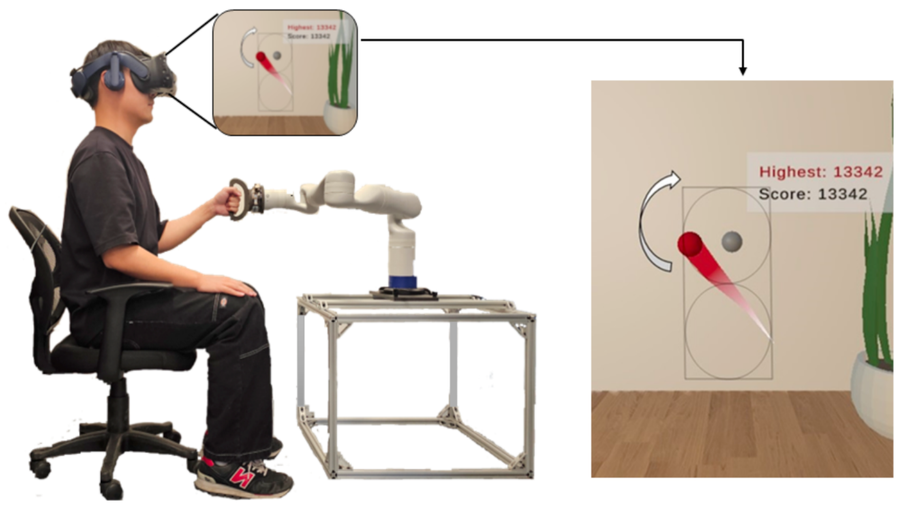
Normalizing Task-Oriented Human-Robot Interaction for Large-Scale Virtual Environments

Burak Balta*, Khandaker Nusaiba Hafiz*, Jonathan Realmuto
{bbalt008, khafi001, jonathan.realmuto} @ucr.edu

Introduction

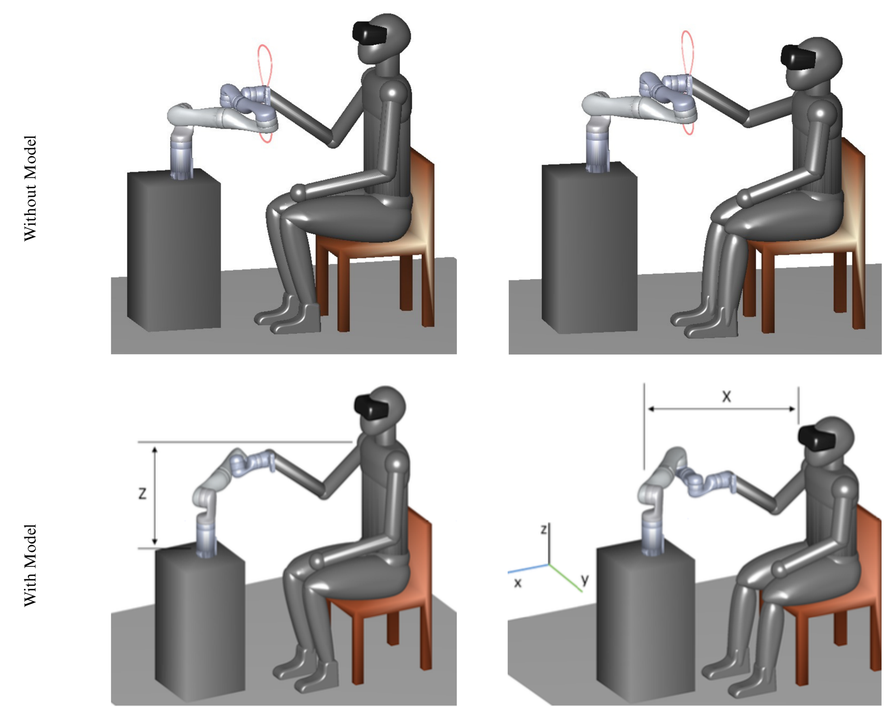
- **Physical simulation platforms** have become essential in **experimental studies** by providing safe and repeatable conditions to improve control algorithms for **powered exoskeletons and prosthetics**.



Human-Robot Interaction Setup in a VR Environment

Challenge & Research Goal

- Variations in physical attributes can lead to inconsistent task difficulty—for example, shorter participants may be disadvantaged, as shown below. This paper addresses this problem by adapting key interaction parameters to each individual, ensuring consistent and fair performance.



Long Participant (at the home position) Short Participant(at the home position)

Experimental Setup

- We performed MATLAB-based simulations of human–robot interaction. In this environment, a human arm—modeled as a two-link, four-joint system—interacts with a 7-DOF Kinova Gen 3 Robot controlled via task-space impedance controller.We defined the dynamic equations to capture the coupled behavior of the human arm and the robot, implemented as shown below;

$$(1)\quad \begin{bmatrix} M_h(q_h) & 0 \\ 0 & M_r(q_r) \end{bmatrix} \begin{bmatrix} \ddot{q}_h \\ \ddot{q}_r \end{bmatrix} + \begin{bmatrix} C_h(q_h,\dot{q}_h) & 0 \\ 0 & C_r(q_r,\dot{q}_r) \end{bmatrix} \begin{bmatrix} \dot{q}_h \\ \dot{q}_r \end{bmatrix} + \begin{bmatrix} g_h(q_h) \\ g_r(q_r) \end{bmatrix} = \begin{bmatrix} \tau_h \\ \tau_r \end{bmatrix} + \begin{bmatrix} J_h(q_h)^T F_{r,h} \\ J_r(q_r)^T F_{h,r} \end{bmatrix}$$

- M, C, g : mass, Coriolis, and gravitational vectors, respectively.
- τ_h, τ_r : human and robot torques.
- J_h, J_r : human and robot Jacobian matrices.
- $F_{r,h}$, $F_{h,r}$: interaction wrenches.

$$(2)\quad F_{h,r} = K_c\Big(S_{r,h} - S_{r,h,0}\Big) - K_d\Big(J_r(q_r)\dot{q}_r - J_h(q_h)\dot{q}_h\Big),$$

$$(3)\quad F_{r,h} = K_c\Big(S_{h,r} - S_{h,r,0}\Big) - K_d\Big(J_h(q_h)\dot{q}_h - J_r(q_r)\dot{q}_r\Big),$$

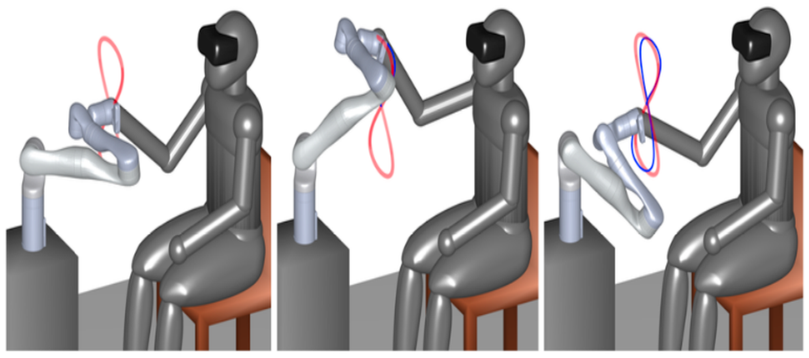
$$(4)\quad [S_{i,j}] = \log\left(T_i^{-1}T_j\right),$$

$$(5)\quad S = [\omega_x \quad \omega_y \quad \omega_z \quad v_x \quad v_y \quad v_z]^\top,$$

$$(6)\quad \tau_h = J_h(q_h)^\top\Big(K_{p,h}S_{h,d} - K_{d,h}J_h(q_h)\dot{q}_h\Big) + g_h(q_h),$$

$$(7)\quad \tau_r = J_r(q_r)^\top\Big(K_{p,r}S_{r,d0} - K_{d,r}J_r(q_r)\dot{q}_r\Big) - b\dot{q}_r + g_r(q_r).$$

- T_i, T_j : transformation matrices of the end-effectors.
- S : screw representing the error from the desired transformation.
- ω_x, ω_y, ω_z : angular velocity components.
- v_x, v_y, v_z : linear velocity components.



A sequence of the human-robot interaction task at three different time instances.

Normalizing the Configuration

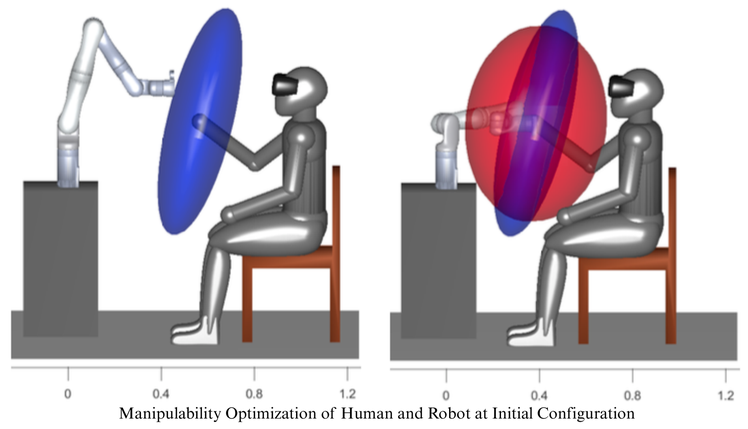
- To ensure consistent task difficulty, all participants start from the same human arm configuration by maximizing manipulability. Robot's initial pose is optimized by minimizing the ratio of the longest to shortest axis of its translational manipulability ellipsoid to ensure isotropic dexterity.

$$(8)\quad \mu_h = \sqrt{\det(J_{v,h}J_{v,h}^\top)}$$

- μ_h : Yoshikawa's manipulability index of the human arm.

$$(9)\quad \mu_r = \sqrt{\frac{\lambda_1}{\lambda_3}}$$

- μ_r : Manipulability ratio of the robot's end-effector.



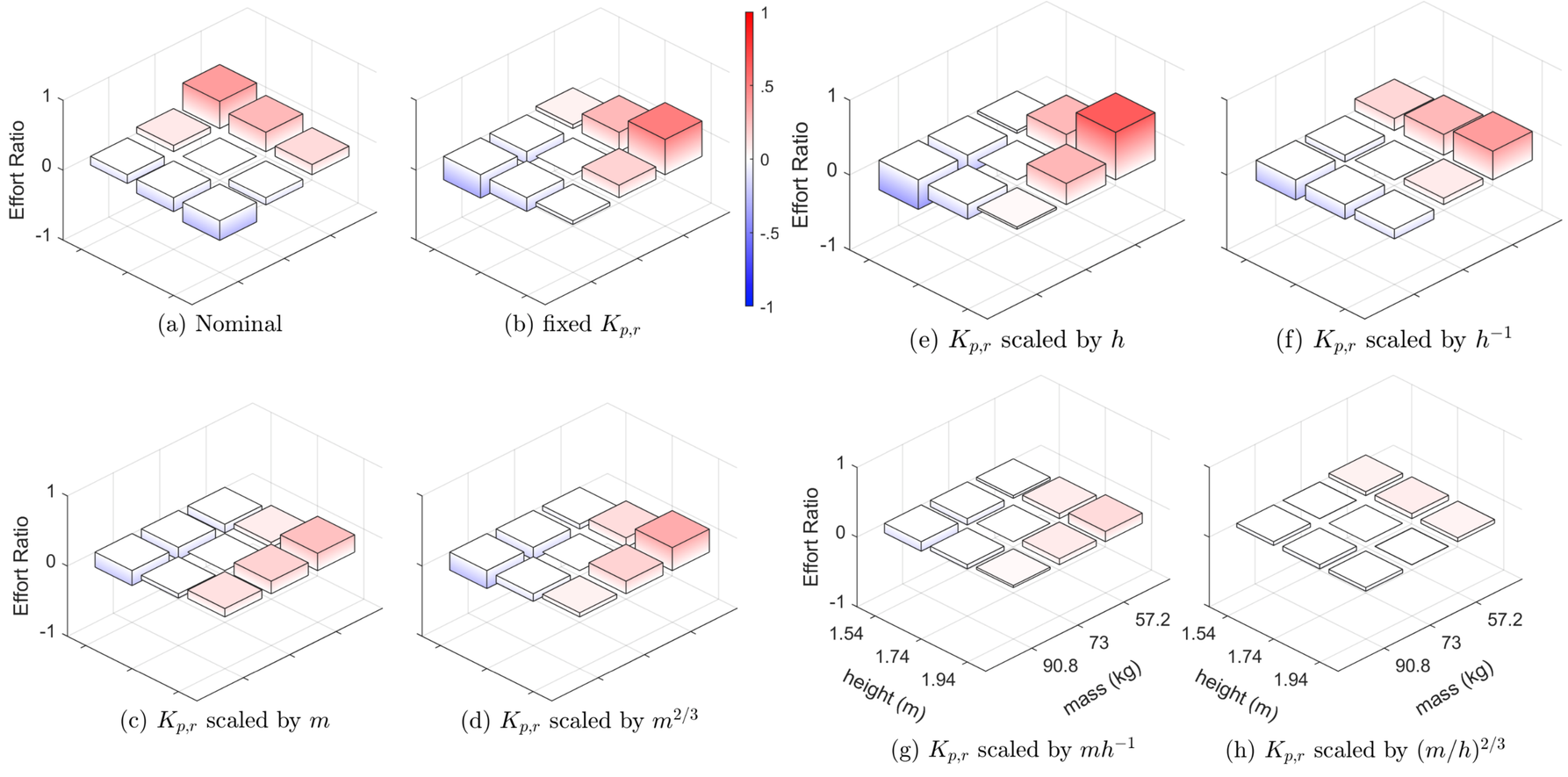
Manipulability Optimization of Human and Robot at Initial Configuration

- To ensure fairness, the task trajectory is scaled to each participant's height, keeping the movement within their reachable workspace while maintaining consistent task difficulty.

$$(9)\quad p_d(t) = \begin{bmatrix} x_c \\ A_y \sin(2t) \\ z_c + A_z \sin(t) \end{bmatrix}$$

- $p_d(t)$: desired task-space trajectory of the hand,
- $A_y = 0.06 \cdot h, \quad A_z = 0.12 \cdot h$: trajectory amplitudes scaled to participant height h.

Results and Discussion



(a) Nominal (b) fixed $K_{p,r}$ (e) $K_{p,r}$ scaled by h (f) $K_{p,r}$ scaled by h^{-1}

(c) $K_{p,r}$ scaled by m (d) $K_{p,r}$ scaled by $m^{2/3}$ (g) $K_{p,r}$ scaled by mh^{-1} (h) $K_{p,r}$ scaled by $(m/h)^{2/3}$

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