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

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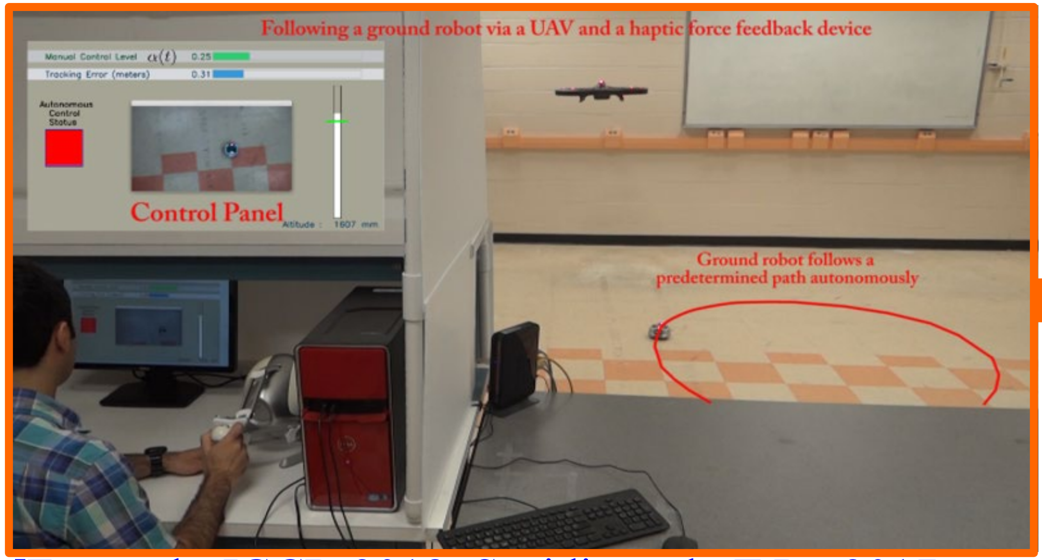
Interdisciplinary &
Intelligence Research

I2R Research Overview



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

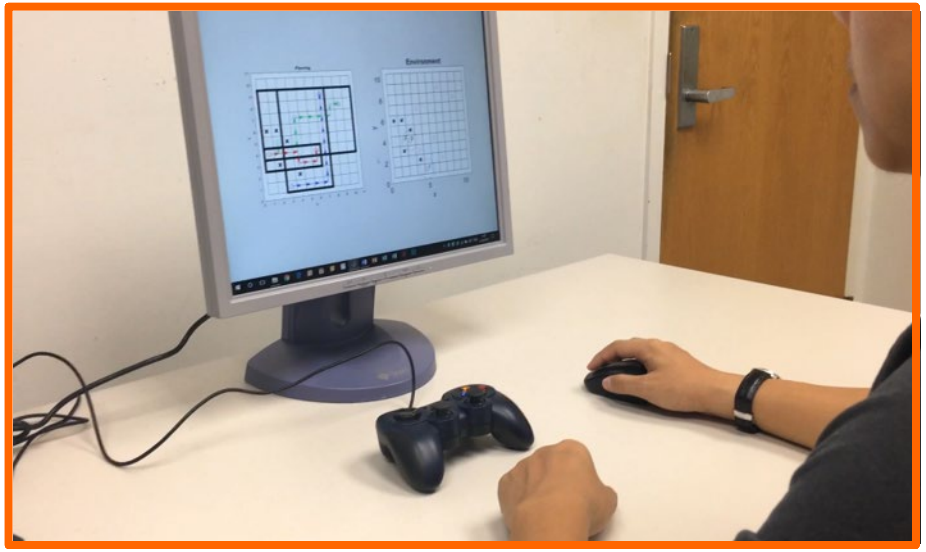
[Saeidi et. al., IROS 2017]

[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

1



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

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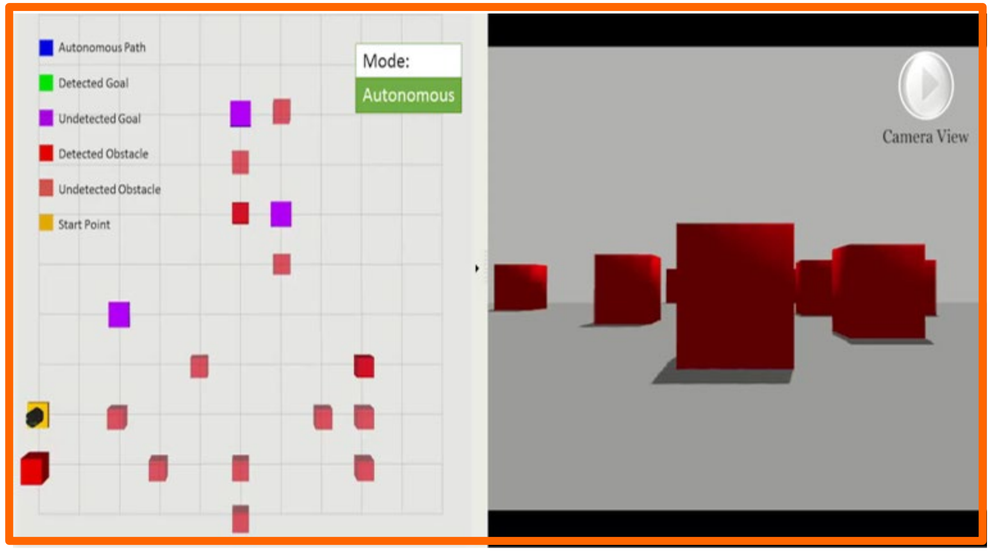
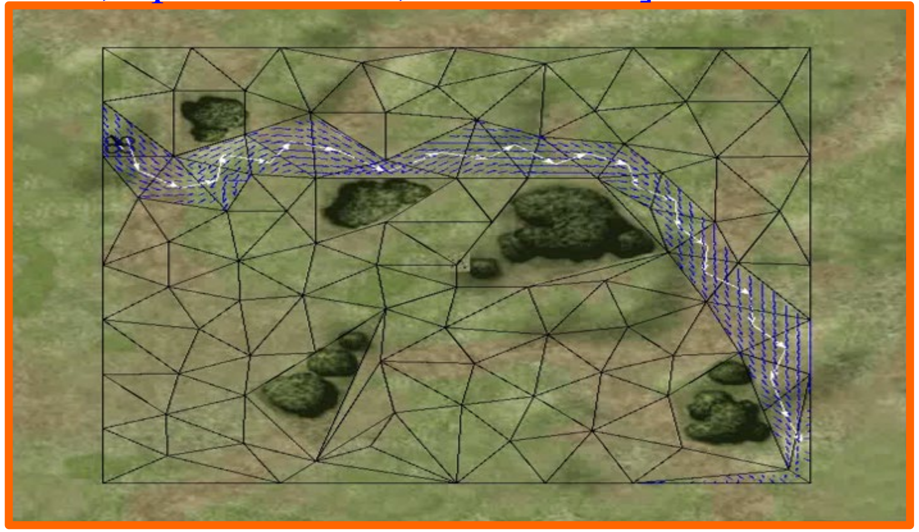
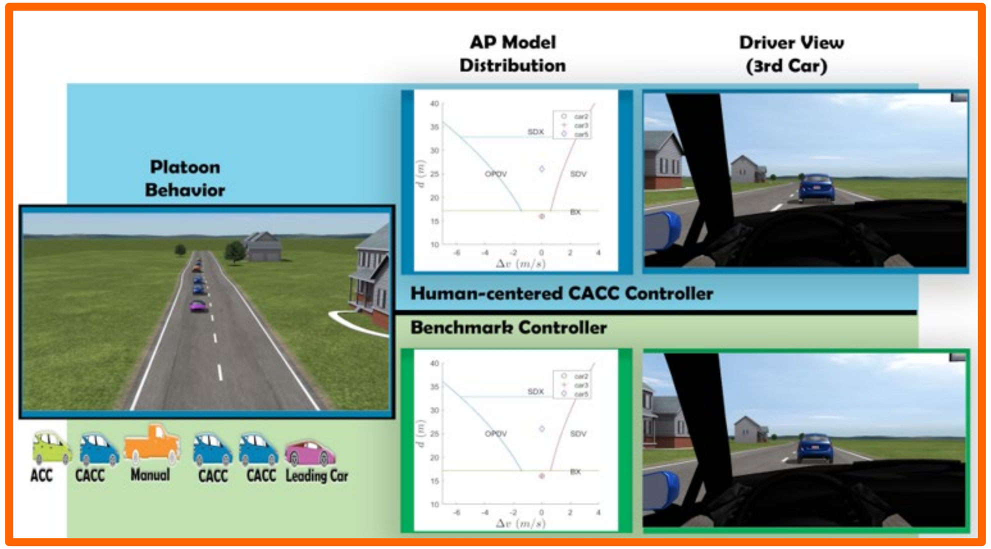


[Mahani & Wang, DSCC 2016]

3



[Mahani & Wang, DSCC 2018]

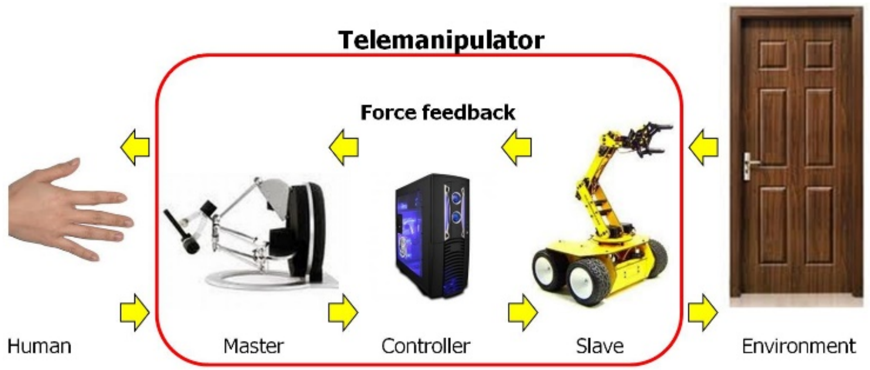


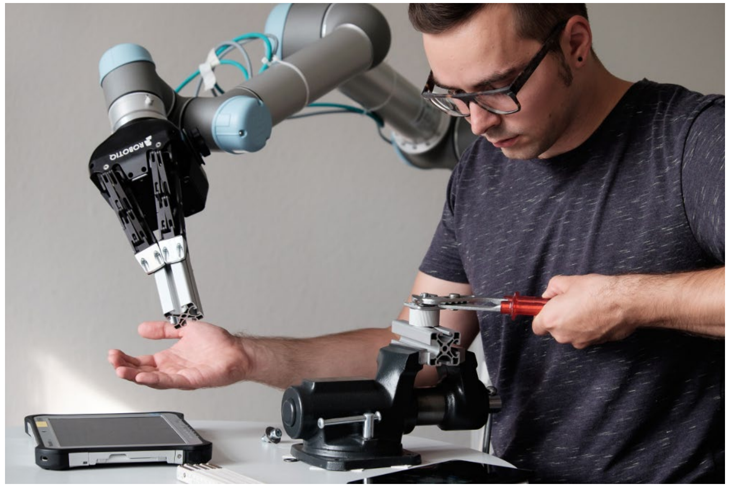
[Wang et. al., SAE WCX 2018; Li & Wang, T-ITS 2017; Dey et. al., T-ITS 2016; Wang & Wang, DSCC 2016]

Why is Trust Important?

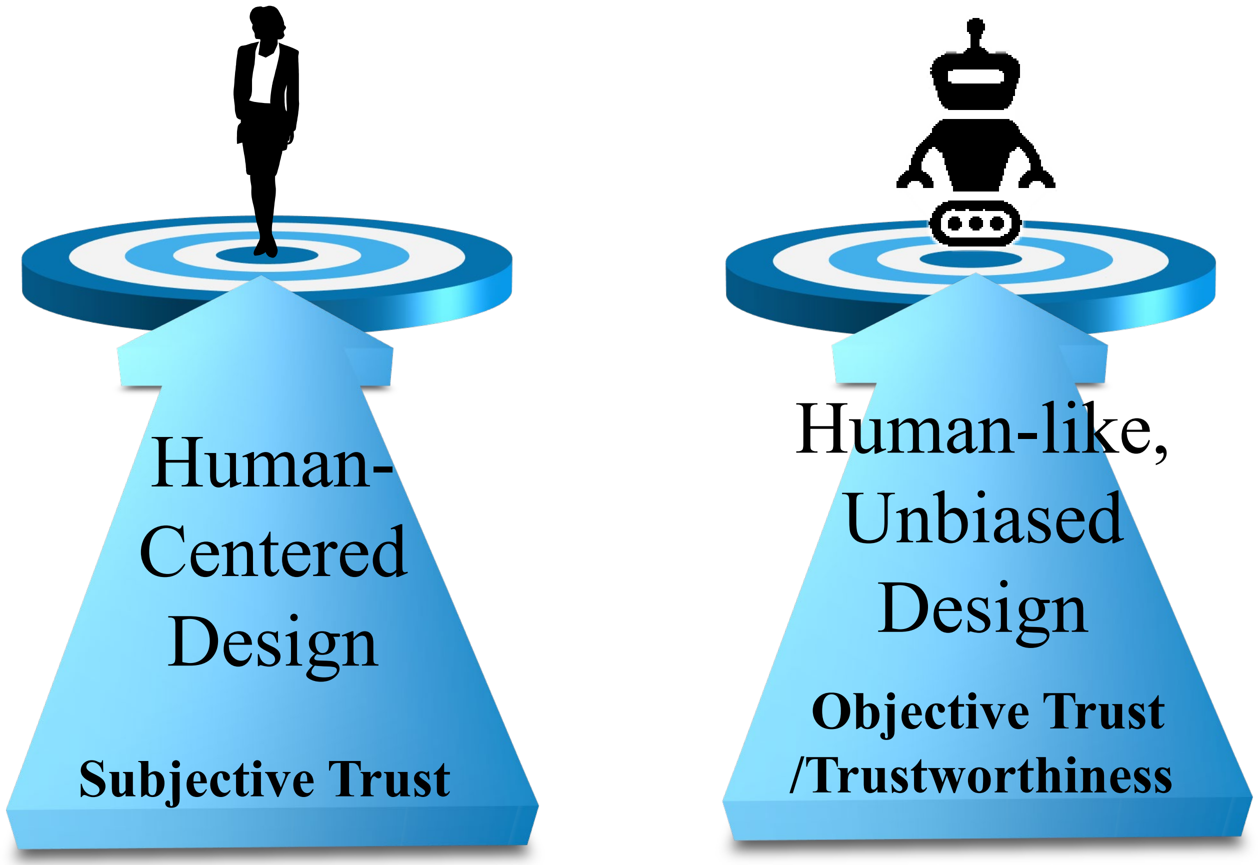
- Adversarial, unpredictable, risky situations: Does a human trust autonomy to perform a task or prefer to do it by themselves? To what extent does the human trust autonomy?

- 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

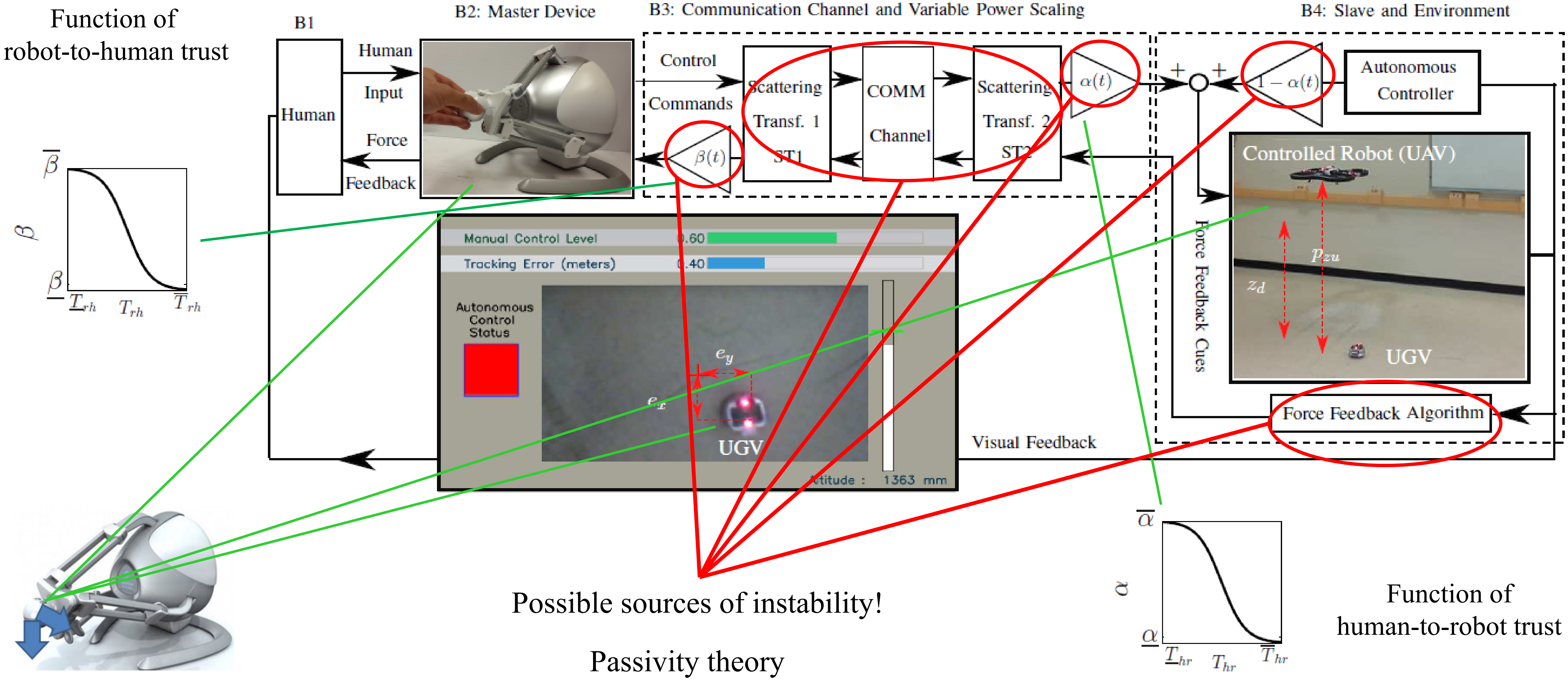
[Wang et. al. ACC 2015, CPS 2015; Wang & Zhang ed., Spring 2017; Mizanoor & Wang, Mechatronics, 2018]

- RoboTrust for multi-robot systems

[Saeidi et. al., IROS 2017]

Mixed-Initiative Bilateral Haptic Teleoperation of Mobile Robots based on Mutual Trust Analysis

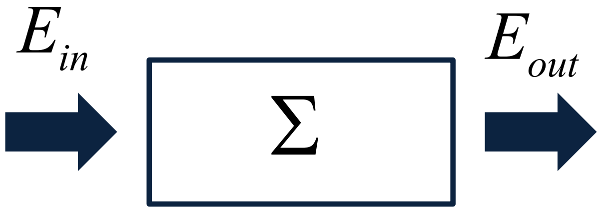
[Saeidi et. al, T-Ro 2017; Saeidi et. al. ACC 2016; Fu et. al., ACC 2016]



Mixed-Initiative Bilateral Haptic Teleoperation of Mobile Robots based on Mutual Trust Analysis

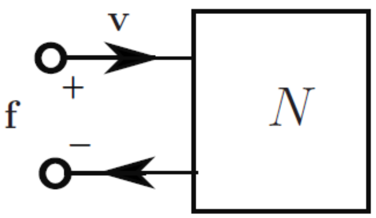
[Saeidi et. al. ACC 2016; IEEE T-Ro 2017; Fu et. al., ACC 2016]

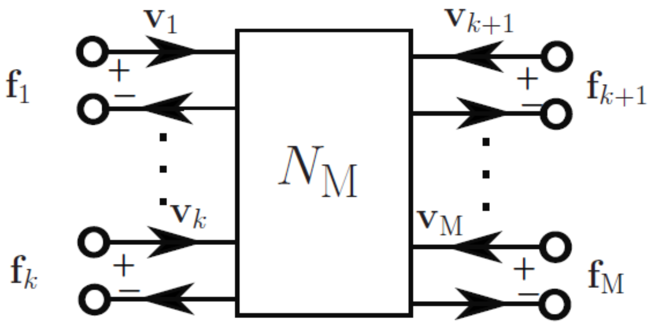
Passivity Theory & Port Network Theory



$$\Sigma : \dot{x} = f(x(t), u(t), t)$$
$$E_{out} \leq E_{in}$$

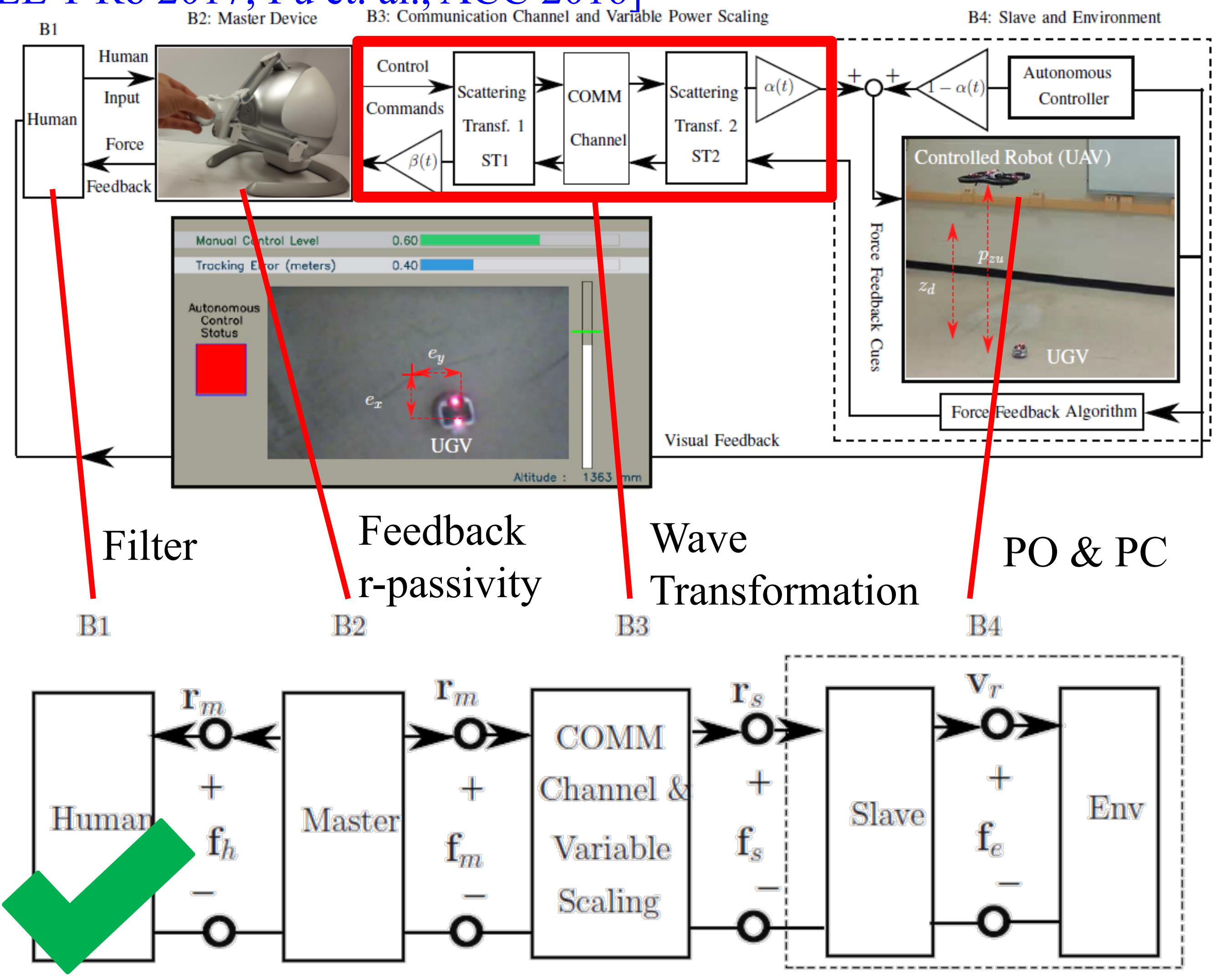
- Passive systems are stable
- Interconnection of passive n ports results in a larger passive system





$\int_0^t \mathbf{I}^\mathrm{T}(\tau)\mathbf{O}(\tau)d\tau + E(0) \geq 0$ must hold for $\mathbf{I}^\mathrm{T}(t)\mathbf{O}(t) \triangleq \mathbf{v}_1^\mathrm{T}(t)\mathbf{f}_1(t) + \cdots + \mathbf{v}_\mathrm{M}^\mathrm{T}(t)\mathbf{f}_\mathrm{M}(t)$

In teleoperation, force and velocity commands form the power ports



Port-based model for the mixed-initiative bilateral haptic teleoperation

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]

Master

Comm. Channel

Slave

Dynamics of Master Haptic Device

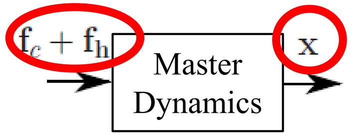
$$M(\mathbf{x})\ddot{\mathbf{x}} + C(\mathbf{x},\dot{\mathbf{x}})\dot{\mathbf{x}} = \mathbf{f}_c, + \mathbf{f}_h \qquad \mathbf{f}_c = -\mathbf{f}_{\text{local}} - \mathbf{f}_m$$

$$\mathbf{f}_{\text{local}} = B\dot{\mathbf{x}} + K\mathbf{x},$$

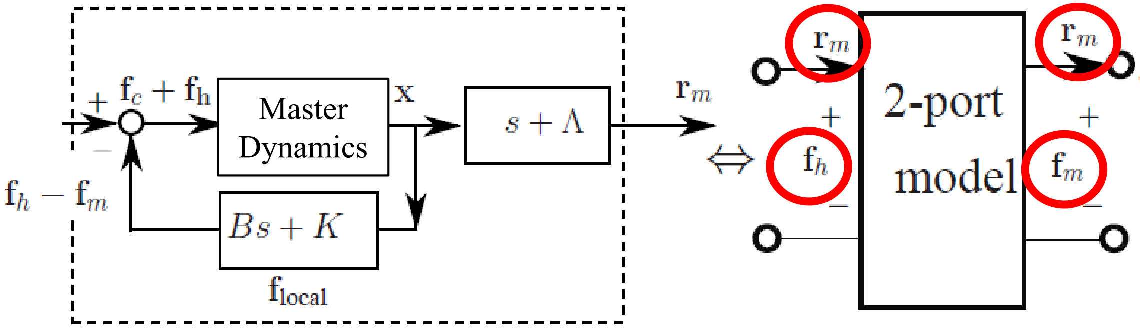
$$B = \text{diag}[b_1, ..., b_n] \in \mathbb{R}^{n\times n}, b_j > 0, j = 1, ..., n,$$

$$K = \text{diag}[k_1, ..., k_q, 0, ..., 0] \in \mathbb{R}^{n\times n},$$

$$k_i > 0, i = 1, ..., q \leq n$$



Feeback *r* passive master



Feedback r – Passivity of the Master

$$\mathbf{r}_m = \dot{\mathbf{x}} + \Lambda\mathbf{x}$$

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

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

$$S_{hd}(t) := \dot{\mathbf{x}}^{\mathrm{T}}[B - \frac{1}{2}(M\Lambda + \Lambda M)]\dot{\mathbf{x}} + \mathbf{x}^{\mathrm{T}}\Lambda K\mathbf{x} - \mathbf{x}^{\mathrm{T}}\Lambda C\dot{\mathbf{x}} \geq 0,$$

$$\mathbf{r}_m^{\mathrm{T}}(t)(\mathbf{f}_h(t) - \mathbf{f}_m(t)) = \dot{V}_{hd}(t) + S_{hd}(t)$$

$$\int_0^t \mathbf{r}_m^{\mathrm{T}}(\tau)(\mathbf{f}_h(\tau) - \mathbf{f}_m(\tau))d\tau = V_{hd}(t) - V_{hd}(0) + \int_0^t S_{hd}(\tau)d\tau \geq -V_{hd}(0).$$

Passivity inequality

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]

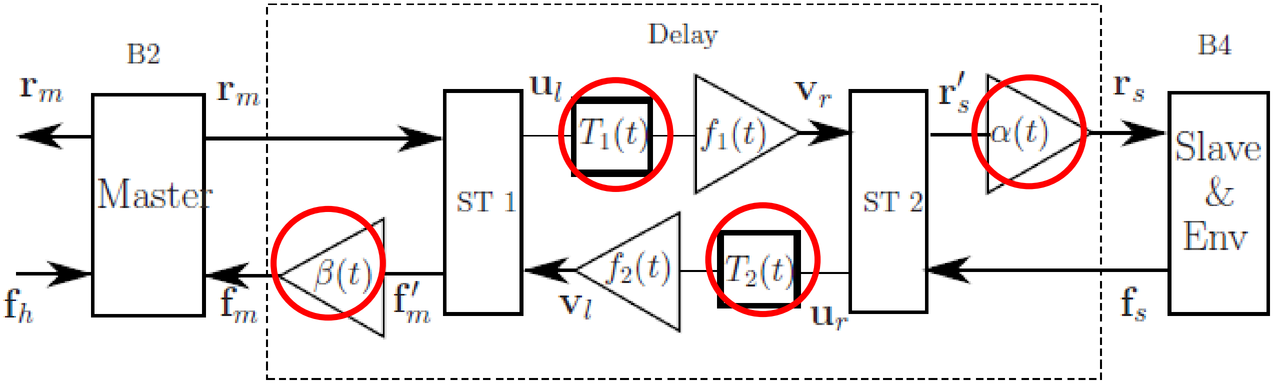
Master

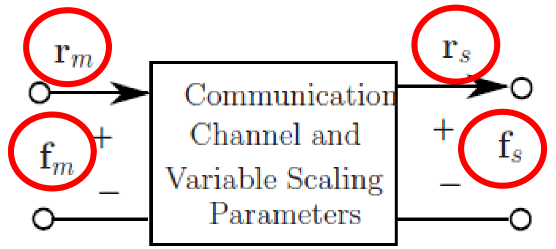
Comm. Channel

Slave

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





Scattering/wave transformation

$$\mathbf{u}_l = \sqrt{\frac{\beta}{2b}}(\mathbf{f}'_m + b\mathbf{r}_m), \quad \mathbf{v}_l = \sqrt{\frac{\beta}{2b}}(\mathbf{f}'_m - b\mathbf{r}_m), \quad \mathbf{u}_r = \sqrt{\frac{\alpha}{2b}}(\mathbf{f}_s - b\mathbf{r}'_s), \quad \mathbf{v}_r = \sqrt{\frac{\alpha}{2b}}(\mathbf{f}_s + b\mathbf{r}'_s)$$

$$f_i = \sqrt{1 - \dot{T}_{i\,\max}}, \quad i = 1, 2,$$

$b > 0$: Characteristic impedance

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

$\dot{T}_{i\,\max}$: The maximum rate of increase of time-varying delay $T_i(t)$

Passivity inequality

$\int_0^t \mathbf{r}_m^{\mathrm{T}}(\tau)\mathbf{f}_m(\tau) - \mathbf{r}_s^{\mathrm{T}}(\tau)\mathbf{f}_s(\tau)d\tau \geq 0$ assuming $E(0) = 0$

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]

Master

Comm. Channel

Slave

Passivity of the Slave using PO & PC

Passivity observer (PO):

An energy observer function

$$E_{obs}(t) = \int_0^{t^-} \mathbf{r}_s^{\mathrm{T}}(\tau)\mathbf{f}_s(\tau)d\tau$$

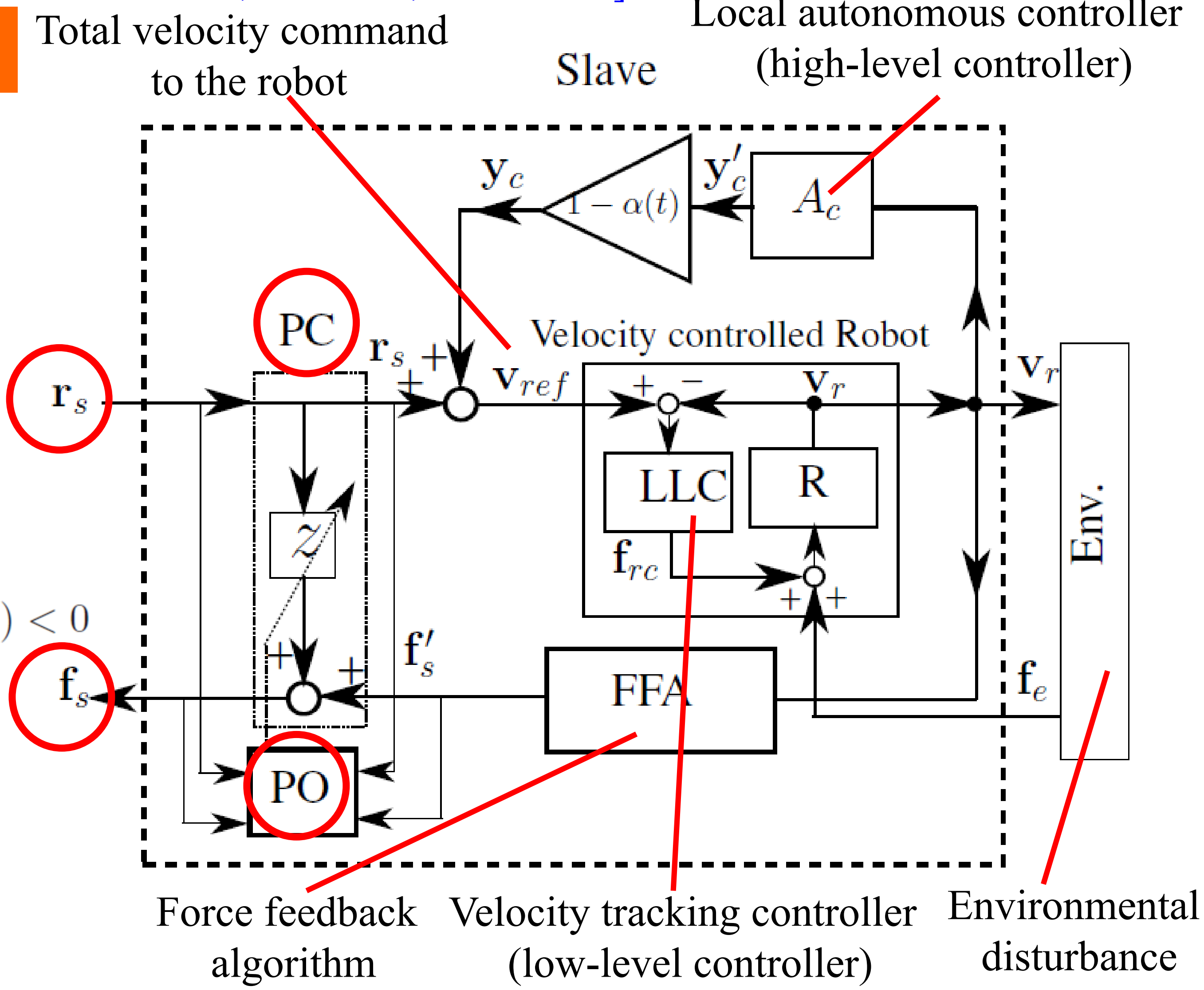
Passivity controller (PC):

a time-varying dissipation activation function

$$z(t) = \begin{cases} -\frac{\mathbf{r}_s^{\mathrm{T}}(t)\mathbf{f}_s'(t)}{||\mathbf{r}_s(t)||_2^2} & \textit{if } E_{obs}(t) = 0 \;\&\; \mathbf{r}_s^{\mathrm{T}}(t)\mathbf{f}_s'(t) < 0 \\ 0 & \textit{otherwise} \end{cases}$$

$$\mathbf{f}_s(t) = \mathbf{f}_s'(t) + z(t)\mathbf{r}_s(t)$$

Passivity of the slave $\int_0^t \mathbf{r}_s^{\mathrm{T}}(\tau)\mathbf{f}_s(\tau)d\tau \geq 0$



A Mixed-Initiative Haptic Teleoperation Strategy for Mobile Robotic Systems Based on Bidirectional Computational Trust Analysis

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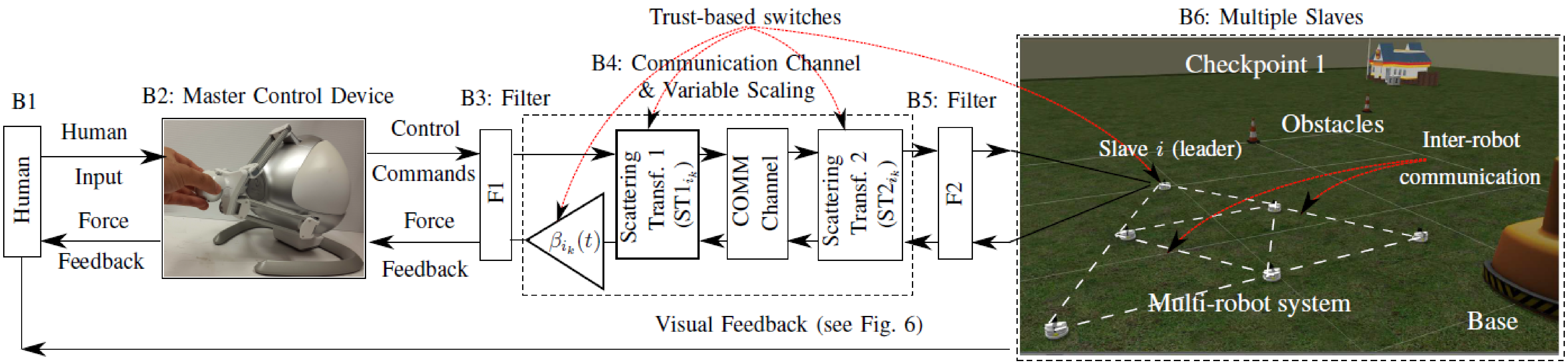
Trust-Based Leader Selection for Bilateral Haptic Teleoperation of Multi-Robot Systems

[Saeidi et. al. IROS 2017]



- Multi-robot collective position tracking and synchronization
- RoboTrust:
  - Human-to-robot trust: dynamic criterion to select leader → improved performance
  - Robot-to-human trust: dynamically scale the haptic force feedback → 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

$$\dot{\mathbf{p}}_i(t) = \mathbf{v}_i(t), \text{ for } i = \{1, 2, ..., N\}$$

$$v_l(t) = r_{s_k}(t), \quad \text{for leader } i = l$$

$$v_i(t) = -\sum_{j \in \mathcal{N}_i \backslash l} a_{ij}(p_i - p_j) - a_{il}(p_i - p_l), \quad \forall i \neq l,$$

$$\dot{p}_l(t) = r_{s_k}(t)$$

$$\dot{\mathbf{p}}_f(t) = -L_f \mathbf{p}_f(t) - A_f(\mathbf{p}_f(t) - \mathbf{1}p_l(t)),$$

Error Dynamics

$$\tilde{\mathbf{p}}_f(t) = \mathbf{p}_f(t) - \mathbf{1}p_l(t), \quad \tilde{\mathbf{v}}_f(t) = \dot{\mathbf{p}}_f(t) - \mathbf{1}\dot{p}_l(t)$$

$$M_f = L_f + A_f$$

position synchronization

$$\dot{\tilde{\mathbf{p}}}_f = \dot{\mathbf{p}}_f(t) - \mathbf{1}\dot{p}_l(t) = -M_f\tilde{\mathbf{p}}_f(t) - \mathbf{1}r_{s_k}(t)$$

$$\dot{\tilde{\mathbf{v}}}_f = -M_f\tilde{\mathbf{v}}_f(t) - \mathbf{1}\dot{r}_{s_k}(t)$$

velocity synchronization

Performance Improvement Analysis

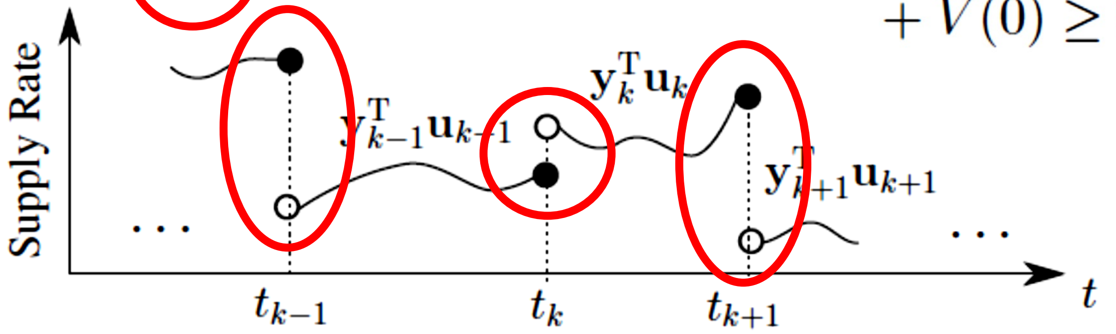
$$P_{r_i}(t) = -\tilde{\mathbf{p}}_f^{\mathrm{T}}(t)\dot{\tilde{\mathbf{p}}}_f(t), \qquad P_{r_i}(t) = -\tilde{\mathbf{v}}_f^{\mathrm{T}}(t)\dot{\tilde{\mathbf{v}}}_f(t)$$

$$\tilde{\mathbf{p}}_f^{\mathrm{T}}(t)\dot{\tilde{\mathbf{p}}}_f < 0 \qquad \tilde{\mathbf{v}}_f^{\mathrm{T}}(t)\tilde{\mathbf{v}}_f < 0$$

Passivity Def. for Switched I/Os

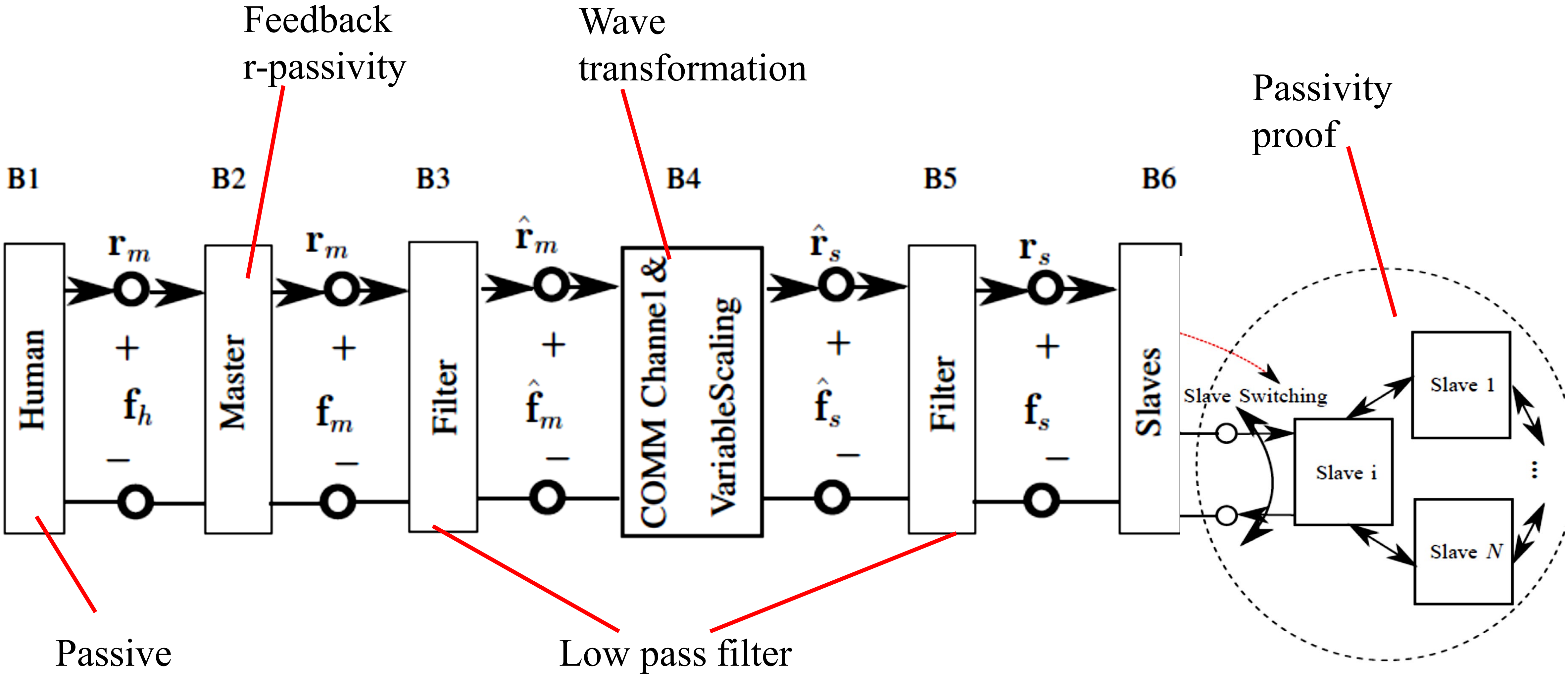
Definition 1: A system Z with discontinuous supply rate, and/or switched inputs/outputs with a common storage function is passive if the following holds [12]

$$\sum_{k=0}^{S-1}\left\{\int_{t_k^+}^{t_{k+1}} \mathbf{y}_k^{\mathrm{T}}(\tau)\mathbf{u}_k(\tau)d\tau\right\} + \int_{t_S^+}^{t} \mathbf{y}_S^{\mathrm{T}}(\tau)\mathbf{u}_S(\tau)d\tau + V(0) \geq 0$$



Trust-Based Leader Selection for Bilateral Haptic Teleoperation of Multi-Robot Systems

[Saeidi et. al. IROS 2017]



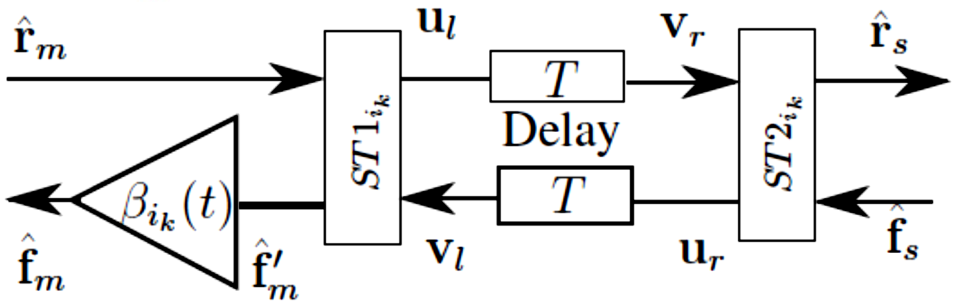
Port-based model for the bilateral haptic teleoperation of a multi-robot system

Trust-Based Leader Selection for Bilateral Haptic Teleoperation of Multi-Robot Systems

[Saeidi et. al. IROS 2017]

Passivity Definition & Wave Variable Transformation

$$\sum_{k=0}^{S-1}\left\{\int_{t_k^+}^{t_{k+1}}\left(\hat{\mathbf{r}}_{m_k}^{\mathrm{T}}(\tau)\hat{\mathbf{f}}_{m_k}(\tau)-\hat{\mathbf{r}}_{s_k}^{\mathrm{T}}(\tau)\hat{\mathbf{f}}_{s_k}(\tau)\right)d\tau\right\}$$
$$+\int_{t_S^+}^{t}\left(\hat{\mathbf{r}}_{m_S}^{\mathrm{T}}(\tau)\hat{\mathbf{f}}_{m_S}(\tau)-\hat{\mathbf{r}}_{s_S}^{\mathrm{T}}(\tau)\hat{\mathbf{f}}_{s_S}(\tau)\right)d\tau \geq 0.$$



$$\mathbf{v}_r=\sqrt{\frac{1}{2b_{i_k}}}(\hat{\mathbf{f}}_{s_k}+b_{i_k}\hat{\mathbf{r}}_{s_k}),\ \mathbf{v}_l=\sqrt{\frac{\overline{\beta}_{i_k}}{2b_{i_k}}}(\hat{\mathbf{f}}'_{m_k}-b_{i_k}\hat{\mathbf{r}}_{m_k}),$$
$$\mathbf{u}_r=\sqrt{\frac{1}{2b_{i_k}}}(\hat{\mathbf{f}}_{s_k}-b_{i_k}\hat{\mathbf{r}}_{s_k}),\ \mathbf{u}_l=\sqrt{\frac{\underline{\beta}_{i_k}}{2b_{i_k}}}(\hat{\mathbf{f}}'_{m_k}+b_{i_k}\hat{\mathbf{r}}_{m_k})$$

Proof of Passivity

$$\hat{\mathbf{r}}_{m_k}^{\mathrm{T}}(t)\beta_{i_k}(t)\hat{\mathbf{f}}'_{m_k}(t)=\frac{\beta_{i_k}(t)}{2}\left[\frac{\mathbf{u}_l^{\mathrm{T}}(t)\mathbf{u}_l(t)}{\underline{\beta}_{i_k}}-\frac{\mathbf{v}_l^{\mathrm{T}}(t)\mathbf{v}_l(t)}{\overline{\beta}_{i_k}}\right]$$

$$\hat{\mathbf{r}}_{s_k}^{\mathrm{T}}(t)\hat{\mathbf{f}}_{s_k}(t)=\frac{1}{2}[\mathbf{v}_r^{\mathrm{T}}(t)\mathbf{v}_r(t)-\mathbf{u}_r^{\mathrm{T}}(t)\mathbf{u}_r(t)]$$

$$\sum_{k=0}^{S-1}\left[\int_{t_k^+}^{t_{k+1}}(\hat{\mathbf{r}}_{m_k}^{\mathrm{T}}(\tau)\hat{\mathbf{f}}_{m_k}(\tau)-\hat{\mathbf{r}}_{s_k}^{\mathrm{T}}(\tau)\hat{\mathbf{f}}_{s_k}(\tau))d\tau\right]$$
$$\geq\frac{1}{2}\left[\int_{t_S-T}^{t_S}\mathbf{u}_l^{\mathrm{T}}(\tau)\mathbf{u}_l(\tau)d\tau+\int_{t_S-T}^{t_S}\mathbf{u}_r^{\mathrm{T}}(\tau)\mathbf{u}_r(\tau)d\tau\right]$$
$$\int_{t_S^+}^{t}(\hat{\mathbf{r}}_{m_S}^{\mathrm{T}}(\tau)\hat{\mathbf{f}}_{m_S}(\tau)-\hat{\mathbf{r}}_{s_S}^{\mathrm{T}}(\tau)\hat{\mathbf{f}}_{s_S}(\tau))d\tau$$

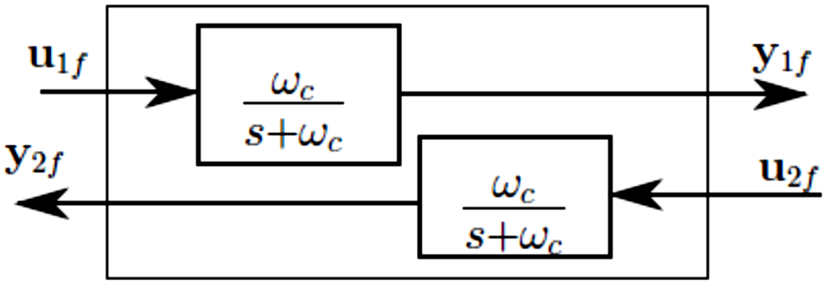
$$\vdots$$

$$\geq\frac{1}{2}\left[\int_{t-T}^{t}\mathbf{u}_l^{\mathrm{T}}(\tau)\mathbf{u}_l(\tau)d\tau+\int_{t-T}^{t}\mathbf{u}_r^{\mathrm{T}}(\tau)\mathbf{u}_r(\tau)d\tau\right]\geq 0$$

Trust-Based Leader Selection for Bilateral Haptic Teleoperation of Multi-Robot Systems

[Saeidi et. al. IROS 2017]

Passive Filtering



Two-port filter.

$$\mathbf{y}_k^{\mathrm{T}}(t)\mathbf{u}_k(t) \triangleq$$

$$\mathbf{u}_{1f_k}^{\mathrm{T}}(t)\mathbf{y}_{2f_k}(t) - \mathbf{u}_{2f_k}^{\mathrm{T}}(t)\mathbf{y}_{1f_k}(t) = 0.$$

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

Passivity of the Slave Side

$$\dot{\mathbf{p}}(t) = (\Omega(t) - I)L\mathbf{p}(t) + D_{i_k}(t)r_{s_k}(t)$$

$$\Omega(t) = \mathrm{diag}[D(t)]$$

$$D_{i_k}(t) = [\delta_{1_k}(t)\cdots\delta_{N_k}(t)]^{\mathrm{T}} \in R^{N\times 1}$$

$$\delta_{i_k}(t) = \begin{cases} 1 & \text{if slave } i \text{ is the leader} \\ 0 & \text{otherwise} \end{cases}$$

The multi-robot system is passive with

$$V_{f_s}(t) = \frac{1}{2}\mathbf{p}^{\mathrm{T}}(t)L\mathbf{p}(t) \geq 0$$

input $r_{s_k}(t)$

output $f_{s_k}(t) = D_{i_k}(t)^{\mathrm{T}}L\mathbf{p}(t)$

Trust-Based Leader Selection for Bilateral Haptic Teleoperation of Multi-Robot Systems

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Thank You!

Students, Postdocs, & Alumni


Dr. Hamed Saeidi


Dr. Rahman Mizanoor


Dr. Behzad Sadr

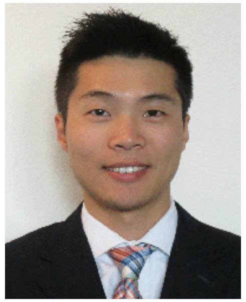

Mr. Adam Spencer


Mr. Xiaotian Wang


Mr. Zhanrui Liao


Ms. Qiuchen Wang


Mr. Foster McLane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