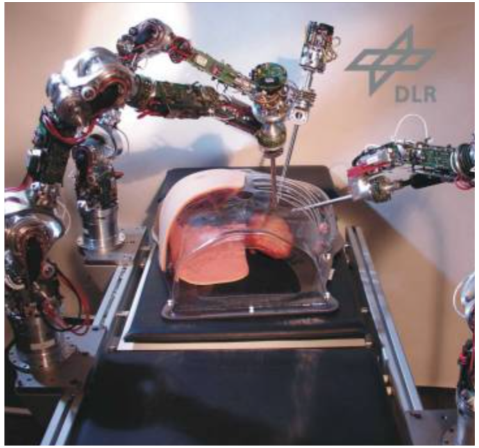
Robot-Assisted Surgery on Soft Tissue Dynamics

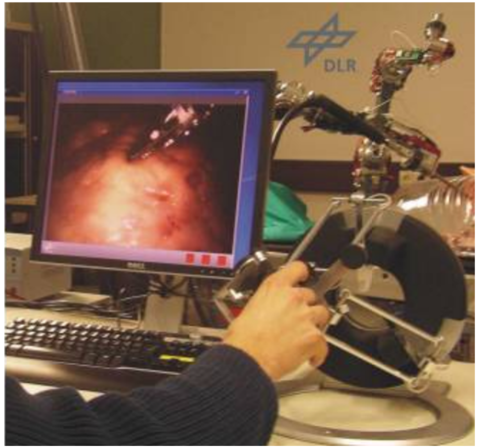
Felix Cruz, David Hoang, Shannon Lin, Andrew Setiadi

Background/Motivation

Robot-assisted surgery (RAS)

- Allows surgery to be much more minimally invasive
- Allows for higher success rates and faster recovery times
- Requires accurate and precise force application and positioning relative to the contact environment
- Robotic-assisted needle positioning platforms make use of 1 DOF motion when coming into contact with patients' soft tissue in the operating room for procedures such as:
    - Biopsies
    - Targeted drug delivery
    - Imaging (endoscopy)



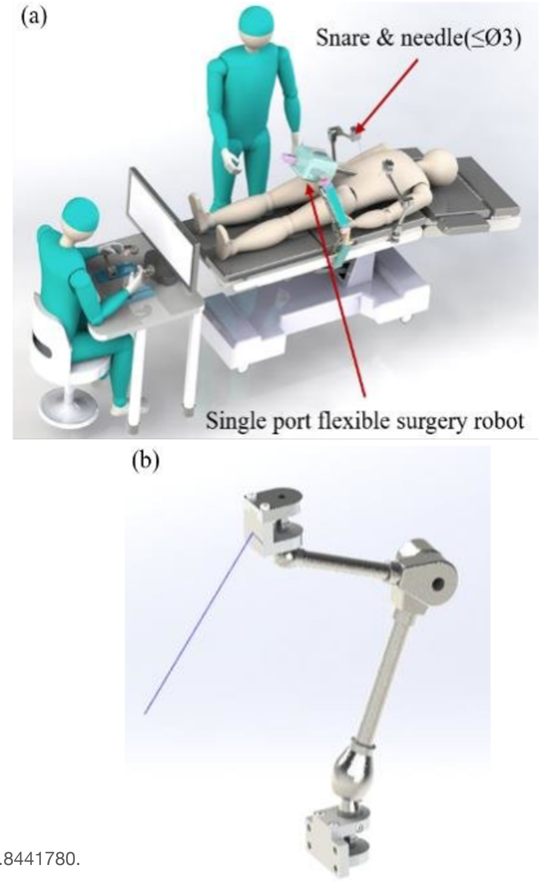


[1] Okamura A. M. (2009). Haptic feedback in robot-assisted minimally invasive surgery. Current opinion in urology, 19(1), 102–107. https://doi.org/10.1097/MOU.0b013e32831a478c

Background/Motivation continued

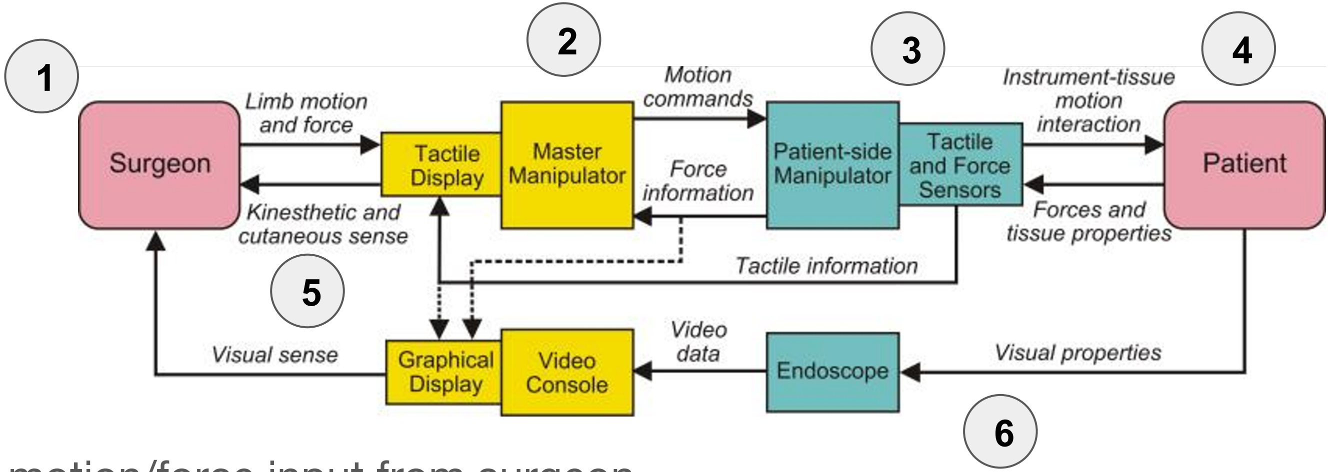
Issues and Solutions

- Contact environment isn’t purely static and solid nor perfectly elastic
- Hard for the surgeon to ‘feel’ the environment they work with and how it responds to the robot’s actions
  - Errors in RAS most often occur due to errors from surgeon when tele operating the instrument
- Adding haptic/tactile feedback can reduce these errors



[2] Ahn, Jeongdo & Hwang, Minho & Kwon, Dong-Soo. (2018). Kinematic Analysis of Needle-like Overtube Supporting Robot. 38-43. 10.1109/URAI.2018.8441780.

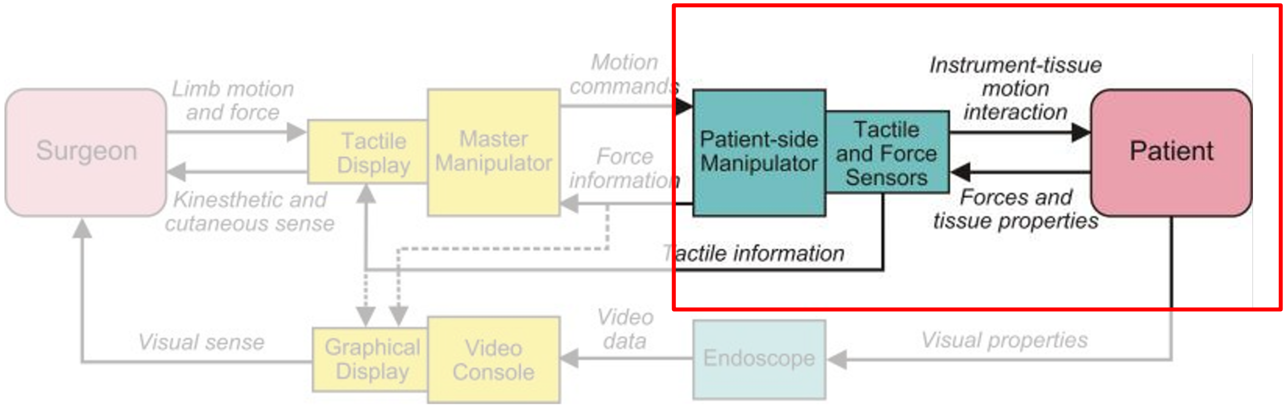
Overall Control System



1. Limb motion/force input from surgeon
2. Tactile Display/Master Manipulator
3. Patient-side Manipulator
4. Instrument-tissue interaction with patient
5. Force feedback in form of kinesthetic and cutaneous sense
6. Additional visual feedback

[1] Okamura A. M. (2009). Haptic feedback in robot-assisted minimally invasive surgery. Current opinion in urology, 19(1), 102–107. https://doi.org/10.1097/MOU.0b013e32831a478c

Project Focus

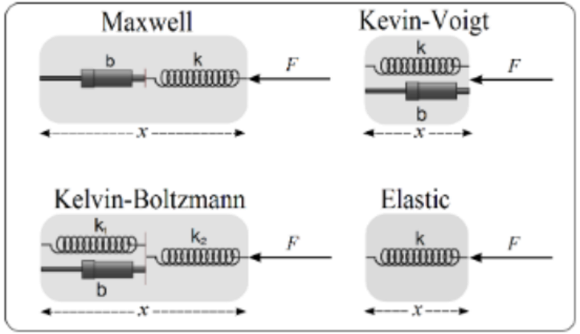


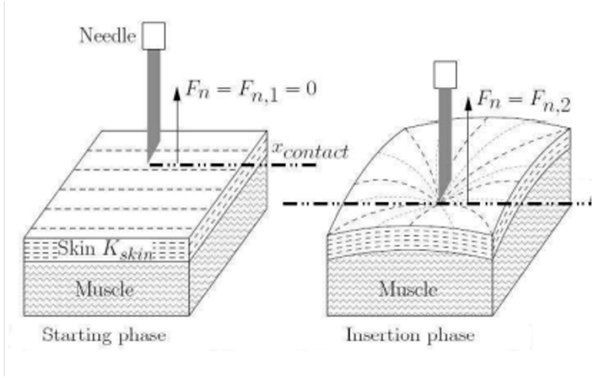
For this project, we are choosing to focus on the instrument-tissue motion interaction (i.e. the force controller). The system is defined as the robot arm and the tissue of interest. The universe is defined as the rest of the components involved in RAS, including the visual aids, displays, and the surgeon.

[1] Okamura A. M. (2009). Haptic feedback in robot-assisted minimally invasive surgery. Current opinion in urology, 19(1), 102–107. https://doi.org/10.1097/MOU.0b013e32831a478c

Key Assumptions

1. Robot has **one DOF** (i.e. a needle going up and down)
2. Robot **motion is modeled as a mass-spring-damper system**
3. The contact environment (soft tissue) is **static, viscoelastic, homogeneous, and isotropic**
    a. Modeled using a **Kelvin-Boltzmann spring damper model**
4. Tissue surface is **planar** with robot DOF normal to surface (i.e. not accounting for variance in surface topography)
5. Ideal measurements and robot response (no time delay)
6. Small force inputs with low-frequency changes
7. Initial conditions are zero (needle and tissue in contact with no force applied)

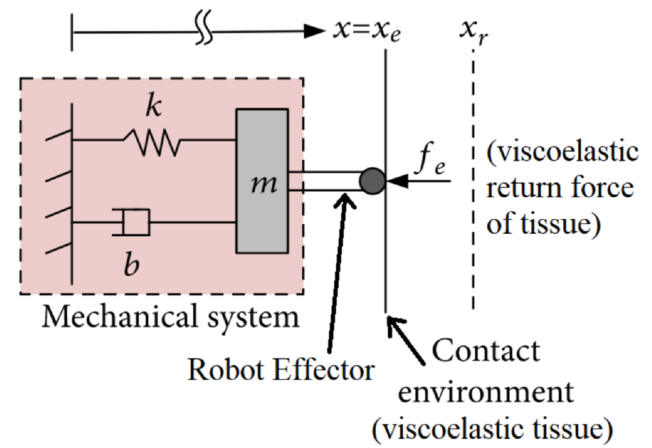


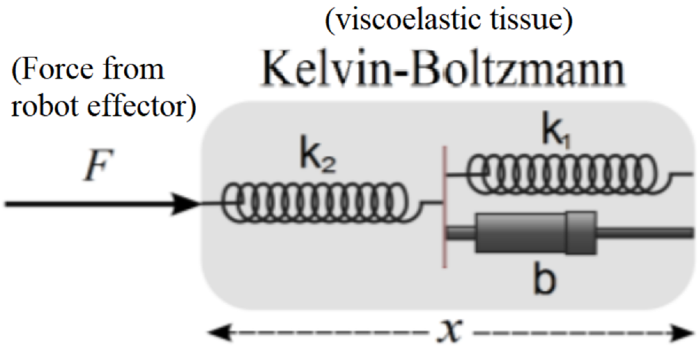


[3] Moreira, Pedro & Liu, Chao & Zemiti, Nabil & Poignet, Philippe. (2012). Soft Tissue Force Control Using Active Observers and Viscoelastic Interaction Model. Proceedings - IEEE International Conference on Robotics and Automation. 10.1109/ICRA.2012.6224958.

Design Overview

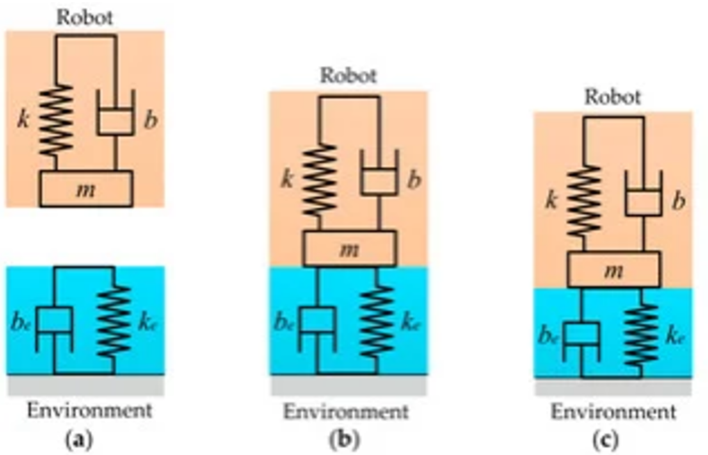
- Robot motion modeled as second-order mass-spring- damper system
- Tissue response modeled with Kelvin-Boltzmann spring damper system
- Two feedback loops will be created in Simulink:
    1. Position feedback loop
    2. Force feedback loop
- A PID controller will be introduced to regulate the output behavior

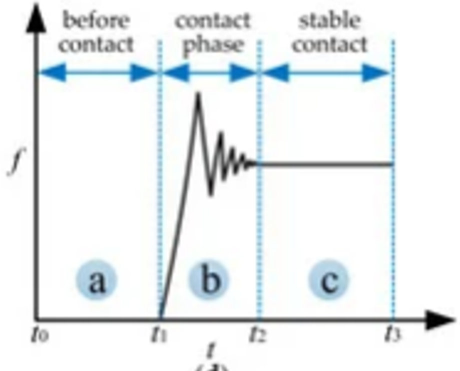




Design Overview

- **Performance goals**
  - Minimal oscillation
  - Minimal overshoot
  - Critical damping
  - Reduced steady state error
  - Reduced settling time
  - Stable output
- **Operational constraints**
  - Generated velocity and force values are limited by the base programming and mechanics of the robot
  - Generated position values are limited by the physical constraints of the tissue and robot effector





(d)

Models and Transfer Functions

Spring-Mass-Damper Model

$$\frac{du}{dt} = v(t)$$

$$m\frac{dv}{dt} = -\gamma\, v(t) - k\, u(t) + f(t)$$

TF

$$\frac{U(s)}{F(s)} = \frac{1}{ms^2 + \gamma s + k}$$

where

m = 0.01 kg

γ = 100 Ns/m

k = 300 N/m

Kelvin-Boltzmann Model

$$F(t) = \beta x(t) + \alpha \dot{x}(t) - \gamma \dot{F}(t)$$

TF

$$\frac{F(s)}{X(s)} = \frac{1+\gamma s}{\beta + \alpha s}$$

where

$\beta = \frac{k_1 k_2}{k_1+k_2}$ = 190.2 N/m

$\alpha = b\frac{k_2}{k_1+k_2}$ = 27.2 Ns/m

$\gamma = \frac{b}{k_1+k_2}$ = 0.0345 s

PID Tuning

TABLE I
EFFECTS OF INDEPENDENT P, I, AND D TUNING

Closed-Loop Response	Rise Time	Overshoot	Settling Time	Steady-State Error	Stability
Increasing K_P	Decrease	Increase	Small Increase	Decrease	Degrade
Increasing K_I	Small Decrease	Increase	Increase	Large Decrease	Degrade
Increasing K_D	Small Decrease	Decrease	Decrease	Minor Change	Improve

We have the option of choosing between P, PI, and PID controllers to optimize the output behaviour. We will determine this using the **Simulink PID tuning tool.**

Ang, K.H. and Chong, G.C.Y. and Li, Y. (2005) PID control system analysis, design, and technology. IEEE Transactions on Control Systems Technology 13(4):pp. 559-576.

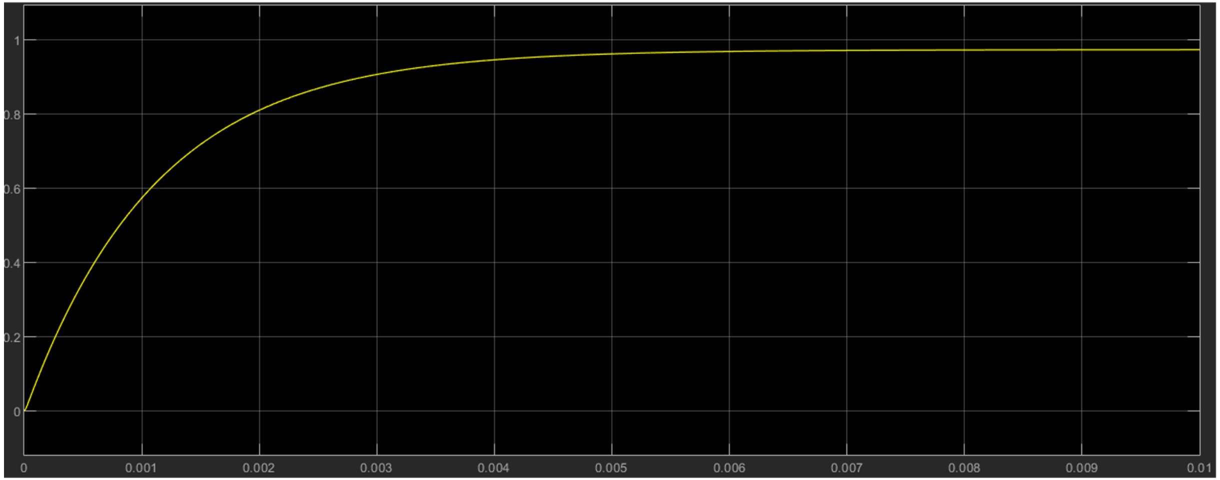
PID Tuning - P

Controller Parameters

	Tuned
P	111.0762
I	n/a
D	n/a
N	n/a

Performance and Robustness

	Tuned
Rise time	0.0102 seconds
Settling time	0.0182 seconds
Overshoot	0 %
Peak	0.986
Gain margin	Inf dB @ Inf rad/s
Phase margin	90.7 deg @ 211 rad/s
Closed-loop stability	Stable



The P controller yields a very quick rise and settling time with no overshoot, though there is some steady-state error (desired force of 1 N).

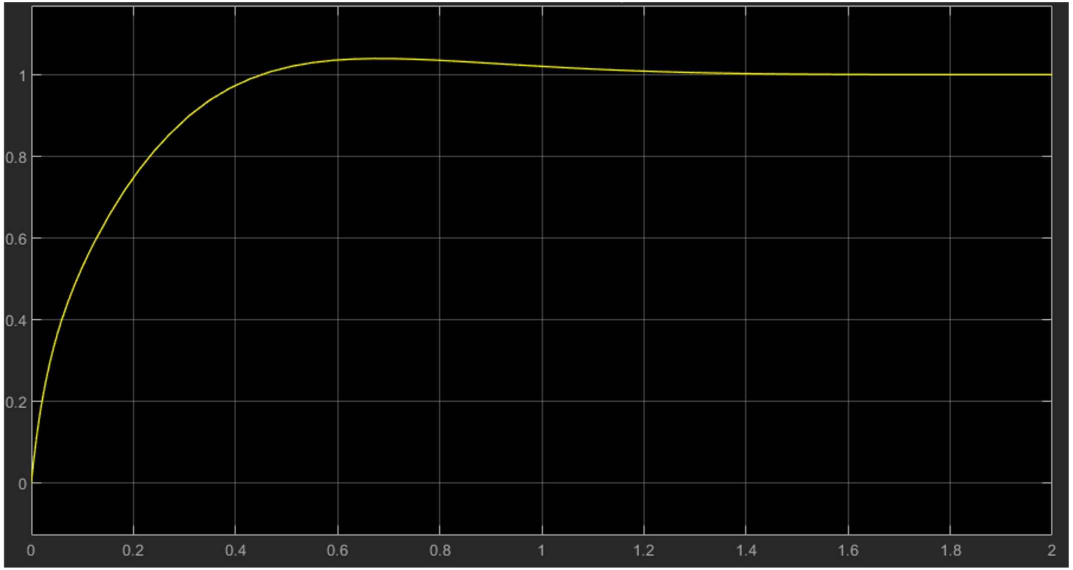
PID Tuning - PI

Controller Parameters

	Tuned
P	1.6276
I	14.6499
D	n/a
N	n/a

Performance and Robustness

	Tuned
Rise time	0.272 seconds
Settling time	0.992 seconds
Overshoot	13.8 %
Peak	1.14
Gain margin	Inf dB @ Inf rad/s
Phase margin	60 deg @ 5.31 rad/s
Closed-loop stability	Stable



The PI controller fixes the steady-state error, but there is now some overshoot and the settling time has increased drastically.

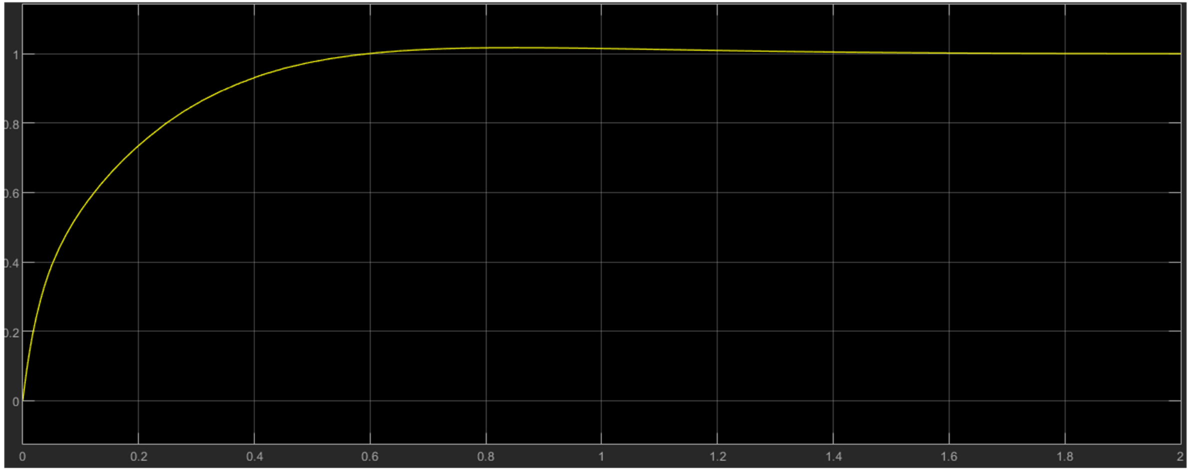
PID Tuning - PID

Controller Parameters

	Tuned
P	2.0919
I	12.6381
D	-0.022865
N	9.1294

Performance and Robustness

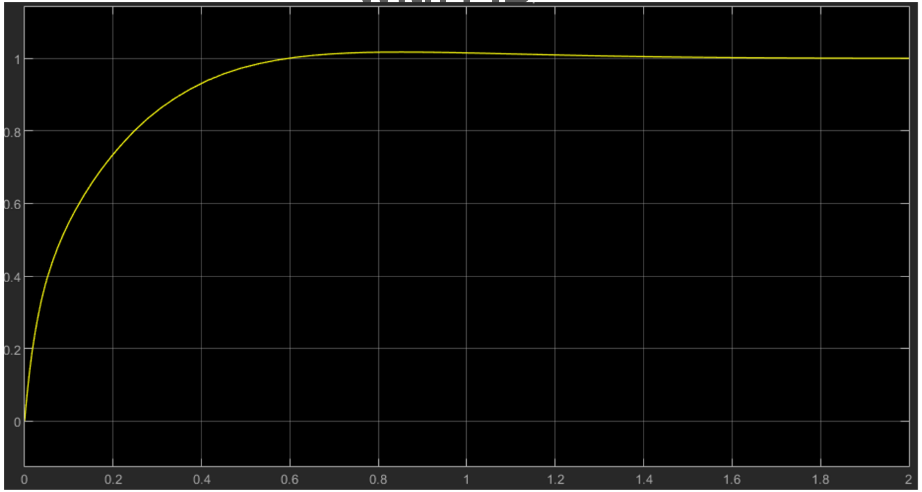
	Tuned
Rise time	0.291 seconds
Settling time	1.03 seconds
Overshoot	7.98 %
Peak	1.08
Gain margin	Inf dB @ Inf rad/s
Phase margin	69 deg @ 5.31 rad/s
Closed-loop stability	Stable



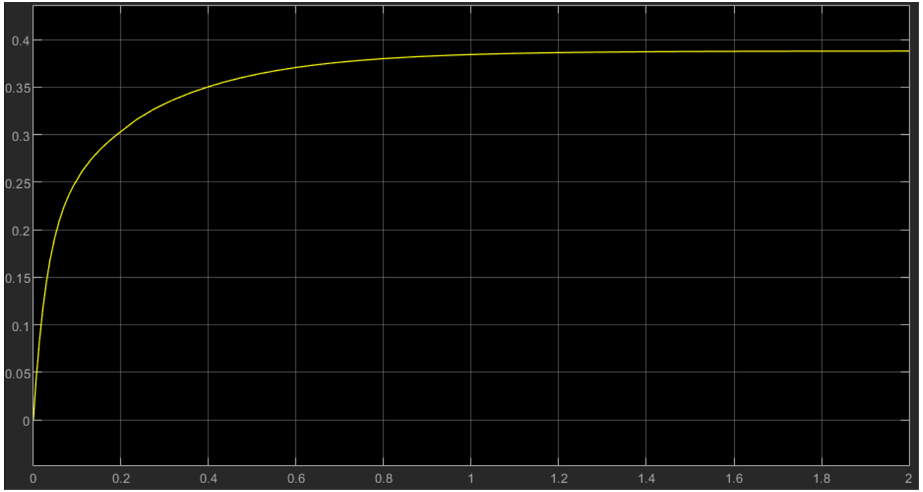
The PID controller maintains the steady-state value while reducing some of the overshoot. The settling time is similar to the PI controller. Because we are **prioritizing accuracy, we chose to implement the PID controller.**

With PID versus without PID

With PID

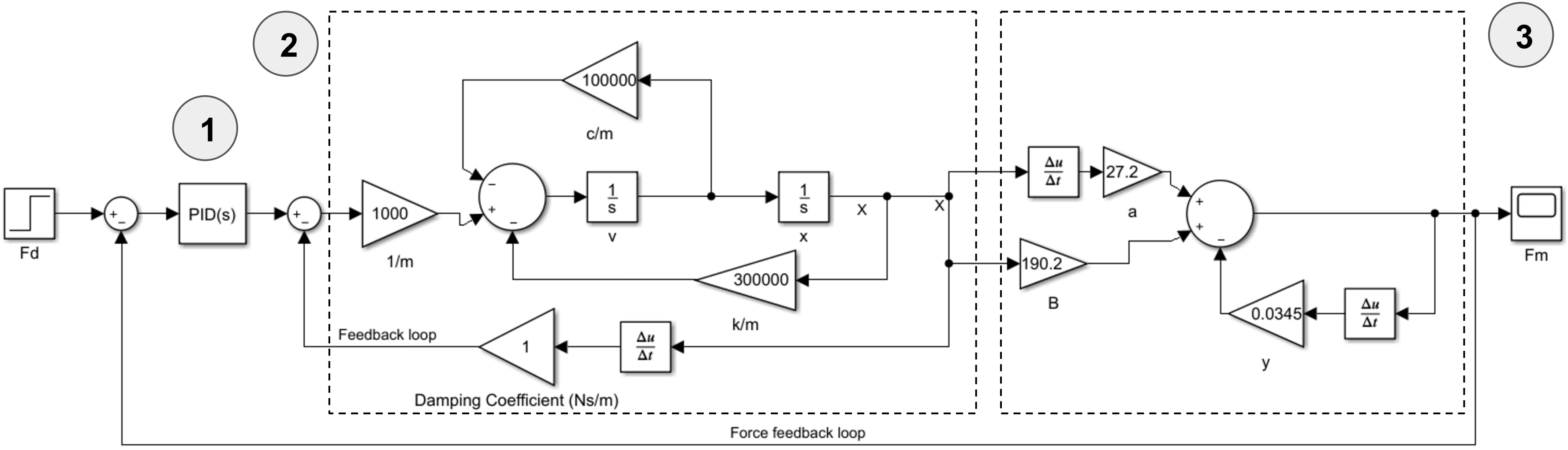


Without PID



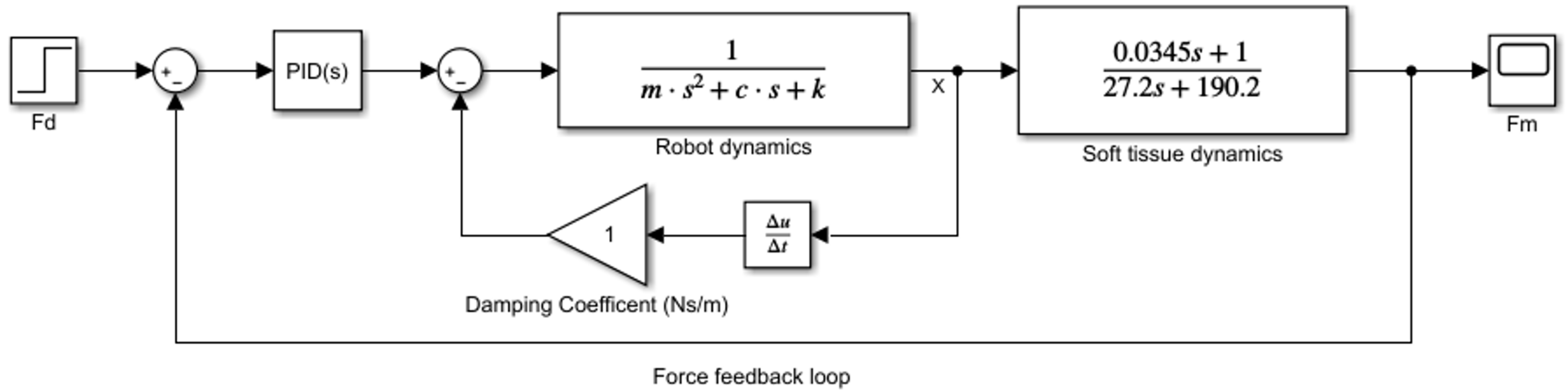
The PID controller is able to fix the steady-state error without compromising the settling time or introducing extreme overshoot, whereas without the PID controller the system has a steady-state error of ~0.6.

Simulink Diagram



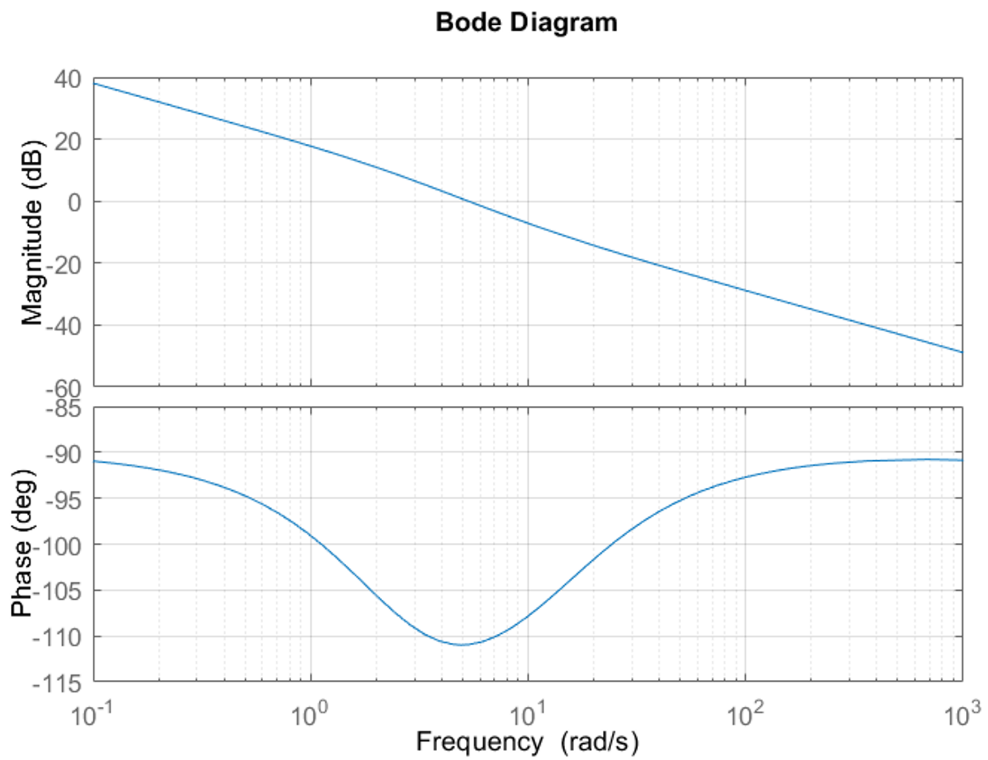
1. PID controller
2. Robotic arm dynamics
3. Soft-tissue dynamics (Kelvin-Boltzmann)

Simulink Diagram



Linearized version of system with transfer functions

Sensitivity Analysis (Bode Plot)



For the entire closed-loop system:

- Higher gain values at lower frequencies
- Lower gain at high frequencies implies reduction of shaky movements
- System is stable within this frequency range as phase does not reach -180°
- Infinite gain margin

Challenges & Errors in Simulation

- Very high gain was needed to reach the desired steady-state value in the linearized transfer function system
    - Discrepancies between nonlinear and linearized models?
- No obvious parameters for robot model
    - Not all robotic systems may be simplified to a spring-mass damper systems
- Increases in settling time could be significant and dangerous when there is a measurement delay between the surgeon’s movement and the time the force is applied to the tissue
- Overshoot percent becomes significant at higher values that may cause damage to the soft tissue if the output force greatly surpasses the desired input

Advantages & Disadvantages of Simulation Use

Advantages 

- Patient does not have to be physically involved or harmed for the best course of treatment to be determined
- Experimental outcomes can be reproduced, tested, and optimized for each patient with various trials

Disadvantages 

- Biological systems are oftentimes nonlinear and difficult to predict with solely linear models
- Time delays are not always ideal in robotic systems therefore simulations which make this assumption are limited
- Simulated and manual surgeries utilize different components of surgical competency
    - i.e. communication and fast decision-making skills

Discussion & Future Steps

Implications for broader medical field

- Increased accuracy of RAS simulations, allows for improved training of future surgeons in medical school
- Allows for application of RAS to biological systems that require more sensitivity and accuracy

Future Steps

- Implementing haptic feedback system
- Integrating an improved impedance control model
- Testing for a clinical syndrome:
    - Stiffness of soft tissues can be increased due to pathologies such as calcifications (e.g. osteosarcomas, calcinosis) and scarring (e.g. hepatic cirrhosis, pulmonary fibrosis)
        - Leads to increase in stiffness in the parameters of the Kelvin-Boltzmann Model for soft tissues

Thank you!

Questions or Comments?

References

1. Ahn, Jeongdo & Hwang, Minho & Kwon, Dong-Soo. (2018). Kinematic Analysis of Needle-like Overtube Supporting Robot. 38-43. 10.1109/URAI.2018.8441780.
2. Ang, K.H. and Chong, G.C.Y. and Li, Y. (2005) PID control system analysis, design, and technology. IEEE Transactions on Control Systems Technology 13(4):pp. 559-576.
3. Li, Chao, et al. “Efficient Force Control Learning System for Industrial Robots Based on Variable Impedance Control.” Sensors, vol. 18, no. 8, Aug. 2018, p. 2539. DOI.org (Crossref), https://doi.org/10.3390/s18082539.
4. Moreira, Pedro & Liu, Chao & Zemiti, Nabil & Poignet, Philippe. (2012). Soft Tissue Force Control Using Active Observers and Viscoelastic Interaction Model. Proceedings - IEEE International Conference on Robotics and Automation. 10.1109/ICRA.2012.6224958.
5. Okamura A. M. (2009). Haptic feedback in robot-assisted minimally invasive surgery. Current opinion in urology, 19(1), 102–107. https://doi.org/10.1097/MOU.0b013e32831a478c
6. Yo Kobayashi, Pedro Moreira, Chao Liu, Philippe Poignet, Nabil Zemiti, et al.. Haptic Feedback Control in Medical Robots Through Fractional Viscoelastic Tissue Model. EMBC: Engineering in Medicine and Biology Conference, Aug 2011, Boston, United States. pp.6704-6708,10.1109/IEMBS.2011.6091653.lirmm-00623166