TRUST-BASED CONTROL, DECISION-MAKING, AND MOTION PLANNING FOR HUMAN-ROBOT COLLABORATION SYSTEMS

Yue Wang, Ph.D.
Associate Professor
Interdisciplinary & Intelligent Research (I2R) Laboratory
Department of Mechanical Engineering, Clemson University

Control Systems and the Quest for Autonomy
A Symposium in Honor of Professor Panos J. Antsaklis
October 28, 2018
I2R Research Overview

[Fu et. al., JGCD 2018; Saeidi et. al., T-Ro 2017; Saeidi et. al., ACC 2016; Fu et. al., ACC 2016]

[Saeidi et. al., IROS 2017]

[Mizanoor & Wang, Mechatronics, 2018; Sadr & Wang, TASE 2017; Sadr et. al., CASE 2016]

[Jiang & Wang, CPHS 2018; Liao et. al., ACC 2017; Wang, TCST 2016; Wang, ACC 2016]
I2R Research Overview

[Zheng et. al., DSCC 2018; Wang et. al., TiiS 2018; Spencer et. al., IROS 2016]

[Wang et. al., SAE WCX 2018; Li & Wang, T-ITS 2017; Dey et. al., T-ITS 2016; Wang & Wang, DSCC 2016]

[Mahani & Wang, DSCC 2018]
Why is Trust Important?

- Adversarial, unpredictable, risky situations: Does a human trust autonomy to perform a task or prefer to do it by themselves? To what extent does the human trust autonomy?

- Collaborative tasks: Human’s acceptance and willingness work together with robots to achieve improved performance and balanced human experience.
Computational Trust Models

Our Trust Models

- Time-series trust model
  [Wang et al. Springer 2014; Sadrfaridpour et al. Springer 2015; Rahman et al. DSCC 2015a; Saeidi & Wang, CDC 2015; Saeidi et al. ACC 2016; Sadrfaridpour et al. CASE 2016; Rahman et al. CASE 2016a; Spencer et al., IROS 2016; Mahani & Wang, DSCC 2016; Saeidi et al. T-Ro, 2017; Sadrfaridpour & Wang, TAES 2017]
- Dynamic Bayesian Network (DBN) trust model
  [Wang et al., ACM TiiS, 2018]
- Robot-to-human trust model
  [Walker et al. MSCI 2015; Rahman et al. CASE 2016a]
- Mutual trust model
- RoboTrust for multi-robot systems
  [Saeidi et al., IROS 2017]
Mixed-Initiative Bilateral Haptic Teleoperation of Mobile Robots based on Mutual Trust Analysis

[Saeidi et. al, T-Ro 2017; Saeidi et. al. ACC 2016; Fu et. al., ACC 2016]

Possible sources of instability!
Passivity theory

Function of robot-to-human trust

Possible sources of instability!
Passivity theory

Function of human-to-robot trust
Passivity Theory & Port Network Theory

- Passive systems are stable
- Interconnection of passive $n$ ports results in a larger passive system

\[ \Sigma : \dot{x} = f(x(t), u(t), t) \]

\[ E_{\text{out}} \leq E_{\text{in}} \]

In teleoperation, force and velocity commands form the power ports

\[ f^T(\tau)O(\tau)d\tau + E(0) \geq 0 \text{ must hold for } f^T(t)O(t) \triangleq v^T(t)f_1(t) + \cdots + v^T_M(t)f_M(t) \]
Mixed-Initiative Bilateral Haptic Teleoperation of Mobile Robots based on Mutual Trust Analysis

[Saeidi et. al. ACC 2016; IEEE T-Ro 2017; Fu et. al., ACC 2016]

Dynamics of Master Haptic Device

\[
M(x)\ddot{x} + C(x, \dot{x})\dot{x} = f_c + f_h \
f_c = -f_{local} - f_m \
f_{local} = B\dot{x} + Kx,
\]

\(B = \text{diag}[b_1, \ldots, b_n] \in \mathbb{R}^{n \times n}, b_j > 0, j = 1, \ldots, n,\)
\(K = \text{diag}[k_1, \ldots, k_q, 0, \ldots, 0] \in \mathbb{R}^{n \times n},\)
\(k_i > 0, i = 1, \ldots, q \leq n\)

Feedback \(r - \) Passivity of the Master

\[
r_m = \dot{x} + \Lambda x
\]

\(\Lambda = \text{diag}[\lambda_1, \lambda_2, \ldots, \lambda_q, 0, \ldots, 0] \in \mathbb{R}^{n \times n} \text{ with } \lambda_i > 0\)

\(V_{hd}(t) := \frac{1}{2} [r_m^T M r_m + x^T (K + \Lambda B - \Lambda M \Lambda) x] \geq 0\)

\(S_{hd}(t) := \dot{x}^T [B - \frac{1}{2} (M \Lambda + \Lambda M)] \dot{x} + x^T \Lambda K x\)

\(-x^T \Lambda C \dot{x} \geq 0,\)

\[
r_m^T(t)(f_h(t) - f_m(t)) = \dot{V}_{hd}(t) + S_{hd}(t)
\]

\[
\int_0^t r_m^T(\tau)(f_h(\tau) - f_m(\tau))d\tau = V_{hd}(t) - V_{hd}(0) + \int_0^t S_{hd}(\tau)d\tau \geq -V_{hd}(0).
\]
Mixed-Initiative Bilateral Haptic Teleoperation of Mobile Robots based on Mutual Trust Analysis

[Saeidi et. al. ACC 2016; IEEE T-Ro 2017; Fu et. al., ACC 2016]

Passivity of the Communication Channel with Variable Time-Delay & Variable Scaling

Block diagram for the communication channel with time-varying delays and variable power scaling

B3: Communication Channel and Variable Scaling Parameters

Passivity inequality

\[ \int_0^t r_m^T(\tau)f_m(\tau) - r_s^T(\tau)f_s(\tau)d\tau \geq 0 \] assuming \( E(0) = 0 \)

Master

Comm. Channel

Slave

Scattering/wave transformation

\[ u_i = \sqrt{\frac{\beta}{2b}}(f'_m + br_m), \quad v_i = \sqrt{\frac{\beta}{2b}}(f'_m - br_m), \quad u_r = \sqrt{\frac{\alpha}{2b}}(f_s - br'_s), \quad v_r = \sqrt{\frac{\alpha}{2b}}(f_s + br'_s) \]

\[ f_i = \sqrt{1 - \dot{T}_{i,\text{max}}}, \quad i = 1, 2, \quad b > 0: \text{ Characteristic impedance} \]

\[ \frac{dT_i}{dt} \leq \dot{T}_{i,\text{max}} \leq 1, i = 1, 2 \]

\( \dot{T}_{i,\text{max}} \): The maximum rate of increase of time-varying delay \( T_i(t) \)
Passivity of the Slave using PO & PC

Passivity observer (PO): An energy observer function
\[
E_{obs}(t) = \int_0^t r_s^T(\tau)f_s(\tau)d\tau
\]

Passivity controller (PC): a time-varying dissipation activation function
\[
z(t) = \begin{cases} 
-\frac{r_s^T(t)f_s'(t)}{||r_s(t)||_2^2} & \text{if } E_{obs}(t) = 0 \& r_s^T(t)f_s'(t) < 0 \\
0 & \text{otherwise}
\end{cases}
\]

\[
f_s(t) = f_s'(t) + z(t)r_s(t)
\]

Passivity of the slave \[
\int_0^t r_s^T(\tau)f_s(\tau)d\tau \geq 0
\]
A Mixed-Initiative Haptic Teleoperation Strategy for Mobile Robotic Systems Based on Bidirectional Computational Trust Analysis

Interdisciplinary & Intelligence Research Lab
Department of Mechanical Engineering
Clemson University
Trust-Based Leader Selection for Bilateral Haptic Teleoperation of Multi-Robot Systems

[Saeidi et. al. IROS 2017]

- Multi-robot collective position tracking and synchronization
- RoboTrust:
  - Human-to-robot trust: dynamic criterion to select leader $\rightarrow$ improved performance
  - Robot-to-human trust: dynamically scale the haptic force feedback $\rightarrow$ reduced workload
- Passivity approaches for switched systems
Trust-Based Leader Selection for Bilateral Haptic Teleoperation of Multi-Robot Systems

[Saeidi et. al. IROS 2017]

Robot Dynamics

\[
\dot{v}_i(t) = r_{sk}(t), \quad \text{for leader } i = l
\]
\[
v_i(t) = -\sum_{j \in \mathcal{N}_i \setminus l} a_{ij}(p_i - p_j) - a_{il}(p_i - p_l), \quad \forall i \neq l,
\]
\[
\dot{p}_i(t) = v_i(t), \quad \text{for } i = \{1, 2, \ldots, N\}
\]

Error Dynamics

\[
\ddot{p}_f(t) = p_f(t) - 1p_l(t)
\]
\[
\dot{v}_f(t) = \dot{p}_f(t) - 1\dot{p}_l(t)
\]
\[
\dot{p}_f = L_f \dot{p}_f(t) - A_f (p_f(t) - 1p_l(t))
\]
\[
\dot{v}_f = \dot{p}_f(t) - 1\dot{p}_l(t)
\]
\[
\dot{r}_{sk}(t) = \dot{r}_{sk}(t)
\]

Performance Improvement Analysis

\[
P_{r_i}(t) = -\dot{p}_f^T(t)\dot{p}_f(t), \quad P_{r_i}(t) = -\dot{v}_f^T(t)\dot{v}_f(t)
\]
\[
\dot{p}_f^T(t)\dot{p}_f < 0, \quad \dot{v}_f^T(t)\dot{v}_f < 0
\]

Passivity Def. for Switched I/Os

Definition: A system \( Z \) with discontinuous supply rate, and/or switched inputs/outputs with a common storage function is passive if the following holds [12]

\[
\sum_{k=0}^{S-1} \left\{ \int_{t^+_k}^{t^+_{k+1}} y_k^T(t)u_k(t)dt \right\} + \int_{t^+_S}^{t} y_S^T(t)u_S(t)dt + V(0) \geq 0
\]

\[
y_{k+1} = y_k\ y_{k-1} = y_{k-1}\ u_{k+1} = u_{k+1}\ u_k = u_k
\]
Trust-Based Leader Selection for Bilateral Haptic Teleoperation of Multi-Robot Systems

[Saeidi et. al. IROS 2017]

Port-based model for the bilateral haptic teleoperation of a multi-robot system
Trust-Based Leader Selection for Bilateral Haptic Teleoperation of Multi-Robot Systems

[Saeidi et. al. IROS 2017]

Passivity Definition & Wave Variable Transformation

\[
\begin{align*}
\sum_{k=0}^{S-1} \left\{ \int_{t_k^+}^{t_{k+1}} \left( \dot{\mathbf{r}}_{mk}^T(\tau) \mathbf{f}_m(\tau) - \dot{\mathbf{r}}_{sk}^T(\tau) \mathbf{f}_s(\tau) \right) d\tau \right\} \\
+ \int_{t_s}^{t} \left( \dot{\mathbf{r}}_{ms}^T(\tau) \mathbf{f}_{ms}(\tau) - \dot{\mathbf{r}}_{ss}^T(\tau) \mathbf{f}_{ss}(\tau) \right) d\tau \geq 0.
\end{align*}
\]

\[\begin{align*}
\mathbf{v}_r &= \sqrt{\frac{1}{2b_{ik}}} (\dot{\mathbf{f}}_{sk} + b_{ik} \dot{\mathbf{r}}_{sk}), \\
\mathbf{v}_l &= \sqrt{\frac{\beta_{ik}}{2b_{ik}}} (\dot{\mathbf{f}}_{mk}' - b_{ik} \dot{\mathbf{r}}_{mk}), \\
\mathbf{u}_r &= \sqrt{\frac{1}{2b_{ik}}} (\dot{\mathbf{f}}_{sk} - b_{ik} \dot{\mathbf{r}}_{sk}), \\
\mathbf{u}_l &= \sqrt{\frac{\beta_{ik}}{2b_{ik}}} (\dot{\mathbf{f}}_{mk}' + b_{ik} \dot{\mathbf{r}}_{mk}).
\end{align*}\]

Proof of Passivity

\[
\begin{align*}
\dot{\mathbf{r}}_{mk}^T(t) \beta_{ik}(t) \dot{\mathbf{f}}_{mk}(t) &= \beta_{ik}(t) \left[ \frac{\mathbf{u}_l^T(t) \mathbf{u}_l(t)}{2} \mathbf{v}_l^T(t) \mathbf{v}_l(t) \right] \\
\dot{\mathbf{r}}_{ss}^T(t) \dot{\mathbf{f}}_{ss}(t) &= \frac{1}{2} [\mathbf{v}_r^T(t) \mathbf{v}_r(t) - \mathbf{u}_r^T(t) \mathbf{u}_r(t)] \\
\sum_{k=0}^{S-1} \left[ \int_{t_k^+}^{t_{k+1}} \left( \dot{\mathbf{r}}_{mk}^T(\tau) \mathbf{f}_m(\tau) - \dot{\mathbf{r}}_{sk}^T(\tau) \mathbf{f}_s(\tau) \right) d\tau \right] \\
&\geq \frac{1}{2} \left[ \int_{t_s-T}^{t} \mathbf{u}_l^T(\tau) \mathbf{u}_l(\tau) d\tau + \int_{t_s-T}^{t} \mathbf{u}_r^T(\tau) \mathbf{u}_r(\tau) d\tau \right] \\
&\geq \frac{1}{2} \left[ \int_{t-T}^{t} \mathbf{u}_l^T(\tau) \mathbf{u}_l(\tau) d\tau + \int_{t-T}^{t} \mathbf{u}_r^T(\tau) \mathbf{u}_r(\tau) d\tau \right] \geq 0.
\end{align*}
\]
Passivity of the Slave Side

The multi-robot system is passive with

\[
\dot{p}(t) = (\Omega(t) - I)Lp(t) + D_{ik}(t)r_{sk}(t)
\]
\[
\Omega(t) = \text{diag}[D(t)]
\]
\[
D_{ik}(t) = [\delta_{1k}(t) \cdots \delta_{Nk}(t)]^T \in R^{N \times 1}
\]
\[
\delta_{ik}(t) = \begin{cases} 
1 & \text{if slave } i \text{ is the leader} \\
0 & \text{otherwise}
\end{cases}
\]

The relative position of the leader robot with its neighbors as haptic feedback

input $r_{sk}(t)$

output $f_{sk}(t) = D_{ik}(t)^T Lp(t)$
Trust-Based Leader Selection for Bilateral Haptic Teleoperation of Multi-Robot Systems

Interdisciplinary & Intelligence Research Lab
Department of Mechanical Engineering
Clemson University
Thank You!

Students, Postdocs, & Alumni

Dr. Hamed Saeidi  Dr. Rahman Mizanoor  Dr. Behzad Sadr  Mr. Adam Spencer  Mr. Xiaotian Wang  Mr. Zhanrui Liao  Ms. Qiuchen Wang

Mr. Foster McLane  Mr. Longsheng Jiang  Mr. Maziar Mahani  Mr. Fangjian Li  Mr. Huanfei Zheng  Mr. Jonathan Todd  Mr. James Svacha