Q1 (20 marks): Please find, read, and summarize the following paper. Write one page that clarifies your "main observations and findings" and connect it to the concepts taught in the course, in particular motor augmentation, in telerobotic systems, that was discussed in the course. Link: https://ieeexplore-ieeeorg.proxy.library.nyu.edu/stamp/stamp.jsp?tp=&arnumber=8594645

The given research paper was written by D. Zhang, B. Xiao, B. Huang, L. Zhang, J. Liu and G. Yang, and published on 2nd April 2019, with the title: "A Self-Adaptive Motion Scaling Framework for Surgical Robot Remote Control."

The paper proposes a mechanism to improve master-slave control human-robot interaction done in teleoperation. The mechanism is self-adaptive motion scaling which can be performed during teleoperation in order to provide the surgeon seamless and intuitive control. The operator, surgeon, can retain precise control when conducting delicate manipulation, while the movement to a remote target, robot arm, is accelerated via adaptive motion scaling. The proposed framework is comprised of three components: 1) situation awareness, regarded as an online pattern recognition of different operational situations (e.g., tool-tissue interaction, dexterous and bimanual operation), 2) skill level awareness, user-specific factors determined by skill assessments, and 3) task awareness, task-specific factors are incorporated into the framework to ensure generalizability of the system.

To assess the proposed motion scaling framework's usability and robustness, detailed user studies were conducted on a da Vinci Research kit (dVRK), which included the Patient Side Manipulators (PSMs), the Endoscopic Camera Manipulator (ECM) and the Master Tool Manipulators (MTMs). To conduct parameter estimation and model training, a database for ring transfer task was collected in-house. Data for each trial included both kinematics and stereo vision data, which was captured through the endoscope. Seven non-clinical participants participated in the user studies. Six of the participants were right-handed, while one of them was left-handed. Three of the subjects have teleoperation experience, and two of them were familiar with the dVRK. One of the participants has been using the dVRK system for four years, while the other one had six-month experience.

After the study, a survey was conducted to collect subjective feedback from the subjects. All the subjects agreed that they feel significantly more natural and comfortable when using the adaptive mode. Analyzing the metrics defined in the study, a comparison of results between two different modes, it was concluded that with the proposed self-adaptive motion scaling framework, the teleoperation efficiency and the overall operators' performance could be significantly improved.

The results of user studies, shows that the self-adaptive motion scaling framework is proved to have the ability to seamlessly adjust the scaling ratio, which results in improved efficiency of teleoperation. The subjects confirm this finding and remark it is noticeable mainly because of reduced clutching, task completion time and total path length of the master robot. The improvements of the average control speed and the control efficiency are also shown in the numbers. The self-adaptive motion scaling framework can be readily adapted to other surgical tasks.

In class, we spoke about mechatronic technologies that have been used to augment motor control capabilities of surgeons. One such device we spoke about is a tremor-cancellation mechatronic device designed to compensate for surgeons' natural hand tremors during micro-surgeries. Second example we spoke about was workspace down-scaling techniques in Leader-Follower telerobotic surgical systems for reducing the burden of fine motor control on surgeons. There were also discussions on force-enabled virtual guidance (is an active sensory augmentation scheme) and haptics-based forbidden-region virtual fixtures (which is an active motor augmentation scheme). These devices have been used to provide guidance and avoidance, respectively, based on patient-specific anatomy and surgical trajectories, during robotic assisted surgeries. The mechanism described in the paper is yet another example of mechatronic technologies used to augment motor control capabilities of surgeons.

Q2 (20 marks): Please research and find and explain 1 page of your observations and finding of how (a) fluorescent imaging modality and (b) CT angiogram are used in da Vinci surgical systems. Explain the functionality, motivations, benefits, and applications, also how they connect to the concept of sensory augmentation that was discussed in the course.

a) **fluorescent imaging modality**

Explain the functionality, motivations, benefits, and applications, also how they connect to the concept of sensory augmentation that was discussed in the course.

Firefly Fluorescence Imaging

The da Vinci surgical system comes equipped with a fluorescence imaging vision system called Firefly. Firefly is intended to provide real-time endoscopic visible and near-infrared fluorescence imaging. The system enables surgeons to perform minimally invasive surgery using standard endoscopic visible light as well as visual assessment of vessels, blood flow, and related tissue perfusion, and at least one of the major extra-hepatic bile ducts (cystic duct, common bile duct and common hepatic duct), using near infrared imaging. An imaging sensor in the endoscope detects the near infrared signal that is used to highlight the white light image with false color that provides the surgeon with an augmented view of the tissue, thereby giving the surgeon the ability to see vasculature and tissue perfusion.

Firefly system also enables surgeons to switch between standard, visible light and near-infrared imaging during minimally invasive procedures. When the system is used in conjunction with an injectable fluorescent dye, tissue with blood flow is highlighted in green color and tissue without blood flow appears gray in the surgeon's view. The system adds a new way to visualize biliary duct in conjunction with standard, visible light in bile-duct imaging and X-ray examination of the bile ducts during surgery.

In class, we learned about several types of sensory augmentations including ones done via visual, auditory, and haptic cueing channels. An example spoken about was vision-based sensory augmentation has been used to help surgeons to navigate surgical tools with respect to registered pre-operative medical images that are partially superimposed with intra-operative information. We learned that the goal of sensory augmentation is to provide superior awareness of interaction with tissue during surgery. Firefly, along the same lines, provides visual augmentation by illuminating tissue with near-infrared fluorescence imaging. It is also important to acknowledge that the system is delivered through passive (not actuated) cueing channels.

b) CT angiogram are used in da Vinci surgical systems.

Explain the functionality, motivations, benefits, and applications, also how they connect to the concept of sensory augmentation that was discussed in the course.

https://www.intuitive.com/en-us/products-and-services/da-vinci/vision/iris

The da Vinci surgical system comes equipped with an anatomical visualization service imaging vision system called Iris. Iris allows surgeons to bring their operation plans into the operating room. Using Computed tomography scan technologies (CT scans), a segmented 3D model of patient's anatomy is created that can be used to help prepare the surgeon for the case. During the surgery, the model can be viewed at the da Vinci Surgeon Console using Tilepro and manipulated on your mobile device. Iris makes surgical pre-planning to more effective during surgery.

Iris allows surgeons to refine surgeons' preoperative visualization. Surgeons can send patient's de-identified CT scans to Intuitive via the Iris application an iOS device. Intuitive technicians utilize segmentation methods to label anatomical structures and generate a 3D model. After a quality review, the unique, patient-specific model is sent back to the surgeon's mobile device. Then, during pre-surgical planning, Iris can help surgeons visualize their approach to the procedure by facilitating identification of the anatomy.

Surgeons can also collaborate with colleagues and staff by showing them views of the anatomical model on their iOS device. Iris can be used to educate patients about their upcoming procedure by walking them through the 3D image.

The biggest advantage of Iris for surgeons is the ability to reference the models during surgery. Throughout the procedure, the segmented model created by Iris can be viewed in a dual image at the Surgeon Console. The 3D model can also be manipulated at any point on the mobile device near the surgical controls. When using Iris, surgeons never have to leave the console to review their surgical plan or adjust their viewpoint.

In class, we learned about several types of sensory augmentations including ones done via visual, auditory, and haptic cueing channels. An example spoken about was vision-based sensory augmentation has been used to help surgeons to navigate surgical tools with respect to registered pre-operative medical images that are partially superimposed with intra-operative information.

We learned that the goal of sensory augmentation is to provide superior awareness of interaction with tissue during surgery. Iris too provides visual augmentation by allowing surgeons to view the 3D models of the patient’s CT angiograms during the procedure on the console.

Q3(20 marks): Please find, read, and summarize the following paper. Write one page that clarifies your "main observations and findings" and connect it to the concepts taught in the course, in particular, sensory augmentation for people with a lack of biological limb.

https://iopscience-iop-org.proxy.library.nyu.edu/article/10.1088/1741-2552/aba6da/ **sensory augmentation for people with a lack of biological limb.**

The given research paper was written by Patrick G Sagastegui Alva, Silvia Muceli, S Farokh Atashzar, Lucie William and Dario Farina, and published on 13th October 2020, with the title: "Wearable multichannel haptic device for encoding proprioception in the upper limb."

The research paper focuses on the design, implementation, and evaluation of a wearable multichannel haptic wireless closed-loop armband, driven by surface electromyography (EMG) and provides sensory feedback encoding proprioception. The device is made with a focus on vibrotactile stimulation. The researchers investigate the encoding of multiple degrees of freedom of proprioception through multichannel closed loop stimulation. In order to do this, an armband comprising eight vibrators is built. With this system and a myocontrol interface, the researchers evaluated the ability of users to utilize the provided sensory feedback to complete a reaching task without visual feedback and in the presence of unpredictable perturbations of the reference control system. The proposed device provides information about spatial motion of the user's limb to give the user concurrent awareness about the limb' position in space so that the user can steer the control consequently. The distributed pattern of vibration provides positional information in parallel with the user's natural proprioception.

The study included two experimental sessions run in two days. Nine able-bodied participants were included in the experiments. Two experiments were conducted in the study over two days. Experiment 1 was focused on determining the individual's sensitivity to the vibration system and the ability to discriminate different stimulation parameters. The setup required participants to be seated in front of a table with the dominant (right) arm in a rest position (palm facing inwards and thumb pointing upwards) over an arm support. An initial assessment of the sensation threshold was included with Experiment 1, a vibration intensity discrimination test, and a final re-assessment of the sensation threshold. In experiment 2, the reliability and performance to control the position of the hand in closed-loop were evaluated. This was done through the delivery of different feedback patterns around the forearm to map the direction of the wrist. The task consisted of reaching 20 random targets in a virtual environment.

The sensation threshold depended on the actuator position and increased over time. The maximum resolution for stimuli discrimination was four. Using this resolution, four patterns of vibrotactile activation with different spatial and magnitude properties were generated to evaluate their performance in enhancing proprioception.

The results showed that the sensation threshold depended on the actuator position and increased over time. The highest resolution for stimuli discrimination was four. Under this resolution, four patterns of vibrotactile activation each with different spatial and magnitude properties were generated to evaluate their performance in enhancing proprioception. It was discovered that optimal vibration pattern varied among the participants. When the feedback was used in closed-loop control, the task success rate, completion time, execution efficiency, and average target-cursor distance improved for the optimal stimulation pattern compared to the condition without visual or haptic information on the cursor position.It was concluded that participants were able to exploit the proprioceptive information conveyed by the proposed vibrotactile device to overcome the perturbation imposed by the control system. This proved that the proposed device showed significant flexibility in controlling the stimulation parameters and reconstructing the perturbed proprioception. With the aid of the vibrational feedback, the user was able to recover the performance which was comparable with that of visual feedback.

In class, we learned about several types of sensory augmentations including ones done via visual, and haptic cueing channels. We learned that the goal of sensory augmentation is to provide superior awareness of interaction with objects for individuals who have lost a biological limb. In the research paper, the device was tested in able-bodied users and benchmarks were provided for future implementation in amputees. The primary motivation of the research was to simulate the proprioception impairment occurring in individuals with limb deficiency. The paper showed the importance and significance of vibrotactile feedback and the corresponding potential for recovering the lost proprioception. Even with the use of the proposed armband, the user would have the option of combining visual and vibrotactile feedback, which may result in a multimodal approach to compensate for the lost proprioception. This device is an example of visual and haptic cueing channel enabled sensory augmentation for individuals lacking a limb.

Q4 (20 marks): Let us assume that for a telerobotic system, we have the following hybrid matrix:

$$\begin{bmatrix} F_h(s) \\ -V_e(s) \end{bmatrix} = \begin{bmatrix} 0.1 & \frac{1-s}{1+s} \\ \frac{2-s}{2+s} & 0.2 \end{bmatrix} \begin{bmatrix} V_h(s) \\ F_e(s) \end{bmatrix}$$

> **Calculate Z_{to} also Z_{to-max} and $Z_{to-min.}$**

> **Now assume the hybrid matrix is changed to the following:**

$$\begin{bmatrix} F_h(s) \\ -V_e(s) \end{bmatrix} = \begin{bmatrix} 0 & \frac{1-s}{1+s} \\ \frac{2-s}{2+s} & 0 \end{bmatrix} \begin{bmatrix} V_h(s) \\ F_e(s) \end{bmatrix}$$

Now calculate Z_{to} also Z_{to-maz} and $Z_{to-min.}$ and based on the results, explain how the operator would feel the environment for very low frequencies ($\omega \to 0$) and how she/he would feel the environment for very high frequencies ($\omega \to \infty$). Does the behavior of the telerobotic systems which would have such a hybrid matrix is frequency dependent?

a) Calculate Zto also $Zto\text{–}ma$x and $Zto\text{–}min$

$$Let \begin{bmatrix} 0.1 & \dfrac{1-s}{1+s} \\ \dfrac{2-s}{2+s} & 0.2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

$$F_h = h_{11}v_h + h_{12}Z_e v_e = 0.1v_h + \frac{1-s}{1+s}(Z_e v_e)$$

$$-v_e = h_{21}v_h + h_{22}Z_e v_e = \frac{2-s}{2+s}v_h + 0.2(Z_e v_e)$$

$$Reorganizing\ this\ equation\ we\ get$$

$$v_h = \frac{-(v_e + h_{22}Z_e v_e)}{h_{21}} = \frac{-(v_e + 0.2Z_e v_e)}{\dfrac{2-s}{2+s}}$$

$$Z_{to} = \frac{F_h}{v_h} = h_{11} - \frac{h_{12}h_{21}Z_e}{1 + h_{22}Z_e} \ (after\ simplying\ using\ previous\ equations)$$

$$Z_{to} = 0.1 - \frac{\frac{1-s}{1+s} \times Z_e \times \frac{2-s}{2+s}}{1 + 0.2Z_e}$$

$$Z_{to_{min}} = Z_{to}|_{Z_e \to 0}$$

$$Z_{to_{min}} = h_{11} - \frac{h_{12}h_{21}Z_e}{1 + h_{22}Z_e} = 0.1$$

$$Z_{to_{max}} = Z_{to}|_{Z_e \to \infty}$$

$$Z_{to_{max}} = Z_{to_{min}} + \frac{-h_{12}h_{21}}{h_{22}}$$

$$Z_{to_{max}} = h_{11} - \frac{h_{12}h_{21}Z_e}{1 + h_{22}Z_e} = 0.1$$

$$= 0.1 - \frac{\frac{1-s}{1+s} \times \frac{2-s}{2+s}}{0.2}$$

b)

> **Now assume the hybrid matrix is changed to the following:**

$$\begin{bmatrix} F_h(s) \\ -V_e(s) \end{bmatrix} = \begin{bmatrix} 0 & \frac{1-s}{1+s} \\ \frac{2-s}{2+s} & 0 \end{bmatrix} \begin{bmatrix} V_h(s) \\ F_e(s) \end{bmatrix}$$

Now calculate Zto also $Zto\text{–}maz$ and $Zto\text{–}min$. and based on the results, explain how the operator would feel the environment for very low frequencies ($\omega \to 0$) and how she/he would feel the environment for very high frequencies (ω

$\to\infty$). Does the behavior of the telerobotic systems which would have such a

hybrid matrix is frequency dependent?

$$Let \begin{bmatrix} 0 & \frac{1-s}{1+s} \\ \frac{2-s}{2+s} & 0 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

$$F_h = h_{11}v_h + h_{12}Z_e v_e = 0 \times v_h + \frac{1-s}{1+s}(Z_e v_e) = \frac{1-s}{1+s}(Z_e v_e)$$

$$-v_e = h_{21}v_h + h_{22}Z_e v_e = \frac{2-s}{2+s}v_h + 0 \times (Z_e v_e) = \frac{2-s}{2+s}v_h$$

$$Reorganizing\ this\ equation\ we\ get$$

$$v_h = \frac{-(v_e + h_{22}Z_e v_e)}{h_{21}} = \frac{-(v_e + 0 \times Z_e v_e)}{h_{21}} = \frac{-(v_e)}{\frac{2-s}{2+s}}$$

$$Z_{to} = \frac{F_h}{v_h} = h_{11} - \frac{h_{12}h_{21}Z_e}{1 + h_{22}Z_e}\ (after\ simplying\ using\ previous\ equations)$$

$$Z_{to} = 0 - \frac{\frac{1-s}{1+s} \times Z_e \times \frac{2-s}{2+s}}{1 + 0 \times Z_e} = -\frac{\frac{1-s}{1+s} \times Z_e \times \frac{2-s}{2+s}}{1}$$

$$Z_{to_{min}} = Z_{to}|_{Z_e \to 0}$$

$$Z_{to_{min}} = h_{11} = 0$$

$$Z_{to_{max}} = Z_{to}|_{Z_e \to \infty}$$

$$Z_{to_{max}} = Z_{to_{min}} + \frac{-h_{12}h_{21}}{h_{22}}$$

$$= 0 - \frac{\frac{1-s}{1+s} \times \frac{2-s}{2+s}}{approaches\ 0} = \infty$$

As ω$(s) \rightarrow 0$,

$$Z_{to} = -\frac{\frac{1-s}{1+s} \times Z_e \times \frac{2-s}{2+s}}{1} = -Z_e$$

This means that the impedance felt by the leader is the same but in the opposite direction as the impedance in the environment.

As ω$(s) \rightarrow \infty$,

$$Z_{to} = -\frac{\frac{1-s}{1+s} \times Z_e \times \frac{2-s}{2+s}}{1} = -Z_e$$

This means that the impedance felt by the leader is the same but in the opposite direction as the impedance in the environment.

For intermediate frequency values between (0, ∞) it has been shown that the impedance felt by the leader is frequency dependent.

Q5 (20marks): Simulate the behavior of an enhanced Two-Channel Transparent Telerobotic Architecture ($C5 = -1$, $C_6 = 231$, $C4 = 0$) for 70 seconds, considering the following parameters:

- **No Communication Delay**
- $Z_m = \frac{2s+13}{0.1s+1}$
- $Z_s = \frac{0.5s+3}{0.1s+1}$
- Z_h: a mass-damping model with a mass of 2 kg and damping of 9 N.s/m
- Z_e: a mass damping model with a mass of 0.1 kg and damping of 0.5 N.s/m
- $f_e^* = 0$
- $f_h^* = \sin(1t) + \cos(2t) + \sin(3t)$

(A) What is Zto of this system?

(B) Plot the velocity of the leader robot versus the velocity of the follower robot. Also, plot the interactive force (F_h) at the leader robot felt by the user versus the force at the environment side (F_e). Compare, evaluate, and discuss the transparency and performance of the system (Force tracking and Velocity tracking).

Hints:

- If you need any derivative block in Simulink, you can either use Simulink's derivation block or replace any derivation with the following transfer function $\frac{s}{0.01s+1}$ for this project (as a suggestion which may help).
- If your signals are not smooth, you can put a low pass filter in front of the signals you are sending; for example $\frac{1}{0.1s+1}$.
- For ODE solver, you can choose the variable step for ODE 15s or you can choose fixed-step ODE4 and have a step length of 0.001seconds. Sometimes changing ODE solver helps with some unexpected issues.
- If you get an "algebraic loop error", it tells you which signal is the problem; you just need to put a z^{-1} operator in front of that signal. Sometimes passing signals through z^{-1} before sending it to the other side of the communication network helps.

a) What is Zto of this system?

In an ideal transparency scenario,

$$Let \quad \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

$$F_h = h_{11}v_h + h_{12}Z_e v_e = 0 \times v_h + 1 \times (Z_e v_e) = (Z_e v_e)$$
$$-v_e = h_{21}v_h + h_{22}Z_e v_e = -v_h + 0 \times (Z_e v_e) = -v_h$$

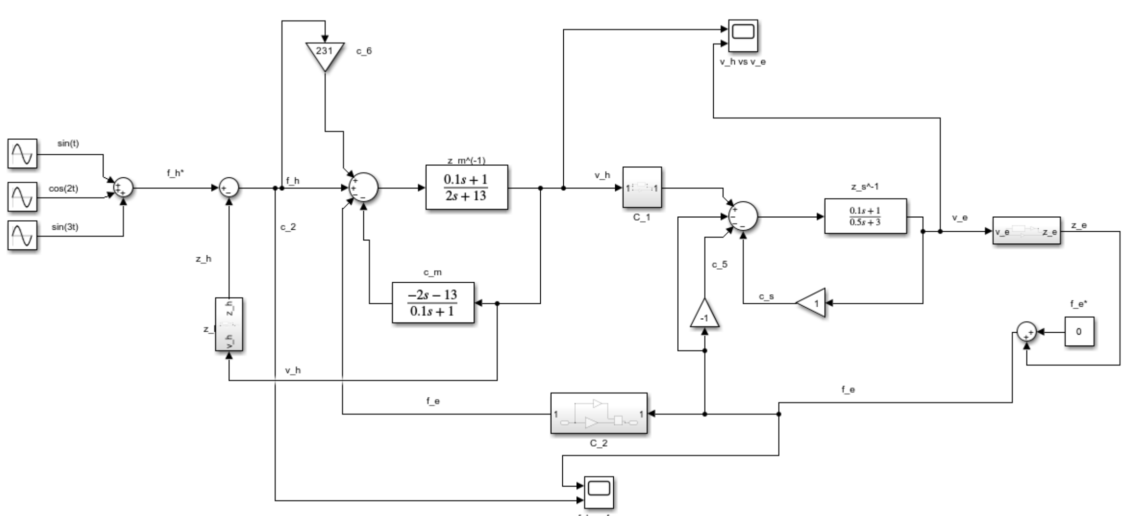
$$Reorganizing\ this\ equation\ we\ get$$

$$v_h = \frac{-(v_e + h_{22}Z_e v_e)}{h_{21}} = \frac{-(v_e + 0 \times Z_e v_e)}{h_{21}} = \frac{-(v_e)}{-1} = v_e$$

$$Z_{to} = \frac{F_h}{v_h} = h_{11} - \frac{h_{12}h_{21}Z_e}{1 + h_{22}Z_e}\ (after\ simplying\ using\ previous\ equations)$$

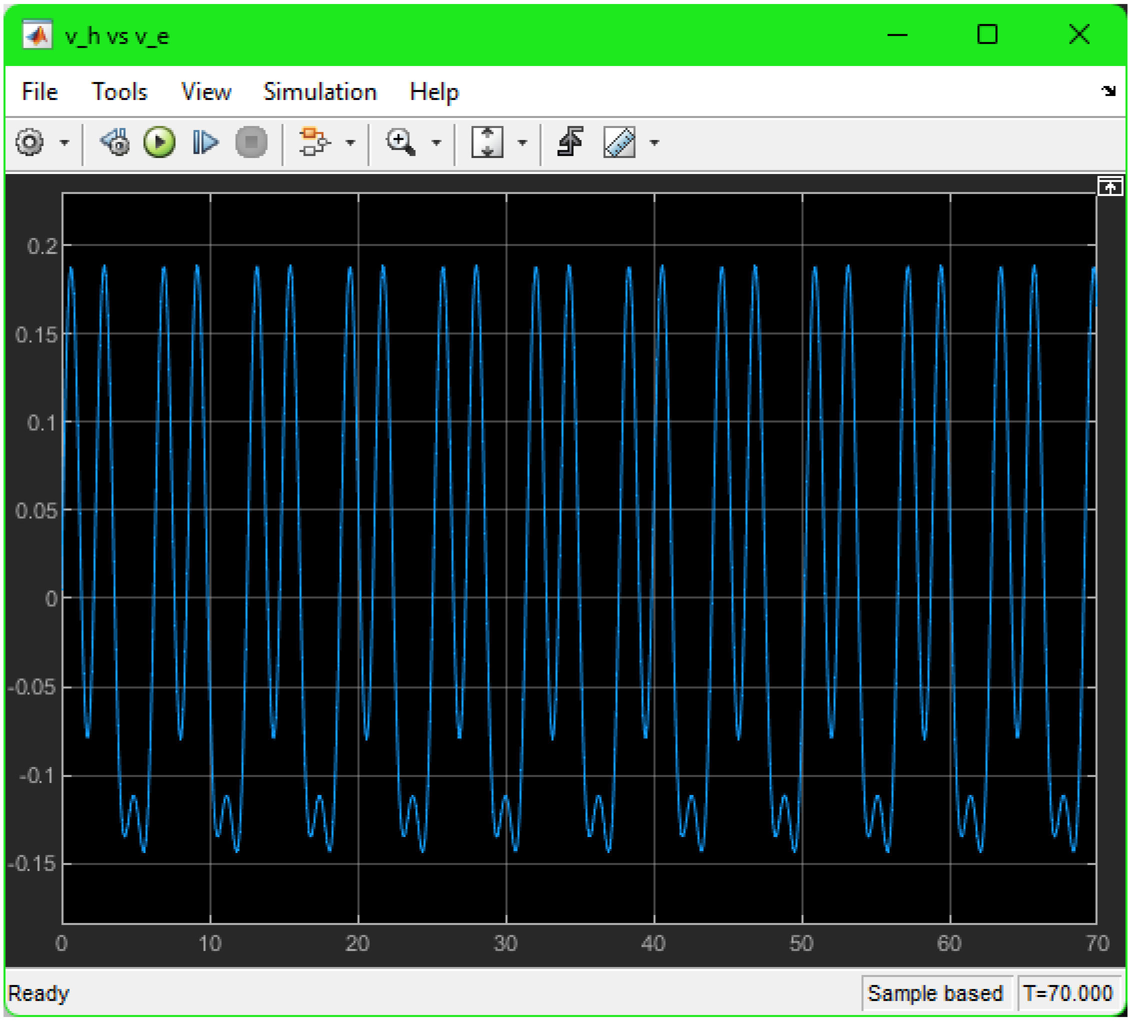
$$Z_{to} = 0 - \frac{1 \times Z_e \times -1}{1 + 0 \times Z_e} = Z_e$$

b) Plot the velocity of the leader robot versus the velocity of the follower robot. Also, plot the interactive force (Fh) at the leader robot felt by the user versus the force at the environment side (Fe). Compare, evaluate, and discuss the transparency and performance of the system (Force tracking and Velocity tracking).



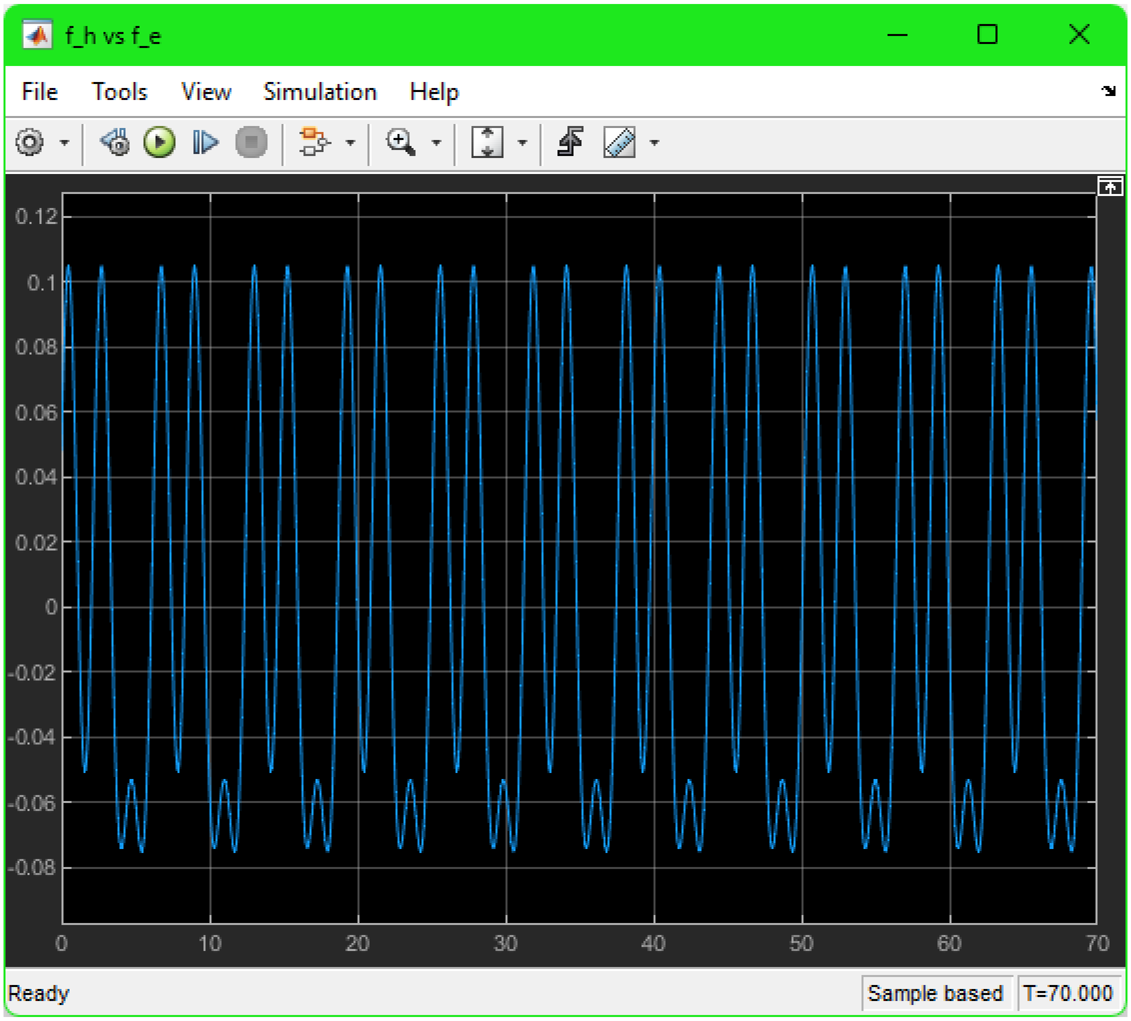
Velocity tracking

v_h vs v_e



Force tracking

f_h vs f_e



Compare, evaluate, and discuss the transparency and performance of the system (Force tracking and Velocity tracking).

As seen in the graphs above, f_h vs f_e is overlapping as well as v_h vs v_e is also overlapping. This shows that the system has achieved transparency. This is expected to happen because we have configured the circuit to match the ideal scenario where you have kinematic correspondence ($v_h = v_e$) as well as ideal force response ($f_h = f_e$) and $h_{11} = 0$, $h_{22} = 0$ and $h_{12} = -h_{21} = 1$. The system performs according to expectation because there is no echo on follower and leader side, which leads to perfect force tracking as well as perfect velocity tracking.