System Identification For Constrained Robots (Appendix)

Bohao Zhang*, Daniel Haugk*, and Ram Vasudevan

APPENDIX A
VALIDATION EXPERIMENT RESULTS (ESTIMATED TORQUE)

To validate the identified parameters, we compared the estimated torque and the measured torque. A different dataset from the one used for parameter identification was used for this comparison. The validation results for the left leg, the right leg, the left arm, and the right arm are depicted in Figure 1.

APPENDIX B
VALIDATION EXPERIMENT RESULTS (FORWARD INTEGRATION)

We also assessed the simulation quality by measuring the discrepancy between the simulation and ground truth data, where the identified parameters are plugged into the system dynamics. We performed simulations using MATLAB ode15s with the identified parameters plugged into the system dynamics. We provided the control inputs by applying zero-order hold (ZOH) to the torques recorded from the same validation experiment and compared the difference between the simulated trajectories and the recorded trajectories. Because we only apply discrete open-loop control, it is inevitable that the simulation eventually diverges from the ground truth. As a result, we only performed comparison on relatively short horizons. We treated the beginning of each segment of the dataset as the initial condition and simulated forward in ode15s until the end of the segment. To evaluate the difference between the simulation and the ground truth, we use the L_2-norm for each joint $j \in \{1, \ldots, n_q\}$. The plots of trajectories for the left leg, the right leg, the left arm, and the right arm can be found in Figure 2.

APPENDIX C
VALIDATION EXPERIMENT RESULTS (TRACKING ERROR)

To further evaluate the utility of the identified parameters, we perform a trajectory tracking task in the real-world. We considered an inverse dynamics controller. We incorporate the identified parameters into an inverse dynamics controller to show that these parameters can enhance tracking performance in controller design. The desired trajectories for all actuated joints were chosen to be sine waves with a maximum velocity of 1.8, 3, and 5 rad/s. These were distinct trajectories from those used for identification and cross-validation.

The tracking error for all actuated joints for the desired trajectories can be found in Table I, II, and III.

Actuated Joints	Left	Right
hip-roll	(1.015, 2.218)	(1.598, 3.478)
hip-yaw	(0.692, 1.582)	(0.735, 1.765)
hip-pitch	(0.802, 2.027)	(1.087, 3.151)
knee	(1.408, 3.614)	(1.310, 3.711)
toe-A	(1.602, 3.505)	(0.471, 2.583)
toe-B	(1.962, 3.825)	(0.774, 2.703)
shoulder-roll	(0.627, 2.452)	(0.805, 2.715)
shoulder-pitch	(0.330, 0.916)	(0.617, 1.665)
shoulder-yaw	(0.121, 0.755)	(0.178, 0.666)
elbow	(0.170, 0.952)	(0.151, 0.696)

TABLE I: Tracking error of the inverse dynamics controller incorporated with **identified parameters** over all actuated joints for desired trajectories with a maximum speed of 1.8 rad/s. We report the (mean, maximum) values of the tracking error in **degrees**.

Actuated Joints	Left	Right
hip-roll	(1.542, 2.499)	(1.179, 3.495)
hip-yaw	(1.177, 3.723)	(0.827, 2.361)
hip-pitch	(1.204, 2.477)	(1.033, 2.984)
knee	(1.205, 3.199)	(1.007, 3.349)
toe-A	(1.506, 3.283)	(0.486, 2.654)
toe-B	(1.923, 3.415)	(0.782, 2.750)
shoulder-roll	(0.274, 1.282)	(0.264, 0.910)
shoulder-pitch	(0.328, 0.717)	(0.260, 0.932)
shoulder-yaw	(0.113, 0.597)	(0.097, 0.647)
elbow	(0.104, 0.800)	(0.153, 0.671)

TABLE II: Tracking error of the inverse dynamics controller incorporated with **identified parameters** over all actuated joints for desired trajectories with a maximum speed of 3 rad/s. We report the (mean, maximum) values of the tracking error in **degrees**.

Actuated Joints	Left	Right
hip-roll	(1.985, 3.848)	(0.917, 3.126)
hip-yaw	(1.398, 3.399)	(1.323, 3.807)
hip-pitch	(1.343, 3.810)	(1.005, 2.045)
knee	(1.283, 3.546)	(1.135, 3.042)
toe-A	(1.217, 3.297)	(0.419, 2.869)
toe-B	(1.781, 3.492)	(0.679, 2.519)
shoulder-roll	(0.172, 0.755)	(0.099, 0.481)
shoulder-pitch	(0.317, 0.808)	(0.131, 0.612)
shoulder-yaw	(0.146, 0.547)	(0.106, 0.909)
elbow	(0.131, 0.746)	(0.144, 0.473)

TABLE III: Tracking error of the inverse dynamics controller incorporated with **identified parameters** over all actuated joints for desired trajectories with a maximum speed of 5 rad/s. We report the (mean, maximum) values of the tracking error in **degrees**.

* Authors share equal contribution

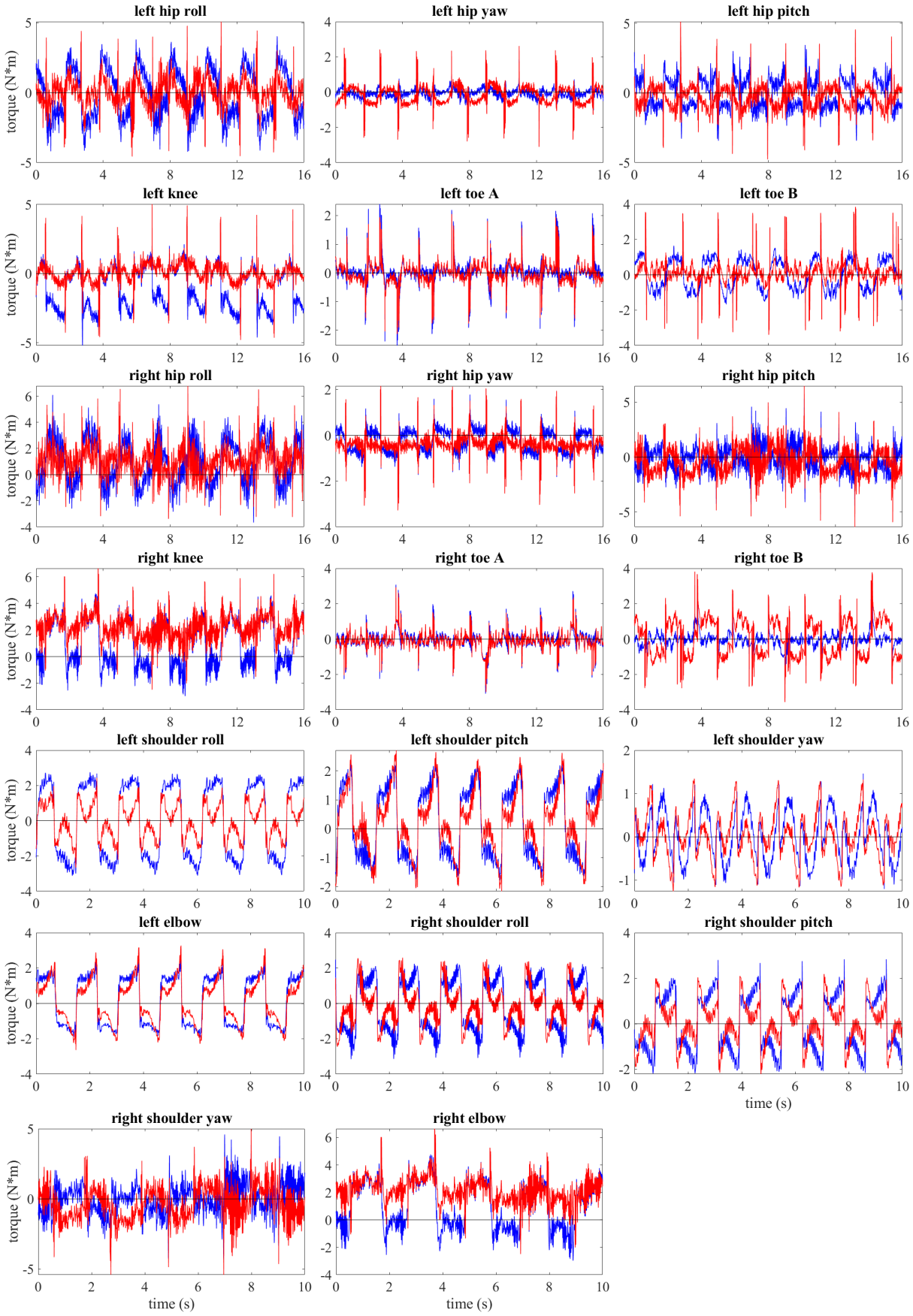

Fig. 1: Validation experiment by comparing measured torque and estimated torque on the right leg, the left arm, and the right arm, respectively. The **torque residual based on identified parameters** is plotted in **red**. The **torque residual based on manufacturer provided parameters** is plotted in **blue**. The data shown is distinct from that used in identification.

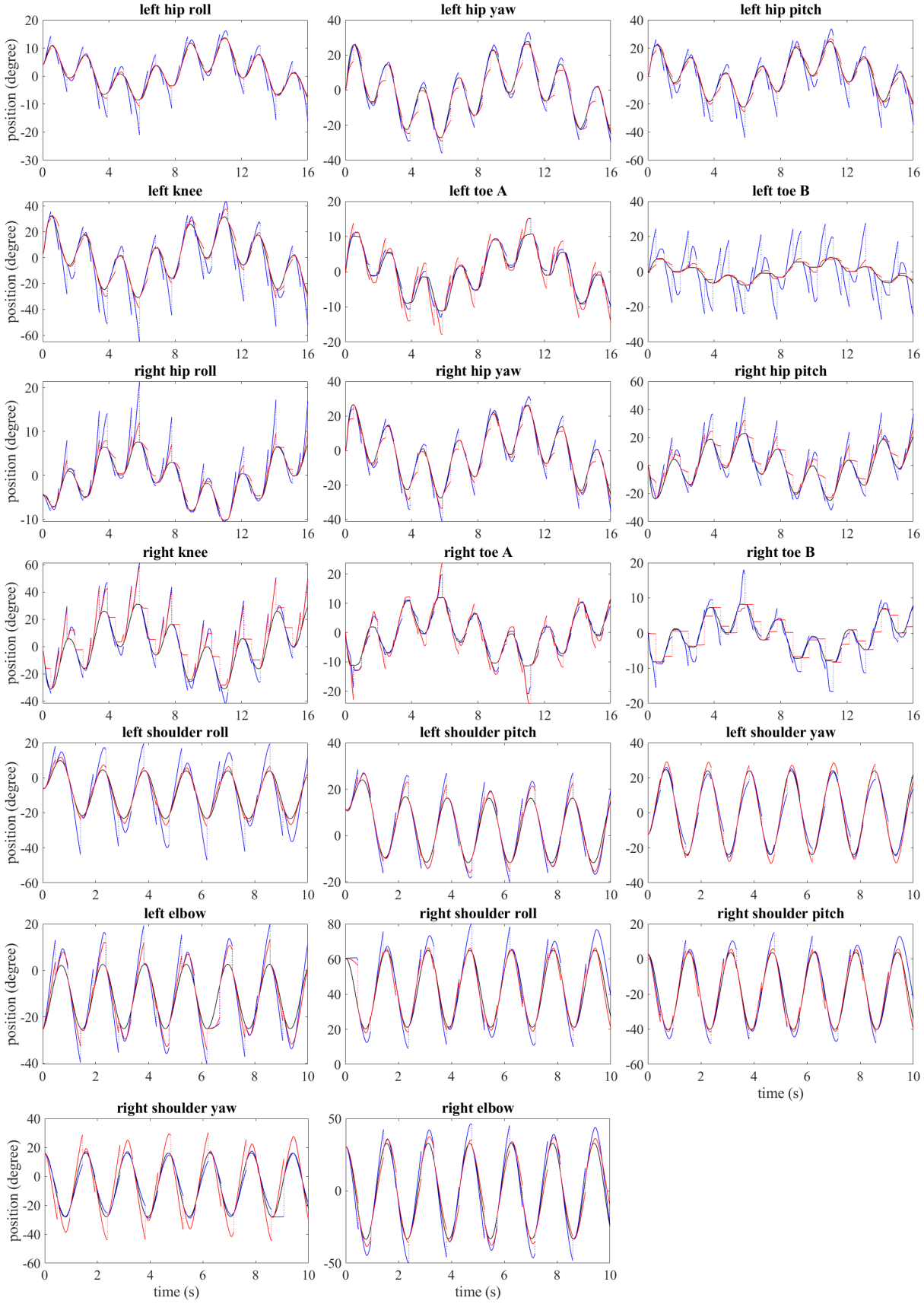

Fig. 2: Validation experiment by comparing the estimated trajectory from ode15s forward integration and the ground truth data set on the right leg, the left arm, and the right arm, respectively. The **measured trajectory** is plotted in **black**. The **estimated trajectory using identified parameters** is plotted in **red**. The **estimated trajectory using manufacturer provided parameters** is plotted in **blue**. Note that we performed the validation by separating the data set into 31 segments, where the initial condition of the ode15s simulation starts from the beginning of each segment. The estimated trajectory between two adjacent segments is connected with vertical dotted lines.