac{J_{mass}}{i^2}. \tag{10}$$

Q3. You can find the solution Simulink model also in MyCourses.

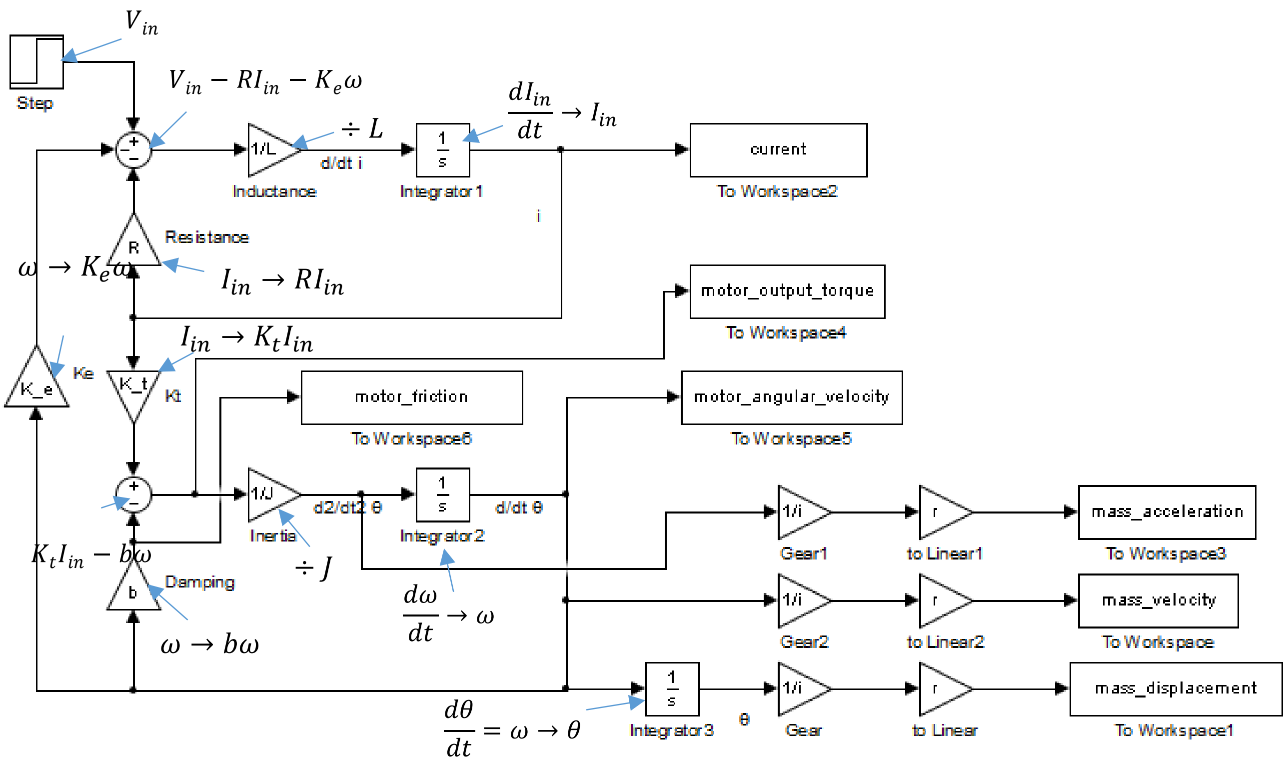


FIGURE 1. SIMULINK MODEL

The upper part of the model represents the electrical circuit of the motor, which consists of the input voltage and the inductance and resistance of the windings. The input voltage creates current in the windings and the increase rate is limited by the inductance. The electrical part is coupled to the mechanical part of the motor, which is represented by the lower half of the model, with the torque constant K_t. The torque constant converts current to electromechanical torque. Reducing the damping torque from the electromechanical torque produces the accelerating torque, which causes rotation of the rotor and the mass. The rotating speed of the rotor is coupled back to the electrical circuit with the back-emf constant K_e which reduces the effective voltage that creates current.

First, let's modify the equation for the electrical circuit of the DC motor equation to supply our needs better:

$$V_{in} = L\frac{dI_{in}}{dt} + RI_{in} + K_e\omega \tag{11}$$

$$\frac{dI_{in}}{dt} = \frac{V_{in} - RI_{in} - K_e\omega}{L} \tag{12}$$

The corresponding equation for the mechanical circuit is:

$$K_t I_{in} = J\frac{d\omega}{dt} + b\omega \tag{13}$$

$$\frac{d\omega}{dt} = \frac{K_t I_{in} - b\omega}{J} \tag{14}$$

You can find the equation parts attached to the model figure 3 above.

Q4. When the target velocity is reached, current and velocity both are constant i.e. their derivatives are zero. Thus, from equations 14 and 16,

$$I_{in} = \frac{b\omega}{K_t}, \tag{15}$$

$$V_{in} = RI_{in} + K_e\omega, \tag{16}$$

$$V_{in} = R\frac{b\omega}{K_t} + K_e\omega, \tag{17}$$

Target motor shaft angular velocity can be derived from target mass velocity:

$$\omega = \frac{v \cdot i}{r}. \tag{18}$$

The final equation will be:

$$V_{in} = \left(\frac{Rb}{K_t} + K_e\right)\left(\frac{v \cdot i}{r}\right), \tag{19}$$

and substituting the numerical values gives 43.1V.

Q5.

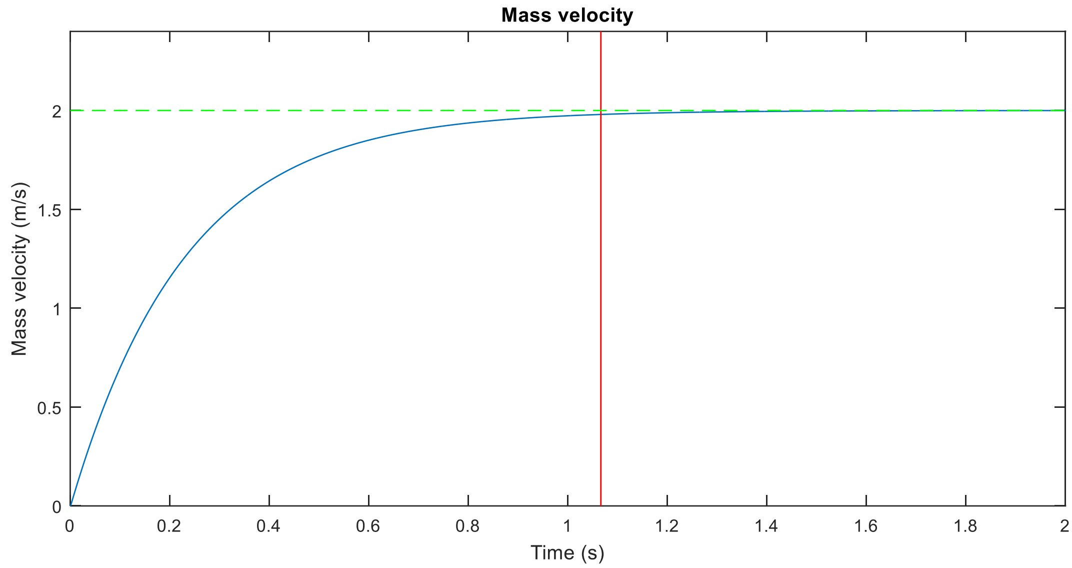


FIGURE 2. MASS VELOCITY

The required velocity is achieved quite slowly because of the inertia of the load mass. Also the inductance of the windings slows down the response. The velocity-dependent terms damping (bω) and back-emf (kω) reduce the accelerating torque and thus the acceleration. It takes about 1.07 seconds to reach the 2 m/s velocity with a 99 % precision. In theory, the velocity never completely reaches the target velocity.

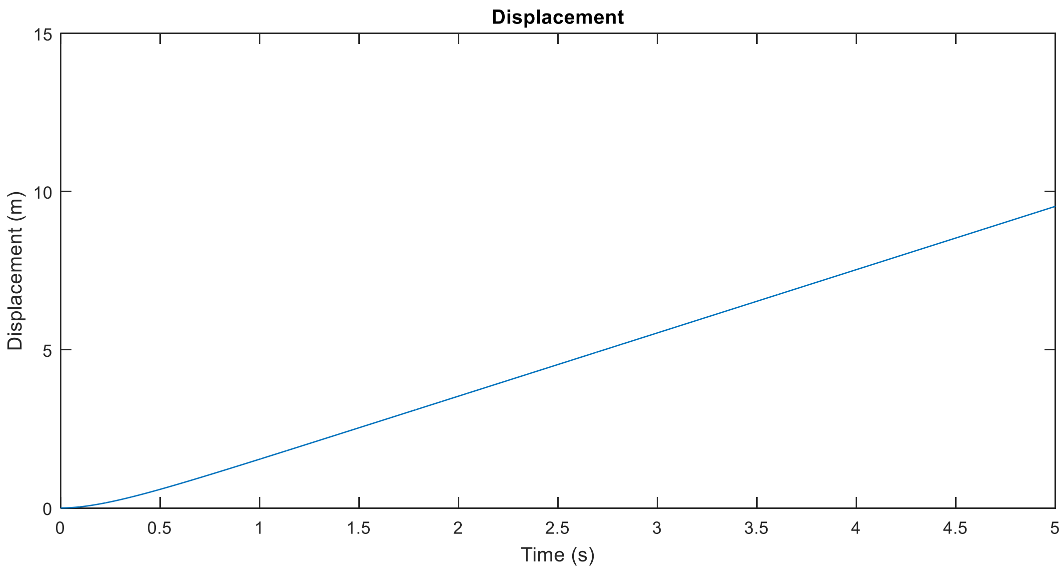


FIGURE 3. MASS DISPLACEMENT

The displacement plot is almost linear after 1 second. That is when the velocity approximately reaches the target i.e. steady state.

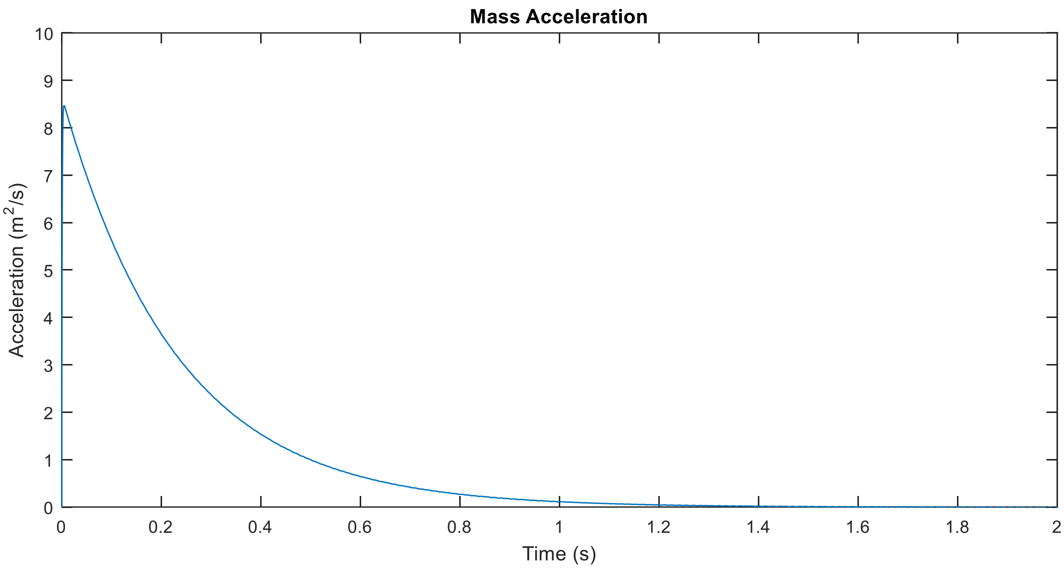


FIGURE 4. MASS ACCELERATION

The mass acceleration is quite high at first, when the velocity is still slow. This is when the motor is able to provide the largest torque. As the angular velocity increases, the increased back emf reduces the available torque and thus also the acceleration.

Q6. Input power to the motor is the product of the input voltage and the current in the windings.

$$P_{in} = UI$$

Output torque is the torque that is used to accelerate the load i.e. the torque produced by the electromagnetic force subtracted with the torque lost in the internal damping/friction.

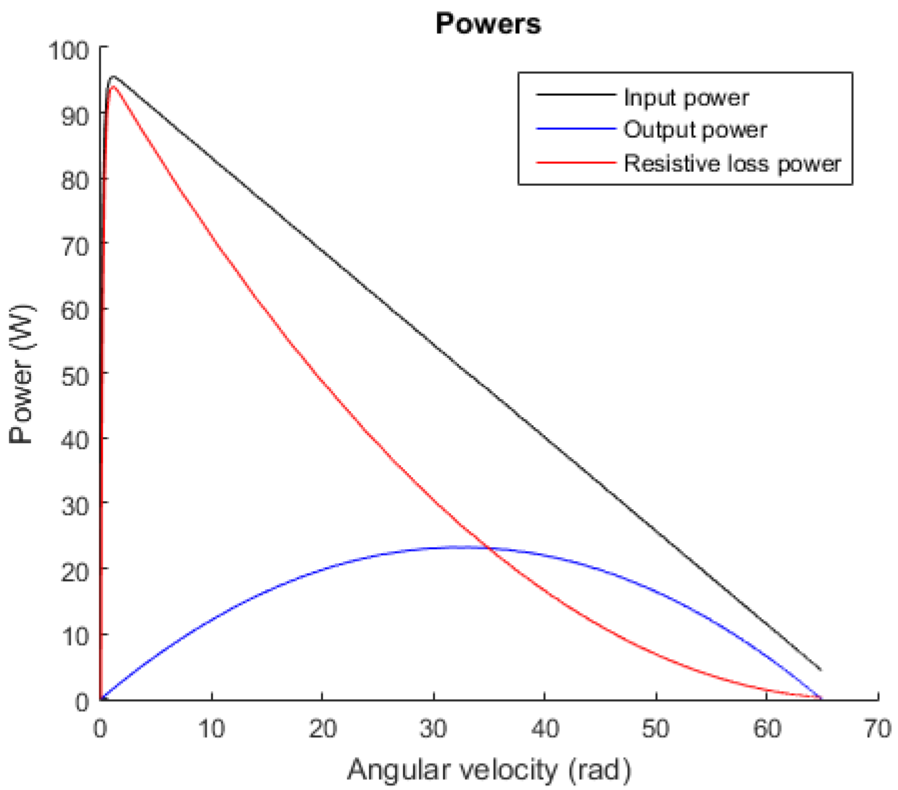
$$T = K_t I - b\omega$$

Output power is a product of the output torque and angular velocity.

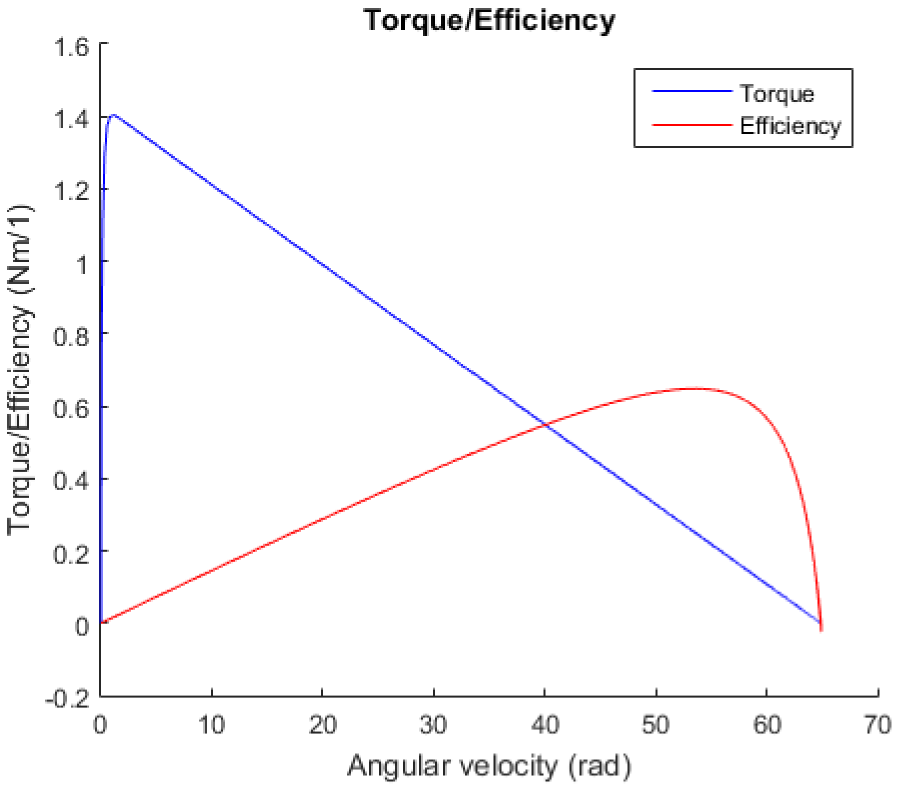
$$P_{out} = T\omega$$

Resistive losses in the windings are a product of the winding resistance and square of the winding current.

$$P_{res} = RI^2$$



Because the input voltage is constant and the input current declines with a constant slope, also the input power declines with a constant slope to almost zero when the angular speed is increased. Resistive losses are at their largest with slow velocity since the back emf does not reduce the effective voltage at the winding. Resistive losses do not reduce linearly with the speed since the relation to current is exponential. Output power peaks in the middle of the velocity range since it is a product of the linearly declining torque and angular velocity.



Torque reduces towards zero with the increasing velocity. In this figure, at very low speed, the curve is affected by the inductance of the windings. The simulated motor is small, very low power motor which has a pretty poor efficiency, peaking at 65 %. Since efficiency is the output power, i.e. product or torque and velocity, divided with the input power, it is initially zero because of zero velocity. With maximum rpm it is also zero since the motor can no longer produce any output torque, but instead all the torque produced by the electromagnetic force is lost in damping and friction.