Amirkabir University of Technology
(Tehran Polytechnic)

Advanced Robotics

Robust Impedance Control for Dual User Haptic Training System

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Chapter 01: Introduction

Benefits of Using Teleoperation methods in various applications.

Introduction

- Benefits

  - ✓ Teleoperation methods have been used in many applications, particularly in high-risk tasks, from bomb disposal and space exploration to surgery.

  - ✓ In surgical applications of teleoperation, surgeons need to insert instruments through a small incision in the patient's body, which is called **Minimally Invasive Surgery (MIS).**

  - ✓ In this type of surgery, the provision of visual and tactile signals is challenging. Even though by providing 2D images to the surgeon, his/her **understanding of Depth** is impaired.

Introduction

- Haptic Technology

  ✓ Providing **Haptic Feedback** is very useful in teleoperation applications owing to giving a sense of presence for a user who does not have direct access to the environment.

  ✓ Dual user haptic systems are also used to **perform cooperative tasks**, for instance, in robot-assisted MIS for training purposes.

Introduction

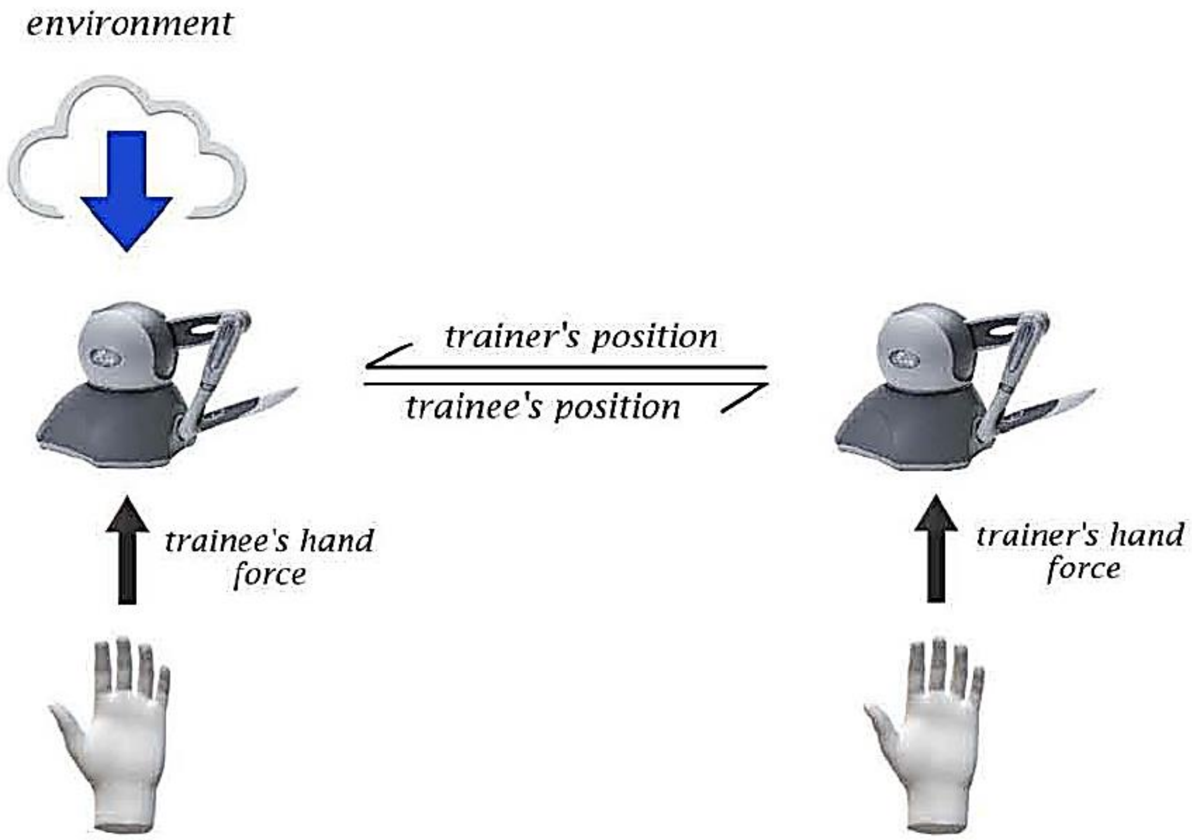
- Traditional and Modern approaches

  ✓ In traditional training, the trainer **holds the trainee 's hands** to correct his/her movements.

  ✓ In modem surgical training, the novice can gain a better understanding of the surgical process **through feedback from the expert provided by the haptic system.**

Introduction

- Proposed Framework



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Chapter 02: Control Structure

Introduce the proposed control scheme.

Control Structure

- Operating Modes

  ✓ When the trainee is doing the surgery without any considerable error, **loose impedance control** is applied to his/her haptic device.

  ✓ Once the trainee performs a wrong maneuver, the trainer will push the pedal to correct him/her. At this moment, the control system is switched to the second mode, which is called a **tight impedance control.**

Control Structure

- Dynamic Model

✓ The General n-DoF dynamical model of the trainer and the trainee's haptic devices **in the joint space** are given by:

$$M_i(q_i)\ddot{q}_i + C_i(q_i, \dot{q}_i)\dot{q}_i + G_i(q_i) = \tau_i + J_i^T f_{ext_i}$$

$$\begin{cases} f_{h1} & when \quad i=1 \\ f_{h2} - f_e & when \quad i=2 \end{cases}$$

$\longrightarrow$ **Trainer**

$\longrightarrow$ **Trainee**

Control Structure

- Dynamic Model

  ✓ The dynamic formulation is written **in Cartesian space** as follows so that impedance controllers can be applied to the system.

$$\boxed{M_{x_i}(x_i)\ddot{x}_i + C_{x_i}(x_i,\dot{x}_i)\dot{x}_i + G_{x_i}(x_i) = J_i^{-T}\tau_i + f_{ext_i}}$$

$$\begin{aligned} M_{x_i}(x_i) =& J_i^{-T} M_i(q_i) J_i^{-1} \\ C_{x_i}(x_i,\dot{x}_i) =& J_i^{-T}(C_i(q_i,\dot{q}_i) - M_i(q_i)) J_i^{-1}\dot{J}_i) J_i^{-1} \\ G_{x_i}(x_i) =& J_i^{-T} G_i(q_i). \end{aligned}$$

Control Structure

- Useful Properties

$$\underline{m} I_{n\times n} \leq M_x(x) \leq \overline{m} I_{n\times n}$$

$$\| C_x(x,\dot{x}) \| \leq \gamma_c \| \dot{x} \|$$

$$\| G_x(x) \| \leq \gamma_g$$

$$\xi^T \left(\dot{M}_x(x) - 2C_x(x,\dot{x}) \right) \xi = 0$$

Control Structure

- Controller

  ✓ The controller produces a desired dynamic behavior between the human operator and the haptic console , which is **robust to the parametric uncertainties and hard nonlinearities.**

  ✓ The desired impedance in the time domain is:

$$M_{d_i}(\ddot{x}_{d_i} - \ddot{x}_i) + B_{d_i}(\dot{x}_{d_i} - \dot{x}_i) + K_{d_i}(x_{d_i} - x_i) = f_{m_i}$$

  ✓ The impedance error is defined as:

$$I_i(t) = M_{d_i}\ddot{e}_i + B_{d_i}\dot{e}_i + K_{d_i}e_i - f_{m_i}$$

Control Structure

- SMC

✓ Sliding mode structure based on impedance control is applied for tracking the trainer's position by the trainee's haptic device as well as **achieving zero impedance error in the presence of uncertainty in dynamics.**

$$s_i = \int_0^t M_{d_i}^{-1} I_i(\tau) d\tau = 0$$

Control Structure

- Control Law

✓ When the trainee is doing the surgery, and the trainer approves his/her movements with reasonable error, the following control torque is applied on his/her console:

$$\tau_i = J_i^T(\hat{M}_{x_i} a_{x_i} + \hat{C}_{x_i}\dot{x}_i + \hat{G}_{x_i} - f_{ext_i})$$

$$a_{x_i} = M_{d_i}^{-1}(M_{d_i}\ddot{x}_d + B_{d_i}\dot{e}_i + K_{d_i}e_i - f_{ext_i} + M_{d_i}K_{g_i}\mathrm{sgn}(s_i)).$$

Control Structure

- ## Closed Loop System

✓ The Closed-Loop dynamic equation:

$$\ddot{x}_i = a_{x_i} + M_{x_i}^{-1}(\tilde{M}_{x_i} a_{x_i} + \tilde{C}_{x_i}\dot{x}_i + \tilde{G}_{x_i})$$

$$\tilde{M}_{x_i} = M_{x_i} - \hat{M}_{x_i},\ \tilde{C}_{x_i} = C_{x_i} - \hat{C}_{x_i},\ \tilde{G}_{x_i} = G_{x_i} - \hat{G}_{x_i}$$

$$M^{-1}\tilde{M} = M^{-1}\hat{M} - I =: E.$$

$$\ddot{x}_i = a_{x_i} + \boxed{E a_{x_i} + M_{x_i}^{-1}(\tilde{C}_{x_i}\dot{x}_i + \tilde{G}_{x_i})}$$

$$\|\eta_i\| = \|E a_{x_i} + M_{x_i}^{-1}(\tilde{C}_{x_i}\dot{x}_i + \tilde{G}_{x_i})\| \leq \boxed{\rho_i(s,t)}$$

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Chapter 03: Stability Analysis

Investigating each subsystem and overall system stability.

Stability Analysis

- Lyapunov Method

  ✓ Consider the following Lyapunov function candidate for both trainer and trainee's console as:

$$V = s_i^2/2$$

Stability Analysis

- Dwell-time stability analysis

  ✓ Dwell-time stability analysis is a technique used to analyze the stability of a class of dynamical systems known as **switching systems.**

  ✓ The dwell-time of a switching system refers to the minimum amount of time that the system must spend in each mode before it is allowed to switch to another mode.

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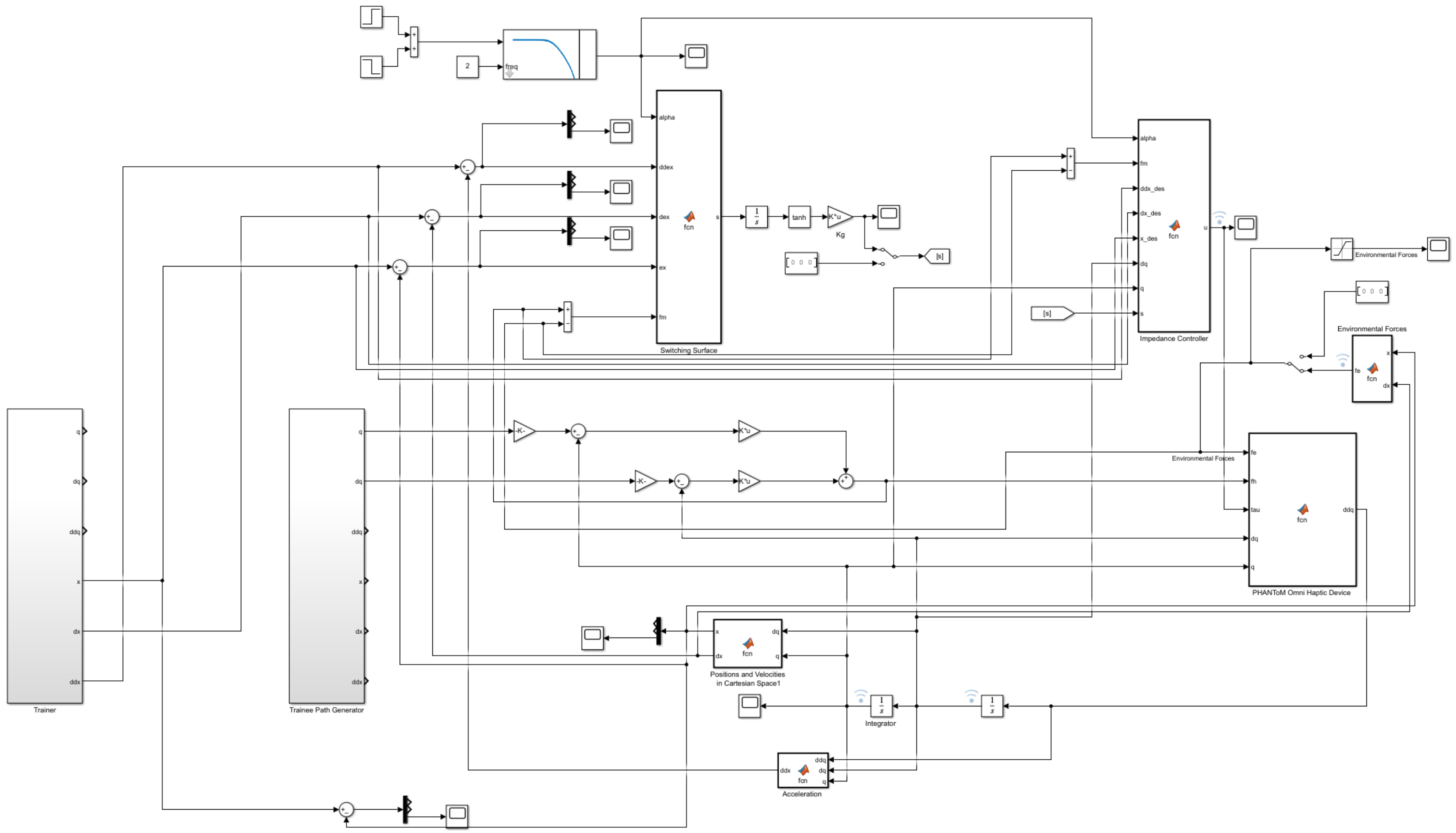
Chapter 04: Simulation

Simulating the desired scenarios using MATLAB.

Simulation

- Overall Block diagram

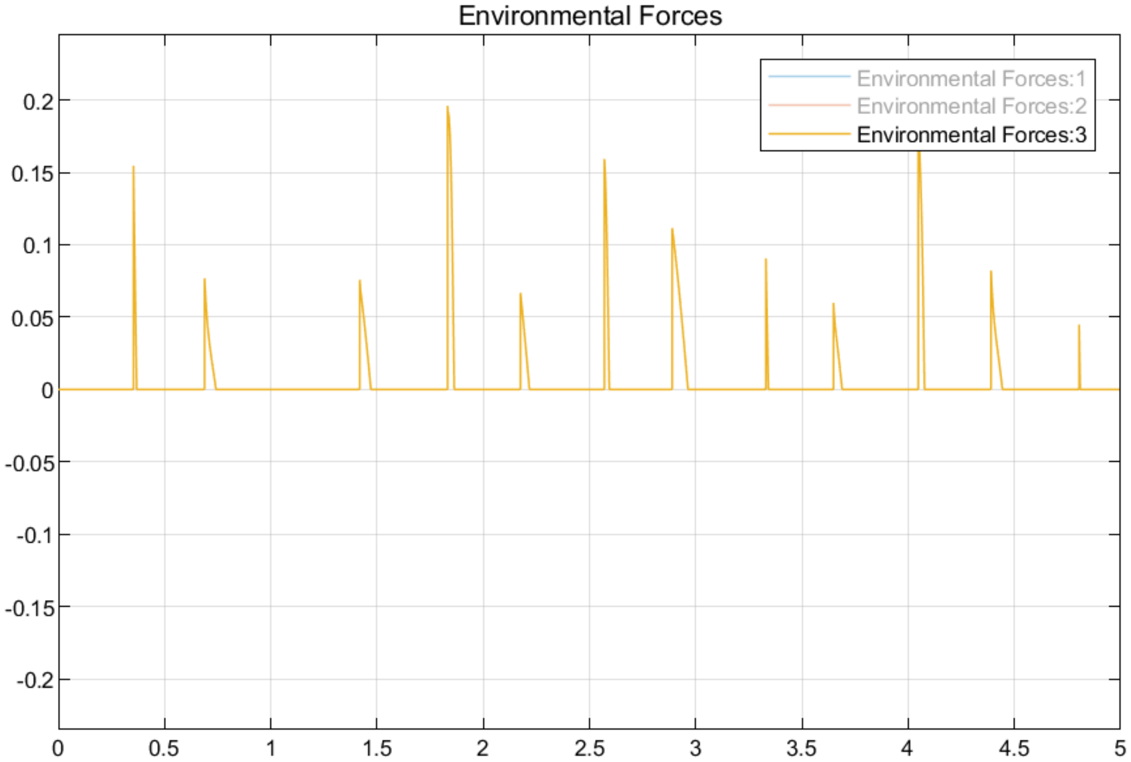


Simulation

- Environmental Force

  ✓ Hunt-Crossley contact model:

$$f_{env} = \begin{cases} K_e x^n(t) + B_e \dot{x}(t) x^n(t) & x > 0 \\ 0 & x \leq 0 \end{cases}$$



Simulation

- Expert Force Generation

  ✓ A sinusoidal signal with the required amplitude is applied to the inverse dynamics model. The generated torque is then exerted to the forward dynamics.

  ✓ a pulse with an amplitude of 1 N for 0.05 s is applied to the trainer's hand force at T = 1 s. Then the resulting signal is considered as a trainee's hand force.

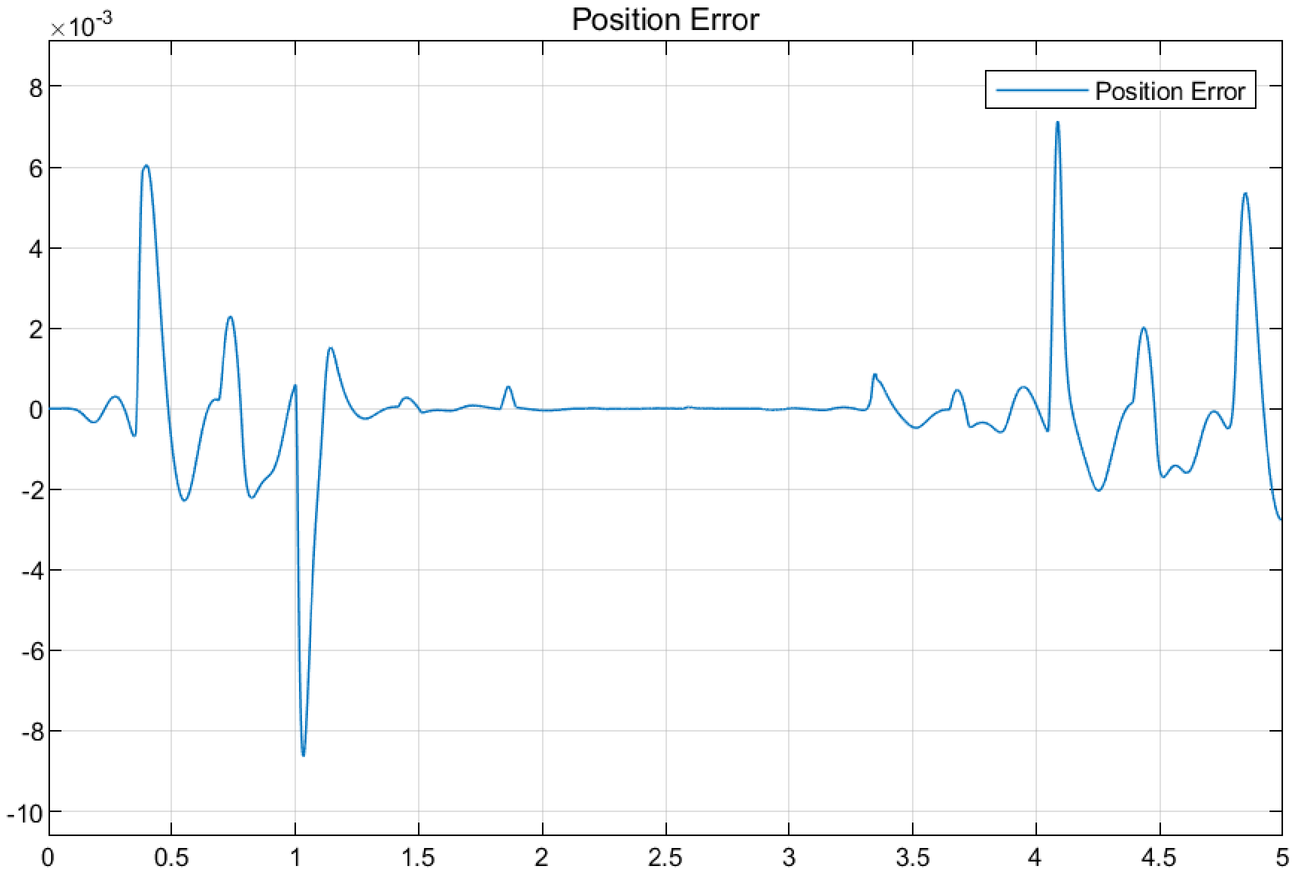
Simulation

- Desired Impedance Parameters

$M_{d_l} = 0.001I_{3\times 3}$, $B_{d_l} = 4I_{3\times 3}$ and $K_{d_l} = 100I_{3\times 3}$ to $M_{d_t} = 0.0001I_{3\times 3}$, $B_{d_t} = 20I_{3\times 3}$ and $K_{d_t} = 1000I_{3\times 3}$

Simulation

- Position Error



Seminar - Control

Chapter 05: Conclusion

Horizon ahead!

Conclusion

- ✓ Dual user haptic training systems have shown tremendous potential in teleoperated surgery. These systems use force feedback devices to provide a sense of touch to both the surgeon and the trainee, allowing them to **practice surgery in a safe and controlled environment.**

- ✓ Advancements in haptic technology, such as more advanced force feedback devices, will allow for a more realistic sense of touch in the training environment.

Conclusion

- ✓ Additionally, the integration of virtual reality technology will enable the creation of more realistic and immersive training scenarios.

- ✓ Another area of future research is the **use of artificial intelligence (AI) to optimize the training process**. AI algorithms can analyze the trainee's performance and provide personalized feedback, enabling more efficient and effective training.

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Chapter 06: References

Introducing The References used in This Presentation.

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Thanks for Your Attention