NRI: Shape Morphing Arm Robotic (SMART) Manipulators for Simultaneous Safe Human-Robot Interaction and High Performance in Manufacturing

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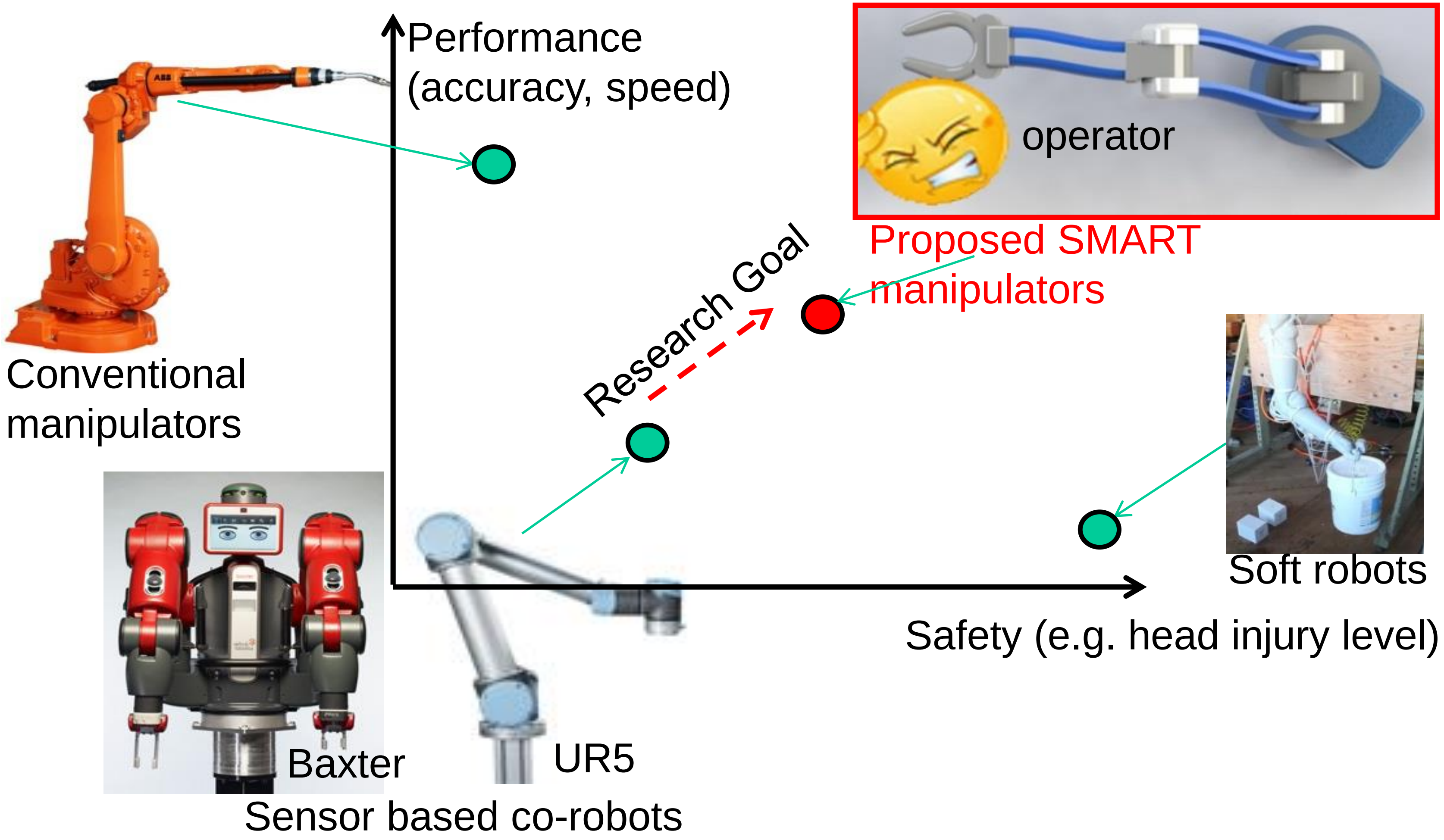
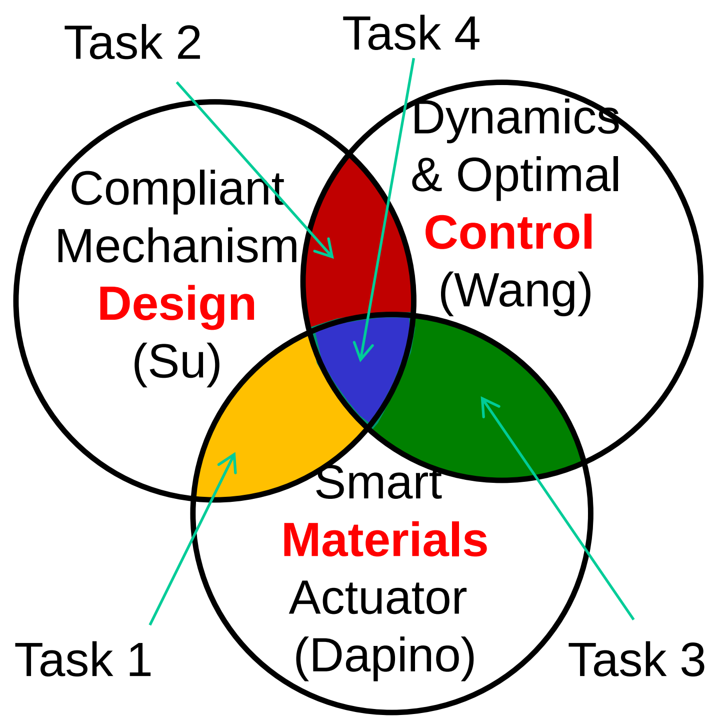
Motivations and Research Goals

- **Conventional:** design for performance, safety by control
- **Objective: safety by design, performance by control**



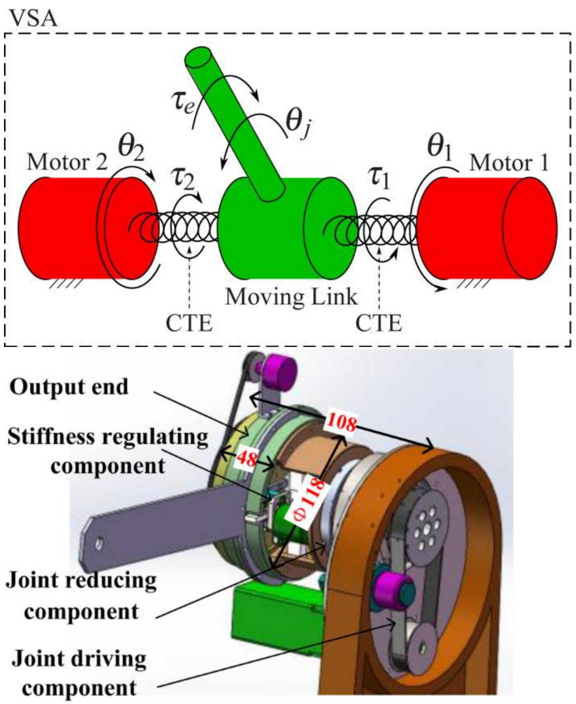
Research Team and Tasks

- Research Tasks
  - TASK 1: Develop a compliant mechanism and smart material actuator co-design framework for SMART links (Su, Dapino)
  - TASK 2: Develop a control law and compliant mechanism co-design framework of SMART links with safety constraints (Su, Wang)
  - TASK 3: Investigate methods for simultaneously controlling link motion and stiffness for achieving maximum performance under HIC constraint (Wang, Dapino)
  - TASK 4: Integrate a comprehensive compliance design, stiffness modulation, and motion control framework of multi-linked SMART manipulators (Su, Dapino, Wang)

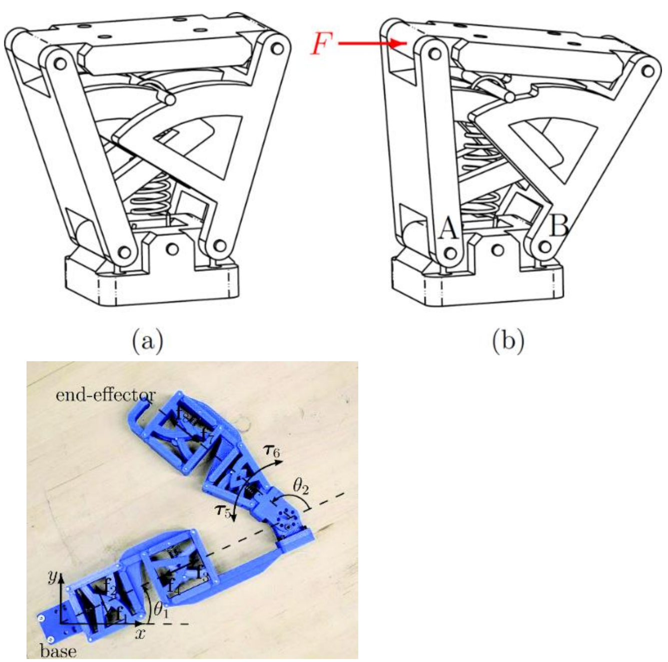


Current Solutions of Corobots

- **Sensor based: vision for collision detection, torque/force sensor at joints**
- **Variable stiffness actuators (VSA): series elastic actuators/joints**
- **Mechanical Fuse: maximum force/torque limit**



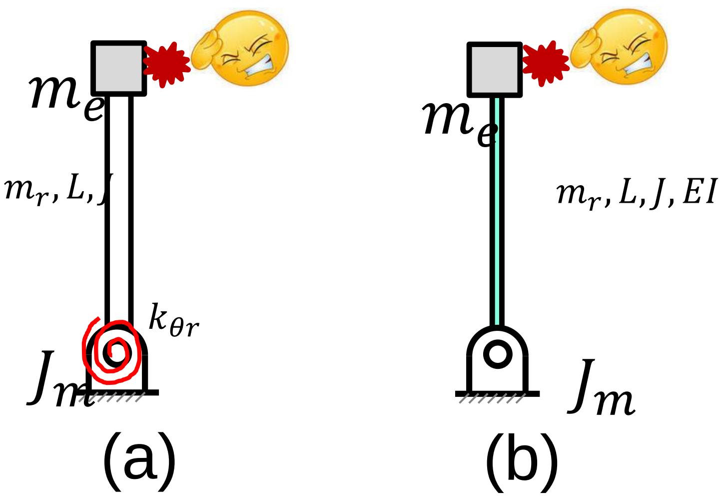
Design of Variable Stiffness Actuator Based on Modified Gear–Rack Mechanism, Wang et al., ASME JMR, 2016.



Force Capabilities of Two-Degree-of-Freedom Serial Robots Equipped With Passive Isotropic Force Limiters, Zhang et al., ASME JMR, 2016

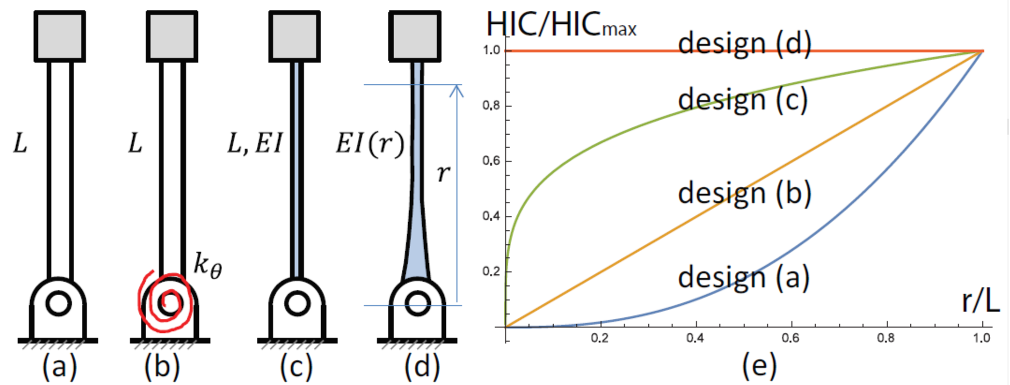
Comparison of Compliant Link and Compliant Joints

- **Compare safety criteria: HIC distribution/impact force**
- **Compare the control performance: natural frequency and bandwidth**



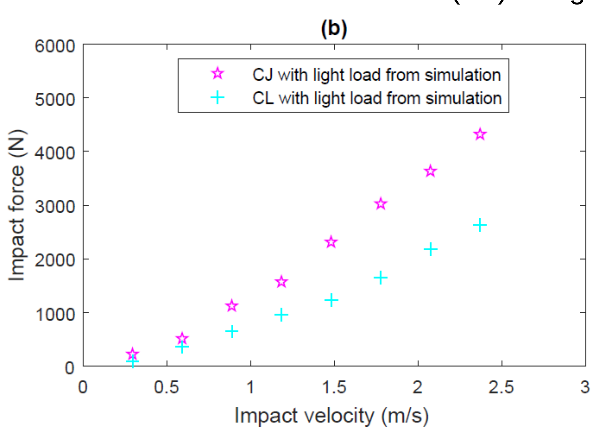
(a) Compliant Joint (CJ) Design

(b) Compliant Link (CL) design



Mode	f_{CJ}	f_U	f_V	f_{RL}
1	37.219	43.107	103.24	$+\infty$

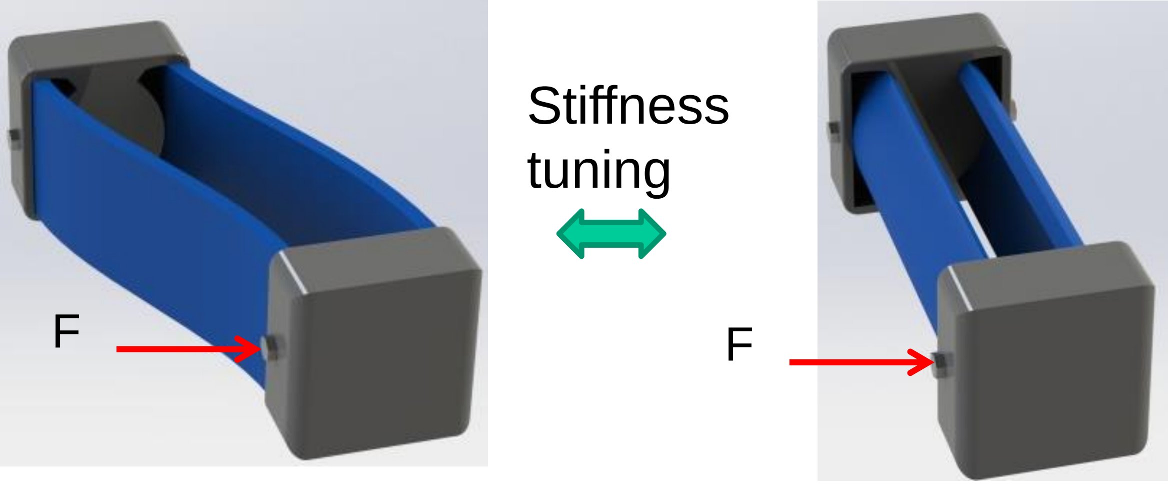
Bandwidth	W_{CJ}	W_U	W_V	W_{RL}
Value	58	187	324	$+\infty$



CL results a significantly smaller impact force than CJ particularly for small m_e/m_r.

The Design Strategy for Variable Stiffness Links

- **Variable stiffness of compliant links via shape morphing, material property tuning**



Flat beams (compliant) E_1, I_1 < E_2, I_2 Curved beams (stiff)

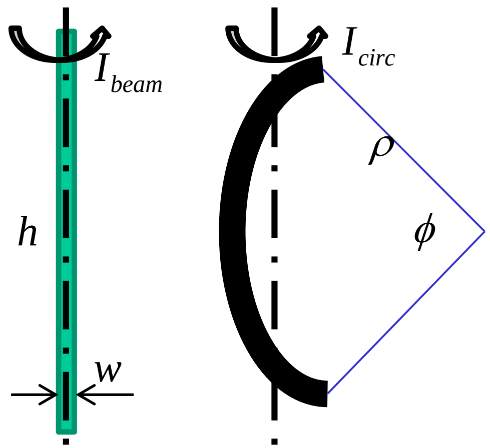
- **Head Injury Criterion (HIC) is determined by mass, velocity and stiffness**

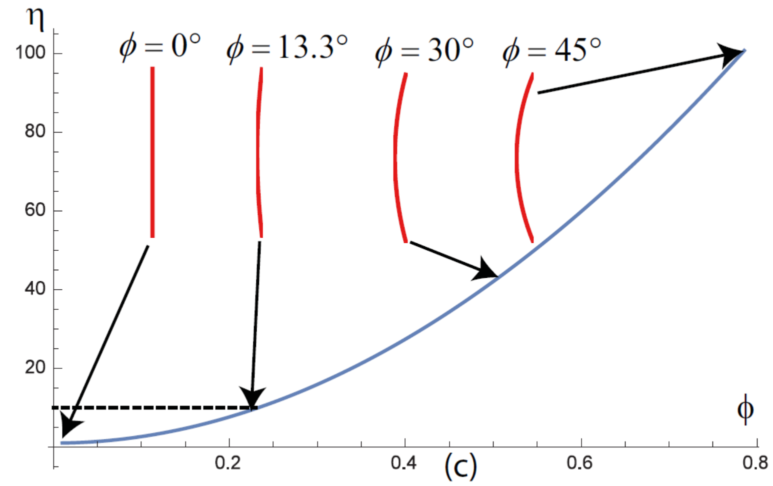
$$\mathrm{HIC} = 1.016\, T \left(k_{eff}^{0.75}\right)\left(\frac{m_{oper}^{-0.75} m_{eff}^{1.75}}{(m_{eff}+m_{oper})^{1.75}}\right)\left(v^{2.5}\right)$$

Variable Stiffness via Shape Morphing

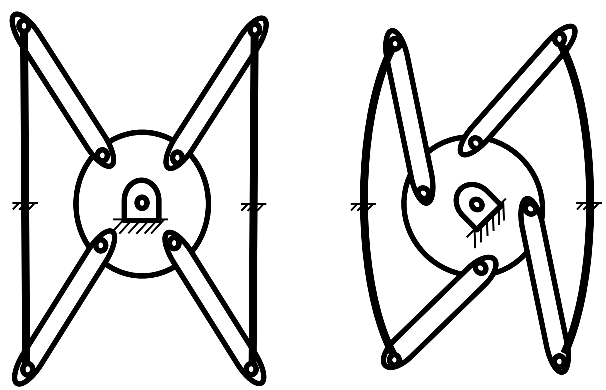
- Moment of inertia of straight beam vs. curved beams
- Shape morphing actuation via four-bar linkages

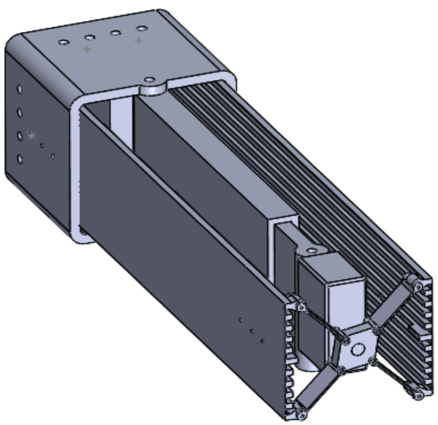
Concept Design

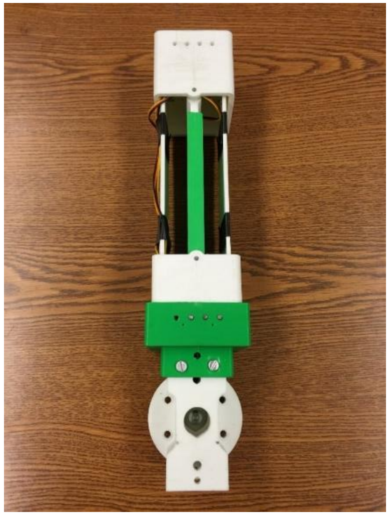




Hardware Implementation





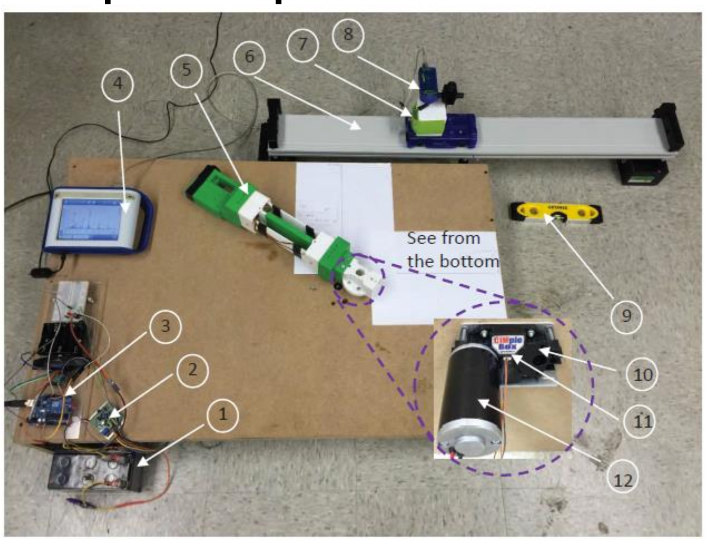


Impact Testing Results

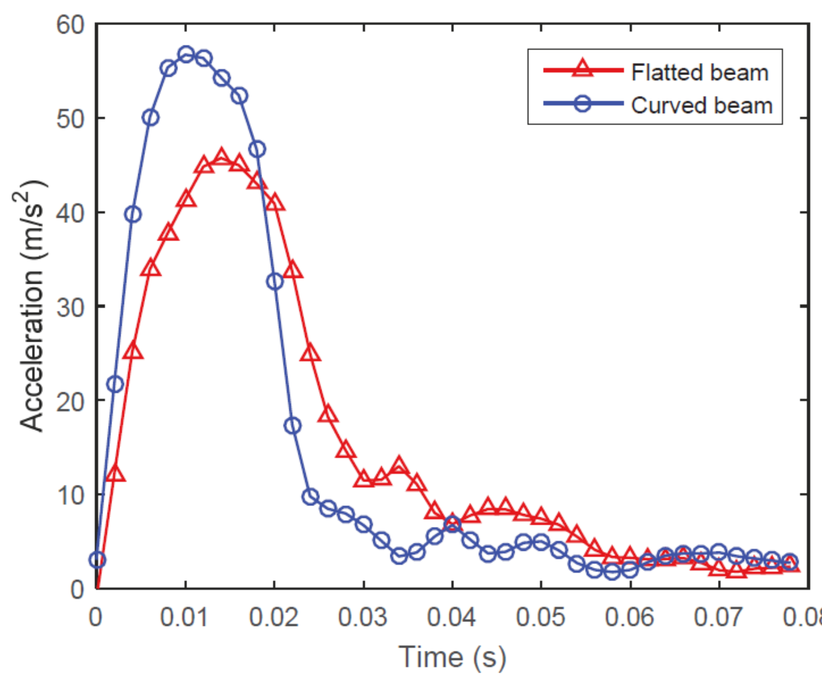
- **Head Injury Criteria (HIC)**
- **Actual stiffness change ratio ≈ 3.6**
- **Impact testing results:**
  - Peak acceleration dropped from 56.7 m/s^2 to 45.7 m/s^2
  - **29%** (210.3 $m^{2.5}/s^{-4}$ to 153.3 $m^{2.5}/s^{-4}$) reduction in HIC at impact speed of 2.2m/s

$$\mathrm{HIC}(\Delta t_{max}) = \max_{\Delta t}\left\{\Delta t\left[\frac{1}{\Delta t}\int_{t_1}^{t_2}\hat{a}\,dt\right]^{2.5}\right\}$$

$$\text{subject to } \Delta t = t_2 - t_1 \leq \Delta t_{max}$$

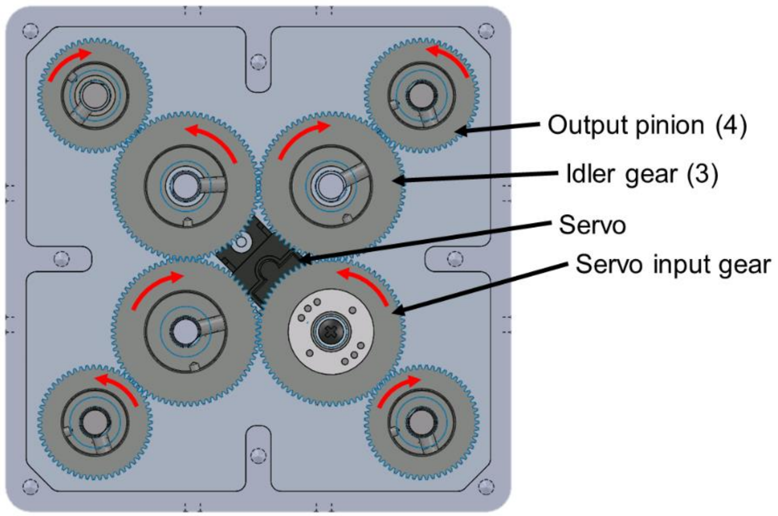


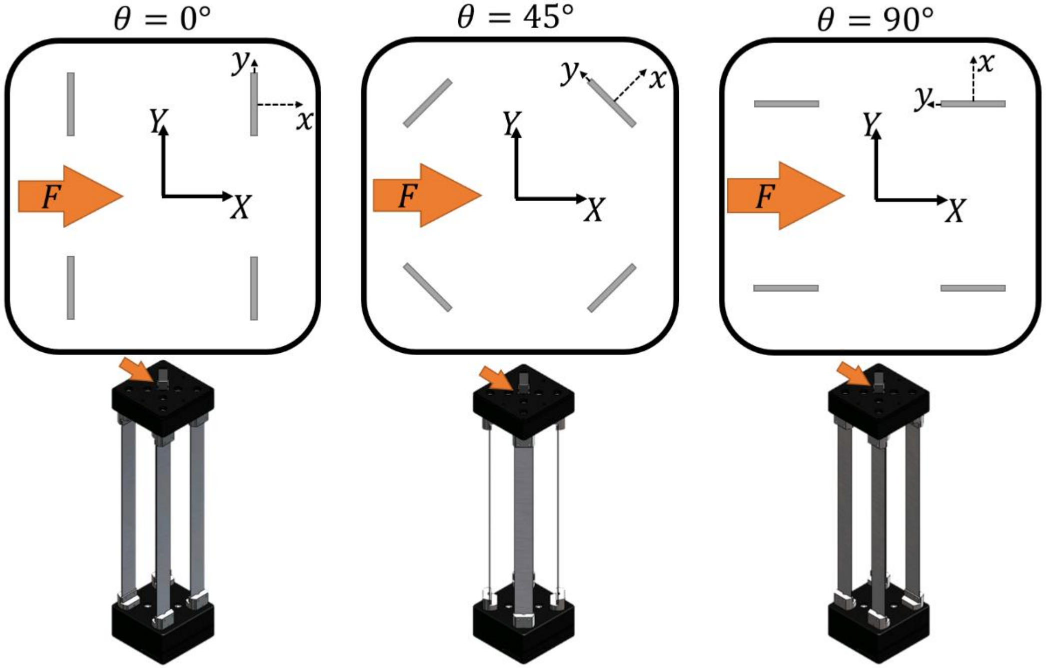
1. Power supply, 2. Speed controller, 3. Micro-controller, 4. PASCO PS-2008A, 5. Morphing arm, 6. PAStrack Dynamics System ME-6962, 7. Force sensor, 8. Acceleration sensor, 9. Stanley Level, 10. Gear box, 11. Encoder, 12. DC motor

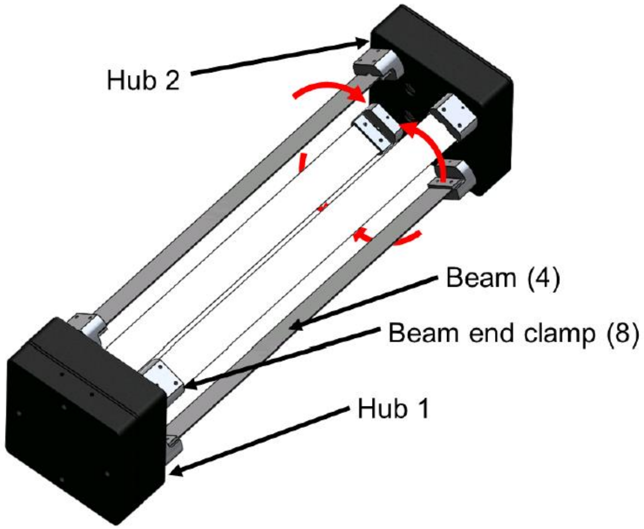


Variable Stiffness by Rotating Beams

- **Synchronized symmetric beams change the second moment of inertia, so that $I(\theta)$ in $k = n\frac{EI}{L^3}$**
- **Aluminum beams, small hobby servos, nylon gears**



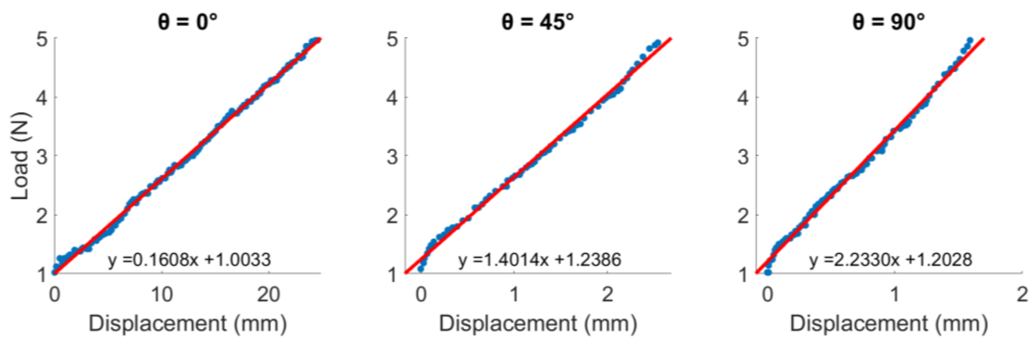




Testing Results

- **Stiffness ratio ≈ 13.9**
- **Analytical model from first principles accounts for buckling & actuation components predicts stiffness variation.**
- $k(\theta) = \frac{k_x + k_y}{2} + \frac{k_x - k_y}{2}\cos(2\theta)$

Load vs Displacement Measurement of Stiffness



Max stiffness: 2.25 N/mm

Min stiffness: 0.16 N/mm

Median stiffness: 1.38 N/mm

Max/min stiffness ratio: 13.9

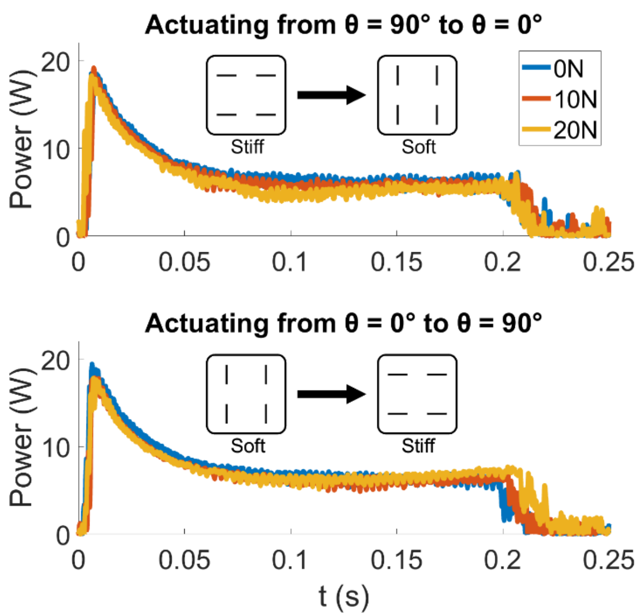
Actuation time: <0.25 s

Peak power draw: 15 W

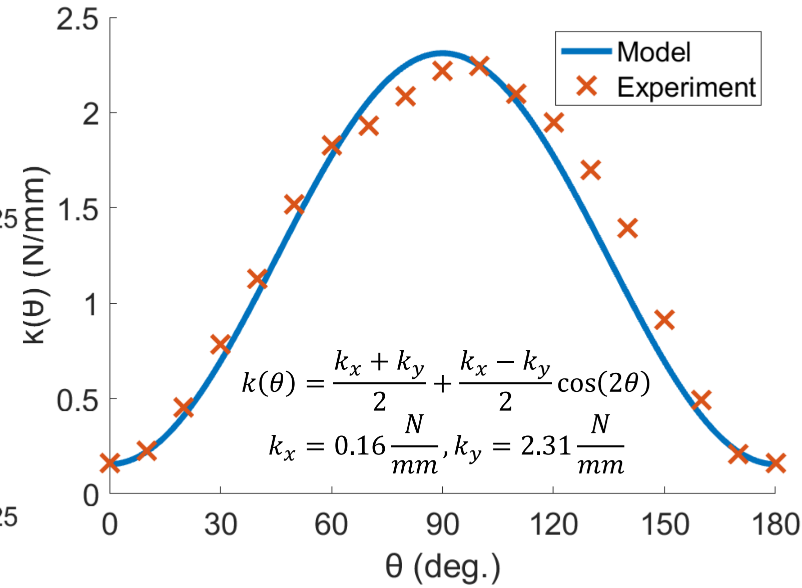
Average power draw: 9 W

Mass of Design: 1.27 kg

Power Consumption Actuating Under Load

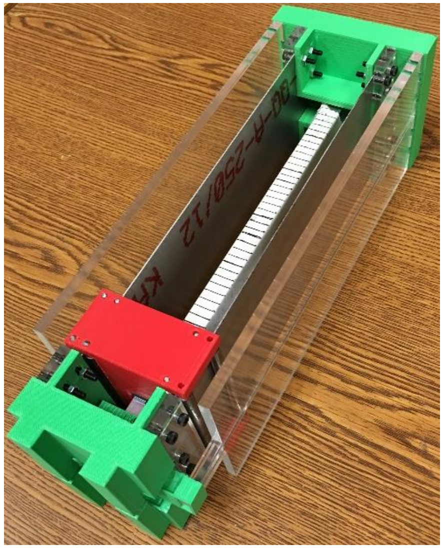


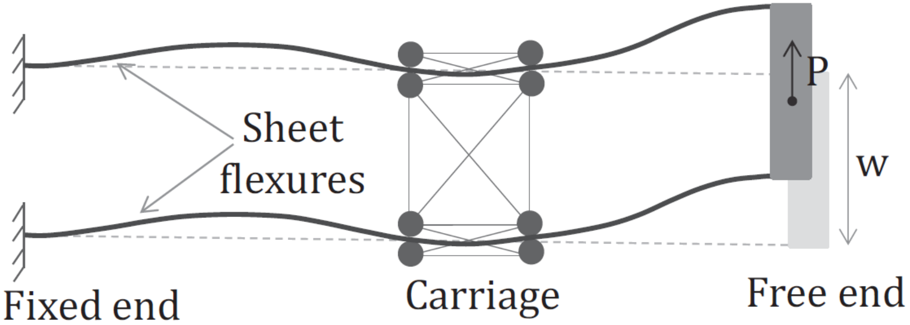
Comparison of Stiffness With Model

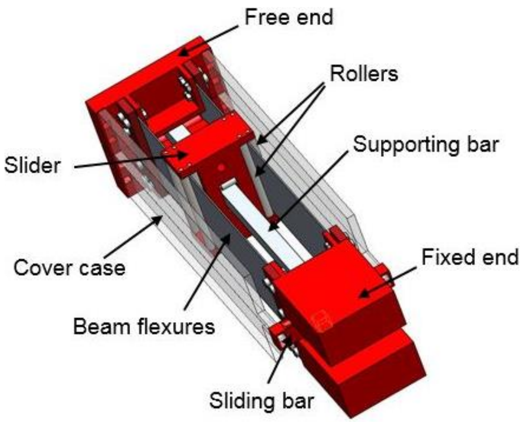


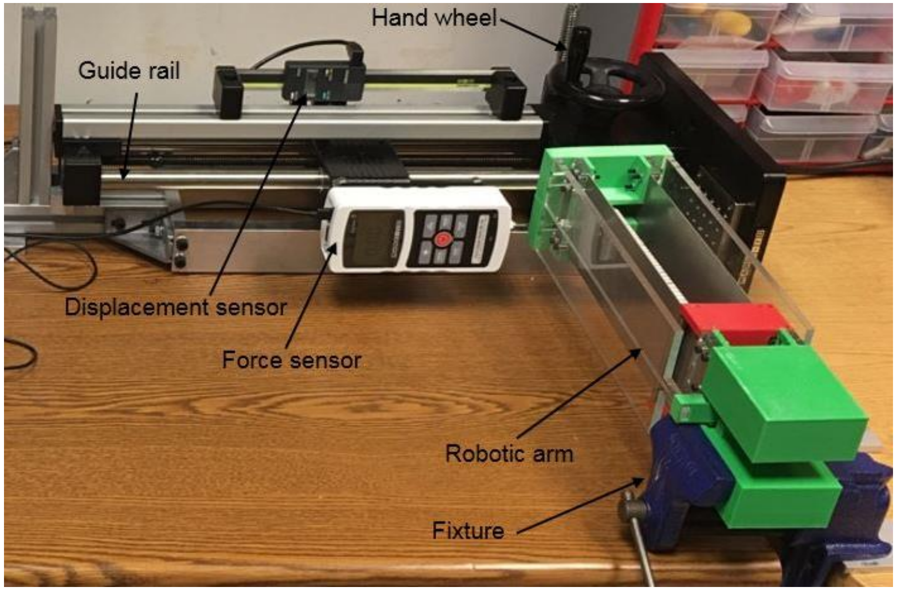
Variable Stiffness by Changing Effective Length

- **Change effective length in $k \propto \frac{EI}{L^3}$**
  - L ranged from 5 to 30 cm.
  - k change from 4.2×10^3 to 193 N/m, about 21.7 fold.
- **Drive carriage by lead screw with DC motor or pneumatic linear actuator.**







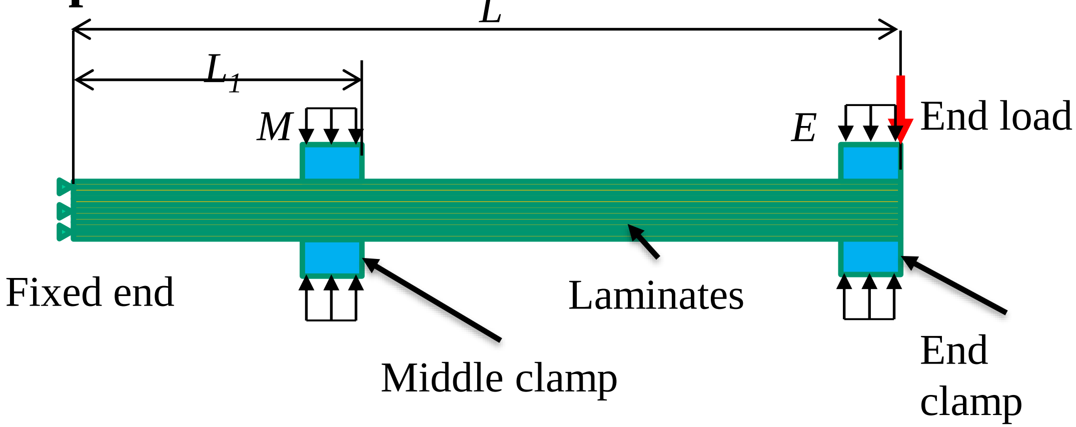


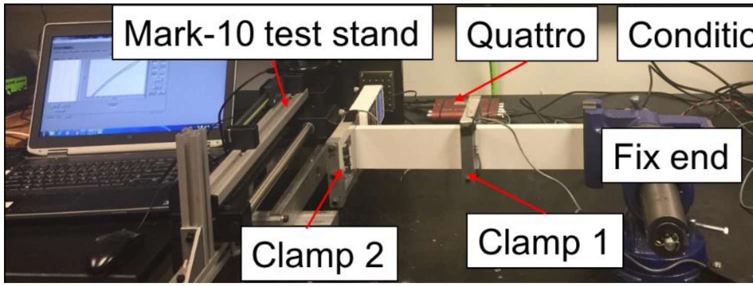
Discrete Layer Jamming Concept (1)

Key Parameters: clamp location, clamp width, friction coefficient, number of clamps, and number of laminates

Stiffness is obtained from force-displacement curves from cantilever bending simulation

Clamp location

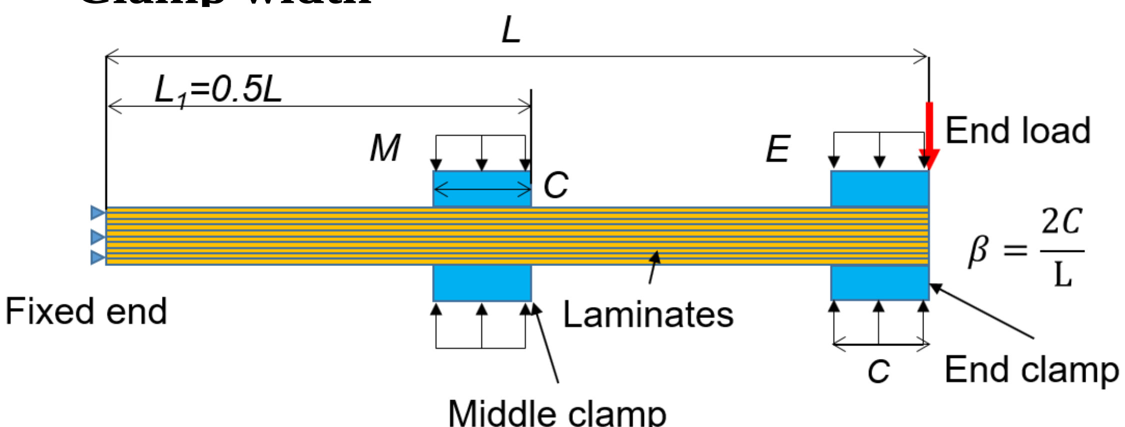


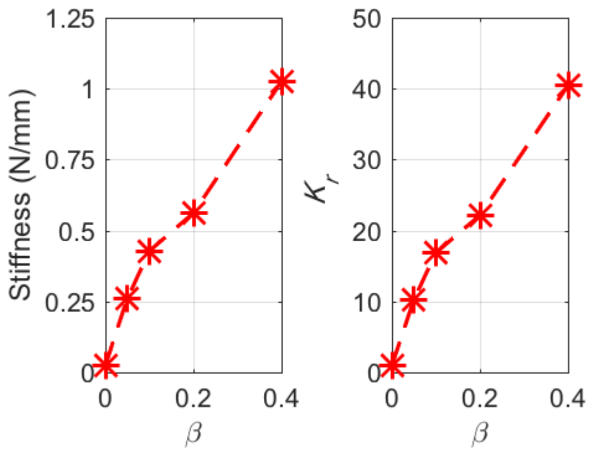


Both stiffness and stiffness ratio have maximum values at $\boldsymbol{\alpha = 0.5}$, i.e. $\boldsymbol{L_1 = 0.5L}$

For middle clamp location, best near middle and worst near ends of the beam

Clamp width



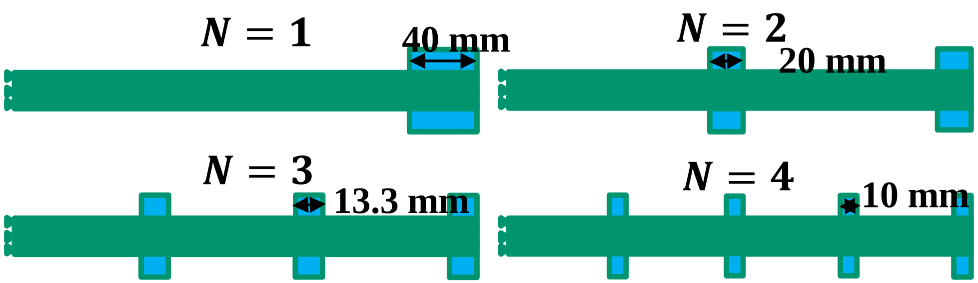


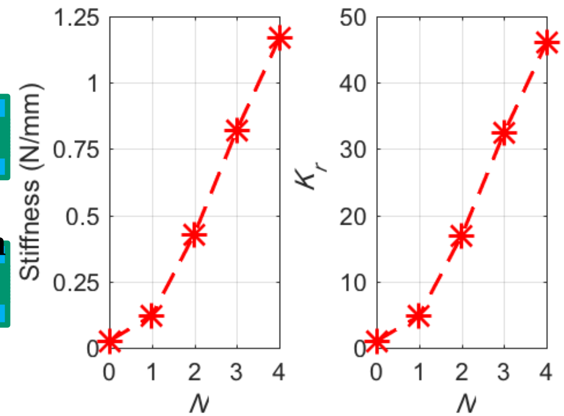
Stiffness increases with clamp width, a 40.4 times stiffness change can be achieved with 40% of the area of the beam clamped

Large, stiff clamps can add bulk to the system

Discrete Layer Jamming Concept (2)

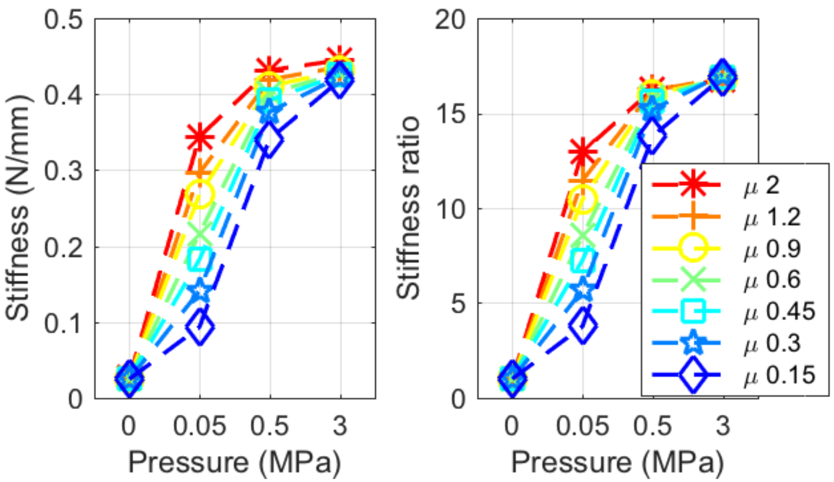
Number of clamps (N)





- The more clamps, the higher the stiffness and stiffness ratio
- 4 clamps yield a maximum stiffness ratio of 46

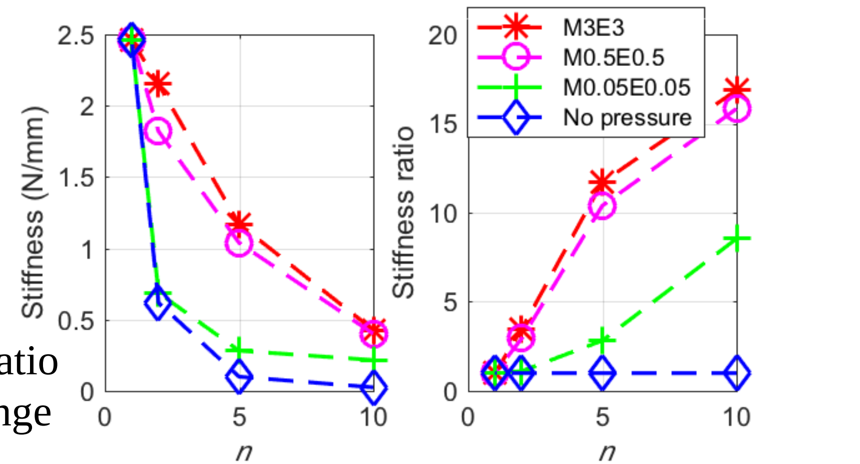
Friction coefficient (μ)



- μ has little effect on stiffness at the no pressure state or M3E3
- Stiffness and stiffness ratio increase significantly with μ at intermediate pressure states
- Maximum stiffness ratios are almost the same for all friction coefficient cases

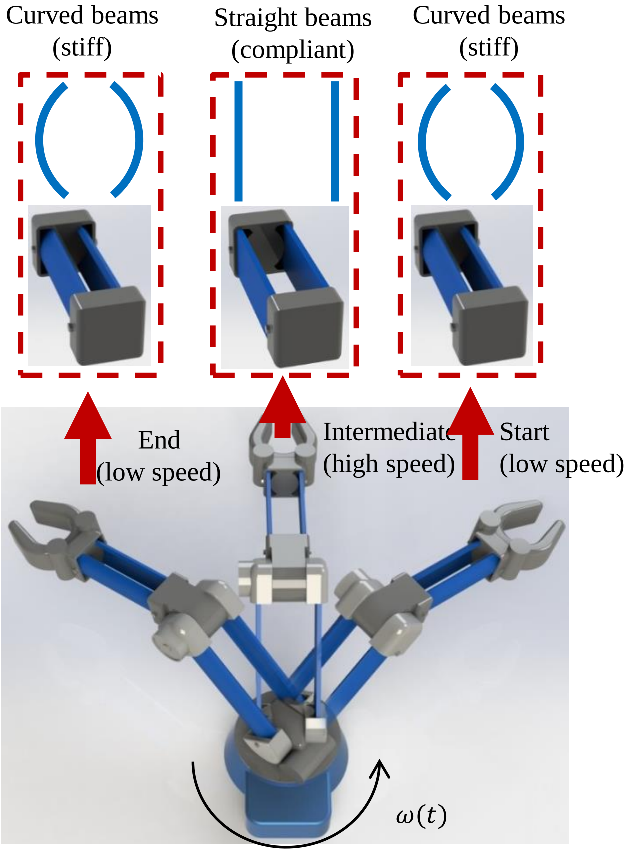
Number of laminates (n)

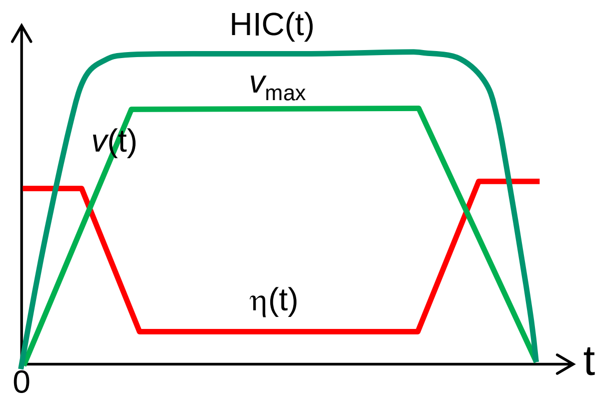
- Same total thickness for all cases: 15.9 mm
- The more number of laminates, the higher the stiffness ratio
- The less number of laminates, the higher the stiffness range



Compliant Links for Corobots

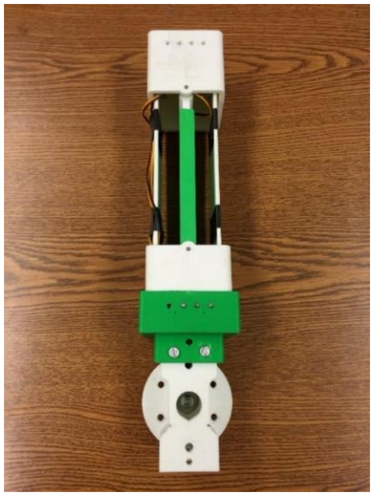
- **Stiffness control theme: high stiffness at low speed, low stiffness at high speed**
- **Keep safety level below a threshold**
- **Under the safety constraint, the higher the stiffness of the robot link, the better of the control performance**

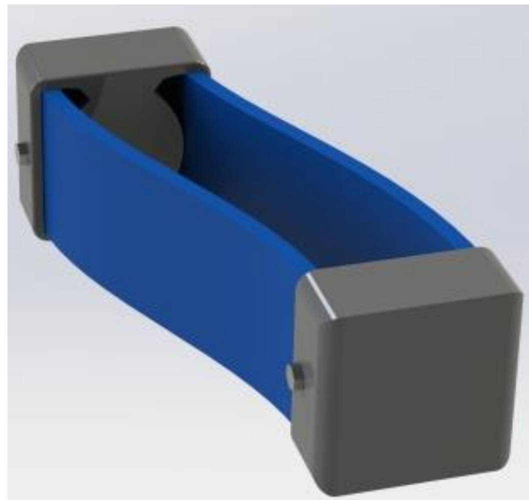


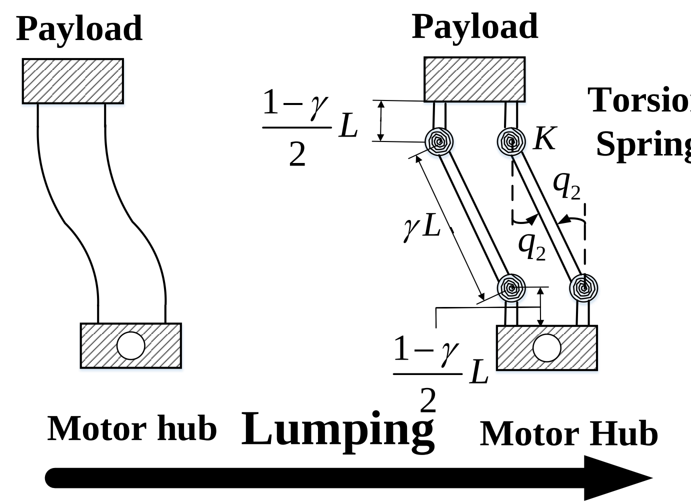


Dynamics Control of Variable Stiffness Link (1)

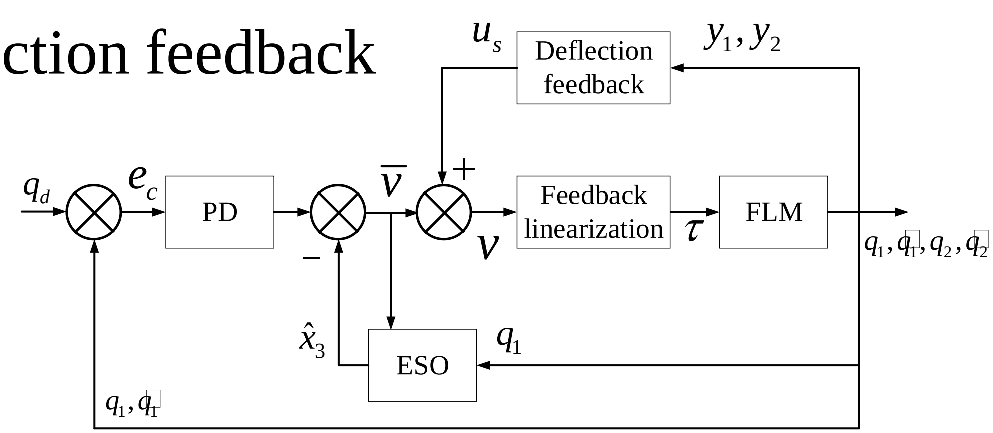
- **Dynamic Modeling: the pseudo-rigid-body model**





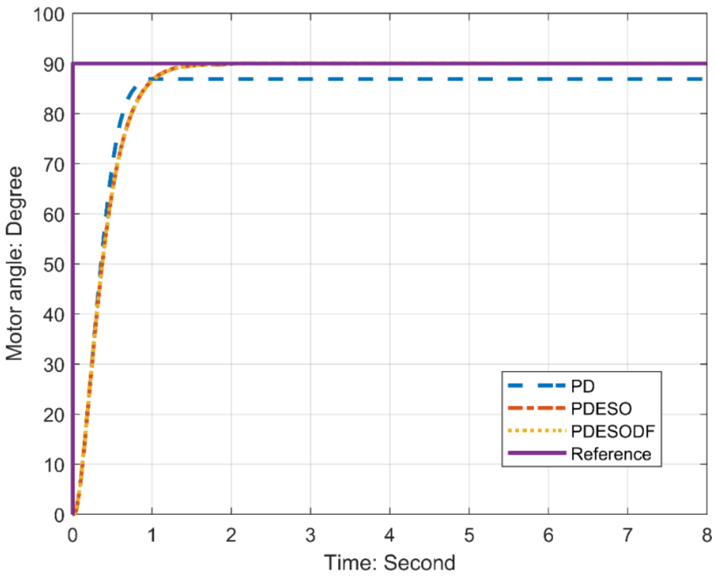


- **Compound control architecture**
  - Uncertainties and disturbances: extended state observer (ESO)
  - Vibration suppression: deflection feedback

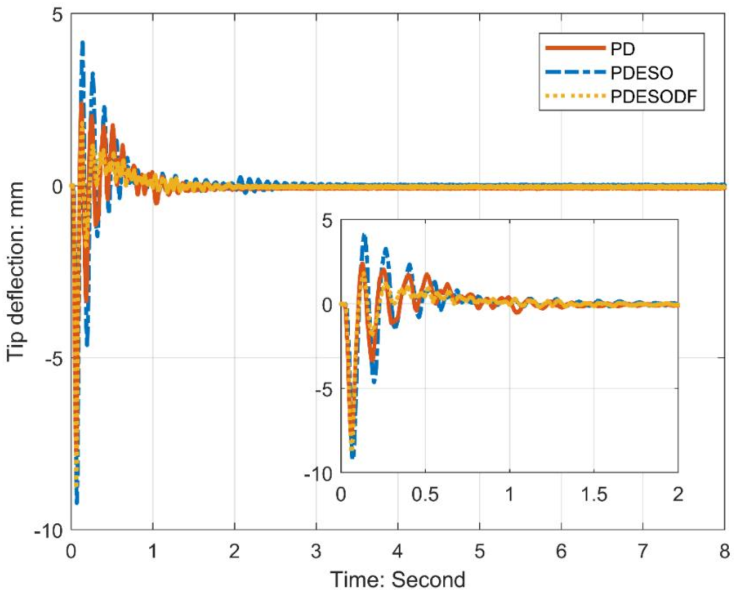


Dynamics Control of Variable Stiffness Link (2)

- **Smaller steady-state error (by uncertainties and disturbance compensation)**

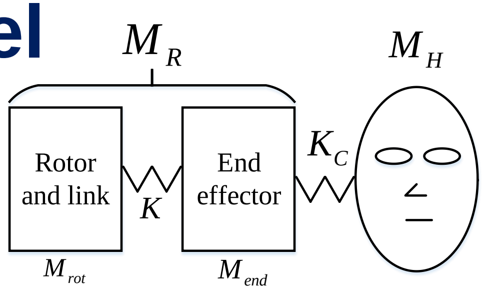


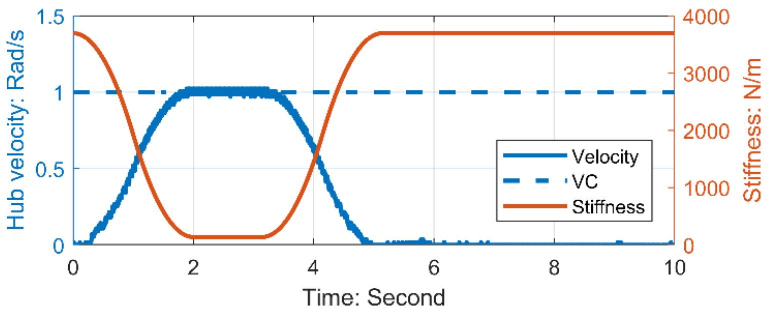
- **Better vibration suppression (by deflection feedback)**

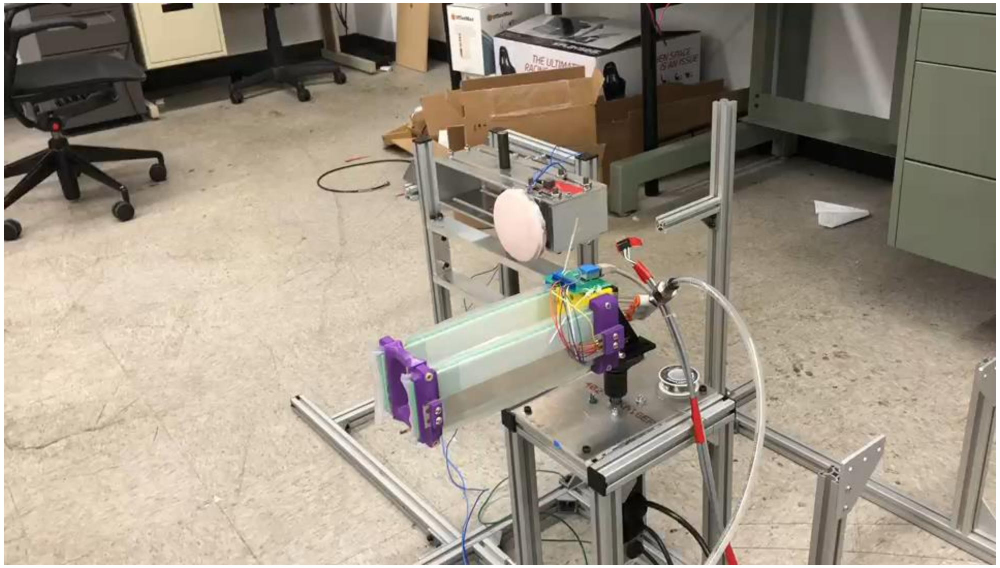


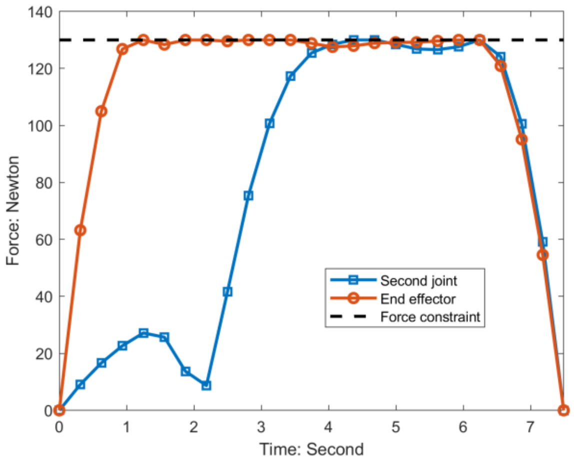
Impact Dynamics of Variable Stiffness Link

- **A mass-spring-mass impact model**
- **Single-link case (by optimal control):**
  - Low-speed: high stiffness
  - High-speed: low stiffness
- **Multi-link case (by optimization)**



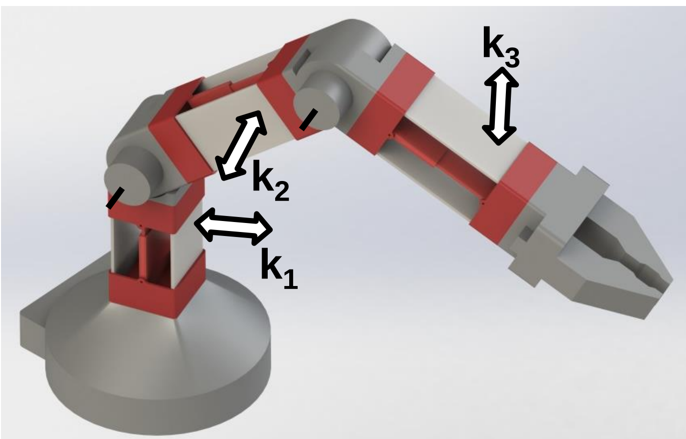


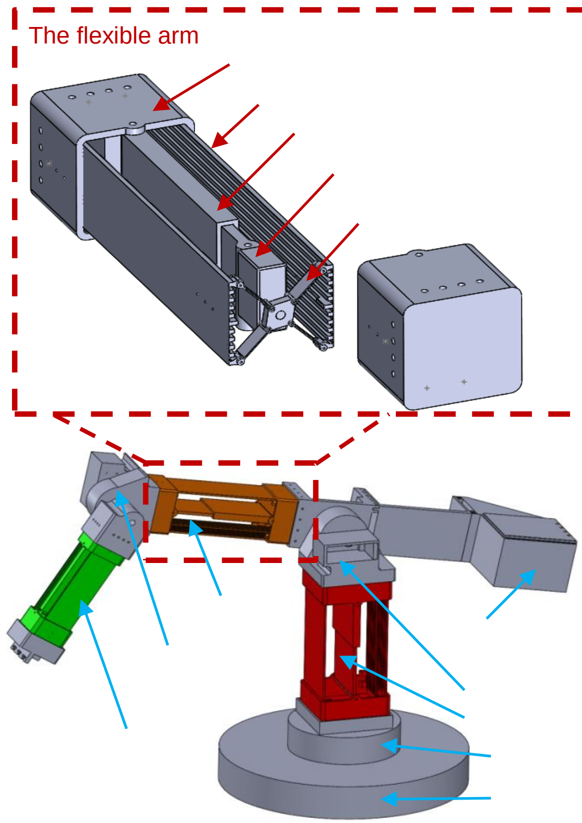




Future Work

- Methods for simultaneously controlling motion and stiffness for achieving maximum performance under safety constraints, and
- Design, stiffness and motion control of multi-linked robotic manipulators with variable stiffness arms





Publications

1. She, Y., Meng, D., Su, H.-J., Song, S, and Wang, J. “Introducing mass parameters to Pseudo–Rigid–Body models for precisely predicting dynamics of compliant mechanisms”. Mechanism and Machine Theory, 2018, 126: 273-294.
2. She, Y., Su, H.-J., Meng, D., Song, S, and Wang, J. “Design and Modeling of a Compliant Link for Inherently Safe Corobots”, ASME Journal of Mechanisms and Robotics. 2018; 10(1):011001 -011001-10.
3. She, Y., Song, S., Su, H.-J., and Wang, J. “Compliant joint or compliant link to address safety for physical human-robot interaction”, The International Journal of Robotics Research, under review.
4. She, Y., Su, H.-J., Meng, D., and Lai C. “Design and Modeling of a Continuously Tunable Stiffness Arm for Safe Human-Robot Interaction”, ASME Journal of Mechanisms and Robotics, under review.
5. T. Morrison, S. Member, C. Li, X. Pei, and H. Su, “A Novel Rotating Beam Link for Variable Stiffness Robotic Arms,” submitted to IEEE Robot. Autom. Lett., 2019.
6. Siyang Song, Yu She, Junmin Wang, and Haijun Su, “Control of Parallel-guiding Flexible Link Manipulators Using Pseudo-Rigid Body Model,” Submitted to Robotics and Autonomous Systems
7. She, Y., Meng, D., Cui, J. and Su, H.-J., “On the Impact Force of Human-Robot Interaction: Joint Compliance vs. Link Compliance.” In: *Proceedings of IEEE 2017 International Conference on Robotics and Automation* (ICRA 2017). May 28-June 3, 2017. Singapore. (2017).
8. She, Y., Meng, D. and Su, H.-J., “Pseudo-Rigid-Body Models for Dynamics of Compliant Robotic Links.” In: *Proceedings of ASME 2017 International Design Engineering Technical Conferences*. Cleveland, OH. (2017): DETC2017- 67949.
9. She, Y., Su, H.-J., Lai, C. and Meng, D, “Design and Prototype of a Tunable Stiffness Arm for Safe Human-Robot Interaction.” In: Proceedings of ASME 2016 International Design Engineering Technical Conferences. Charlotte, NC. (2016): DETC2016-59523.
10. Siyang Song, Yu She, Junmin Wang, and Haijun Su, “Barrier Lyapunov Function Based Control of a Flexible Link CoRobot with Safety Constraints,” Proceedings of the ASME 2018 Dynamic Systems and Control Conference, 2018. **Best paper award.**
11. R. Hu, V. Venkiteswaran and H.-J. Su, “A Variable Stiffness Robotic Arm Using Linearly Actuated Compliant Parallel Guided Mechanism”, Proceedings of 4th IFToMM Symposium on Mechanism Design for Robotics, September 11th - 13th, 2018, Udine, Italy.
12. Zeng, Xianpai., Su, H.-J., “Design, Modeling and Experiment of a Parallel-guided Robotic Arm with Variable Stiffness through Layer Jamming” in preparation
13. Siyang Song, Xianpai Zeng, Yu She, Junmin Wang and Haijun Su, “Modeling and Control for Inherent Safe Robots with Variable Stiffness Link (VSL)” in preparation
14. Yitong Zhou, “Discrete Layer Jamming for Safe Co-Robots” in preparation
15. Yitong Zhou, “Discrete Layer Jamming for Variable Stiffness Co-Robot Arms” in preparation