ME 403
Introduction to Robotics

Laboratory Modules

Fall 2016

These laboratory exercises are grouped into 6 modules and aim to demonstrate the concept of sensor-actuator non-collocation for motion and force controlled robotic systems. Furthermore, the students will be exposed to force control, impedance control and series elastic actuation through these laboratory exercises.

A Single DoF Educational Robot with Series Elastic Actuation

HandsOn-SEA[1,2] is a single DoF admittance type robot featuring series elastic actuation. The device features a built-in force sensing unit that estimates the force applied on the handle by measuring the deflection of a compliant cross flexure pivot intentionally placed between the handle and the pulley. A geared DC motor actuates the pulley-handle module through a friction drive transmission. Figure 1 presents the main design features of HandsOn-SEA.

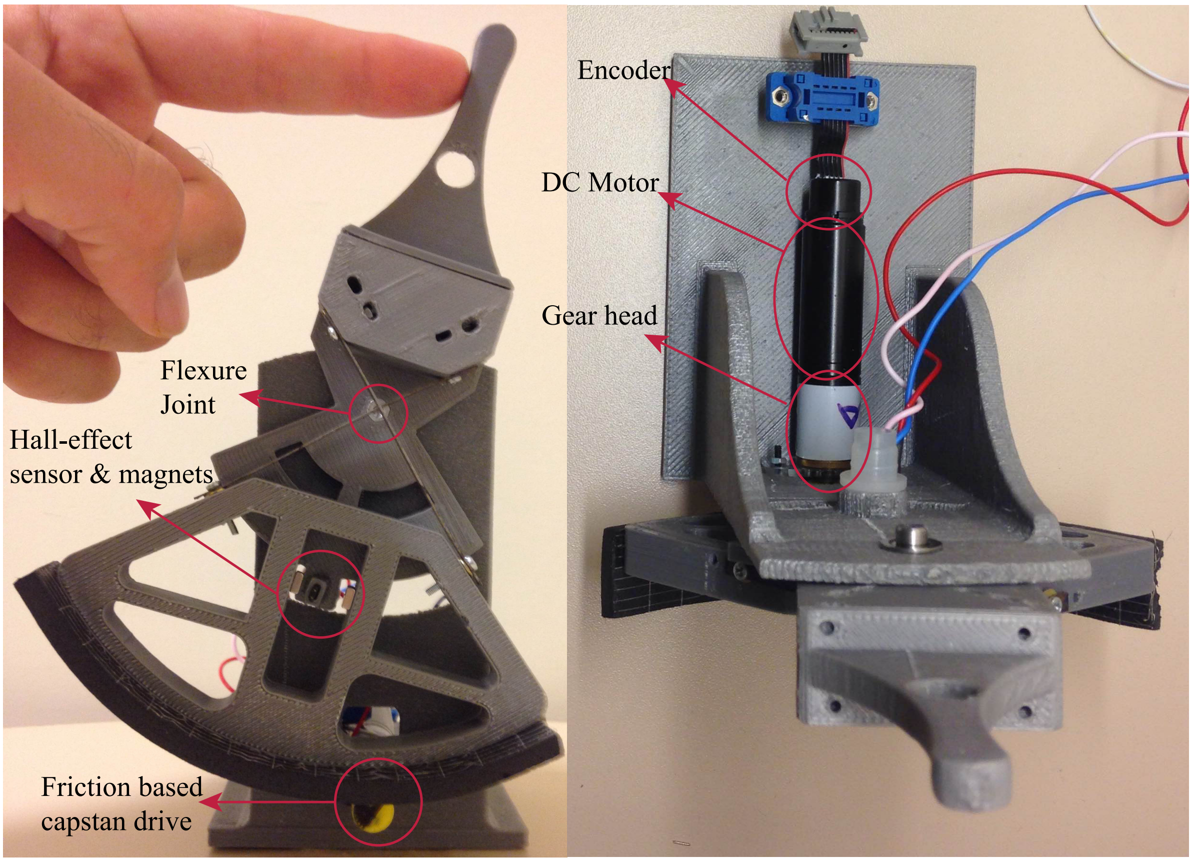

Figure 1: HandsOn-SEA—A single DoF educational robot with series elastic actuation

[1] Ata Otaran, Ozan Tokatli, and Volkan Patoglu, *Hands-On Learning with a Series Elastic Educational Robot*, Springer, Lecture Notes in Computer Science, 2016.

[2] Ata Otaran, Ozan Tokatli, and Volkan Patoglu, HandsOn-SEA*: A Series Elastic Educational Robot for Physical Human Robot Interaction*, IEEE Transactions on Haptics, (in review).

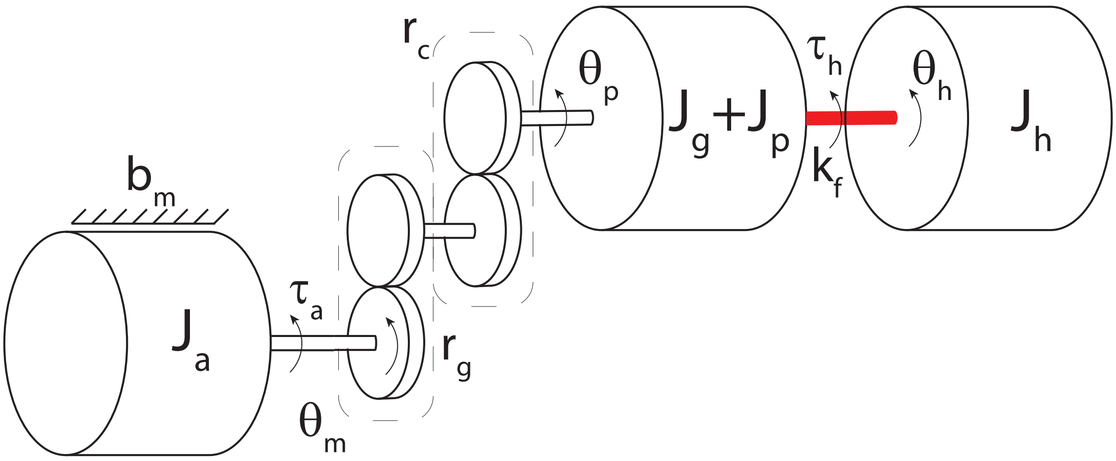

Figure 2: Schematic model HandsOn-SEA

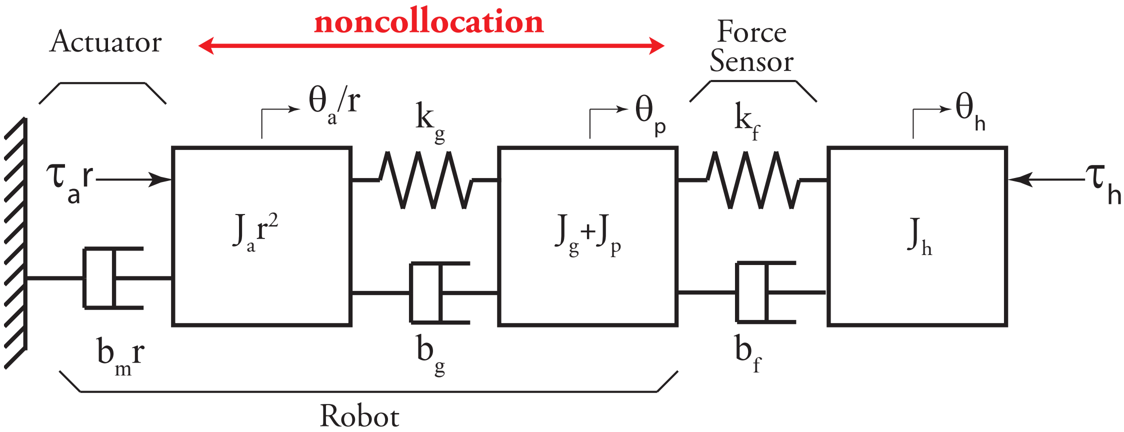

Figure 3: A linear analog of the system model that also captures the sensor-actuator non-collocation. Here k_g and b_g and the inertia distribution between J_a and J_g is an approximate model to capture the effect of first vibration mode of the system. Symbols k_f, b_f signify the force sensor attached to the handle that interacts with the environment. Inertia of the handle is assumed to be negligible.

Table 1: Parameters of HandsOn-SEA

J_a – inertia of the motor	1.3	gr-cm^2
J_g – inertia of the gearhead	0.05	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	84:1	
r_c – capstan reduction ratio	73:9	
k_f – stiffness of the cross flexure pivot	5000	N-mm/rad
L – motor inductance	0.452	mH
R – motor resistance	10.7	Ohm
b_m – cumulative damping of the motor	0.025	N-mm/s
K_m – motor torque constant	16.2	mN-m/A
K_b – motor back-emf constant	61.7	rad/sec/V
τ_m – mechanical time constant	5.31	ms

Module 1

This module is designed to implement motion controllers for and to analyse/experience stability limits of a single DoF motion controlled rigid-body dynamic system.

Pre-Lab Exercises

Please solve the pre-lab exercises 1–6 before attending the lab and prepare a report that presents your work. Your reports will be collected at the beginning of the laboratory session. It is recommended that you keep a copy of your report for yourself.

1 Review what a Bode plot is and learn the significance of the -3 dB magnitude level.

2 Use the data in the file *Bode_example.m* in SUCourse to draw a Bode gain plot in Matlab. Note that the axes of your plot should be logarithmic.

3 Symbolically derive the transfer function between the motor voltage V input and the motor armature position θ_a output of HandsOn-SEA. The substitute the parameters listed in Table 1 to your transfer function. For this analysis, assume k_g is infinitely stiff and reflect the inertia of the gearbox and the pulley to the motor side by multiplying by the square of the appropriate gear ratios.

   Spong book Chapters 6.1–6.2 and the following web site may be useful during your derivations: `http://ctms.engin.umich.edu/CTMS/index.php?example=MotorPosition&section=SystemModeling`

4 Verify that the electrical time constant L/R is much smaller than the mechanical time constant J_a/b_m for the DC motor. Set L/R to zero in order to reduce the previously derived transfer function to a second order one. Compare the step response of the reduced order transfer function to the original one and comment on the difference.

5 Calculate the closed loop transfer function when the position of the motor armature θ_a is regulated using a proportional position controller. 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?

6 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.

Laboratory Exercises

Please solve the exercises 1–2 during the lab and prepare a report that presents your work. Your reports will be collected at the end of the laboratory session.

1 Implement a PD position controller for the DC motor of the device. Try the PD controller gains that you have calculated analytically for the pre-lab exercise. 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 as a part of the pre-lab exercises. Discuss possible reasons of the stability limits you experience during the physical implementation of the controller.

3 Using the sample files provided in SUCourse, collect data with the tuned gains to draw Bode plots of the system and determine the closed-loop position control bandwidth of the device.

Module 2

This module is designed to demonstrate the inherent stability limits of closed-loop control systems that possess sensor-actuator non-collocation, as modelled in Figure 3.

Pre-Lab Exercises

Please solve the pre-lab exercises 1–4 before attending the lab and prepare a report that presents your work. Your reports will be collected at the beginning of the laboratory session. It is recommended that you keep a copy of your report for yourself.

1 Read Sections 7.5–7.6.1(6.5–6.6.1 in some editions), starting with Drive Train Dynamics - from the Spong book. Given the system model in Figure 3, symbolically derive the following transfer functions to capture the effect of joint flexibility: i) Motor torque T_{act} is the input and the motor armature position θ_a is the output, and ii) motor torque T_{act} is the input and the pulley position θ_p is the output. During these calculations, you can neglect k_f and b_f as the system is not interacting with the environment.

2 As a crude approximation of the system, substitute the following parameters to form numerical transfer functions: $J_1 = J_a$, $b_1 = k_b * k_m/R$, $J_2 = J_g + J_p/(r_g * r_p)^2$, $b_2 = b_m$, and $k_2 = 4000/r_g$ Nm/rad.

   Plot two root locus graphs for proportional (PD) controlled system when the position of the motor armature θ_a and scaled position of the pulley $\theta_p * (r_c * r_p)$ are fed back, respectively.

   Comment on the stability and performance of both control architectures as the controller gain is increased. Note that the goal of feedback is to control the position of the pulley θ_p for both architectures.

3 Derive the transfer function between the motor torque T_{act} and the torque estimated by the torque sensor ($T_{sens} = k_f * (\theta_p - \theta_h)$)for the system in Figure 3, when the handle is fixed to a rigid environment. Let $k_f = 5000$ Nmm/rad, $b_f = 0$ and plot root locus graph for proportional (P) controlled system when T_{sens} is fed back. Comment on the stability and performance of of this explicit force control system as the controller gain is increased.

4 Identify the causes of sensor-actuator non-collocation for force controlled system and discuss why explicit force control systems inherently possess sensor actuator non-collocation.

Laboratory Exercises

Please solve the exercises 1–2 during the lab and prepare a report that presents your work. Your reports will be collected at the end of the laboratory session.

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.

Module 3

This module is designed to provide an intuitive understanding of the inherent trade-off between the sensor stiffness and the force controller gain.

Pre-Lab Exercises

Please solve the pre-lab exercises 1–3 before attending the lab and prepare a report that presents your work. Your reports will be collected at the beginning of the laboratory session. It is recommended that you keep a copy of your report for yourself.

1 Use the following formula for calculating the effective stiffness k_{fc} of the cross flexure joint of HandsOn-SEA. The relevant geometric/material properties are listed in Table 2.

$$k_{fc} = \frac{8EI(1 - 3\lambda + 3\lambda^2)cos\alpha}{lL_h} \quad N/rad \tag{1}$$

Table 2: Parameters characterizing the cross flexure joint

Parameter	Value	Unit
Thickness	t = 1	mm
Width	w = 4	mm
Length	l = 59.33	mm
Pivot ratio	λ = 0.68	-
Pivot angle	2α = 90	°
Young's modulus	E = 2*10^5	N/mm^2
Second moment of area	I = w*t^3	mm^4
Distance between center of rotation and handle	L_h=62	mm

2 Repeat Pre-Lab Exercise 3 of Module 2 by replacing k_f with the stiffness k_{fc} of the cross flexure pivot. Compare the controller gains at the limit of stability.

3 Comment on effect of sensor stiffness on stability of explicit force control. Identify and list the advantages and disadvantages of using a more compliant force sensor in terms os stability and performance of the force controlled system.

Laboratory Exercises

Please solve the exercises 1–2 during the lab and prepare a report that presents your work. Your reports will be collected at the end of the laboratory session.

1 Implement PI explicit force controllers with two cross flexure pivots with different levels of compliance. Experimentally determine the highest stable explicit force controller gain that can be implemented for each level of compliance. Observe that the more the force sensor compliance is increased, the more the force controller gains can be increased without inducing instability or chatter.

2 Given that stability limit is directly proportional to the controller gain and sensor stiffness, estimate the stiffness of the new cross flexure pivot based on your experimental data. Compare this value with the analytical stiffness model of this compliant joint.

Module 4

This module is designed to introduce the concept of series elastic actuation and to provide hands-on experience with SEA by demonstrating the mechanical low-pass filtering behavior and low control bandwidth of these systems.

Series Elastic Actuation (SEA)

The underlying idea of SEA is the reallocation of limited loop gain of the system with non-collocated sensor-actuator, to decrease the force sensor stiffness (by a few orders of magnitude), such that the force controller gain can be increased (by a few orders of magnitude). More aggressive force-feedback controller gains are preferred to achieve fast response times and good robustness properties to compensate for hard-to-model parasitic effects, such as friction and backlash.

While SEA can improve force control performance, this improvement comes with the cost of decreased system control bandwidth. In particular, the introduction of the compliant sensing element significantly lowers bandwidth of the resulting force controlled system.

The advantages of SEA include high active backdrivability within the force control bandwidth and low output impedance for the frequencies over the control bandwidth, due to inherent compliance of the force sensing element. Furthermore, the compliant force sensor acts as a mechanical low pass filter for the system against impacts, impulsive loads and high frequency disturbances, such as torque ripple.

Pre-Lab Exercises

Please solve the pre-lab exercises 1–2 before attending the lab and prepare a report that presents your work. Your reports will be collected at the beginning of the laboratory session. It is recommended that you keep a copy of your report for yourself.

1 When the actuator is locked (is not fast enough to react), HandsOn-SEA behaves like a mass-spring system with J_h and k_{fc}, if the neglect the contribution of k_g, which is designed to be orders of magnitude stiffer than k_{fc}. Plot the Bode plot of the J_h-k_{fc} mass-spring system, observe the low pass filtering behaviour that dominates the system dynamics for high frequency inputs, and determine the open-loop bandwidth of the system.

2 The output impedance $Z_{out}(s)$ is characterized by the transfer function when the velocity of the handle $s\theta_h(s)$ 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 $Z_{out}(s)$ 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.

Laboratory Exercises

Please solve the exercises 1–2 during the lab and prepare a report that presents your work. Your reports will be collected at the end of the laboratory session.

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.

Module 5

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 4. This controller consists of an inner velocity control loop, an intermediate force control loop and an outer impedance control loop.

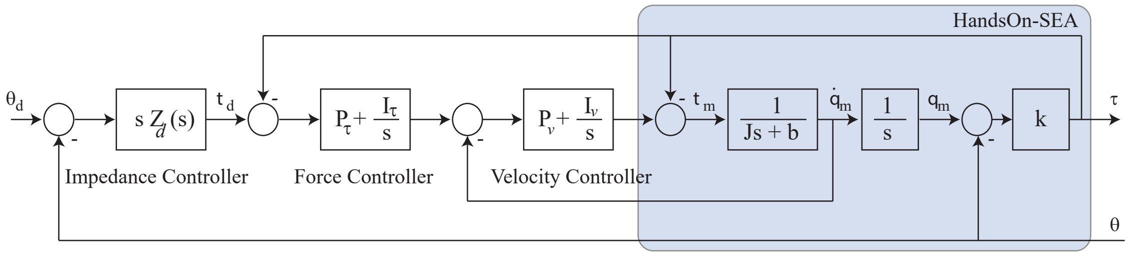

Figure 4: Cascaded controller

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.

Pre-Lab Exercises

Please solve the pre-lab exercises 1–2 before attending the lab and prepare a report that presents your work. Your reports will be collected at the beginning of the laboratory session. It is recommended that you keep a copy of your report for yourself.

1 Using the template provided in SUCourse and form a Simulink model of the cascaded loop controller for HandsOn-SEA.

2 Study Impedance Control in Chapter 9.3.2 of the Spong book. Explain the virtual dynamics the cascaded impedance controller is designed render. Discuss how the inertia of the handle (which is located after the force sensor) affects the rendering performance.

Laboratory Exercises

Please solve the exercises 1–2 during the lab and prepare a report that presents your work. Your reports will be collected at the end of the laboratory session.

1 Compare the Simulink file you have created with the one provided in the lab. Update your model and note the differences.

2 Use the provided Simulink models for control and the associated .m files for visualization of the following experiments:

- *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.
- *Rendering a Virtual Wall*: Desired impedance is set to a stiff spring with some damping to render virtual wall. Note that the virtual wall rendering implements a unidirectional constraint such that the system is free to move with high backdriveability when operating outside the virtual wall, while the controller pushes the user outside acting as a spring when the virtual wall constraint is violated. Increase the stiffness and damping of the virtual wall by changing the gains of the desired impedance block. Discuss the effect of virtual stiffness and damping on the stability of rendering.
- *Rendering a Mass-Spring-Damper*: Desired impedance is set to a mass-spring-damper system with second order dynamics. Calculate the natural frequency of the virtual mass-spring-damper system and note that the virtual system has a resonance at this frequency. Excite the system at frequencies lower and higher than this natural frequency and discuss the system response.

Module 6

This module is designed to demonstrate the bandwidth limitation of SEA by characterizing the small, medium and high force bandwidth of HandsOn-SEA as in Figur 5.

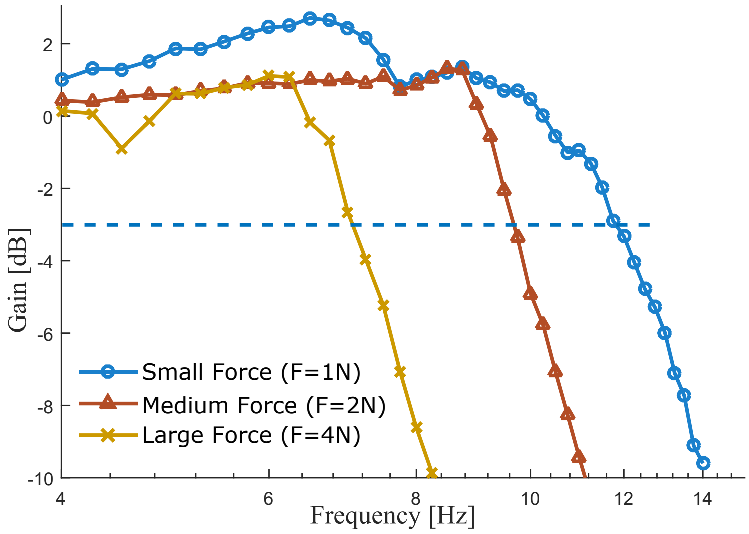

Figure 5: A sample Bode magnitude plot characterizing closed-loop small, medium, and high force bandwidths

Pre-Lab Exercise

You are not required to submit a report for this pre-lab.

1 Watch the lower video at `http://hmi.sabanciuniv.edu/?page_id=992` that demonstrates how to perform the force bandwidth experiments.

2 Download the relevant files from SUCourse and study the instructions on how to use them.

Laboratory Exercises

Please solve the exercises 1–4 during the lab and prepare a report that presents your work. Your reports will be collected at the end of the laboratory session.

1 Characterize the low force control bandwidth of HandsOn-SEA. Provide a copy of your Bode magnitude plot in your lab report. Compare this bandwidth with the position control bandwidth you have characterized in Module 1.

2 Characterize the medium force control bandwidth of HandsOn-SEA. Provide a copy of your Bode magnitude plot in your lab report. Compare this bandwidth with the low force control bandwidth you have characterized in the previous exercise and report the percent decrease.

3 Characterize the large force control bandwidth of HandsOn-SEA. Provide a copy of your Bode magnitude plot in your lab report. Compare this bandwidth with the low force control bandwidth you have characterized in the first exercise and report the percent decrease.

4 Discuss the underlying reasons for the decrease in force control bandwidth of SEA as the reference force magnitude gets larger.