Introduction to Robotics

April 2, 2019

The aim of this set up is to understand the design and control of a single degree of freedom (DoF) robot with series elastic actuation as shown in Figure 1.

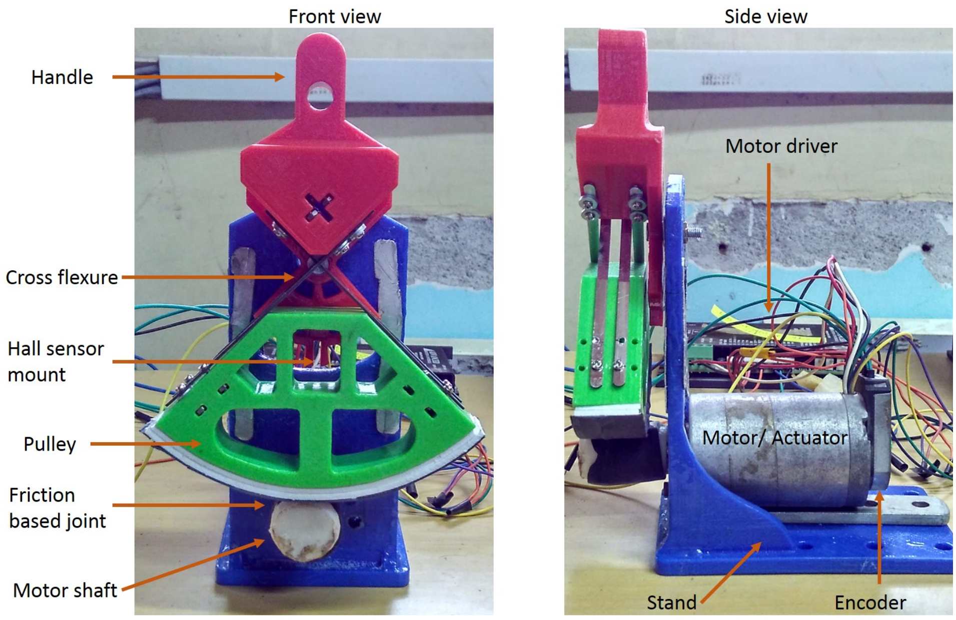

Figure 1: HandsOn-SEA - A single DoF educational robot with series elastic actuation [1]

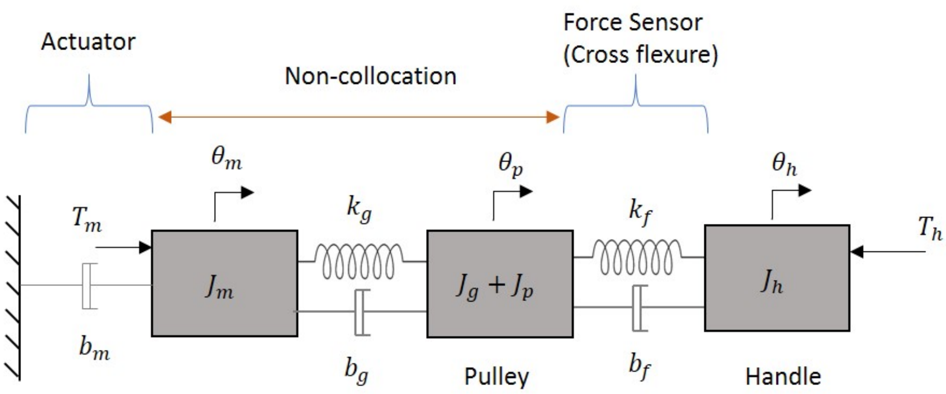

Figure 2: HandsOn-SEA modeled as a connection of linear spring-mass-damper systems. We neglect the effect of k_g and b_g and assume that the friction between the motor shaft and pulley is sufficient to produce no slip.

Table 1: SEA parameters

J_a - inertia of the motor	1.13	gr-cm^2
J_g - inertia of the gearhead	.05	gr-cm^2
J_h - inertia of the handle about the bearing	1.93	gr-cm^2
J_p - inertia of the sector pulley about the bearing	14.7	gr-cm^2
r_g - gearhead reduction ratio	35:1	
r_c - shaft to pulley reduction ratio	73:9	
k_f - stiffness of the cross flexure pivot	5000	N-mm/rad
b_m - Physical damping in the motor		N-mm-s
k_m - motor torque constant	53	N-mm/A

The experiments are divided into four parts as follows:

1. In first part, students will learn the position control of the motor. The motor acts as an actuator to the series elastic actuator (SEA) set up shown in Figure 1.

2. In the second part, students will design a force controller. Observe in Figure 1 that the handle and the pulley are not rigidly attached. The force sensor is made up of a cross flexure (steel plates of small width) and a hall sensor. Cross flexure acts as a flexible link. A hall sensor attached on the handle measures the relative distance between the pulley and the handle. Hence for the known spring stiffness, one can measure the force by measuring the distance. Note that the actuator and the force sensor are non-collocated i.e., the point of actuation and control are separate.

3. The third part consists of designing a controller for backdrivability i.e. force control when the reference force is set to zero.

4. The forth part consists of impedance control of SEA.

Note : Pre-lab assignments as mentioned in each module have to be completed before performing the lab experiments.

1 Position control of DC motor

Pre-lab assignment

1. Model the motor as the mass-damper system as shown in the Figure 2. Symbolically derive the transfer function from motor torque T_m as an input to motor shaft position θ_m as an ouput.

2. Design a proportional controller for the position control of the motor shaft. Draw the root locus plot for this system and comment on how closed loop pole positions are affected as the proportional control gain is increased. According to this analysis, can the system become unstable?

3. Calculate gains for a PD position controller such that the closed loop system possesses critical damping and has a bandwidth of $\omega = 15$ rad/s.

Lab

1. Implement a PD position controller for the DC motor of the device. Try the PD controller gains that you have calculated analytically. Tune these gains empirically until you get the fastest non-overshooting stable step response.

2. Study the root-locus plot of the closed loop transfer function of the motion control system you derived. Discuss possible reasons of the stability limits you experience during the physical implementation of the controller.

2 Force control

Pre-lab assignment

1. Derive the transfer function between the motor torque T_a and the torque estimated by the torque sensor $T_{sens} = k_f(\theta_m - \theta_h)$ for the system shown in Figure 2, when the handle is fixed to a rigid environment. Let $k_f = 5000$ Nmm/rad, bf = 0 and plot root locus graph for proportional (P) controlled system when T_{sens} is fed back. Comment on the stability and performance of this explicit force control system as the controller gain is increased.

Lab

1. Implement a PI explicit force controller based on the force estimations acquired through the deflections of the cross flexure pivot.

2. Starting with low force control gains, empirically tune your controller gains for aggressive but stable response with no chatter. Note the gain level when contact becomes unstable, that is, chatter is observed. Compare this gain with the stability limit of the position controller when link position is fed back. Comment on the relationship between magnitude of these two controller gains.

3 Backdrivability of Series Elastic Actuator

When the actuator is locked, HandsOn-SEA behaves like a mass-spring system with J_h and k_h (neglect the contribution of k_g). The output impedance $Z_{out}(s)$ is characterized by the transfer function when the velocity/position of the handle is the input and the torque at the handle $T_{sens}(s)$ is the output. Symbolically calculate this transfer function and substitute in system parameters. Draw the associated Bode plots of Zout(s) and comment on how the output impedance behaves at low and high frequencies. Compare the output impedance at high frequencies with the Bode plot of the previous question and comment on the similarities.

Lab

1. Implement an actively backdrivable system by setting the desired force in your explicit force controller to zero. Apply low, medium and high frequency inputs to the handle of device with your hand. Repeat the same process when the controller is off. Comment on how the output impedance changes with the gradual increase in frequency for both cases.

2. Apply high frequency torque ripples through the motor while holding the handle. Discuss how this torque ripple is transferred to the handle. Plot the data collected by force sensor during this input and compare it along with the torque ripple input. Comment on the low pass filtering due to motor dynamics and due to compliant sensor.

4 Impedance Control

This module is designed to introduce the cascaded controller architecture for SEA and to evaluate the force tracking performance of the device under cascaded control. The cascaded control architecture for SEA is depicted in Figure 3. This controller consists of an inner velocity control loop, an intermediate force control loop and an outer impedance control loop.

The inner loop of the control structure employs a robust motion controller to compensate for the imperfections of the power transmission system, such as friction, stiction and slip, rendering the motion controlled system into an ideal velocity source within its control bandwidth. The intermediate control loop incorporates force feedback into the control architecture and ensures good force tracking performance under adequately designed inner loop. Finally, the outer loop determines the effective output impedance of the system within the system control bandwidth.

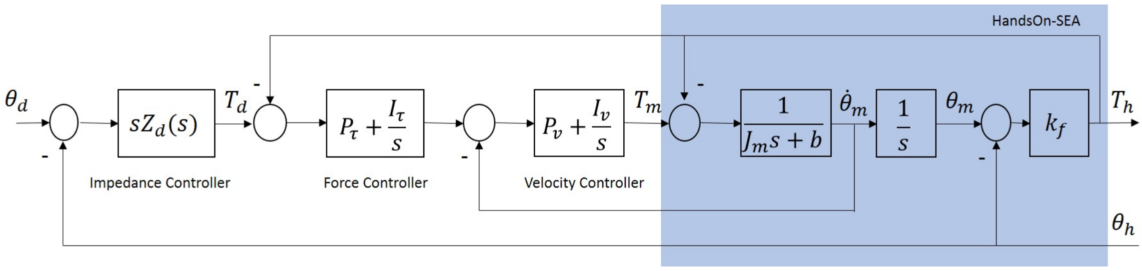

Figure 3: Impedance control architecture

PreLab

1. Determine the time domain equation corresponding to the closed loop system in Figure 3.

Lab

1. Backdrivability: Desired impedance is set to zero such that the system tries to achieve ideal backdrivability. Increase the force controller gain until instability is observed.
2. Rendering a Virtual Wall : Desired impedance is set to a stiff spring with some damping to render virtual wall.

Appendix: Plotting root locus

If the characteristic equation has the form

$$d(s) + Kn(s) = 0$$

Then, define your system transfer function to be $h(s) = n(s)/d(s)$. You can then use the MATLAB command `rlocus` to plot the root locus, i.e, the locii of the roots of the characteristic equation for positive values of K.

References

[1] Otaran, Ata, Ozan Tokatli, and Volkan Patoglu. "Hands-on learning with a series elastic educational robot." International Conference on Human Haptic Sensing and Touch Enabled Computer Applications. Springer, Cham, 2016.