# Robotics ⇔ Haptics

**Sensor Fusion & SLAM to Haptic Device**


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**Passive Haptic Rendering to Robot Simulator**


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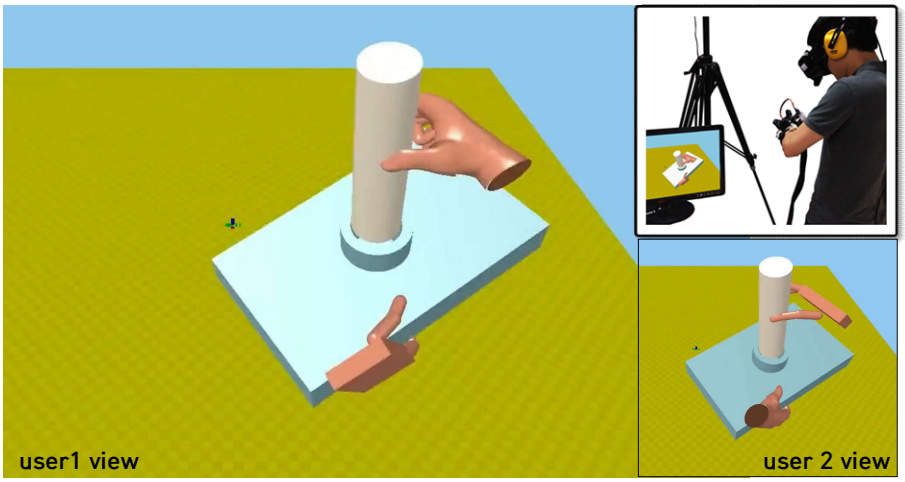
## Remote Dual-User Haptic Interaction

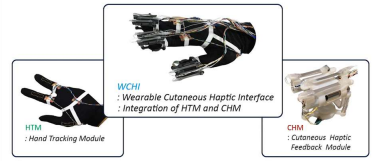


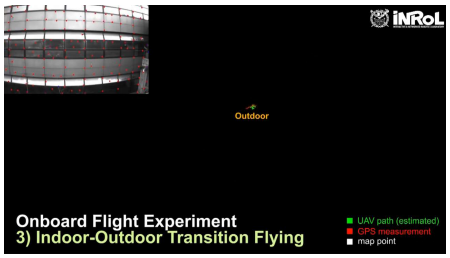

- Remote dual-user virtual collaborative manipulation with time-delay in VR

# Device

## Wearable Cutaneous Haptic Interface

- WCHI = Hand tracking module + Cutaneous haptic feedback module
- HTM: multi-DOF finger/hand tracking using *soft sensors* & *IMUs*
- CHM: 3-DOF cutaneous haptic feedback rendering using *soft sensors* & *a FSR*

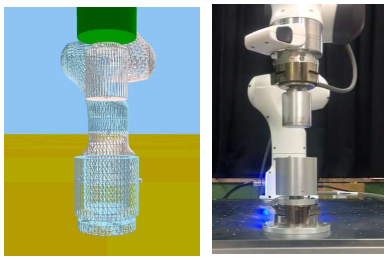



- Sensor fusion, SLAM, soft robotics

# Rendering

## Egg Delivery with WCHI

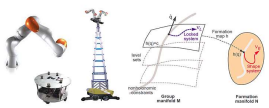



- Fast/stable/accurate robot simulator → ML

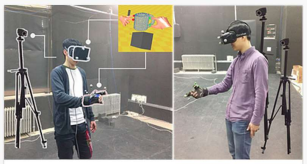


INTERACTIVE & NETWORKED ROBOTICS LABORATORY

Aerial Manipulation



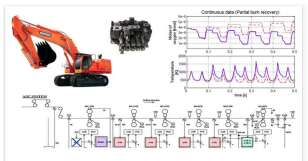
Mechanics/Control



Haptics/VR

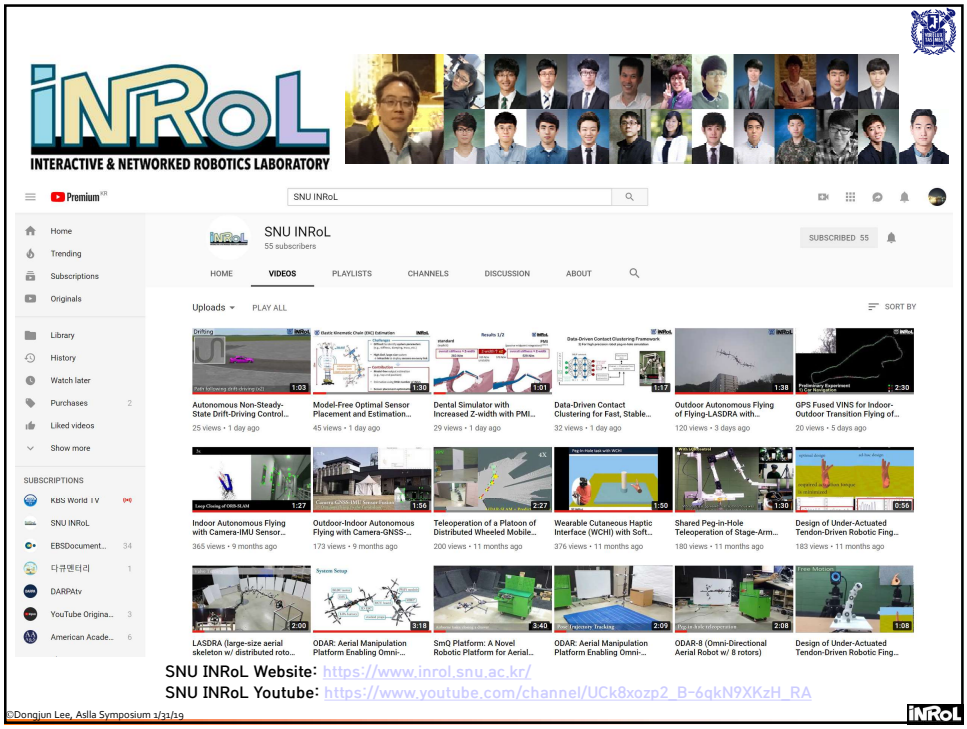
Autonomous Mobility

Telerobotics



Industrial Control

SNU INRoL Website: https://www.inrol.snu.ac.kr/
SNU INRoL Youtube: https://www.youtube.com/channel/UCk8xozp2_B-6qkN9XKzH_RA




SNU INRoL Website: https://www.inrol.snu.ac.kr/

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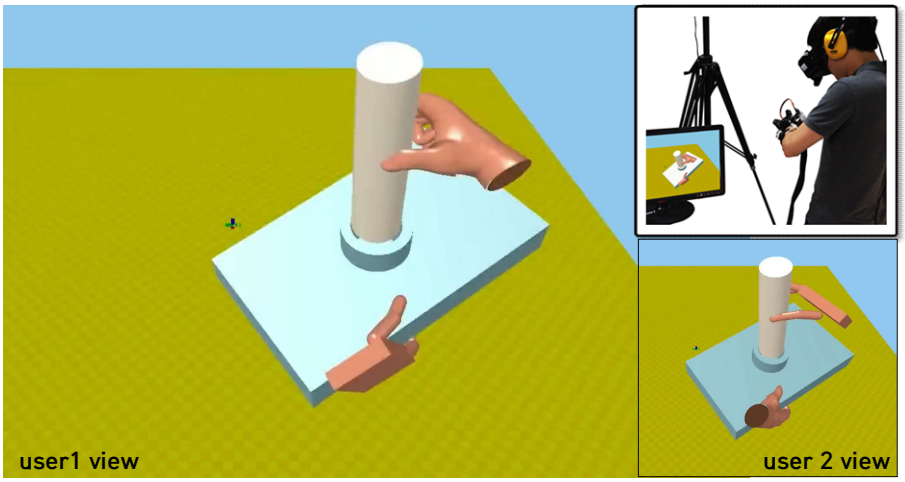
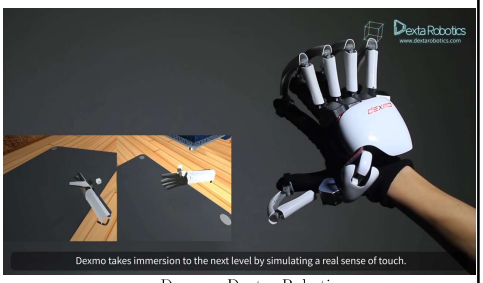


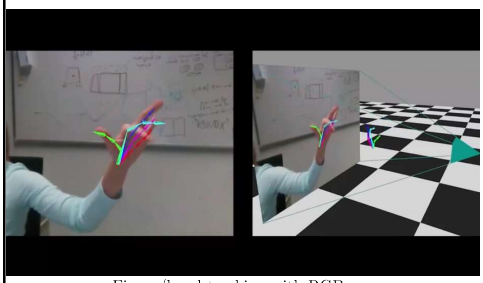

- Remote dual-user virtual collaborative manipulation with time-delay in VR

# State of the Art

• Oculus Touch with haptic feedback




• Dexmo - Dextra Robotics



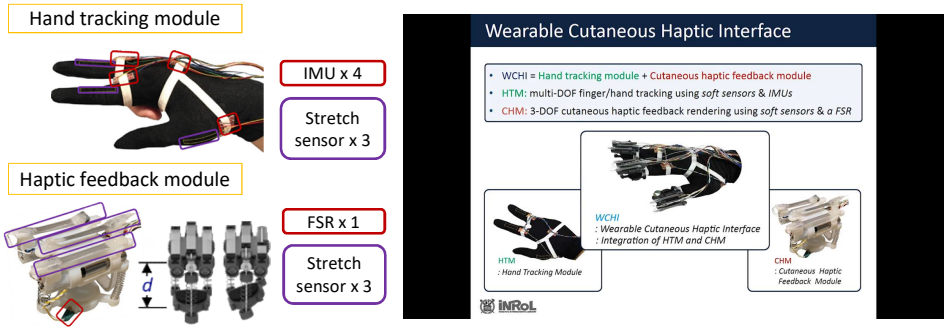
• Finger/hand tracking with RGB-camera

• Leap Motion finger tracking



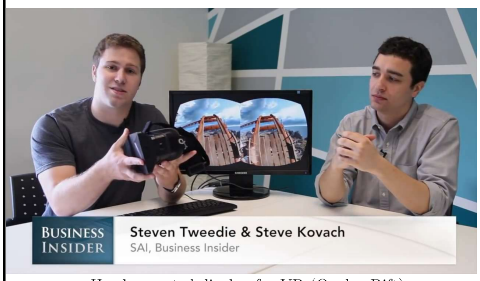
# Wearable Cutaneous Haptic Device (TMech19)

- **Issues on wearable haptic interface**
  - Finger tracking: camera (occlusion), IMU (drift, magnetic interference)
  - Haptic feedback: kinesthetic (bulky), cutaneous (finger tracking)
- **Wearable cutaneous haptic interface**
  - IMU/SS based finger tracking + 3-DOF fingertip cutaneous feedback
  - Drift/noise/interference → 9-DOF IMU sensor fusion + soft sensor (SS)
  - User fingertip variability → closed-loop control w/ FSR ($||F||$) + SS ($\vec{F}$)




Y. Lee, M. Kim, Y. Lee, J. Kwon, Y-L. Park and D. J. Lee, Wearable Cutaneous Haptic Interface for Multi-Fingered Virtual Manipulation, IEEE/ASME Transactions on Mechatronics, 2019 (Online)
Y. Lee, I. Jang and D. J. Lee, Enlarging Just Noticeable Differences of Visual-Proprioceptive Conflict in VR using Haptic Feedback, World Haptics Conference, 2015

# IMU Sensor Fusion




- Head mounted display for VR (Oculus Rift)

- Whole-body tracking with IMUs (Xsense)

- Omni-directional aerial robot (SNU-IRoL, TMECH18)

- Flying large-size aerial skeleton (SNU-INRoL, ICRA19)

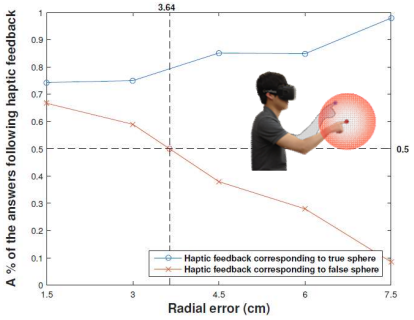


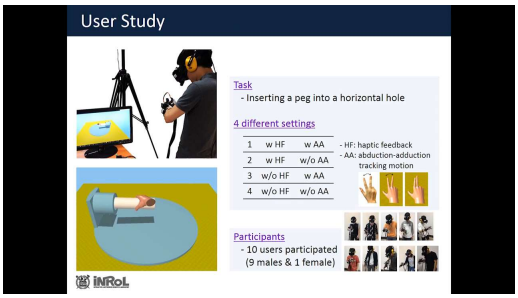
# Flying-LASDRA (ICRA19)

- Autonomous flying with serpentine-like undulatory motion of three-link LASDRA system (3m, 12-DOFs)

# From Perception to Device (WHC15)

- **Wearable cutaneous haptic interface**
  - IMU/SS based finger tracking + 3-DOF fingertip cutaneous feedback
  - Drift/noise/interference → 9-DOF IMU sensor fusion + soft sensor (SS)
  - User fingertip variability → closed-loop control w/ FSR ($||F||$) + SS ($\vec{F}$)
- **WCHI device specification from haptics**
  - Permissible VR finger-tip tracking error increases (1.5cm → 3cm) w/ haptics
  - Abduction-adduction (AA) finger motion important for dexterous VR

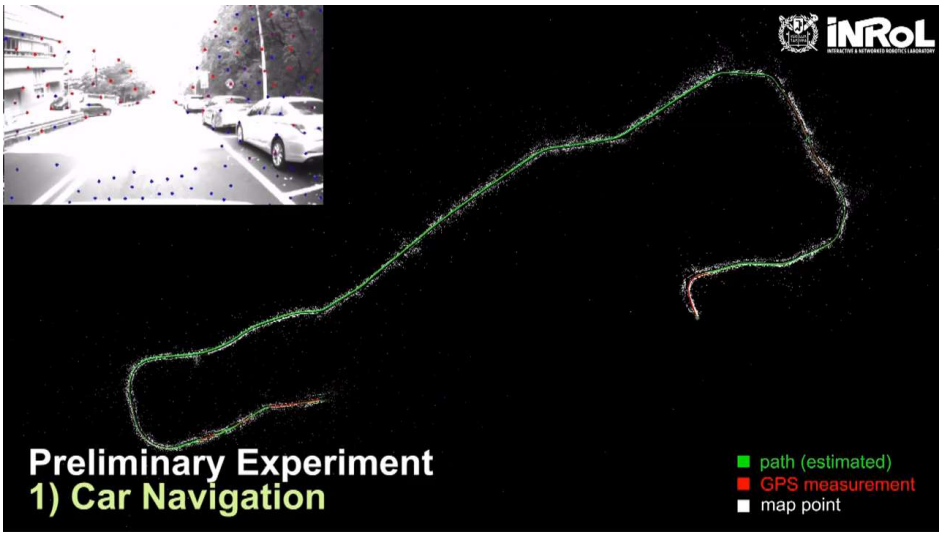



Y. Lee, M. Kim, Y. Lee, J. Kwon, Y-L. Park and D. J. Lee, Wearable Cutaneous Haptic Interface for Multi-Fingered Virtual Manipulation, IEEE/ASME Transactions on Mechatronics, 2018 (To Appear)
Y. Lee, I. Jang and D. J. Lee, Enlarging Just Noticeable Differences of Visual-Proprioceptive Conflict in VR using Haptic Feedback, World Haptics Conference, 2015

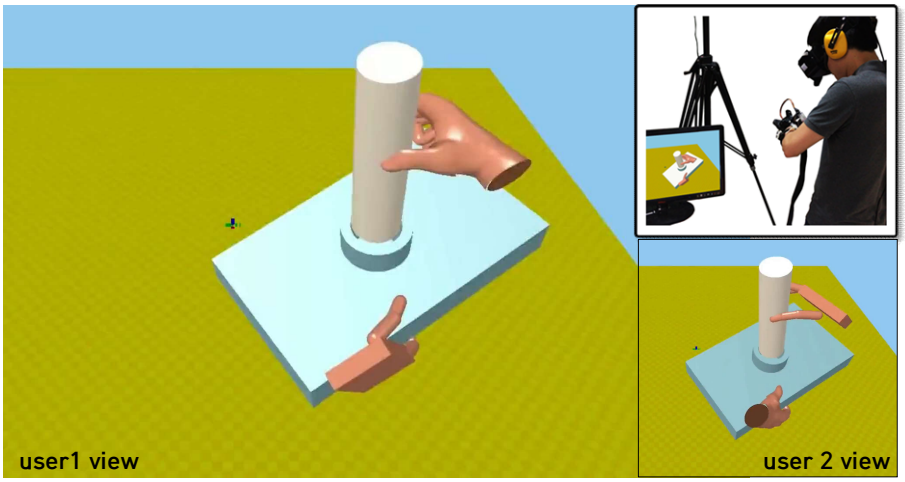


# VIN+GPS SLAM




- Factor-graph-based GPS-VIN (visual-inertial navigation) SLAM for indoor-outdoor operation (KROC19)

# Remote Dual-User Haptic Interaction

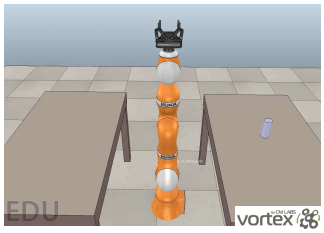



- Remote dual-user virtual collaborative manipulation with time-delay in VR



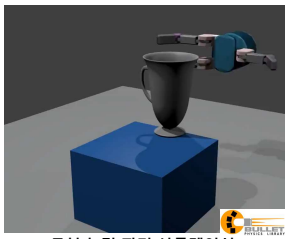
# Open-Source Robot Simulators

● 경량/고강성 물체 시뮬레이션



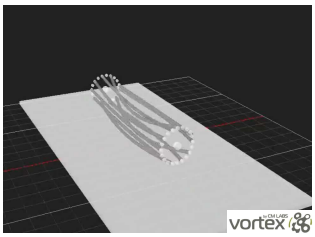

• 조인트 PD-토크제어 시뮬레이션

● 다중접촉 시뮬레이션

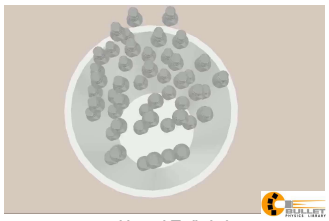


• 로봇손 컵 파지 시뮬레이션

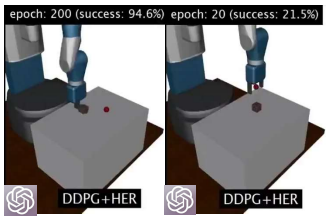
● 유연체 시뮬레이션



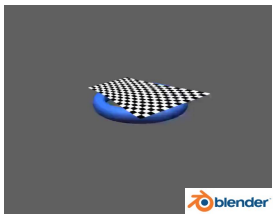

• PRB 유연케이블 시뮬레이션



• M3 볼트 시뮬레이션




• 블록 조작/파지 시뮬레이션




• 게임엔진 유연체 시뮬레이션

# PMI (Passive Midpoint Integration, IJRR17)

- Dynamics integration (PMI in maximal or generalized coordinates)

$$\hat{M}_k\hat{V}_k = M_kV_k - d\bar{\psi}_k^T + \bar{N}_k\lambda_k^n + \bar{D}_k\lambda_k^t \qquad \hat{\star}_k := \frac{\star_{k+1}+\star_k}{2}$$

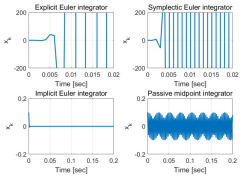
midpoint velocity ↗ potential term ↗ normal contact ↖ tangential friction ↖

- Multi-point constraint (PMI-LCP)

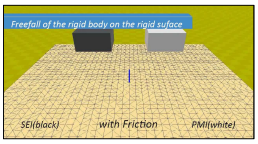
$$0 \le \sigma_k^n \perp \lambda_k^n \ge 0 \quad \sigma_k^n := \bar{N}_k^T\hat{V}_k \in \Re^{l_c} \quad \rightarrow \text{normal direction velocity}$$
$$0 \le \sigma_k^t \perp \lambda_k^t \ge 0 \quad \sigma_k^t := \bar{D}_k^T\hat{V}_k + U\lambda_k^f \in \Re^{l_c\times\bar{p}} \quad \rightarrow \text{tangential direction velocities}$$
$$0 \le \sigma_k^f \perp \lambda_k^f \ge 0 \quad \sigma_k^f := \bar{\mu}\lambda_k^n - U^T\lambda_k^t \in \Re^{l_c} \quad \rightarrow \text{Coulomb friction}$$

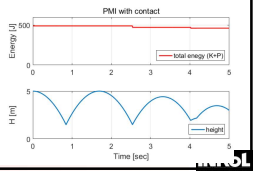
- Physical principle (passivity) preservation in discrete-time

$$\frac{d\mathrm{KE}}{dt} + \frac{d\mathrm{PE}}{dt} = (u+f)^Tv - v^TBv$$
$$\rightarrow \quad (\mathrm{KE+PE})_{k+1} - (\mathrm{KE+PE})_k = [(u_k+f_k)^T\hat{v}_k - \hat{v}_k^TB\hat{v}_k]T_k$$




- Stable simulation of very light/stiff objects
- Contact passivity → enhanced multi-contact stability
- Stable simulation regardless $T_k$
- Damping is really damping
- Modular simulation possible



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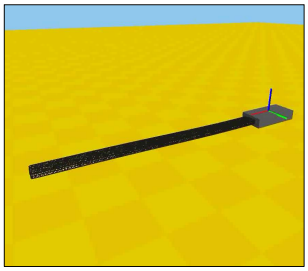
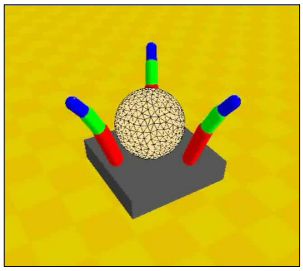
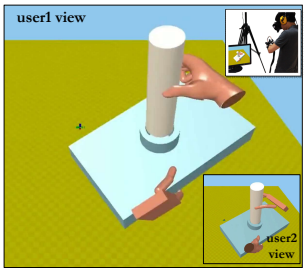


• 알루미늄 빔 진동 시뮬레이션 (11/75/210Hz)



• 텐던 구동부족 로봇손 파지 시뮬레이션




• 다중사용자 원격 가상조립

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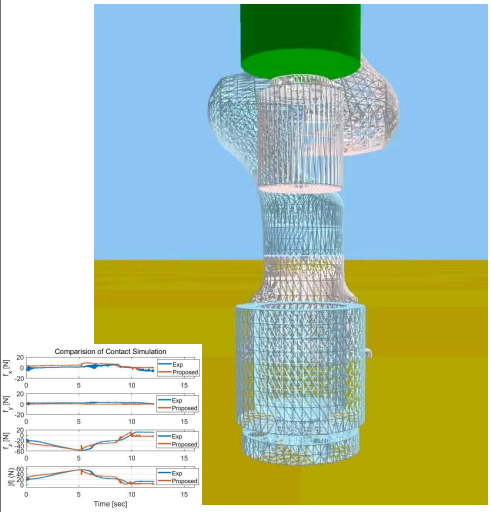
# PMI: Peg-in-Hole Simulation (ICRA19)



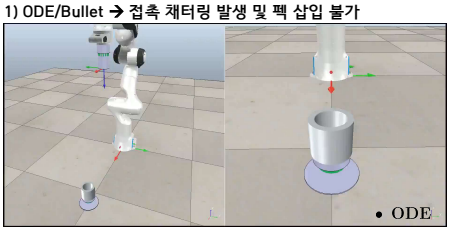

- Fast, stable and accurate peg-in-hole PMI simulation with data-driven multi-point contact solver

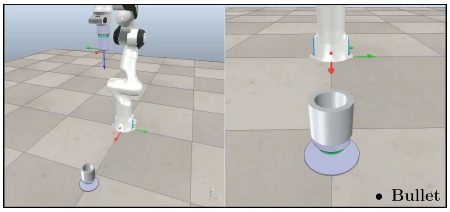
$$\mathrm{RMS}\left(\frac{\|F_{\mathrm{sim}}\|-\|F_{\mathrm{exp}}\|}{\mathrm{mean}(\|F_{\mathrm{exp}}\|)}\right) = 28.88\,\%$$



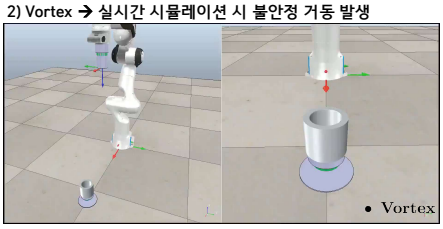
# Open-Source Robot Simulators

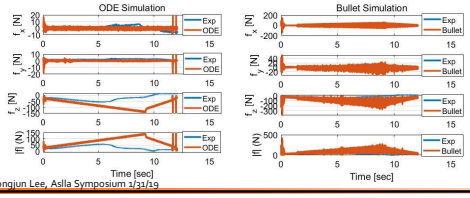
1) ODE/Bullet → 접촉 채터링 발생 및 펙 삽입 불가



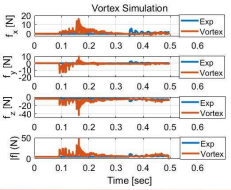

2) Vortex → 실시간 시뮬레이션 시 불안정 거동 발생









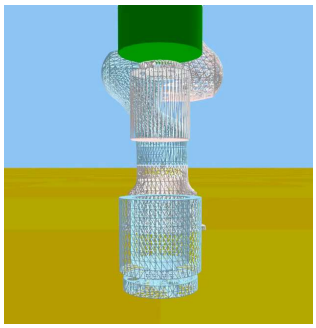

| Performance | |
|---|---|
| Simulator | RMS(%) |
| ODE | 207.06 |
| Bullet | 231.28 |
| Vortex | 101.64 |

# Data-Driven Contact Clustering

- **High-precision peg-in-hole operation & data acquisition**
  - Necessary in robot automation industry field, but not in existing robot simulator
  - Diameter 50mm, **hole tolerance 0.065mm** (below sensor resolution)
  - End-effector impedance control using robot manipulator
  - Perform peg-in-hole task with various peg entry direction/angle
  - Records peg position/rotation/velocities, F/T sensor readings on wrist and base


• Peg-in-hole experiment using PANDA manipulator

• Various entry direction(top) and angle(bottom)

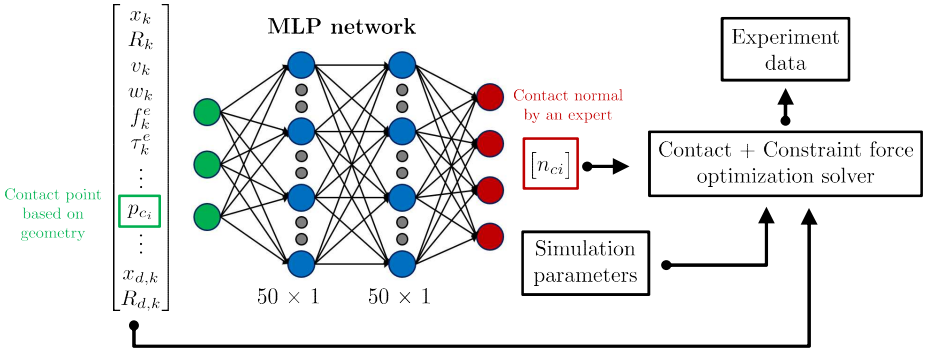


• Peg-in-hole simulation using our developed PMI-based simulator



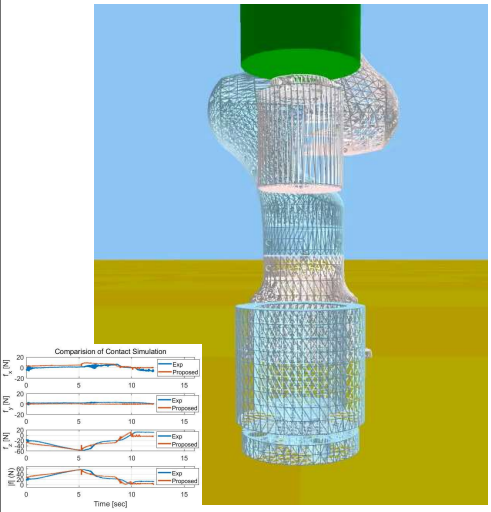
# Data-Driven Contact Clustering

- **Data-driven/learning-based contact clustering**
  - Determine contact point based on **geometry** (max 6 points)
  - **Tune simulation parameters** so that the behavior of the robot is similar to that of the actual experiment
  - **Determines the contact normal by an expert** to match the contact wrench with experiment (like learning from demonstartion)




• Architecture of our data-driven contact clustering

# PMI: Peg-in-Hole Simulation (ICRA19)

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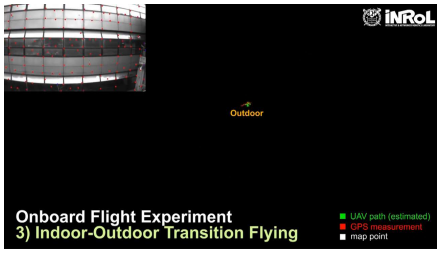
## Device

**Wearable Cutaneous Haptic Interface**

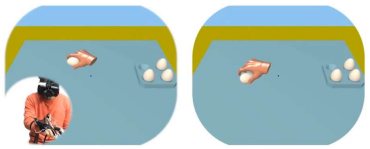
- WCHI = Hand tracking module + Cutaneous haptic feedback module
- HTM: multi-DOF finger/hand tracking using *soft sensors* & *IMUs*
- CHM: 3-DOF cutaneous haptic feedback rendering using *soft sensors* & *a FSR*

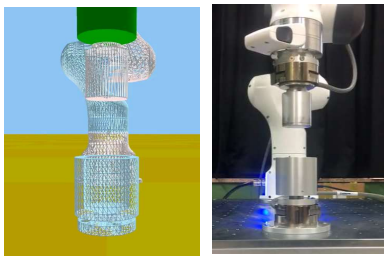




- Sensor fusion, SLAM, soft robotics

## Rendering

**Egg Delivery with WCHI**



- Robot simulator, machine learning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