AALTO UNIVERSITY
School of Engineering
Department of Mechanical Engineering

MEC-E5001 Mechatronic Machine Design Project work
Crane Hook Sway Simulation and Control: “Keikku”

Authors:

Waqas Ahmad 661358

Adel Ansari 661449

Professor:

Kari Tammi

Date of submission: 18/02/2018

MEC-E5001 Mechatronic Machine Design Project work

Crane Hook Sway Simulation and Control: “Keikku” (30 points)

The aim of the project work is to design a device that can demonstrate sway control feature of a crane, i.e. “keikku”. You have been assigned to a group of **two (2)** people and your task is to **1) design and simulate trolley and hook system of an overhead crane and 2) apply sway control on the system.** You need to select the scale of the device yourself.

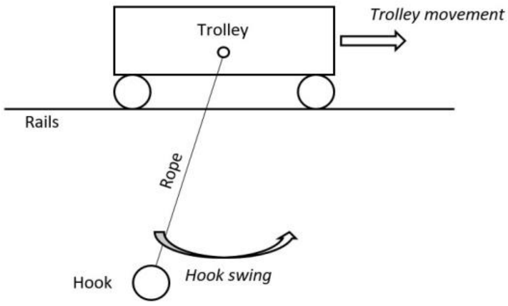


Figure 1: Trolley and hook of a crane.

The project work is laid out as a chronologic step-by-step assignment but it is recommended to be done iteratively so that when problems arise along the way you can go back and make adjustments to previous decisions. Pro tip: It may be easier to design a miniature model, as industrial components are often custom ordered and difficult to find.

Requirements for the project

1. **Design a “keikku” according to the tasks given**. For reference, see example values of the Ilmatar crane listed in Table 1.
2. **Make a report of your work according to the instructions given in this assignment paper.** In the project report, follow the same section titles 1...6 given in the assignment paper. (1. Background study (3 p), 2. Numeric Modelling (6 p), 3. CAD modelling (5 p) and so on…).
3. Make a presentation of your work. Every group will have a 5-minute final presentation during the last week of the course.

Return **three** project files to MyCourses:

1. Project report in .pdf format.
2. Presentation in .pdf or .ppt(x) format.
3. Zipped folder (.zip) for all other required files. (At least .slx and .m)

Table 1. Reference values for the machine.

Rope length	L	0.5-3.0 m
Trolley max speed	v	20 m/min

Trolley movement range	L_2	9 m
Trolley weight	m_1	250 kg
Trolley motor power	P	1.5 KW
Hoist (vertical) max speed	v_2	8 m/min
Hook weight	m_2	5 kg
Lifting capacity	mmax	3200 kg

1. Background study (3 p)

a) Search and select **two** academic articles on the project topic. Minimum amount of text for each article is 60 words.

   i. Describe the main purpose and findings of the article. (2 x 0.5 p)

   To learn about the techniques used in controlling the system such as LQR or model predicted analysis as well as getting familiar with the mathematical model used for our case of study. Furthermore, our aim was to find a recent research that are being carried out for angle measurement besides the novel techniques like potentiometer etc.

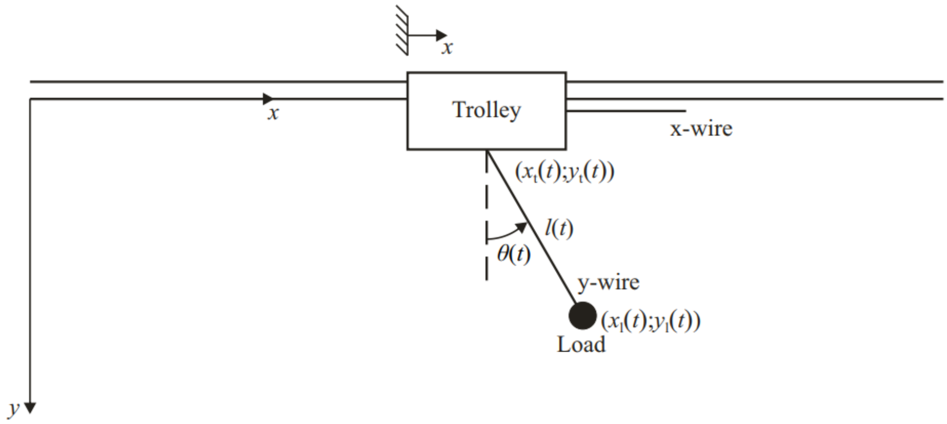
   ii. Describe how the article is related to the project topic. (2 x 0.5 p)

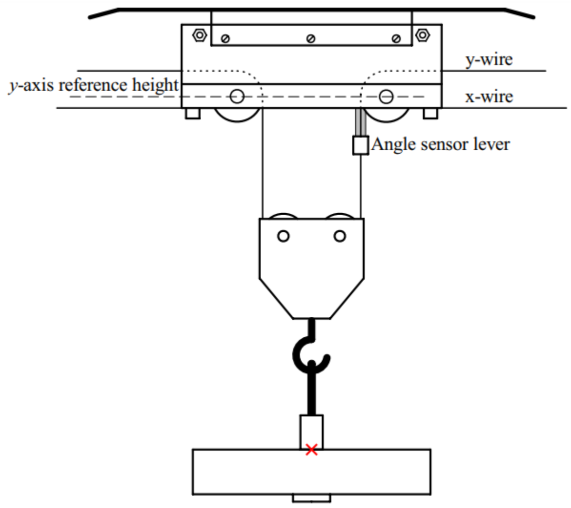
   One of the useful research papers we found was “Development of Anti-Sway Control System for Container Cranes” by Y. Okubo. It discusses a novel idea about controlling the trolley using fuzzy control as well as the use of image processing for the sensor to measure sway. Moreover, the upgraded system was suggested as the system response is relatively slow and there are insufficient precision for advanced requirements of automation. Experiment were carried out to validate the skew control along with evaluation using simulation. Optimal feedback control with the application of LQ theory was used as an optimal control in the system and was discussed in the paper.

   The other useful paper we found was “Anti-Sway Control of Container Cranes: Inclinometer, Observer, and State Feedback” by Yong-Seok Kim. Many things were thoroughly discussed and the durability of the system was experimented. Main idea of the article was to find a potential replacement of conventional angle measuring techniques using image processing techniques etc. Article makes the assumption that the angle can be measured using inclinometer but the speed $\dot{\theta}$ is to be assumed based on three observers to get the exact value.

b) Search for existing inverted pendulum mechanisms for reference and draw a sketch of your own system by hand or with a computer software. There are many different types of mechanisms to move the trolley. In addition, rope angle measurement needs to be considered when designing your mechanics. (The rope does not have to be a real rope, it can be a rigid stick with weight at the end.) **Attach this sketch to your report.** (1 p)

   The figures were drawn to show the mechanism applied in our system and the axis at which the forces are applied to move the trolley. It also shows what it meant to have an angle variation caused by moved the loaded mass.


x
Trolley
x
x-wire
$(x_t(t);y_t(t))$
$l(t)$
$\theta(t)$
y-wire
$(x_l(t);y_l(t))$
Load
y


y-wire
y-axis reference height
x-wire
Angle sensor lever

2. Numeric modelling (6 p)

a) Make force equations for horizontal and vertical forces in your system according to the Newton's Second law of motion. (0.5 p)

The forces were drawn in both x and y directions and were used in a form of kinetic and potential energy in this case.

Kinetic energy (both vertical and horizontal forces) will look as follow:

$$T = \frac{1}{2} m_1 \dot{x}^2 + \frac{1}{2} m_2 v^2$$
$$v^2 = v_x^2 + v_y^2$$
$$v_x = \dot{x} + L\dot{\theta}\cos\theta$$
$$v_y = -L\dot{\theta}\sin\theta$$

Potential energy (vertical body force by gravity) is:

$$U = m_2 g L(1 - \cos\theta)$$

b) Form the **nonlinear** equations of motion that are needed for creating the simulation model of the system. (2 p)

Assumptions:

1. The rope is considered as an inflexible rod.
2. Compared to the payload mass, the rope mass is ignored.
3. No friction exists in the system.
4. The payload (m_2) is regarded as material particle.

Using Lagrangian to solve for the x coordinate system:

$$L = T - U = \frac{1}{2} m_1 \dot{x}^2 + \frac{1}{2} m_2 v^2 - m_2 g L(1 - \cos\theta)$$
$$\frac{\partial L}{\partial x} = 0$$
$$\frac{\partial L}{\partial \dot{x}} = m_1 \dot{x} + m_2(\dot{x} + L\dot{\theta}\cos\theta)$$
$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) = m_1 \ddot{x} + m_2(\ddot{x} + L\ddot{\theta}\cos\theta - L\dot{\theta}^2\sin\theta)$$

The equation of motion is therefore:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) - \frac{\partial L}{\partial x} = F$$
$$m_1 \ddot{x} + m_2(\ddot{x} + L\ddot{\theta}\cos\theta - L\dot{\theta}^2\sin\theta) - m_1 \dot{x} + m_2(\dot{x} + L\dot{\theta}\cos\theta) = F$$
$$(m_1 + m_2)\ddot{x} + m_2 L(\ddot{\theta}\cos\theta - \dot{\theta}^2\sin\theta) = F$$
$$(m_1 + m_2)\ddot{x} + m_2 L\ddot{\theta}\cos\theta - m_2 L\dot{\theta}^2\sin\theta = F \qquad (1)$$

Using Lagrangian to solve for the θ coordinate system:

$$\frac{\partial L}{\partial \theta} = m_2[(\dot{x} + L\dot{\theta}\cos\theta)(-L\dot{\theta}\sin\theta) + (L\dot{\theta}\sin\theta)(L\dot{\theta}\cos\theta)] - m_2 g L sin\,\theta$$

$$\frac{\partial L}{\partial \theta} = -m_2 L\dot{x}\dot{\theta}\sin\theta - m_2 gL\sin\theta$$

$$\frac{\partial L}{\partial \dot{\theta}} = m_2\left[\left(\dot{x} + L\dot{\theta}\cos\theta\right)(L\cos\theta) + \left(-L\dot{\theta}\sin\theta\right)\left(-L\dot{\theta}\sin\theta\right)\right]$$

$$\frac{\partial L}{\partial \dot{\theta}} = m_2 L\dot{x}\cos\theta - m_2 L^2\dot{\theta}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) = m_2 L\ddot{x}\cos\theta - m_2 L\dot{x}\dot{\theta}\sin\theta + m_2 L^2\ddot{\theta}$$

The equation of motion is therefore:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) - \frac{\partial L}{\partial \theta} = 0$$

$$m_2 L\ddot{x}\cos\theta + m_2 L^2\ddot{\theta} + m_2 gLsin\,\theta = 0$$

$$\ddot{x}\cos\theta + L\ddot{\theta} + gsin\,\theta = 0 \tag{2}$$

c) Form the **linear** equations of motion that are needed for creating the simulation model of the system. (2 p)

Linearizing Equation (1) and (2) by considering $\theta = 0$ as the stable equilibrium of the system:

$$(m_1 + m_2)\ddot{x} + m_2 L\ddot{\theta} = F \tag{3}$$

$$\ddot{x} + L\ddot{\theta} + g\theta = 0 \tag{4}$$

Taking a Laplace transform of Equation (4) gives:

$$s^2 X(s) + Ls^2\theta(s) + g\theta(s) = 0$$

$$s^2 X(s) = -\theta(s)\,(Ls^2 + g)$$

$$\frac{\theta(s)}{X(s)} = -\frac{s^2}{Ls^2 + g} \tag{5}$$

$$X(s) = -\frac{\theta(s)\,(Ls^2 + g)}{s^2} \tag{6}$$

Taking a Laplace transform of Equation (3) and using the relationship in Equation (6):

$$(m_1 + m_2)s^2 X(s) + m_2 Ls^2\theta(s) = F(s)$$

$$-(m_1 + m_2)s^2\frac{\theta(s)(Ls^2 + g)}{s^2} + m_2 Ls^2\theta(s) = F(s)$$

$$\frac{\theta(s)}{F(s)} = \frac{1}{[-(m_1 + m_2)(Ls^2 + g) + m_2 Ls^2]}$$

d) What does linearization mean and why is it often necessary in control systems? (0.5p)

Linearization is a linear approximation of a nonlinear system that is valid in a small region around an operating point, a steady-state condition in which all model states are constant. Linearization is needed to design a control system using classical design techniques, such as Bode plot and root locus design.

Linearization also lets you analyze system behavior, such as system stability, disturbance rejection, and reference tracking. Linearization can help us know how the system behaves for small deviations around the point.

In our model, we considered θ=0 as the stable equilibrium of the system and therefore, we will able to move from getting a generic solution to equilibrium solution. There is one theorem that is explained wonderfully by Wikipedia regarding the reason we linearize around the equilibrium for a nonlinear system which is called “Hartman-Grobman Theorem”. Basically the theorem states that the behaviour of a dynamical system near a hyperbolic equilibrium point is qualitatively the same as the behaviour of its linearization near this equilibrium point provided that no eigenvalue of the linearization has its real part equal to 0. Therefore when dealing with such fixed points one can use the simpler linearization of the system to analyze its behaviour.
Further reason why linearization is important is because to implement LQR method, the non-linear equations should have been linearized to be used in optimization of state space function.

3. CAD modelling (5 p)

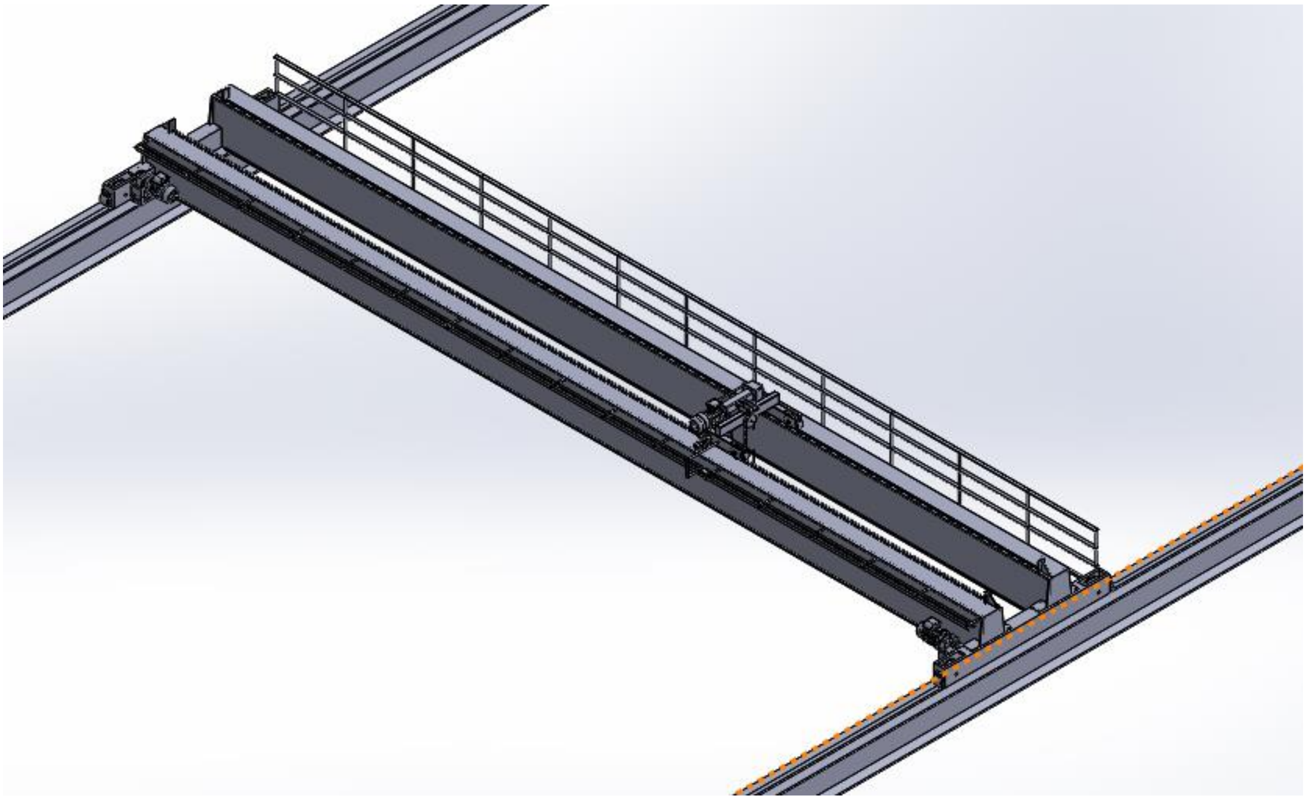
Make a 3D CAD model of your machine. The amount of points you receive from this task is defined by the level of detail of your design. You may use existing projects as reference, but use of readymade models is prohibited. (Models of individual components can be used if available.) **Attach at least one picture of your final design to your report (preferably more than one).**

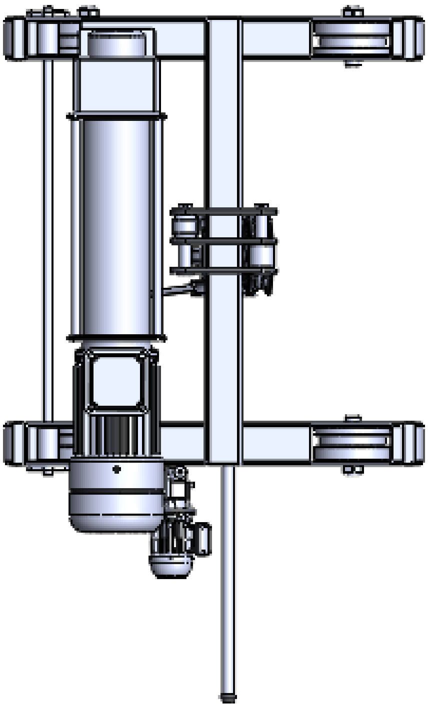
Each subsection is graded the following:

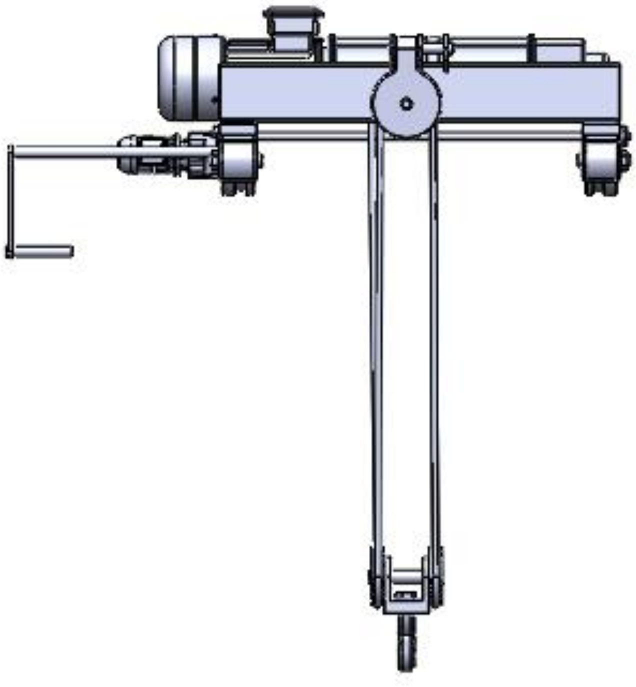
- *0 points – section is not included in the model*
- *0.5 points – section is modelled*
- *1 point – section is modelled in detail*

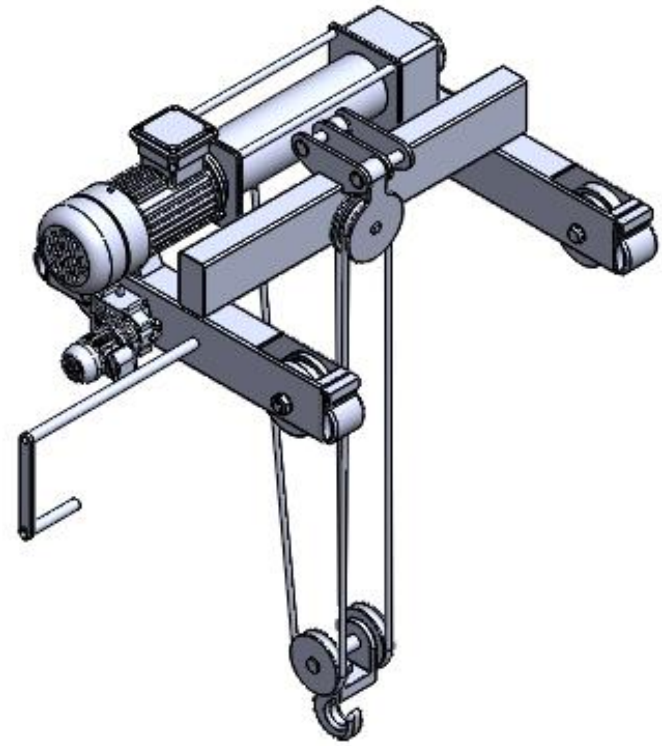
1. Hook, trolley and rail frame modelled
2. Actuator and sensor modelled
3. Bearings and couplings/gears/belts modelled
4. Electronics modelled (e.g. controller and power supply, wires *NOT* needed) 5. Screws, nuts and other fastener systems modelled

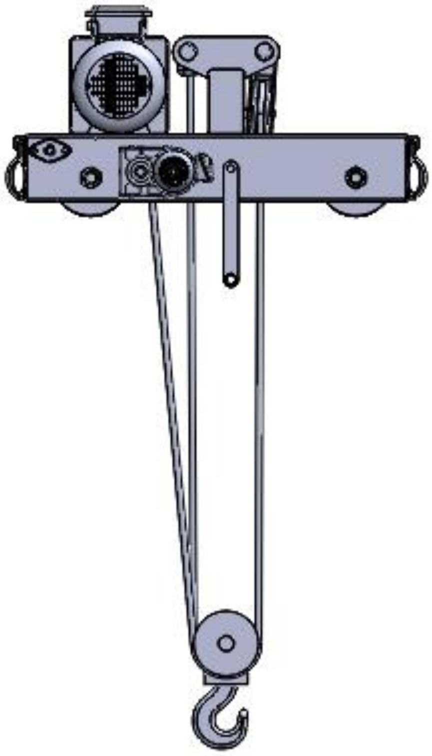
The following 3D models were designed in SolidWorks. Please note that we started by learning how to use the software as beginners and progressed through our design every day slowly.









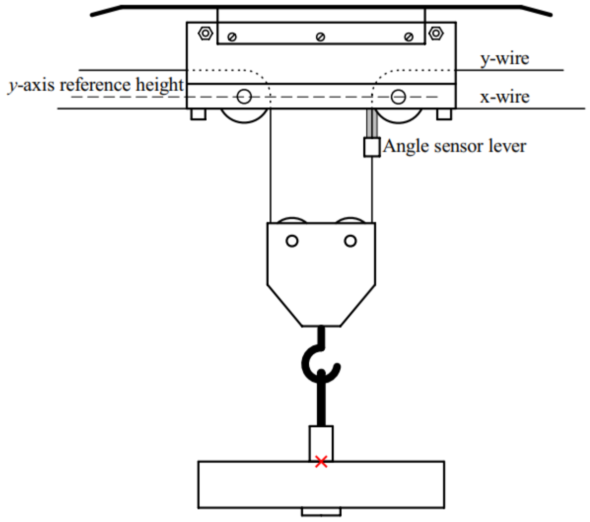


4. Components (6 p)

Select the following components from retailers. For miniature models, for example Sparkfun, Hobby Components, Hobbyking, etc. can be used. Try to select companies that provide datasheets for their products. Justify all the component selection decisions by explaining them briefly. You can use components found from existing inverted pendulum projects.

Actuator (1.5 p)

a) Select an actuator that can move the trolley. Explain in detail how the actuator works. Draw a picture to support the explanation. (1 p)
Note that you need an actuator that is given position as input, not speed. (Alternatively, you may select an additional sensor that measures position.)



The trolley can be moved on the girder, while the load suspended beneath can be raised and lowered, giving the model two degrees of freedom. One steel cable is used to move the trolley using a DC motor, gearing, and a wire drum. The motor is called the x-motor and the wire is called the x-wire. The y-wire is used to control the height of the load using a separate steel cable and similar gearing, wire drum, and a motor called the y-motor. The load is capable of swinging back and forth because it is suspended only in wires. The motors and gearings are placed at the bottom of the right leg together with plugs to interface the sensors and actuators. The actuator selected for our design is "CRANE® 44000".

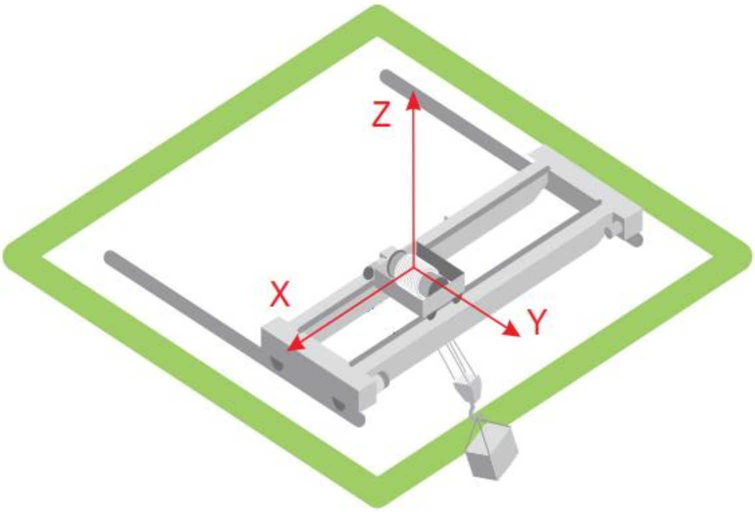
b) Name two advantages and disadvantages for using this type of actuator. These can be general issues or specific cases. (0.5 p)
The actuator we are using in our model is an electrical actuator. They offer the highest precision-control positioning with a range of accuracy of +/- 8 μm. They provide complete control of motion profiles and can include encoders to control velocity, position, torque, and applied force. Their setups are scalable for any purpose or force requirement, and are quiet, smooth, and repeatable. In terms of noise, they are quieter than pneumatic and hydraulic actuators. Moreover, because there are no fluids leaks, environmental hazards are eliminated. As a drawback, the motor chosen

locks in the actuator's force, thrust, and speed limits to a fixed setting. If a different set of values for force, thrust, and speed are desired, the motor must be changed. Furthermore, Electrical actuators are not suited for all environments, unlike pneumatic actuators, which are safe in hazardous and flammable areas.

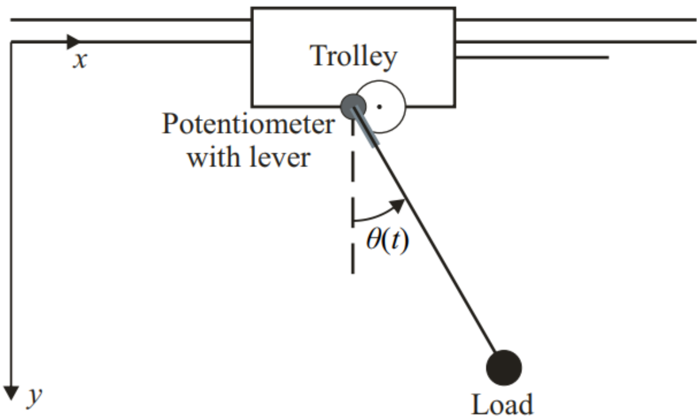
Sensor (1.5 p)

a) Select a sensor that measures angle of the "rope". Explain in detail how the sensor works. Draw a picture to support the explanation. (1 p)

The type sensor that was mounted to measure the angle of the rope suspending the load is "Potentiometer". The following figure is drawn to illustrate the cause of the swing angle as a result of the trolley movement.



The angle of the rope is measured by a potentiometer on the trolley as shown in the following sketch of its positioning. A lever is mounted on the potentiometer and attached to the rope. When the rope swings it pulls the lever, which turns the potentiometer so that it changes its resistance and a different output voltage is measured. The angle then will be calculated based on the height from the load to the trolley related to the x-displacement of the load on the floor.



The implementation of angle measurement can be combined with the use of SeeedStudio Grove Rotary Angle Sensor along with an analog potentiometer with the help of microcontroller such as Ardiuno.

b) Name two advantages and disadvantages for using this type of sensor. These can be general issues or specific cases. (0.5 p)

A few advantages of potentiometers for angle measurement are their absolute measurement instead of relative measurements done by other type of sensors that have encoder. They are simple to wire up (3 lines), a little more robust and most importantly more widely available.

On the other side, depending on the pot, they have limited rotation. They are also vulnerable in applications with any significant vibration.

Power transmission, couplings and bearings (1 p)

Select at least three components related the power transmission, coupling and bearings of your machine.

Motor:

Motor power for industrial application can vary from 10kW to 70kW based on the maximum limit of carrying load capacity of the crane. For the current model we have chosen a motor of 10kW power since our model considered the lifting weight of 3200kg to be lifted. Since the upward movement of the load should be slow therefore, a gear ratio of 50:1 is chosen to ensure the smooth lifting of the weight. While stating these figures, it has to be kept in mind that the control of the crane should incorporate these constraints as it is ideally possibly to move the control of a controllable system anywhere on a given time but the intrinsic properties of the system or plant limit the control as well. Motor has to be stable, robust and shock resistant as well suitable for extreme conditions.

Gear Coupling:

Gear couplings are important aspect of equipment selection since they will define the smooth transmission of power from motor to the hoist, bridge and long travel drives. Torque rating should be as high as 110000 N.m as per provided by the manufacturer, Ameridrives. The selected model is “Amerigear® Class I Gear”. The motor selected to operate along this coupling is “AsepticDRIVE | Bauer Gear Motor” which has a power rating of 0.37 to 2.2 kW.

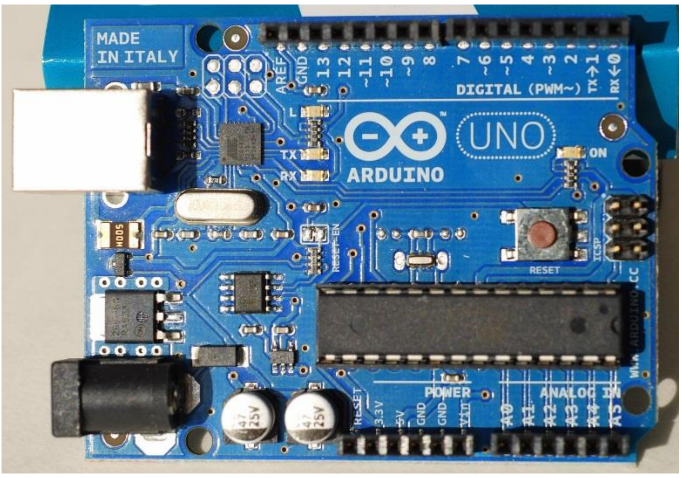
Bearings:

For motor shaft, since the RPM will be high therefore, the choice for bearing would be cylindrical bearing to avoid excessive heating in case of ball bearings. Moreover, thrust bearings will also be provided so that axial motion of the motor can be avoided.

Electric components (2 p)

a) Select a controller. What is the ADC resolution of the controller? (0.5 p)

Arduino Uno is the selected controller for the hobbyist point of view with the ADC resolution value of 10-bit as default. This will return the values between 0 to 1023 for backward compatibility with AVR based boards.



The Duo, Zero and MKR family boards have the capability of 12-bit ADC as well which can be accessed by changing the value of resolution to 12. This will result in the values between 0 to 4095.

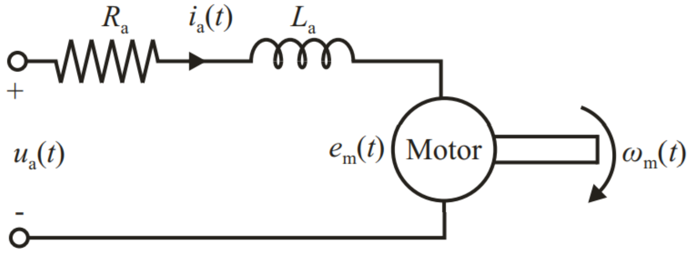
b) Select a power supply or a battery (0.5 p)

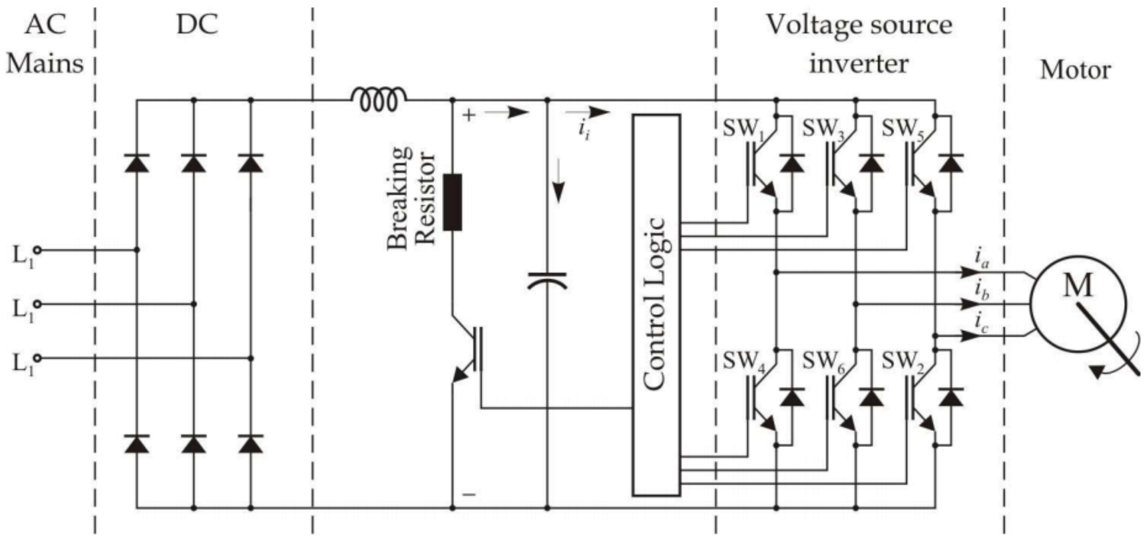
For the selected controller, Arduino Uno, the recommended voltage range is between 5V to 12V. If supplied with less than 7V then this will result in unstable board. However, with the voltage higher than 12 V will cause the heating of the board and can potentially damage the controller circuitry.

Keeping in view the above, remarks, we have chosen Energizer Ultimate 9-volt Batteries (Lithium 9V Battery) to power the Arduino circuit. Details about the data sheet of the batteries is available on Amazon as well as the manufacturer, Energizer, website as well.

c) Draw an electric circuit sketch by hand or using a computer software such as KiCad. Include all the needed basic components (resistors, diodes, transistors, etc.) to your design to make it realizable and safe to use. **Attach this sketch to your report. (1 p)**

Electric model of the Motor can be made through the following circuit:

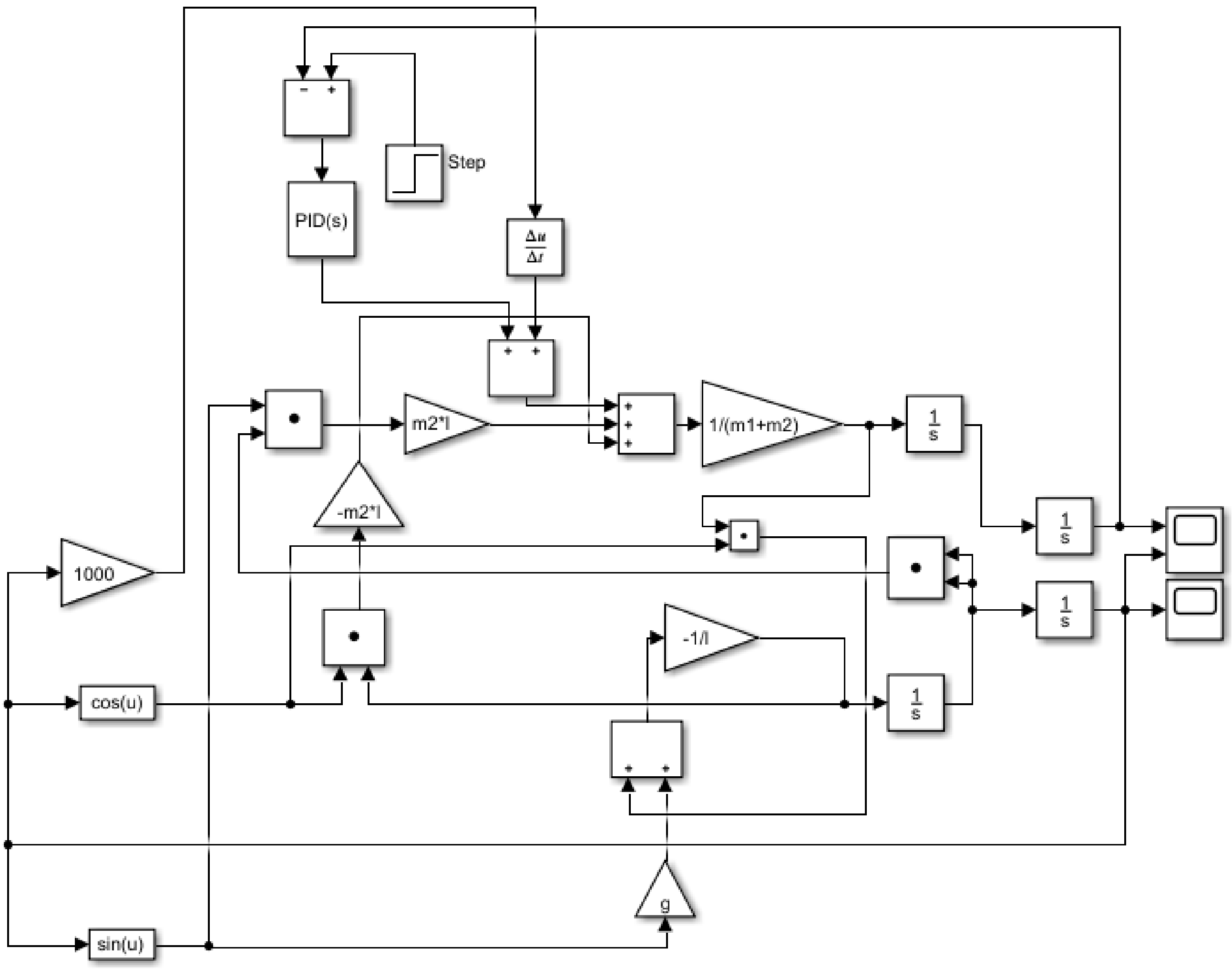




5. Simulation model and control (8 points)

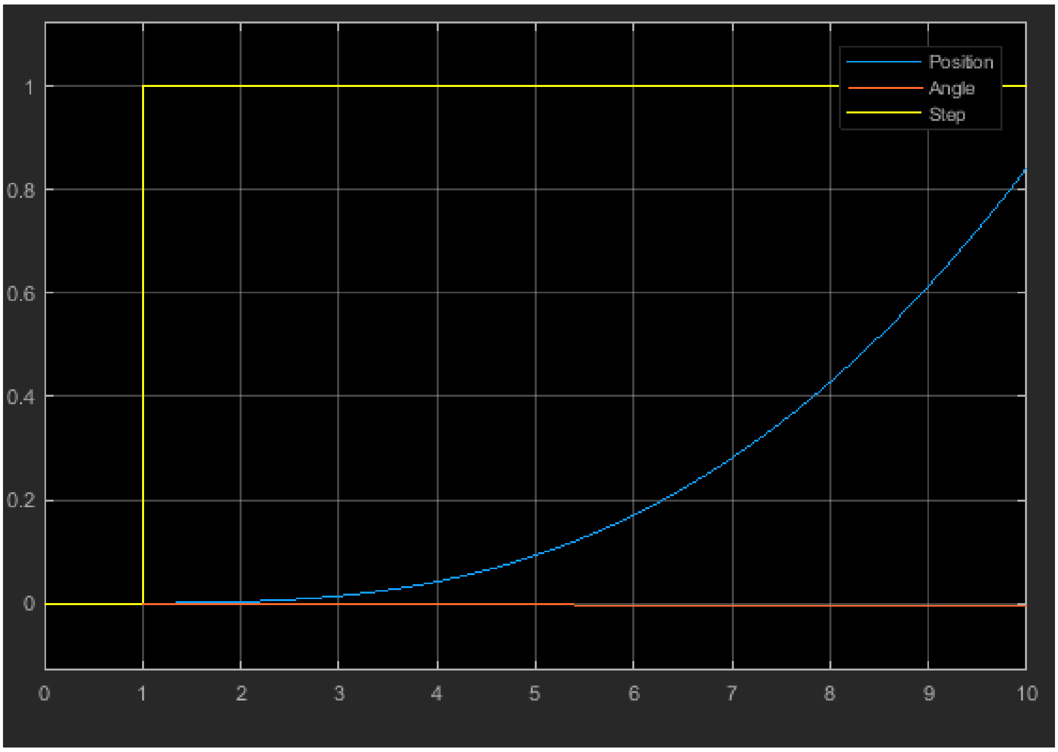
a) Make a Simulink model based on the nonlinear equations made in the *Numeric modeling* –section. Simulate a stepwise movement of the trolley without sway control. **Attach a figure with plots of trolley reference position, actual position, force, and rope angle to your report. (2 p)**

NOTE: We tried to make the controller part from statespace rather than using the method that we had learnt in previous weeks so that the animation can be completed easily but the solution somehow diverged even after trying everything. We discussed it with professor in-person as well after the presentations but he was also unable to resolve the divergence problem. We completed the part of the Simulink model that professor posted in the general discussion forum and tried to run the animation on that as well but this was also fruitless. Last solution for the SimCap but due to limited amount of skill sets in this particular toolbox.



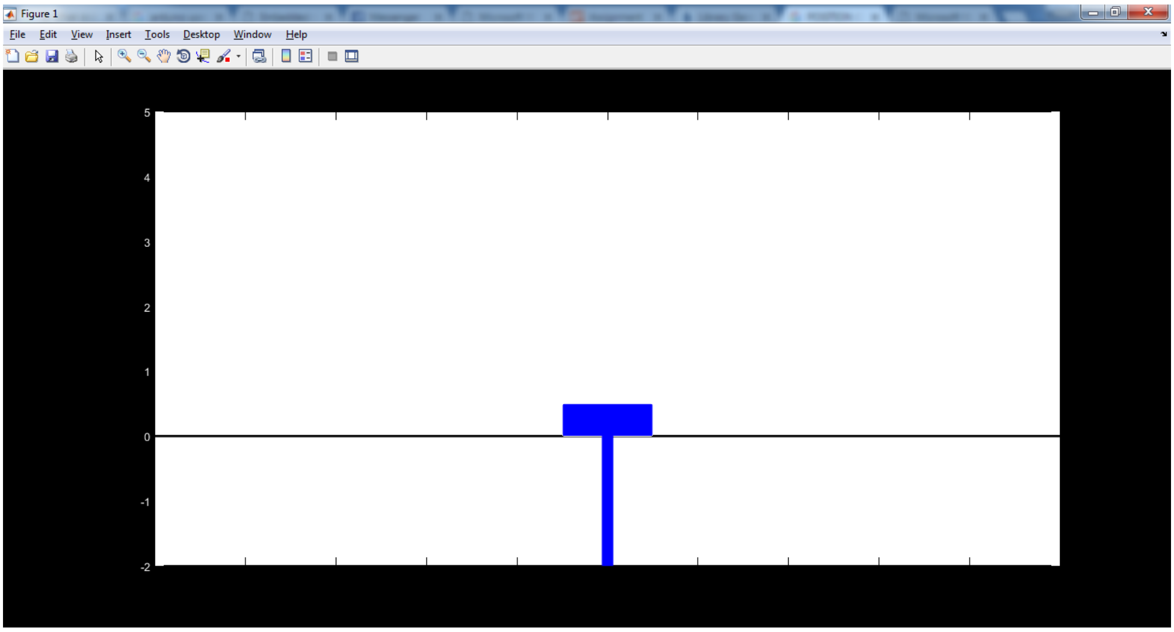
```
l = 0.5              % :0.5:3.0 %rope length
v = 20               % Trolly max speed [m/min]
L_2 = 9              % Trolly movement range [meters]
m1 = 250             % Trolly weigth [kg]
m_max = 3200         % Lifting capacity
m_hook = 5           % hook wight
m2 = m_max+m_hook;
g = 9.81;
simout = sim('Trial_53.slx')
```

Without control:



b) Make a (real-time) dynamic visualization that shows trolley position and rope angle of your system. The visualization can be for example similar to Fig 1 or even a 3D visualization. **The visualization must work in the returned MatLab files to get the points. (2 p) (**Pro tip: type "penddemo" to MatLab command window and run the simulation for inspiration.)

Using lqr_trial7.m file, we were able to make an animation that starts from the following position:



For the moving animation, please refer to the file mentioned above.

```
clear all, close all, clc

m = 3200;
M = 250;
L = 1;
g = -9.81;
d = 0;

s = -1; % pendulum up (s=1)

 A=[0 1 0 0;
    0 0 -m*g/M 0;
    0 0 0 1;
    0 0 -s*(M+m)*g/(M*L) 0];
B=[0 1/(M) 0 s/(M*L)]';

% A = [0 1 0 0;
%     0 -d/M -m*g/M 0;
%     0 0 0 1;
%     0 -s*d/(M*L) -s*(m+M)*g/(M*L) 0];
%
% B = [0; 1/M; 0; s*1/(M*L)];
eig(A)

Q = [1 0 0 0;
    0 1 0 0;
    0 0 10 0;
    0 0 0 100];
R = .0001;

det(ctrb(A,B))

K = lqr(A,B,Q,R);

tspan = 0:.001:10;
```

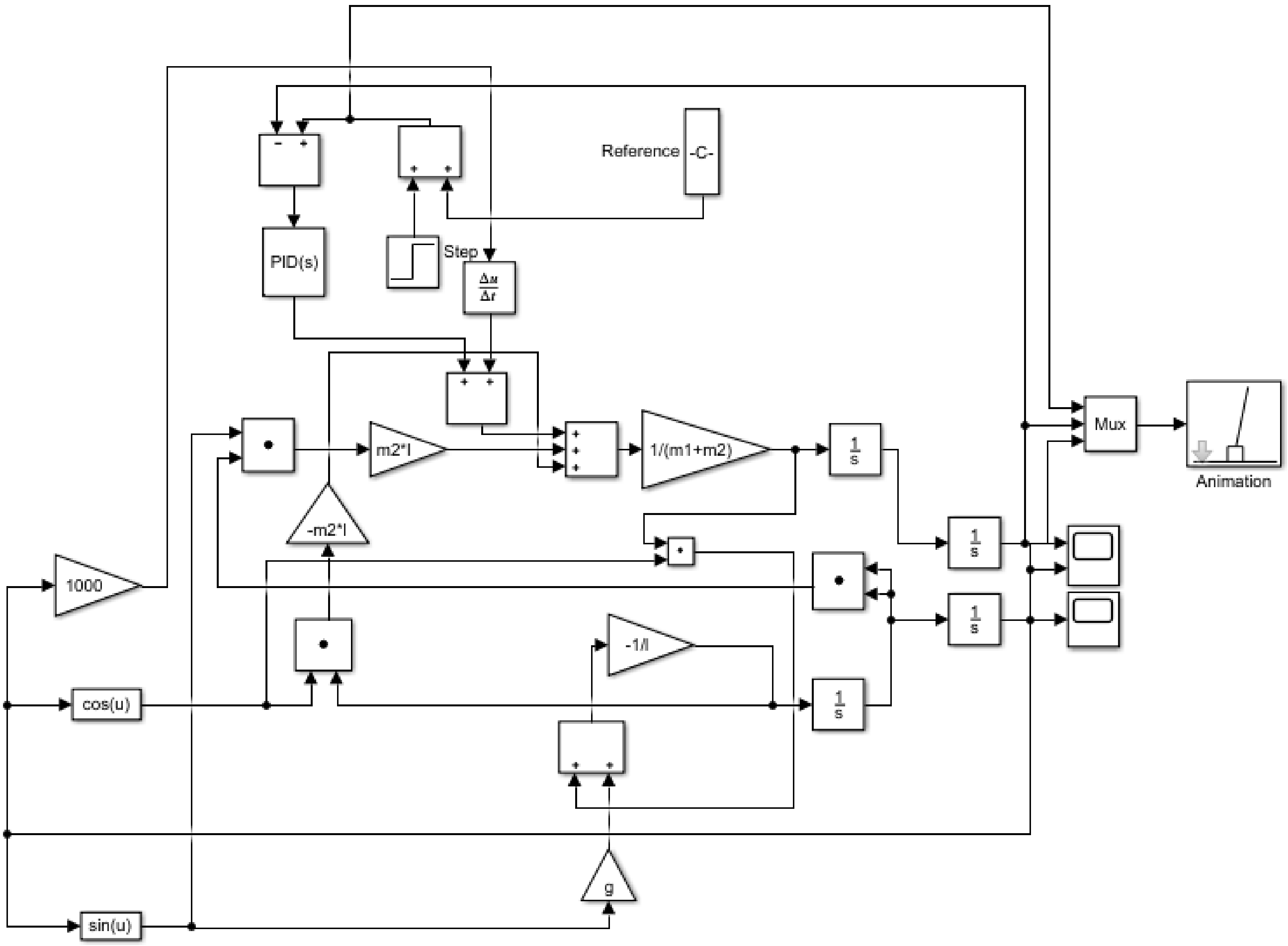
```
if(s==-1)
    y0 = [0; 0; 0; 0];
    [t,y] = ode45(@(t,y)cartpend(y,m,M,L,g,d,-K*(y-[4; 0; 0; 0])),tspan,y0);
elseif(s==1)
    y0 = [-3; 0; pi+.1; 0];
% % [t,y] = ode45(@(t,y)((A-B*K)*(y-[0; 0; pi; 0])),tspan,y0);
    [t,y] = ode45(@(t,y)cartpend(y,m,M,L,g,d,-K*(y-[1; 0; pi; 0])),tspan,y0);
else

end

for k=1:100:length(t)
    drawcartpend_bw(y(k,:),m,M,L);
end

% function dy = pendcart(y,m,M,L,g,d,u)
```

The model was built in Simulink as well:



c) Introduce sway control to your system. Use any means necessary. Document the control and tuning method that you have used and phases how you implemented it. **Attach a figure with plots of reference position of the trolley and rope angle plots with and without the sway control.** This task will be graded upon how well the control works and which method was used for tuning. **Return this model (.slx) and any related script file (.m) to MyCourses. (total 4 p)**

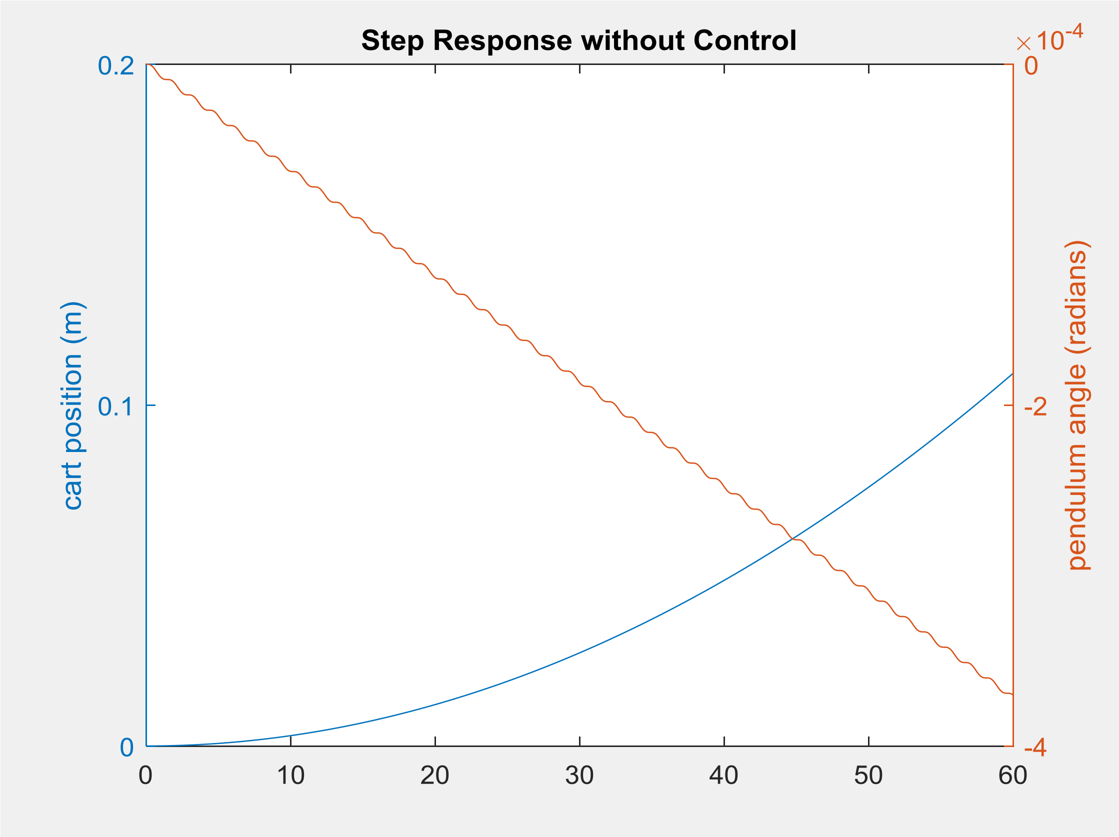
1. Control performance: 0 to 2 points
2. Control and tuning methods: 0 to 2 points are given on the difficulty of the used method. Document how the method was used, no documentation means no points. The methods include for example PID with manual or IMC-based tuning.

For reference: PID with manual tuning gives 0.5 p and Linear Quadratic Regulator (LQR) gives 2p.

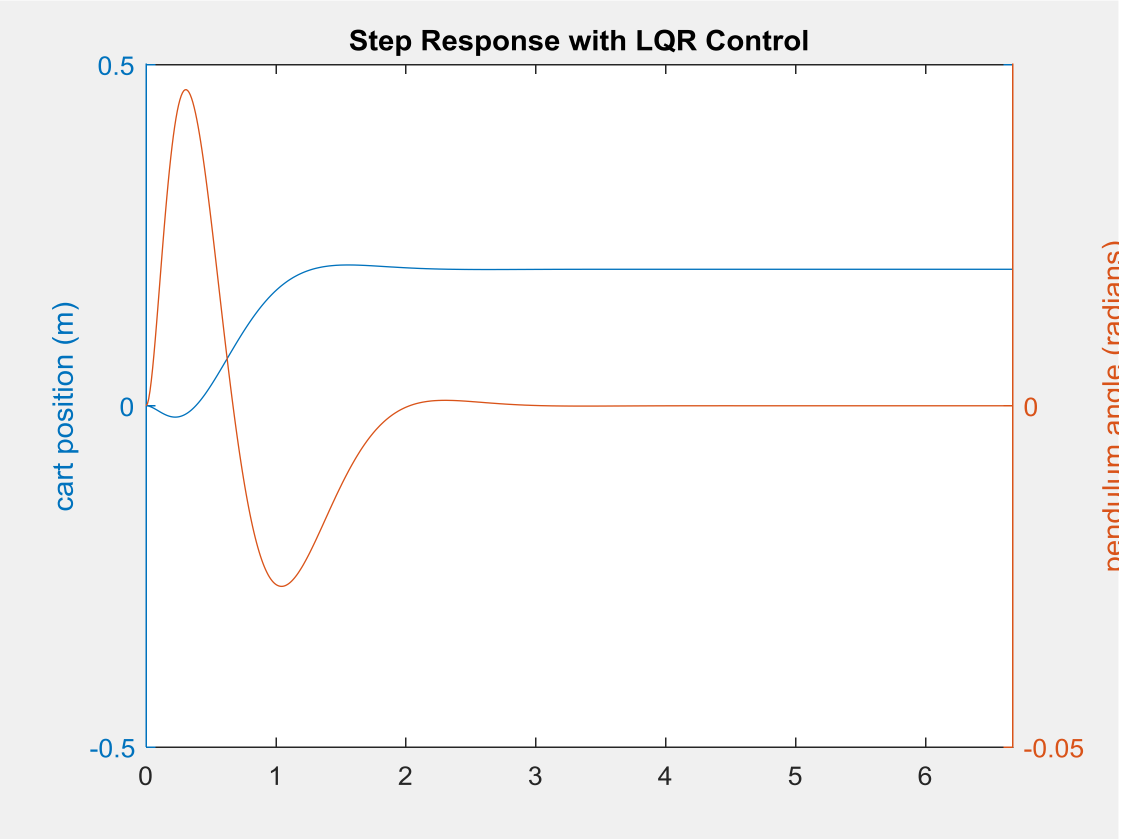
Control related videos for inspiration:
https://www.youtube.com/channel/UCm5mt-A4w61lknZ9lCsZtBw/videos

Since LQR control is utilized in this method to keep the lifted mass in the vertical position while giving a step disturbance to the trolley which will mimic the movement of the trolley under the action of force applied by motor to reach a certain location.

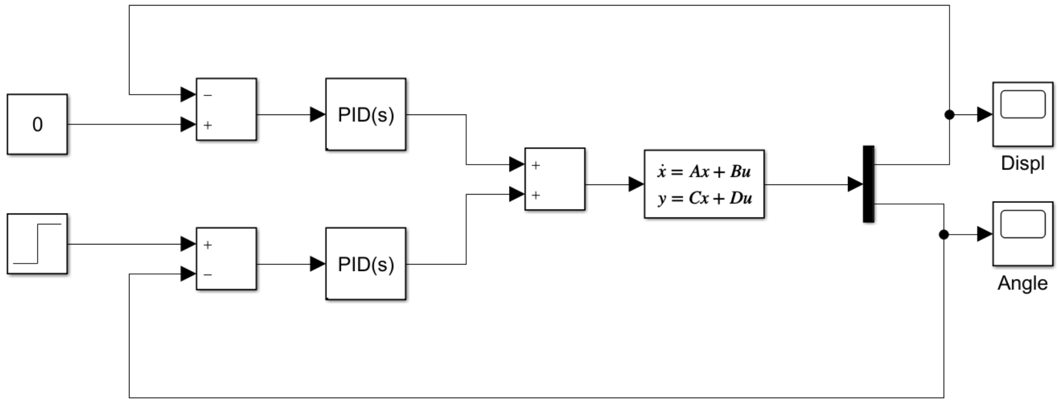
To check the stability of the system in the open loop configuration we can calculate the eigen values of the matrix A which results in one pole on the right side of the origin making the system unstable in open loop.



Next, vector of state feedback control gains K can be calculated based on all four state variables. LQR command returns the optimal controller gain while assuming the plant to be linear, quadratic cost function and the reference equal to zero. Controllability is an important aspect to be considered before designing the controller using LQR. With the satisfactory controllability results, we can drive the system anywhere in a finite time keeping in mind the physical constraints of the system. For the system to be completely state controllable, the controllability matrix must have rank n where the rank of a matrix is the number of linearly independent rows (or columns).
Since the controllability matrix of our system is 4x4 so the rank must be 4 as well which can be seen from the output of the attached code for the assignment. With these additional steps, we confirmed that the system is controllable and the controller to get the desired response can be built. The MATLAB function lqr allows to choose two parameters, R and Q, which will balance the relative importance of the control effort (u) and error (deviation from 0), respectively, in the cost function that are needed to be optimize. The simplest case is to assume R=1, and $Q = CC'$. The cost function corresponding to this R and Q places equal importance on the control and the state variables which are outputs. After running the code with all the above mentioned details we achieve the following response for the given data in the project.



Furthermore, we can improve the response of the system by using the observer model as well. This means that we compare the current state of the plant with the mathematical model so that observed values and theoretical values can be compared and the input to the controller can be adjusted accordingly.




```
l=0.5%:0.5:3.0 %rope length
v=20            %Trolly max speed [m/min]
L_2=9           %Trolly movement range [meters]
m_t=250           %Trolly weigth [kg]
m_max=3200          %Lifting capacity
m_hook=5            %hook wight
m_l=m_max+m_hook;
g=9.81;
s=tf('s')
P_t=(l*s^2+g)/((m_t+m_l)*l*s^4+(m_t*g+m_l*g-m_l*l))
%pretty(P_t)
P_p=s^2/(m_l*l*s^4-(m_t+m_l)*l*s^2-(m_t*g+m_l*g))
%pretty(P_p)

%
sys_tf = [P_t ; P_p];

inputs = {'u'};
outputs = {'x'; 'phi'};

set(sys_tf,'InputName',inputs)
set(sys_tf,'OutputName',outputs)

sys_tf
```

State Space:

```
 s=-1;
 d=1;
 A=[0 1 0 0;
    0 0 m_l*g/m_t 0;
    0 0 0 1;
    0 0 (m_t+m_l)*g/(m_t*l) 0];
B=[0 1/(m_t) 0 1/(m_t*l)]';
C=[1 0 0 0;0 0 1 0];
D=[0;0];
states = {'x' 'x_dot' 'phi' 'phi_dot'};
inputs = {'u'};
outputs = {'x'; 'phi'};
%simout=sim('statespace_simu.slx');
```

```
sys_ss = ss(A,B,C,D,'statename',states,'inputname',inputs,'outputname',outputs);
t = 0:0.01:60;
r =0.2*ones(size(t));
figure(1)
[y,t,x]=lsim(sys_ss,r,t);
[AX,H1,H2] = plotyy(t,y(:,1),t,y(:,2),'plot');
set(get(AX(1),'Ylabel'),'String','cart position (m)')
set(get(AX(2),'Ylabel'),'String','pendulum angle (radians)')
title('Step Response without Control')
co = ctrb(sys_ss);
controllability = rank(co)
Q = C'*C;
Q(1,1)=5000;
Q(3,3)=100;
%
R = 1;
K = lqr(A,B,Q,R)

Ac = [(A-B*K)];
Bc = [B];
Cc = [C];
Dc = [D];

states = {'x' 'x_dot' 'phi' 'phi_dot'};
inputs = {'r'};
outputs = {'x'; 'phi'};

sys_cl = ss(Ac,Bc,Cc,Dc,'statename',states,'inputname',inputs,'outputname',outputs);

t = 0:0.01:60;
r =0.2*ones(size(t));
figure(2)
[y,t,x]=lsim(sys_cl,r,t);
[AX,H1,H2] = plotyy(t,y(:,1),t,y(:,2),'plot');
set(get(AX(1),'Ylabel'),'String','cart position (m)')
set(get(AX(2),'Ylabel'),'String','pendulum angle (radians)')
title('Step Response with LQR Control')
```

6. Feedback (1 point)

Please answer the following questions:

- Did everyone participate to the project equally?
  Yes. All group members had to actively participate in completing the project by solving finding the linear equations, trying different ways to model in Simulink, learn how to design 3D models in CAD, searching for related components and writing the final report.
- How many hours in total did you spend (per person) for the project?
  2 weeks worth of hours.

- How difficult was the project?

  The project was a too challenging as we had to work on something completely new from scratch. However, it was a great practice and interesting project to complete. Learning CAD modelling in this short time was challenging. Also, everything from selecting components, designing a whole model in Simulink and being able to express our design there needed so much work.

- Do you think that the topic of the project was interesting and useful?

  The topic helped us gain so many new skill set since it wasn't boring. However, it required considerably more time than intended. Coping with the project load during the final week as well as completing other course's assignments was an accomplishment.