Teleoperation for Human-humanoid Collaboration

Humanoids 2019 WS on Humanoid Teleoperation
Inria Research Centres in France

- 8 Research Centres
- Local sites

- 54 ERC projects
- 2500 papers
- 1350 PhD researchers
- 180 project teams
- 18 associate teams with foreign universities and research bodies
- 236 million euros budget, 26% of which is self-funded
- 160 start-ups founded

Inria Nancy / Loria
Team Larsen

- smart apartment
- arena
- Pepper
- Tiago
- Franka
- iCubNancy01
- Talos
Human-human collaboration

Can we reach a similar level of seamless collaboration with robots?
Problems in human-robot collaboration

Perceive the human, the environment

Recognize context & action

Predict what is the intention of the human during interaction

Perceive and control the contact forces (pHRI level 0)

Take into account the human in the controller (pHRI level ++)

Lyubova et al, AURO 2016
Malaisé et al, ACHI 2018
Dermy et al, Front Rob&AI 2017
Ivaldi et al, IJSR 2016
Romano et al, RAL 2018 + Otani et al, ICRA 2018
Transfer paradigm: from humans to humanoids

Can we synthesize whole-body collaborative primitives exploiting human demonstrations?
Transfer paradigm: from humans to humanoids

Yes! We can use demonstrations from the human operator.

Tele-operation/retargeting is the whole-body kinesthetic teaching!
• Take into account the entire human dynamics in a multi-task QP controller for collaborative manipulations
• Joint level controller for the robot, but capable of reacting to the human

Human-aware pHRI

Demonstrating collaborative behaviors

EXPERIMENT 1: PICK AND PLACE

Transfer paradigm: from humans to robots
Different forms of teleoperation

Operator:
Motion retargeting
Penco et al. (2018) HUMANOIDS

Ground control:
Teleoperation with shared control
Ivaldi et al. (2016) IJSR
Some problems in “human to humanoids”

1) Human-aware control with demonstrations of complex whole-body behaviors for collaboration, which considers the unfeasible
   ➞ Teleoperation with robust retargeting that filters commands

2) The teleoperator may do something off the script!
   ➞ We need to optimize the controller’s parameters to be robust and “generic” so we can execute any teleoperate movement

3) The teleoperated movement may not be optimal for the robot
   ➞ We need to re-optimize the motion for the robot dynamics
1) teleoperation with a robust retargeting strategy

How do we retarget human motions in real-time to enable robust teleoperation?
1) teleoperation with a robust retargeting strategy

Retargeting in a robust way for tele-operation

Penco et al. (2018) HUMANOIDS
1) teleoperation with a robust retargeting strategy

\[
\begin{align*}
\text{min} & \quad ||Ax - b||^2_W \\
\text{s.t.} & \quad l \leq Cx \leq u
\end{align*}
\]

\[
stack = (l\text{Foot} + r\text{Foot} + \text{head}_\text{sub})/ (\text{com}_\text{sub} + \text{base}_\text{sub} + \text{torso}_\text{sub} + l\text{Arm}_\text{sub} + r\text{Arm}_\text{sub});
\]

**Multi-task QP controller with strict priorities (OpenSoT)**

**ZMP correction**
Retargeting footsteps: not a good idea

Footstep retargeting

$$x_{footR} = o_{footstep}(x_{footmax_R} - x_{footmin_R}) + x_{footmin_R}$$

$$o_{footstep} = \frac{(x_{footH} - x_{footmin_H})}{(x_{footmax_H} - x_{footmin_H})}$$

Whole-body QP controller (switching tasks depending on the FSM)

$$u^* = \arg\min_u \frac{1}{2} \sum_{X_{null}} w_{X_{null}} E_{X_{null}}$$

s. t. $\underline{s} < Au < \bar{s}$

$\underline{s} < u < \bar{s}$

$$u = \arg\min_u \frac{1}{2} \sum_X w_X E_X$$

- Stance foot pose $\text{stance}T_B \in SE(3)$
- Swing foot pose $\text{swing}T_B \in SE(3)$
- CoM ground projection position $p_{CoM} \in \mathbb{R}^2$
- Waist height $z_{\text{waist}} \in \mathbb{R}$ and orientation $\text{waist}R_B \in SO(3)$
- Neck orientation $\text{neck}R_B \in SO(3)$
- Upper-body joint positions $s_{up} \in \mathbb{R}^{n_{up}}$

Experiment 3 - Teleoperation of the iCub
Upper-body movements are retargeted even during the walking

=> the result is not good, delay in correspondance
Teleoperating with walking
Teleoperating with walking

1st QP problem
generate candidate footstep orientation

2nd QP problem
generate CoM trajectory and footstep positions with a MPC formulation, under constraints:
- balance (ZMP inside support polygon)
- stability (CoM not diverging w.r.t. ZMP)
- footstep kinematically feasible

=> better result! The robot walks in its own way
2) auto-tuning the controller for teleoperation

Can we make sure that the robot controller can execute in principle any retargeted human motion in real-time?
2) auto-tuning the controller for teleoperation

Learning the control structure and the parameters that enable the robot to perform a variety of motions
2) auto-tuning the controller for teleoperation

WE RECORD A SEQUENCE OF DOUBLE SUPPORT MOVEMENTS FROM A HUMAN OPERATOR
2) auto-tuning the controller for teleoperation

We define a generic stack of tasks with multiple levels

\[ S = (w_1 T_1 + ... + w_i T_i) / \]

\[ \vdots \]

\[ (w_j T_j + ... + w_n T_m) ; \]

Each level is a weighted combination of all the possible tasks.

\[ S_i = (w_{lf} T_{lf} + w_{rf} T_{rf} + w_{com} T_{com} + \]

\[ + w_{wo} T_{wo} + w_{wh} T_{wh} + w_{n} T_{h} + w_{c} T_{c} + \]

\[ + w_{n} T_{n} + w_{t} T_{t} + w_{la} T_{la} + \]

\[ + w_{ra} T_{ra} + w_{ll} T_{ll} + w_{rl} T_{rl} ) . \]

<table>
<thead>
<tr>
<th>Joint Space</th>
<th>Symbol</th>
<th>Cartesian Space</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>neck</td>
<td>T_n</td>
<td>com</td>
<td>T_{com}</td>
</tr>
<tr>
<td>torso</td>
<td>T_t</td>
<td>waist orientation</td>
<td>T_{wo}</td>
</tr>
<tr>
<td>left arm</td>
<td>T_{la}</td>
<td>waist height</td>
<td>T_{wh}</td>
</tr>
<tr>
<td>right arm</td>
<td>T_{ra}</td>
<td>chest</td>
<td>T_{c}</td>
</tr>
<tr>
<td>left leg</td>
<td>T_{ll}</td>
<td>head</td>
<td>T_{h}</td>
</tr>
<tr>
<td>right leg</td>
<td>T_{rl}</td>
<td>left foot</td>
<td>T_{lf}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>right foot</td>
<td>T_{rf}</td>
</tr>
</tbody>
</table>

Three levels \( \rightarrow \) task selectors

\[ S = (S_1) / \]

\[ (S_2) / \]

\[ (S_3) ; \]

\[
\begin{cases}
    T_k \subseteq S_1 & \text{if } (0 \leq l_k \leq 0.25) \\
    T_k \subseteq S_2 & \text{if } (0.25 < l_k \leq 0.5) \\
    T_k \subseteq S_3 & \text{if } (0.5 < l_k \leq 0.75) \\
    T_k \text{ deactivated} & \text{if } (0.75 < l_k \leq 1)
\end{cases}
\]
2) auto-tuning the controller for teleoperation

Two controller configurations

\[
\bar{S}_{C1} = \left( w_f (\mathcal{T}_{lf} + \mathcal{T}_{rf}) + w_h \mathcal{T}_h \right) / \left( w_{cxy} \mathcal{T}_{cxy} + w_{cz} \mathcal{T}_{cz} + w_t \mathcal{T}_t + w_{wo} \mathcal{T}_{wo} + w_{ha} (\mathcal{T}_h + \mathcal{T}_{rh}) \right) / \left( w_{la} (\mathcal{T}_{lla} + \mathcal{T}_{rla}) \right);
\]

\[
\bar{S}_{C2} = \left( w_f (\mathcal{T}_{lf} + \mathcal{T}_{rf}) + w_o \mathcal{T}_{wo} + w_n \mathcal{T}_n \right) / \left( w_{cxy} \mathcal{T}_{cxy} + w_{wh} \mathcal{T}_{wh} + w_t \mathcal{T}_t + w_a (\mathcal{T}_{la} + \mathcal{T}_{ra}) \right) / \left( w_c \mathcal{T}_c \right);
\]

<table>
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<tr>
<th>Joint Space</th>
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<th>Cartesian Space</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>torso</td>
<td>( \mathcal{T}_t )</td>
<td>com (x,y)</td>
<td>( \mathcal{T}_{cxy} )</td>
</tr>
<tr>
<td>left lower arm</td>
<td>( \mathcal{T}_{lla} )</td>
<td>com height</td>
<td>( \mathcal{T}_{cz} )</td>
</tr>
<tr>
<td>right lower arm</td>
<td>( \mathcal{T}_{rla} )</td>
<td>waist orientation</td>
<td>( \mathcal{T}_{wo} )</td>
</tr>
<tr>
<td>neck</td>
<td>( \mathcal{T}_n )</td>
<td>left foot pose</td>
<td>( \mathcal{T}_{lf} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>right foot pose</td>
<td>( \mathcal{T}_{rf} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>left hand position</td>
<td>( \mathcal{T}_l )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>right hand position</td>
<td>( \mathcal{T}_r )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>head orientation</td>
<td>( \mathcal{T}_h )</td>
</tr>
</tbody>
</table>

<table>
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<th>Cartesian Space</th>
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<td>com (x,y)</td>
<td>( \mathcal{T}_{cxy} )</td>
</tr>
<tr>
<td>torso</td>
<td>( \mathcal{T}_t )</td>
<td>waist orientation</td>
<td>( \mathcal{T}_{wo} )</td>
</tr>
<tr>
<td>left arm</td>
<td>( \mathcal{T}_{la} )</td>
<td>waist height</td>
<td>( \mathcal{T}_{wh} )</td>
</tr>
<tr>
<td>right arm</td>
<td>( \mathcal{T}_{ra} )</td>
<td>chest orientation</td>
<td>( \mathcal{T}_c )</td>
</tr>
<tr>
<td>left leg</td>
<td>( \mathcal{T}_{ll} )</td>
<td>head orientation</td>
<td>( \mathcal{T}_h )</td>
</tr>
<tr>
<td>right leg</td>
<td>( \mathcal{T}_{rl} )</td>
<td>left foot pose</td>
<td>( \mathcal{T}_{lf} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>right foot pose</td>
<td>( \mathcal{T}_{rf} )</td>
</tr>
</tbody>
</table>
2) auto-tuning the controller for teleoperation

<table>
<thead>
<tr>
<th>Control Parameters (28)</th>
<th>Task</th>
<th>SPW (10)</th>
<th>HLS (10)</th>
<th>CG (8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{lf} )</td>
<td>( w_f )</td>
<td>( l_f )</td>
<td>( \lambda_{feet}, \sigma_{feet} )</td>
<td></td>
</tr>
<tr>
<td>( T_{rf} )</td>
<td>( w_f )</td>
<td>( l_f )</td>
<td>( \lambda_{feet}, \sigma_{feet} )</td>
<td></td>
</tr>
<tr>
<td>( T_{com} )</td>
<td>( w_{com} )</td>
<td>( l_{com} )</td>
<td>( \lambda_{com} )</td>
<td></td>
</tr>
<tr>
<td>( T_{wo} )</td>
<td>( w_{wo} )</td>
<td>( l_{wo} )</td>
<td>( \sigma_{waist} )</td>
<td></td>
</tr>
<tr>
<td>( T_{wh} )</td>
<td>( w_{wh} )</td>
<td>( l_{wh} )</td>
<td>( \lambda_{waist} )</td>
<td></td>
</tr>
<tr>
<td>( T_{h} )</td>
<td>( w_h )</td>
<td>( l_h )</td>
<td>( \sigma_{head} )</td>
<td></td>
</tr>
<tr>
<td>( T_{c} )</td>
<td>( w_c )</td>
<td>( l_c )</td>
<td>( \sigma_{chest} )</td>
<td></td>
</tr>
<tr>
<td>( T_{n} )</td>
<td>( w_n )</td>
<td>( l_n )</td>
<td>( \mu_{posture} )</td>
<td></td>
</tr>
<tr>
<td>( T_{t} )</td>
<td>( w_t )</td>
<td>( l_t )</td>
<td>( \mu_{posture} )</td>
<td></td>
</tr>
<tr>
<td>( T_{la} )</td>
<td>( w_a )</td>
<td>( l_a )</td>
<td>( \mu_{posture} )</td>
<td></td>
</tr>
<tr>
<td>( T_{ra} )</td>
<td>( w_a )</td>
<td>( l_a )</td>
<td>( \mu_{posture} )</td>
<td></td>
</tr>
<tr>
<td>( T_{ll} )</td>
<td>( w_l )</td>
<td>( l_l )</td>
<td>( \mu_{posture} )</td>
<td></td>
</tr>
<tr>
<td>( T_{rl} )</td>
<td>( w_l )</td>
<td>( l_l )</td>
<td>( \mu_{posture} )</td>
<td></td>
</tr>
</tbody>
</table>

Minimize \( (f_1(x), - f_2(x), f_3(x)) \)

Minimize \( (f_1(x), - f_2(x)) \)

Among all the solutions from the Pareto front, we are interested to those with optimal solutions are all balanced at least in simulation.

The transfer function for each node. The sum of the incoming signal \(+\) multiplied by 20 makes the transition steep and similar to a step function. The scaled by the weight of that outgoing connection, serves as a component of the incoming signal for the node at the end of that connection. That output then travels through each of the node's outgoing connections and, after being multiplied by the weight, becomes the final signal for that node. That final signal is the sum of contributions from the node's outgoing connections.

NSGA-II
2) auto-tuning the controller for teleoperation

<table>
<thead>
<tr>
<th>Soft Priority Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convergence Gains</td>
</tr>
</tbody>
</table>

### TABLE IV: Convergence Gains (CG) associated to the 20 runs.

<table>
<thead>
<tr>
<th>SFW</th>
<th>CG</th>
<th>Median</th>
<th>IQR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_{ha}$</td>
<td>C1</td>
<td>0.639</td>
<td>0.2131</td>
</tr>
<tr>
<td>$w_f$</td>
<td>C1</td>
<td>0.5357</td>
<td>0.1786</td>
</tr>
<tr>
<td>$w_{cxy}$</td>
<td>C1</td>
<td>0.8368</td>
<td>0.1941</td>
</tr>
<tr>
<td>$w_{wo}$</td>
<td>C1</td>
<td>0.8674</td>
<td>0.4832</td>
</tr>
<tr>
<td>$w_h$</td>
<td>C1</td>
<td>0.3343</td>
<td>0.3101</td>
</tr>
<tr>
<td>$w_n$</td>
<td>C1</td>
<td>0.3256</td>
<td>0.2893</td>
</tr>
<tr>
<td>$w_t$</td>
<td>C1</td>
<td>0.9258</td>
<td>0.245</td>
</tr>
<tr>
<td>$w_{la}$</td>
<td>C1</td>
<td>0.3599</td>
<td>0.3133</td>
</tr>
<tr>
<td>$w_{cz}$</td>
<td>C1</td>
<td>0.7684</td>
<td>0.2191</td>
</tr>
<tr>
<td>$w_a$</td>
<td>C2</td>
<td>0.8406</td>
<td>0.296</td>
</tr>
<tr>
<td>$w_f$</td>
<td>C2</td>
<td>0.5835</td>
<td>0.2144</td>
</tr>
<tr>
<td>$w_{cxy}$</td>
<td>C2</td>
<td>0.9519</td>
<td>0.1984</td>
</tr>
<tr>
<td>$w_{wo}$</td>
<td>C2</td>
<td>0.1613</td>
<td>0.2337</td>
</tr>
<tr>
<td>$w_h$</td>
<td>C2</td>
<td>0.5357</td>
<td>0.2465</td>
</tr>
<tr>
<td>$w_n$</td>
<td>C2</td>
<td>0.4064</td>
<td>0.2419</td>
</tr>
<tr>
<td>$w_t$</td>
<td>C2</td>
<td>0.0656</td>
<td>0.2138</td>
</tr>
<tr>
<td>$w_{la}$</td>
<td>C2</td>
<td>0.1145</td>
<td>0.3756</td>
</tr>
<tr>
<td>$w_{cz}$</td>
<td>C2</td>
<td>0.1879</td>
<td>0.1785</td>
</tr>
</tbody>
</table>

### TABLE VI: Task frequency in each level of the hierarchy.

<table>
<thead>
<tr>
<th>C1</th>
<th>Median</th>
<th>IQR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{hand}$</td>
<td>0.0191</td>
<td>0.033</td>
</tr>
<tr>
<td>$\lambda_{feet}$</td>
<td>0.0577</td>
<td>0.064</td>
</tr>
<tr>
<td>$\sigma_{feet}$</td>
<td>0.0051</td>
<td>0.0059</td>
</tr>
<tr>
<td>$\lambda_{com}$</td>
<td>0.4426</td>
<td>0.1664</td>
</tr>
<tr>
<td>$\sigma_{waist}$</td>
<td>0.0591</td>
<td>0.042</td>
</tr>
<tr>
<td>$\sigma_{head}$</td>
<td>0.0796</td>
<td>0.0234</td>
</tr>
<tr>
<td>$\mu_{posture}$</td>
<td>0.5605</td>
<td>0.2145</td>
</tr>
<tr>
<td>$\lambda_{waist}$</td>
<td>0.5491</td>
<td>0.3791</td>
</tr>
<tr>
<td>$\lambda_{feet}$</td>
<td>0.2486</td>
<td>0.0983</td>
</tr>
<tr>
<td>$\sigma_{feet}$</td>
<td>0.0983</td>
<td>0.1231</td>
</tr>
<tr>
<td>$\lambda_{com}$</td>
<td>0.5911</td>
<td>0.1946</td>
</tr>
<tr>
<td>$\sigma_{waist}$</td>
<td>0.0652</td>
<td>0.0472</td>
</tr>
<tr>
<td>$\sigma_{head}$</td>
<td>0.2778</td>
<td>0.2560</td>
</tr>
<tr>
<td>$\mu_{posture}$</td>
<td>0.5162</td>
<td>0.0821</td>
</tr>
<tr>
<td>$\sigma_{chest}$</td>
<td>0.6052</td>
<td>0.4009</td>
</tr>
</tbody>
</table>
2) auto-tuning the controller for teleoperation

<table>
<thead>
<tr>
<th>Task selectors</th>
<th>C1</th>
<th>C2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Task</strong></td>
<td>$S_1$</td>
<td>$S_2$</td>
</tr>
<tr>
<td>$T_{lh}$, $T_{rh}$</td>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td>$T_{lf}$, $T_{rf}$</td>
<td>18</td>
<td>2</td>
</tr>
<tr>
<td>$T_{cxy}$</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>$T_{wo}$</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>$T_{h}$</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>$T_{n}$</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>$T_{t}$</td>
<td>3</td>
<td>17</td>
</tr>
<tr>
<td>$T_{ila}$, $T_{rila}$</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>$T_{cz}$</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE IV:** Convergence Gains (CG) associated to the 20 learned configurations

**TABLE V:** Soft Priority Weights (SPW) associated to the 20 learned configurations

**TABLE VI:** Task frequency in each level of the hierarchy

**High priority:** Left foot, Right foot, Head

**Medium priority:** Left hand, Right hand, CoM, Waist, Torso

**Low priority:** Arms, Chest
2) auto-tuning the controller for teleoperation

Learning the control structure and the parameters that enable the robot to perform a variety of motions

22 OUT OF 25 RUNS CONVERGE TO A SIMILAR CONTROL CONFIGURATION
The best solution enables the robot to do more tasks that are not in its training sequences and that are shown on-line by the teleoperator!
2) auto-tuning the controller for teleoperation
How to ensure that the teleoperate motions are “optimal” for the robot’s dynamics w.r.t. the task?
3) optimization of the demonstrated motions
3) optimization of the demonstrated motions

- **ProMP Training**
  - $w_0$
  - Initial ProMP Weights
  - $y^r_t$
  - Motion Retargeting
  - $n_{\text{demo}}$
  - Demonstrations From Human

- **Trajectory Generation and Execution**
  - $w_k$
  - $y^r_t$
  - Eq. 6

- **Constrained Optimization**
  - $w_{k+1}$
  - $\mathcal{F}(\tau)$
  - Optimal ProMP Weights

- **Whole-body QP controller**
  - $\dot{q}^*$
  - $q, \dot{q}$
3) optimization of the demonstrated motions

**Roll-out Stage**

1. **Initial ProMP Weights**
   - \( \mathbf{w}_0 \)
   - \( \mathbf{y}_t^r \)
   - \( \mathbf{w}_k \)

2. **Trajectory Generation and Execution**
   - \( \mathbf{y}_t^r \)
   - Eq. 6

3. **Whole-body QP controller**
   - \( \mathbf{q}^*, \mathbf{q}, \mathbf{\dot{q}} \)

4. **Constrained Optimization**
   - \( \mathbf{F}(\mathbf{\tau}) \)
   - \( \mathbf{w}_{k+1} \)
   - \( \mathbf{w}^* \)

**Motion Retargeting**

- \( n_{\text{demo}} \)
- Demonstrations From Human

**ProMP Training**

- (III - C)
- \( \mathbf{y}_t^r \)

**STEP 1**

**STEP 2**

**Demonstrations From Human**
3) optimization of the demonstrated motions

Several Trajectory Demonstrations

Xsens MVN suit

$y_t^h$

Motion Retargeting

$y_t^r$

ProMP Training

Retargeted End-Effector Trajectories

ProMP Trajectories

Motion Retargeting

From Human (III - C)

Initial ProMP Weights

Trajectory Generation and Execution

Whole-body GP controller

Optimal ProMP Weights

Trajectory Generation

(III - D)

Constrained Optimization

Eq. 6

Roll-out Stage

(III - E)
3) optimization of the demonstrated motions
3) optimization of the demonstrated motions

See Gomes’ oral presentation tomorrow in the Optimization session!
3) optimization of the demonstrated motions

\[ F_{\text{initial}} = 416.12 \]

\[ F^* = 253.52 \]

\[ I = 39.07\% \]
Transfer paradigm: from humans to robots

1) **Teleoperation** of locomotion and manipulation relying on a whole-body controller for the humanoid
2) **Optimize** the whole-body controller’s parameters to be robust to unknown motions from the teleoperator
3) **Re-optimize the teleoperated motions** for the robot dynamics
Transfer paradigm: from humans to robots

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Thank you!

Questions?

L. Penco  K. Otani  W. Gomes