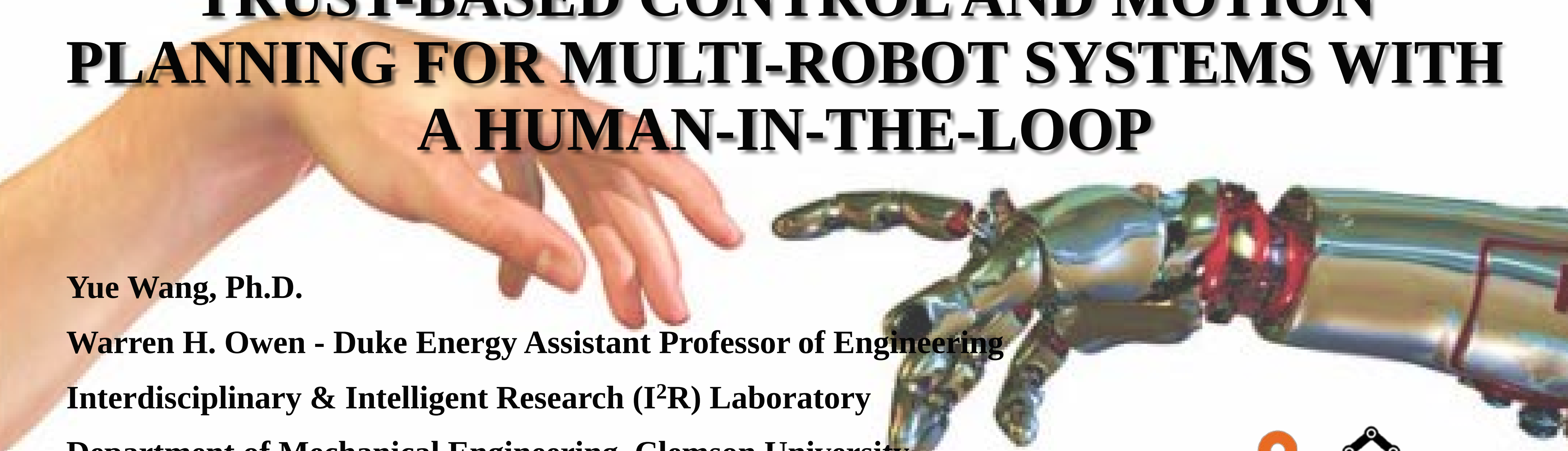
TRUST-BASED CONTROL AND MOTION PLANNING FOR MULTI-ROBOT SYSTEMS WITH A HUMAN-IN-THE-LOOP



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Interdisciplinary &
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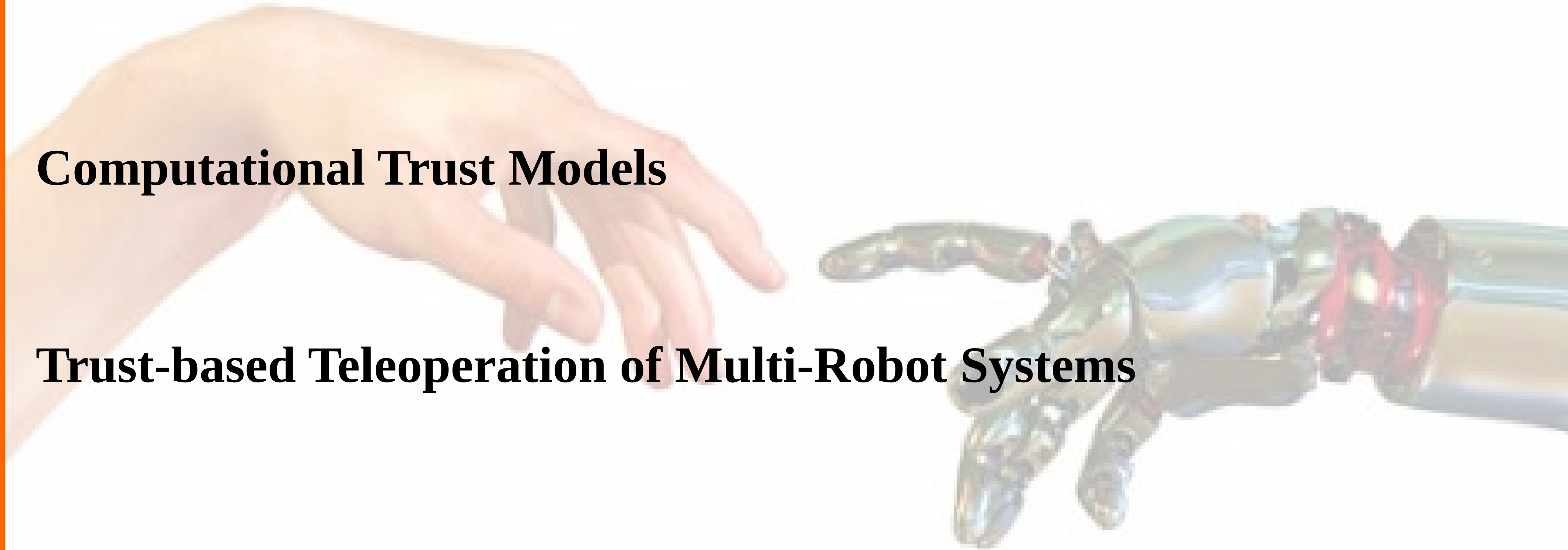

Background and Motivation

Computational Trust Models

Trust-based Teleoperation of Multi-Robot Systems

Trust-based Multi-Robot Symbolic Motion Planning

Conclusions

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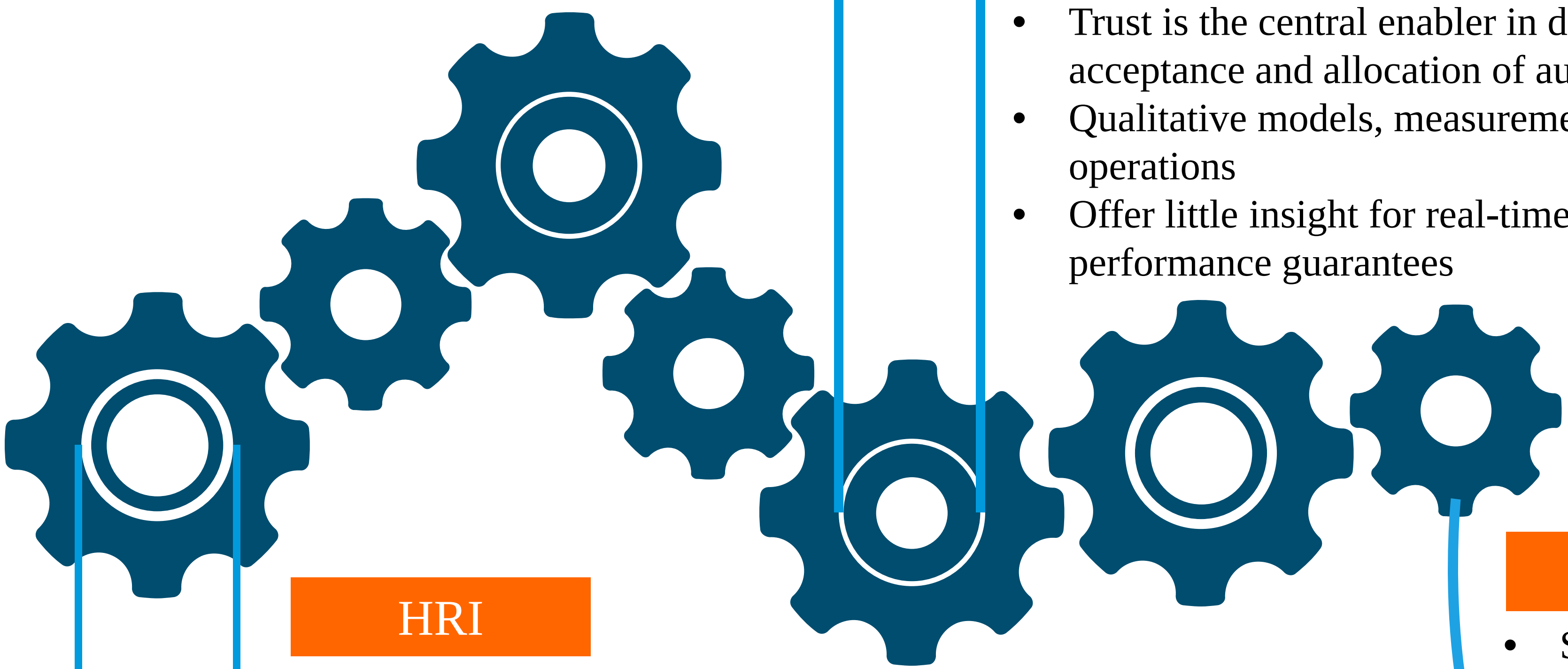
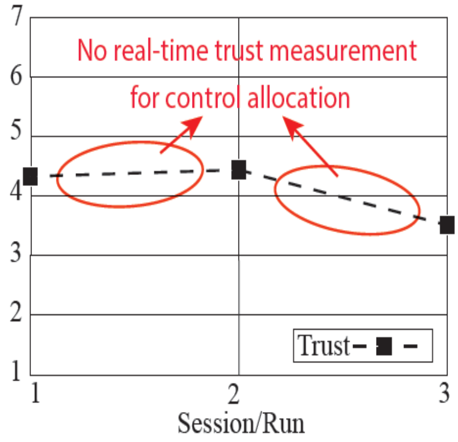


Trust

- Trust is the central enabler in determining human's acceptance and allocation of automation
- Qualitative models, measurements before and after operations
- Offer little insight for real-time robotic operations and performance guarantees



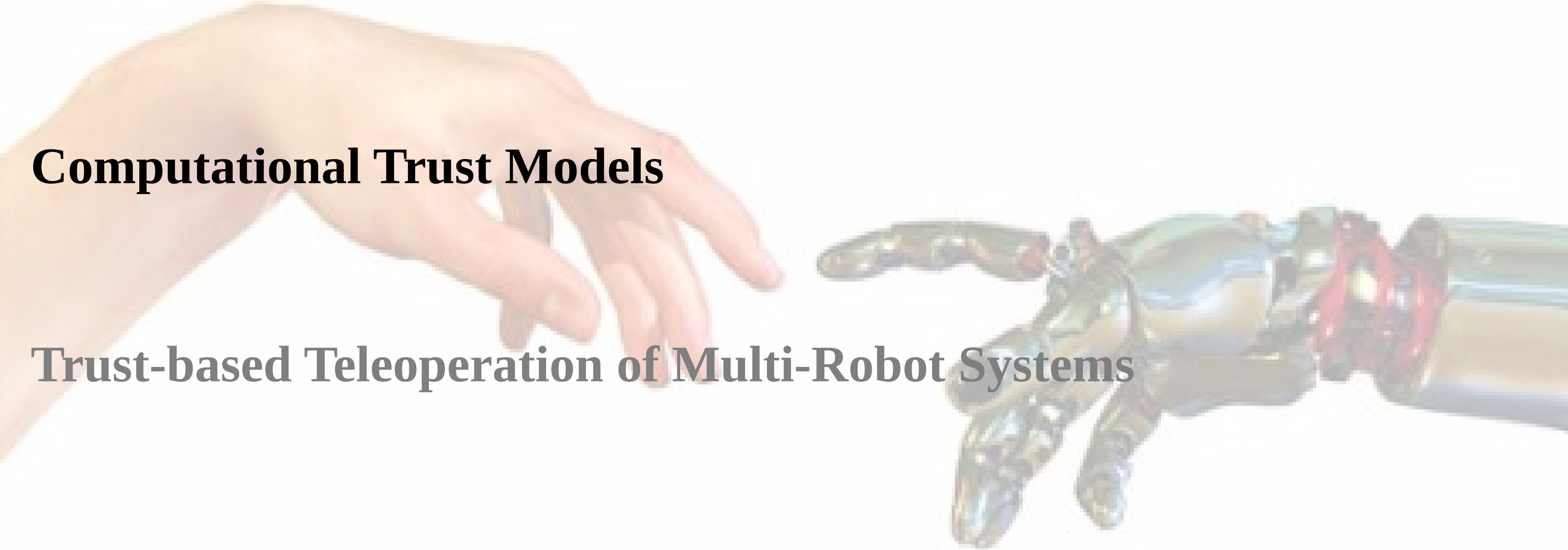
Subjective Trust Measurement

HRI

- Human-machine interface (HMI) design
- Lack understanding of the dynamic interaction for real-time robotic operations in complex and uncertain environments
- Lack system-level performance guarantees and verification
- Human-robot interaction (HRI) in multi-robot systems is especially challenging

Novelty

- Social/Psychological/Physical HRI for real-time robotic operations
- Quantitative analysis
- Embed human factors analysis into control theory, decision theory, and robot motion planning



✓ **Background and Motivation**

✓ **Computational Trust Models**

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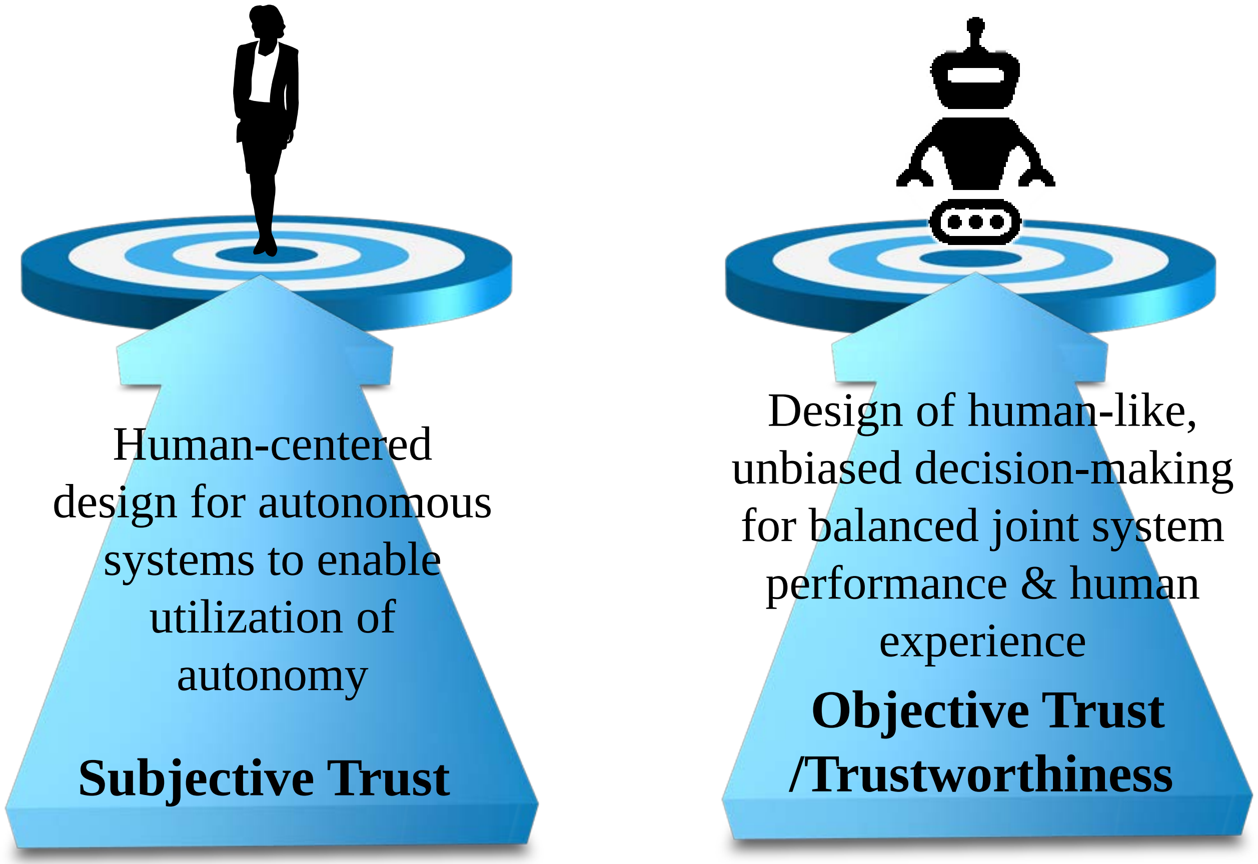
Computational Trust Models

Trust - “the attitude that an agent will help achieve an individual’s goals in a situation characterized by uncertainty and vulnerability.” [Lee & See, *Human Factors*, 2004]



Human-centered design for autonomous systems to enable utilization of autonomy

Subjective Trust

Design of human-like, unbiased decision-making for balanced joint system performance & human experience

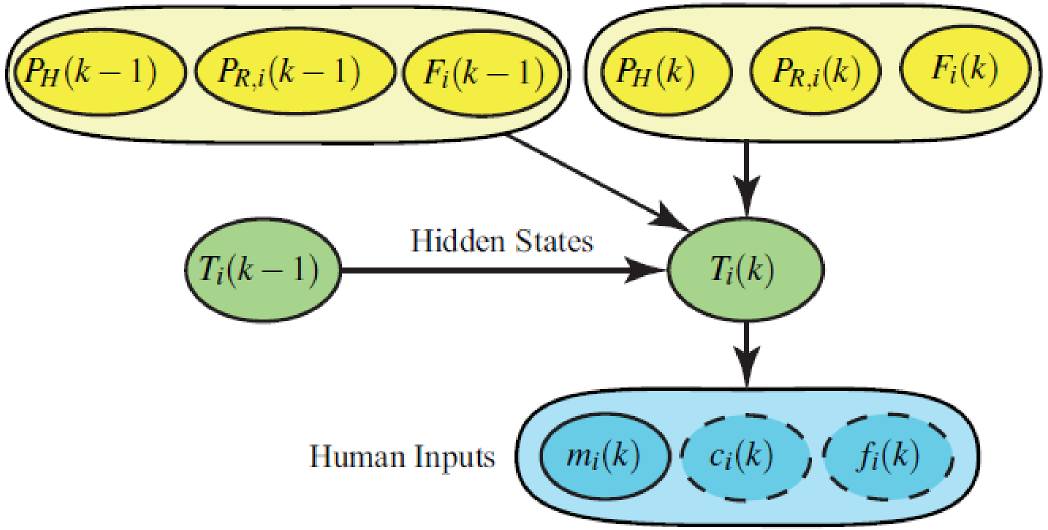
Objective Trust /Trustworthiness

Our Trust Models

- Time-series trust model [Wang et. al. Springer 2014; B. 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]
- Dynamic Bayesian Network (DBN) trust model [Wang et. al., ACM TiiS 2017]
- 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., Springer 2017]
- RoboTrust for multi-robot systems [Saeidi et. al., IROS 2017]

DBN Trust Models

[Wang et. al., ACM TiiS 2017]



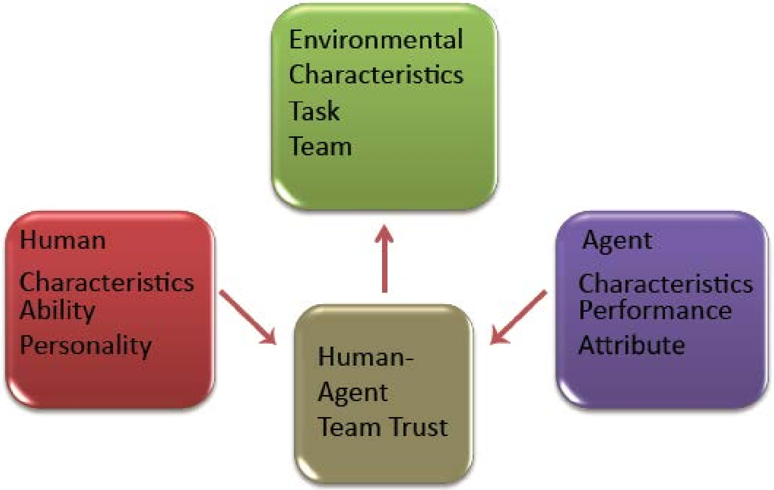
$$\mathrm{Prob}(T_i(t)|P_{R,i}(1:t),P_H(1:t),F_i(1:t),m_i(1:t),c_i(1:t),f_i(1:t),T_i(0))$$
$$= bel(T_i(t)) = \frac{\int \overline{bel}(T_i(t),T_i(t-1))\mathrm{d}T_i(t-1)}{\int\int \overline{bel}(T_i(t),T_i(t-1))\mathrm{d}T_i(t-1)\mathrm{d}T_i(t)}$$

$$\overline{bel}(T_i(t),T_i(t-1))$$
$$= \mathrm{Prob}(m_i(t)|T_i(t),T_i(t-1))\mathrm{Prob}(c_i(t)|T_i(t),T_i(t-1))\mathrm{Prob}(f_i(t)|T_i(t))\cdot$$
$$\mathrm{Prob}(T_i(t)|T_i(t-1),P_{R,i}(t),P_{R,i}(t-1),P_H(t),P_H(t-1),F_i(t),F_i(t-1))bel(T_i(t-1))$$

$$\mathrm{Prob}(T_i(t)|T_i(t-1),P_{R,i}(t),P_{R,i}(t-1),P_H(t),P_H(t-1),F_i(t),F_i(t-1))$$
$$= \mathcal{N}(T_i(t);\bar{T}_i(t),\sigma_i(t)),$$
$$\text{where } \bar{T}_i(t) = AT_i(t-1)+B_1P_{R,i}(t)-B_2P_{R,i}(t-1)+C_1P_H(t)-C_2P_H(t-1)$$
$$+D_1F_i(t)-D_2F_i(t-1).$$

$$\mathrm{Prob}(m_i(t)=1|T_i(t),T_i(t-1)) = (1+exp(-(\omega_1T_i(t)-\omega_2T_i(t-1))))^{-1}$$

Main Factors



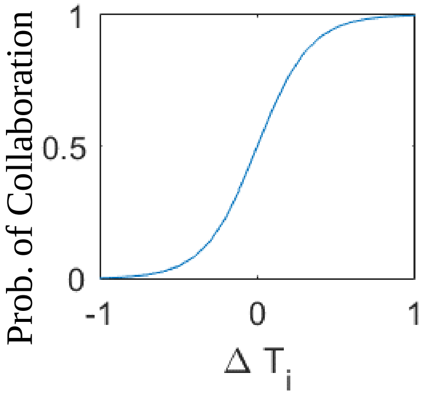
Environmental
Characteristics
Task
Team

Human
Characteristics
Ability
Personality

Human-
Agent
Team Trust

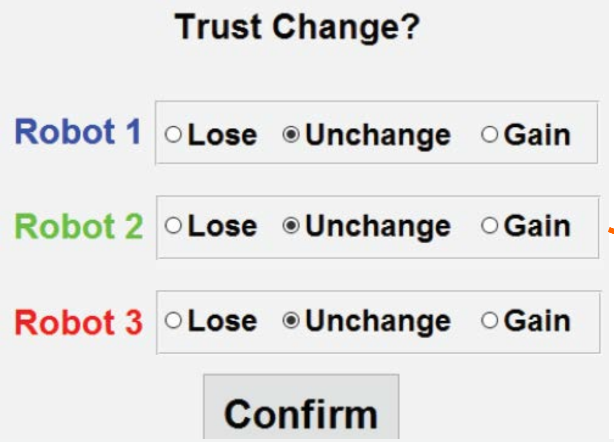
Agent
Characteristics
Performance
Attribute

Autonomy Allocation

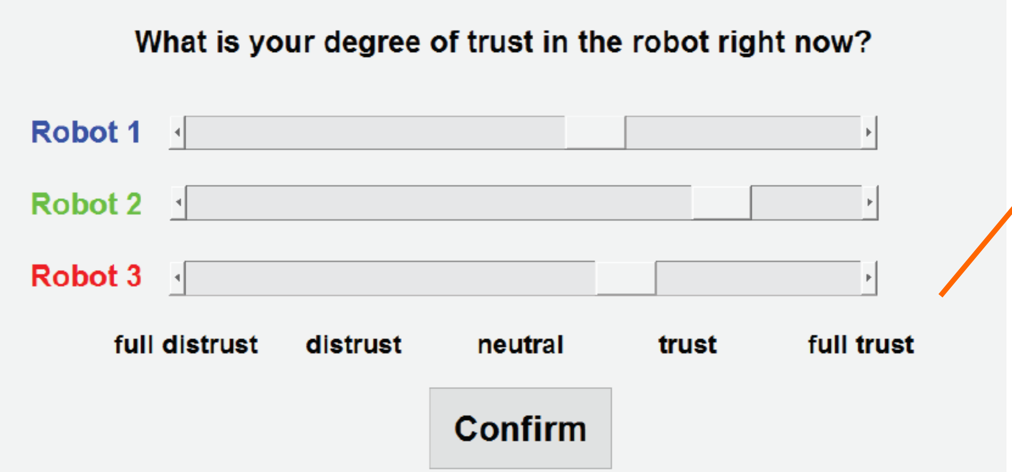


- Xu & Dudek. “OPTIMo: Online probabilistic trust inference model for asymmetric human-robot collaborations”, In *Proc. ACM/IEEE Int. Conf. HRI*, 2015.
- Lee & Moray, “Trust, control strategy, and allocation of function in human-machine systems”, *Ergonomics*,1992.
- Hancock, et al. “A meta-analysis of factors affecting trust in human-robot interaction”, *Human Factors*, 2011.
- Hoff & Bashir, “Trust in Automation: Integrating Empirical Evidence on Factors that Influence Trust”, *Human Factors*, 2014

DBN Trust Models

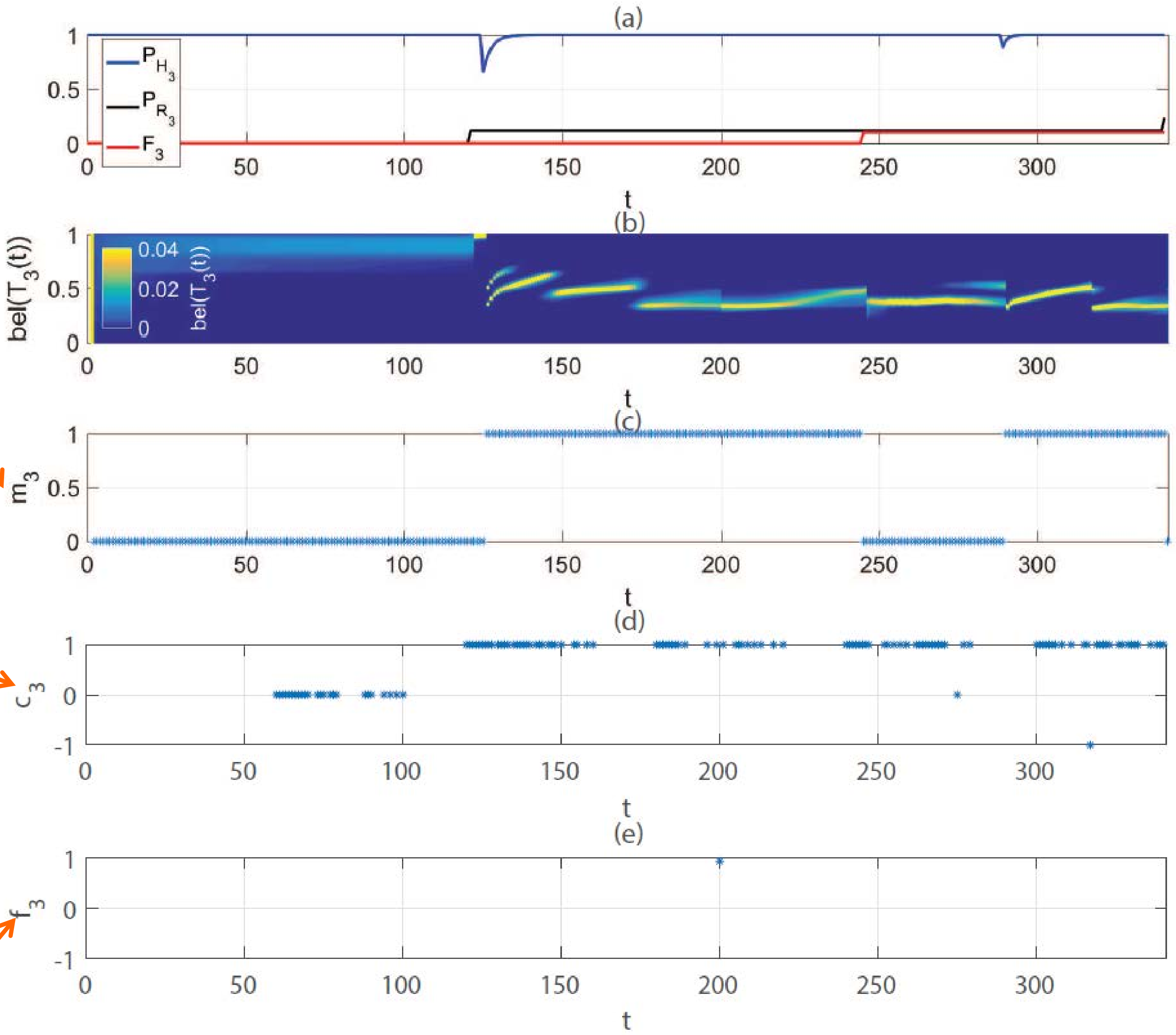

Trust Change?

Robot 1	○ Lose ● Unchange ○ Gain
Robot 2	○ Lose ● Unchange ○ Gain
Robot 3	○ Lose ● Unchange ○ Gain

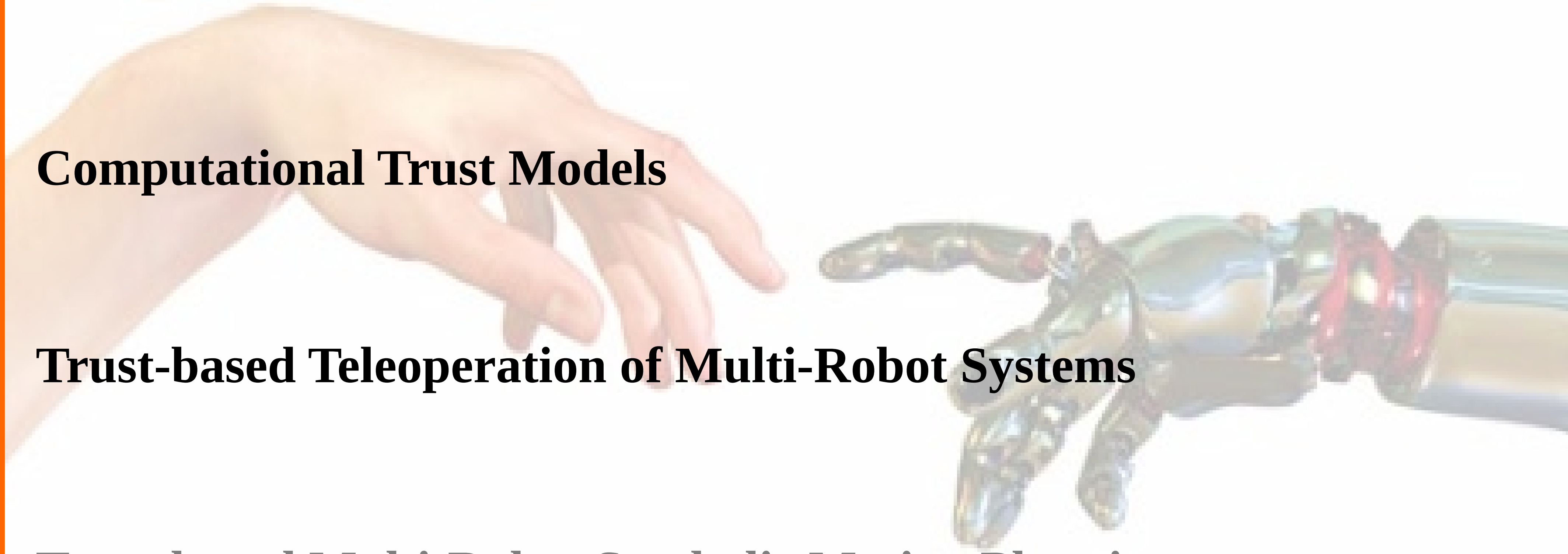

What is your degree of trust in the robot right now?

Robot 1
Robot 2
Robot 3

full distrust | distrust | neutral | trust | full trust



Real-time trust computation: (a) human, robot performance, fault, (b) trust belief, (c) human collaboration, (d) trust change, and (e) direct subjective trust measure



✓ Background and Motivation

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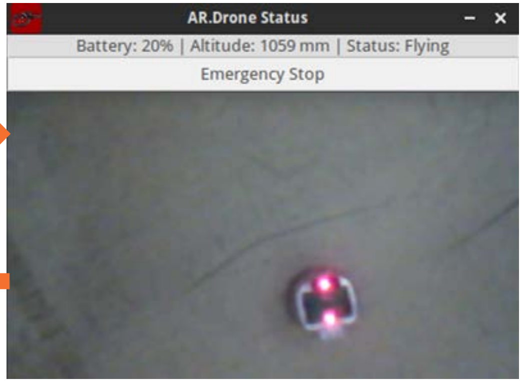
Tele-autonomous Operation of Mobile Robots

Delay

Delay

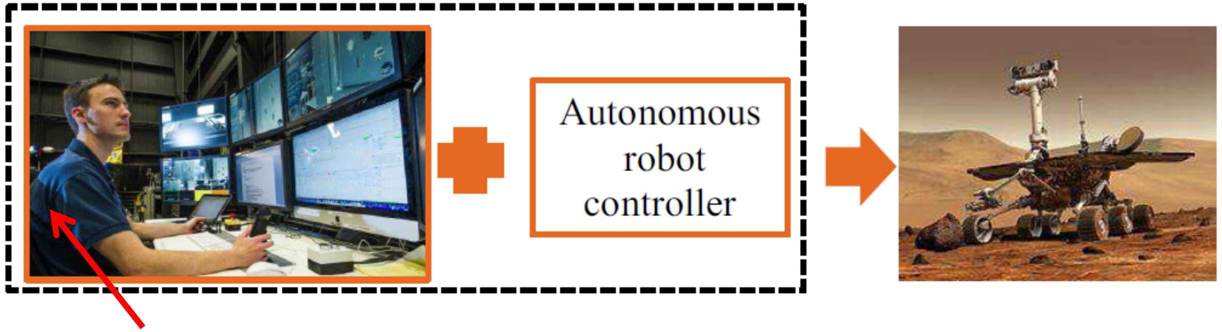


AR.Drone Status

Battery: 20% | Altitude: 1059 mm | Status: Flying

Emergency Stop

(Semi)autonomous Robotic Control Systems



Primary decision-maker

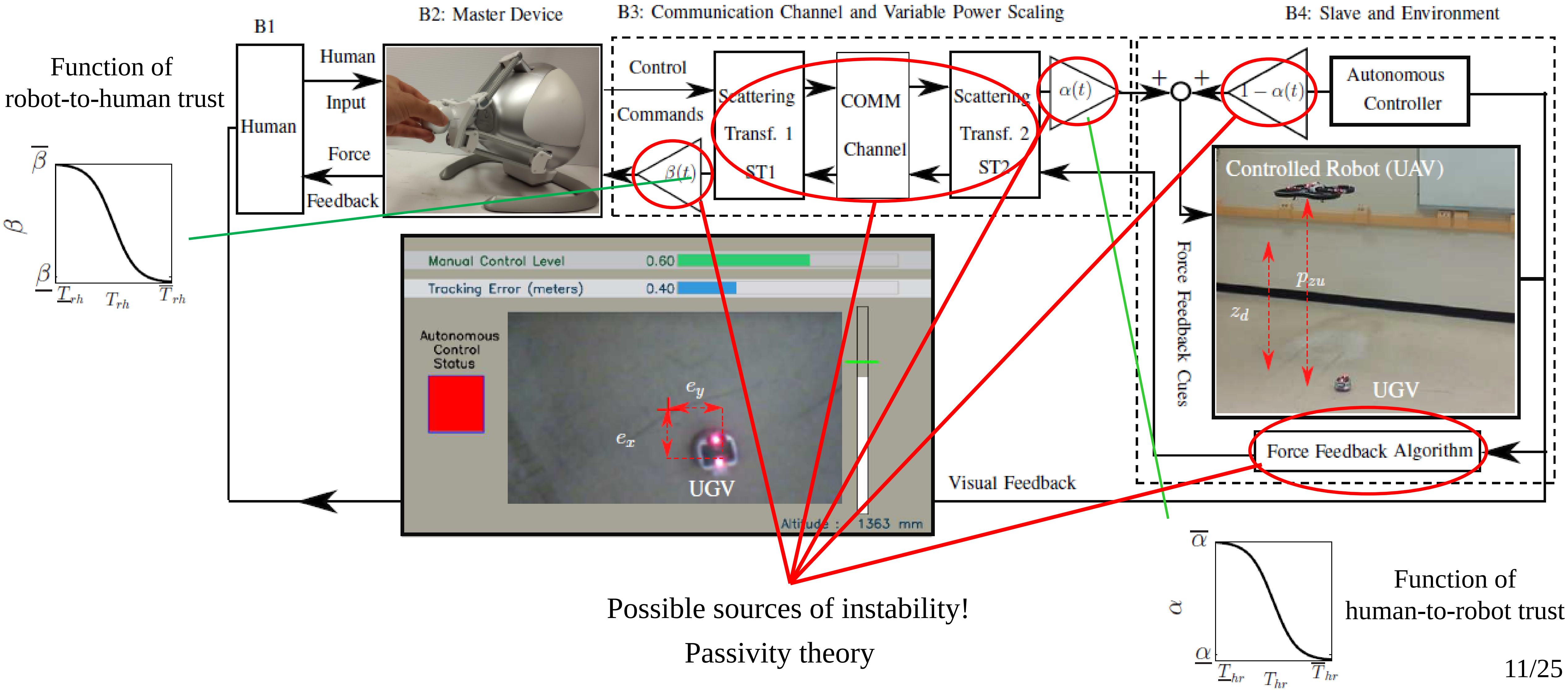
Automated decision aids via **objective computational** trust-based measures

Milder negative effects of improper trust in mobile robotic applications

Improper trust → Disproportionate Autonomy allocation → Decreased task performance and increased human workload

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]



Function of robot-to-human trust

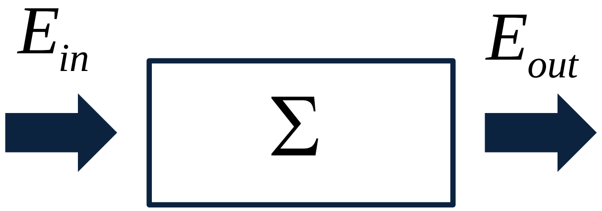
Possible sources of instability!

Passivity theory

Function of human-to-robot trust

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

Passivity Theory & Port Network Theory

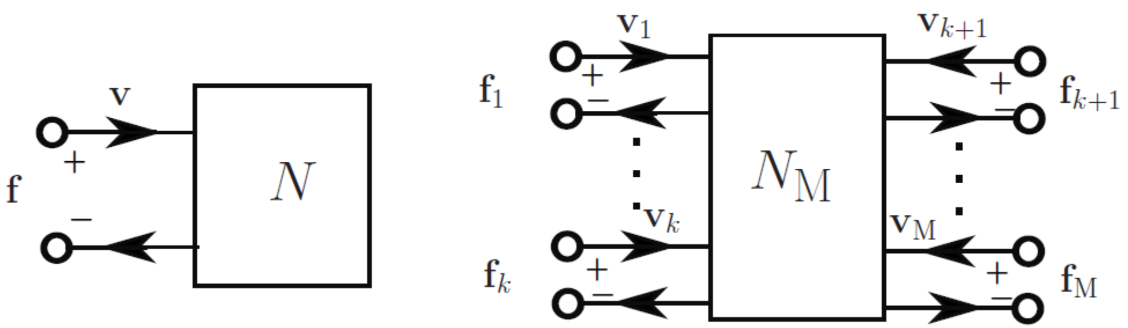


$$\Sigma : \dot{x} = f(x(t), u(t), t)$$

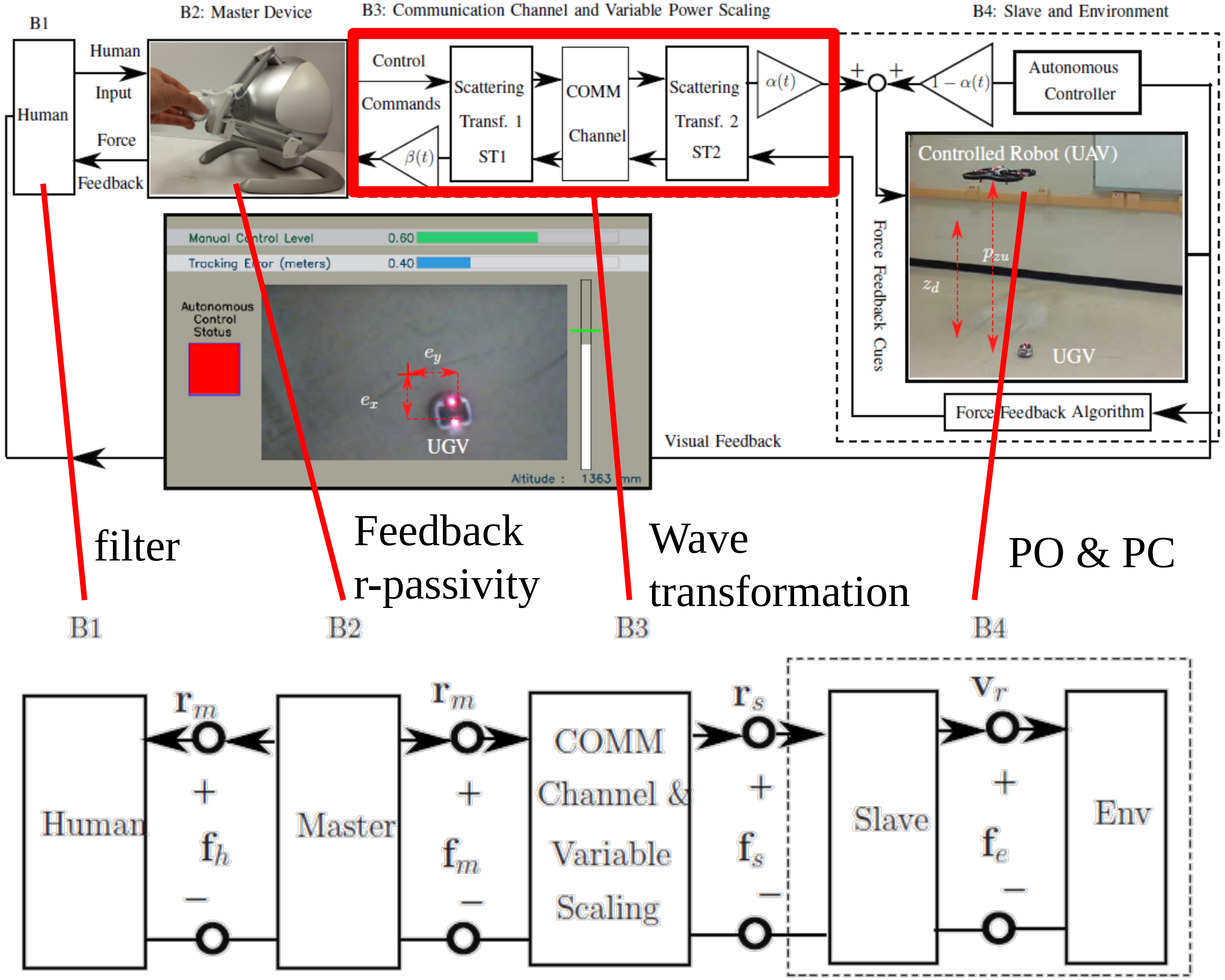
$$E_{out} \leq E_{in}$$

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

In teleoperation schemes force and velocities commands form the power ports



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



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

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

Dynamics of the Master Haptic Device

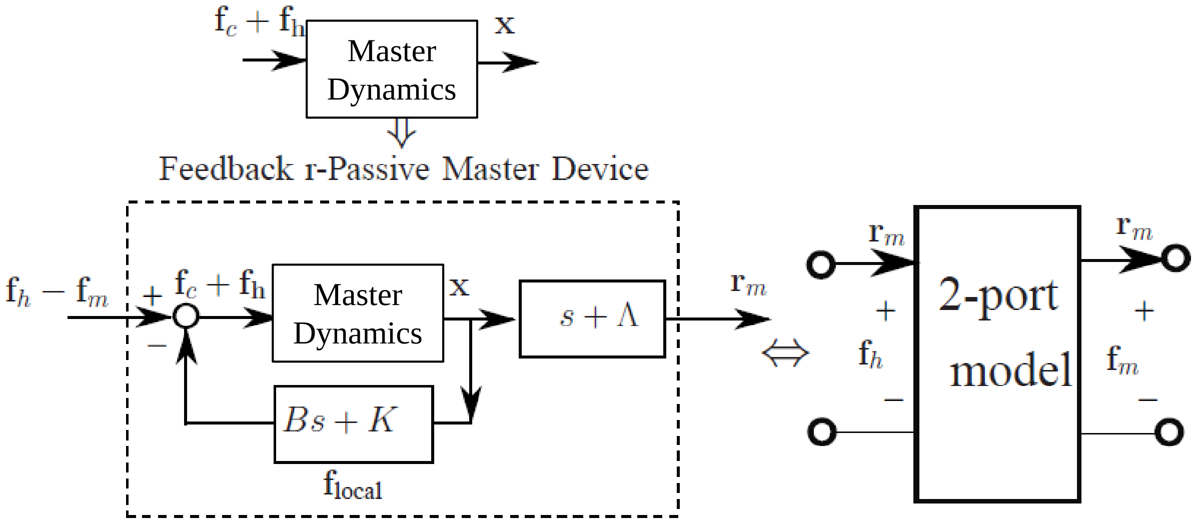
$$M(\mathbf{x})\ddot{\mathbf{x}} + C(\mathbf{x},\dot{\mathbf{x}})\dot{\mathbf{x}} = \mathbf{f}_c + \mathbf{f}_h\,, \quad \mathbf{f}_c = -\mathbf{f}_{\text{local}} - \mathbf{f}_m$$

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

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

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

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



Feedback r – Passivity of the Master

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

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

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

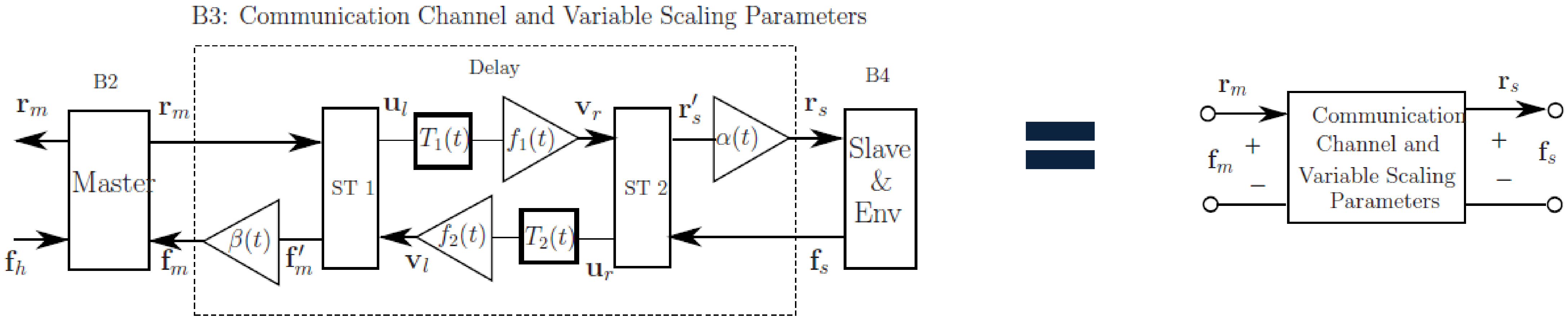
$$\begin{aligned} S_{hd}(t) \;&:=\; \dot{\mathbf{x}}^{\mathrm{T}}[B - \frac{1}{2}(M\Lambda + \Lambda M)]\dot{\mathbf{x}} + \mathbf{x}^{\mathrm{T}}\Lambda K \mathbf{x} \\ &\quad -\mathbf{x}^{\mathrm{T}}\Lambda C\dot{\mathbf{x}} \geq 0, \end{aligned}$$

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

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

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

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



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

Scattering/wave transformation used to guarantee passivity
(i.e. $\int_0^t \mathbf{r}_m^{\mathrm{T}}(\tau)\mathbf{f}_m(\tau) - \mathbf{r}_s^{\mathrm{T}}(\tau)\mathbf{f}_s(\tau)d\tau \geq 0$ assuming $E(0) = 0$)

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

$f_i = \sqrt{1 - \dot{T}_{i\,\max}}, \quad i = 1, 2,$ $\quad b > 0$: 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 $T_i(t)$

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

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

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

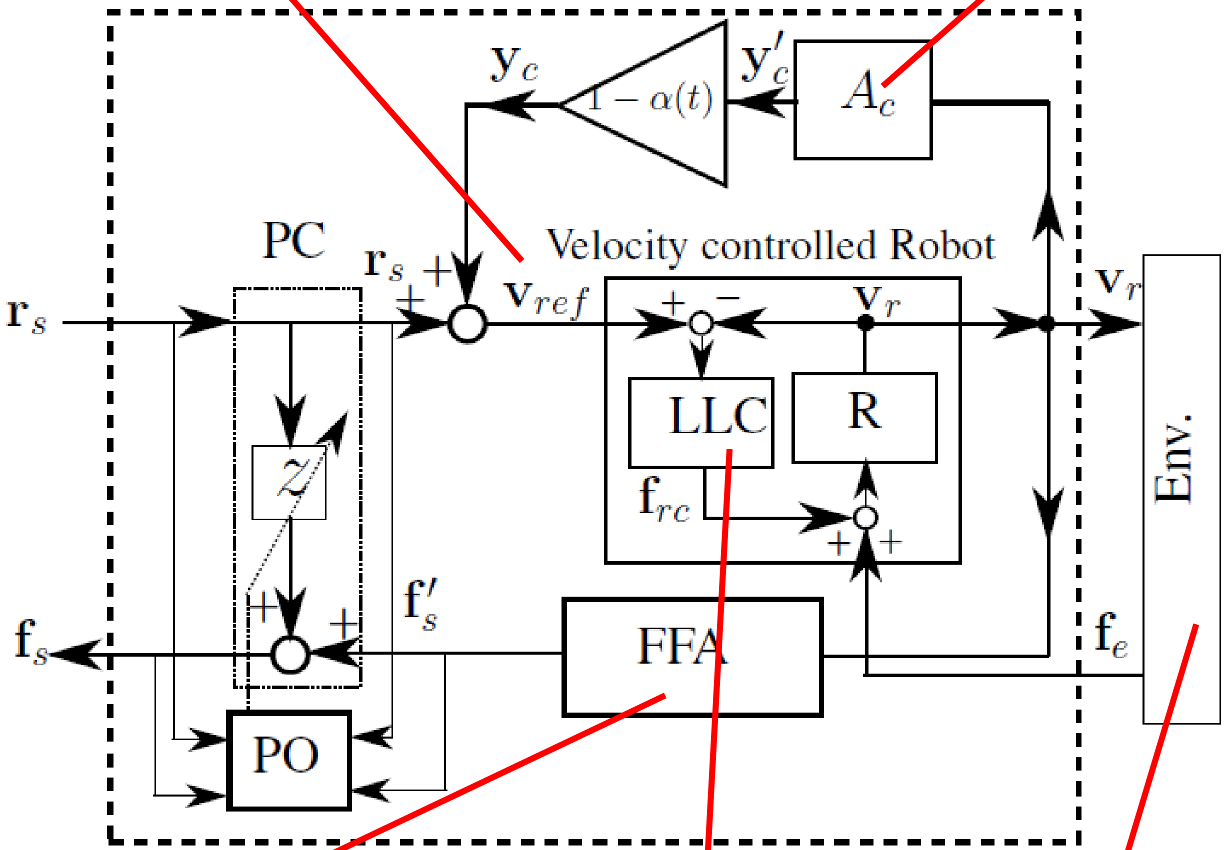
$$\mathbf{f}_s(t) = \mathbf{f}_s'(t) + z(t)\mathbf{r}_s(t)$$

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

Total velocity command to the robot

Slave

Local autonomous controller (high-level controller)



Force feedback algorithm

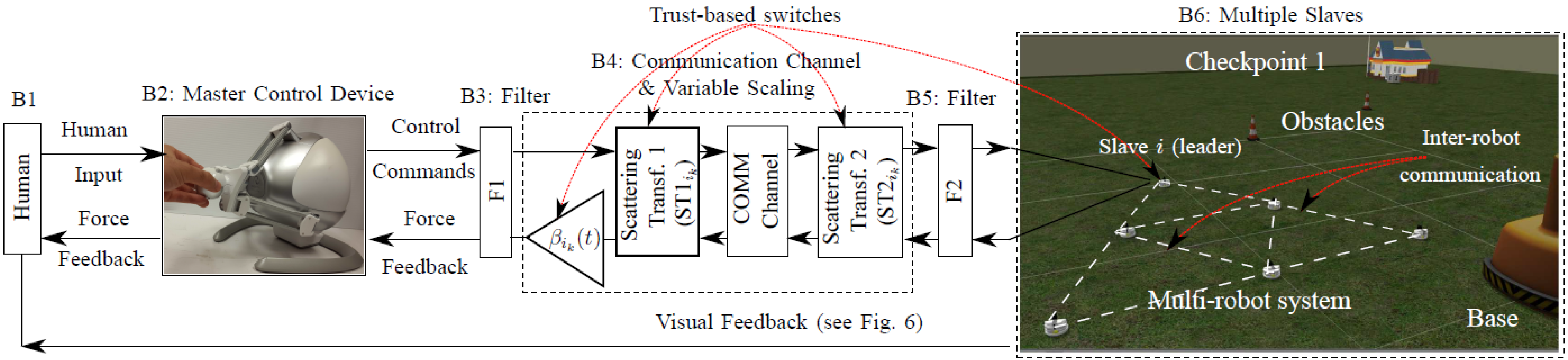
Velocity tracking controller (low-level controller)

Environmental disturbance

Trust-based Bilateral Teleoperation of Multi-Robot Systems [Saeidi et. al. IROS 2017]

Motivation

- Reduced manpower for control of a robot team
- Increased robustness and flexibility of the robotic agents via cooperation



Challenges

- Stability of the proposed scheme under the effects of switching
- Tracking performance of the system under the proposed scheme

Passivity of Switched Systems

[Saeidi et. al. IROS 2017]

Definition 3 [118] For systems with discontinuous supply rate, and/or switched inputs/outputs with a common storage function, the following must hold

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

where t_ks are the time instants that discontinuities in the inputs and outputs or a switching of the system input and output.

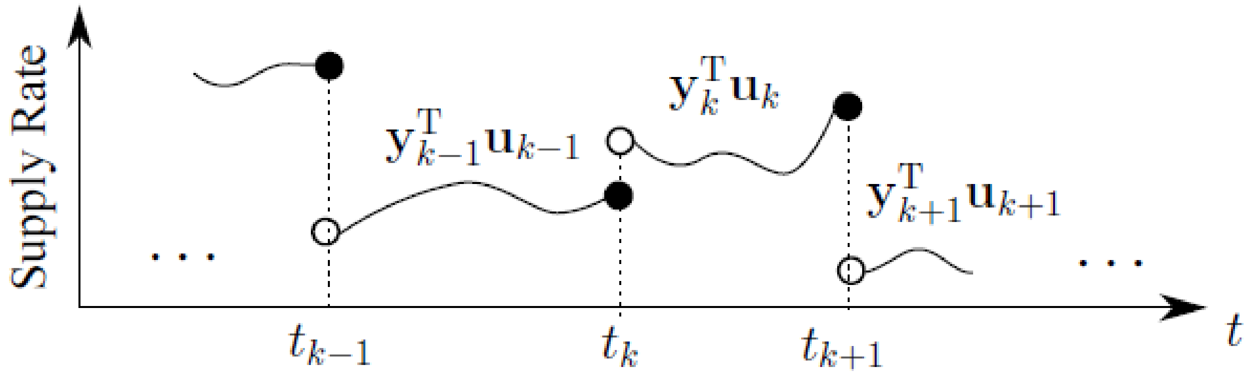
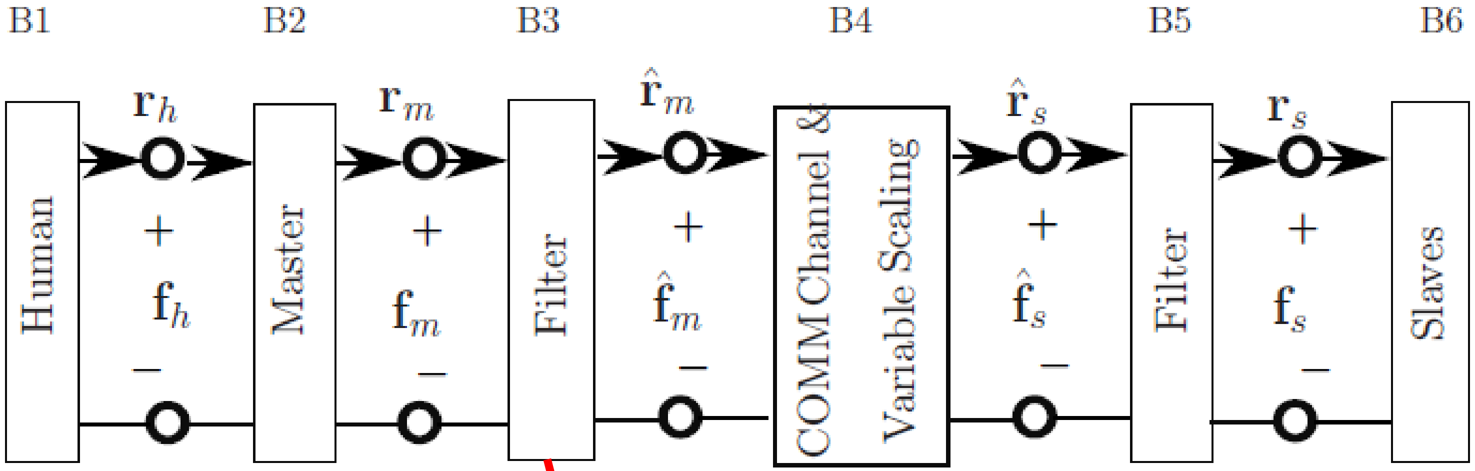


Fig. 2: Discontinuous/switched supply rate.

Passivity of the Trust-based Bilateral Teleoperation of Multi-Robot Systems

[Saeidi et. al. IROS 2017]



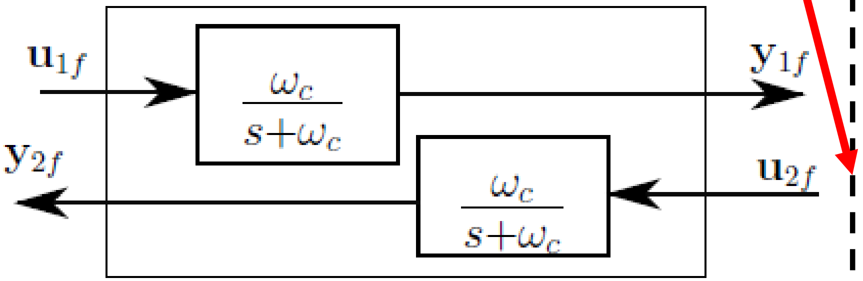
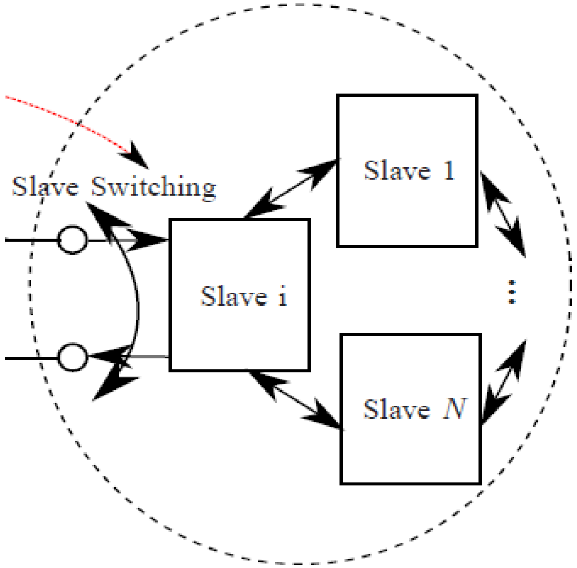


Fig. 5: Two-port filter.

- Select a leader robot with the highest trust level



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

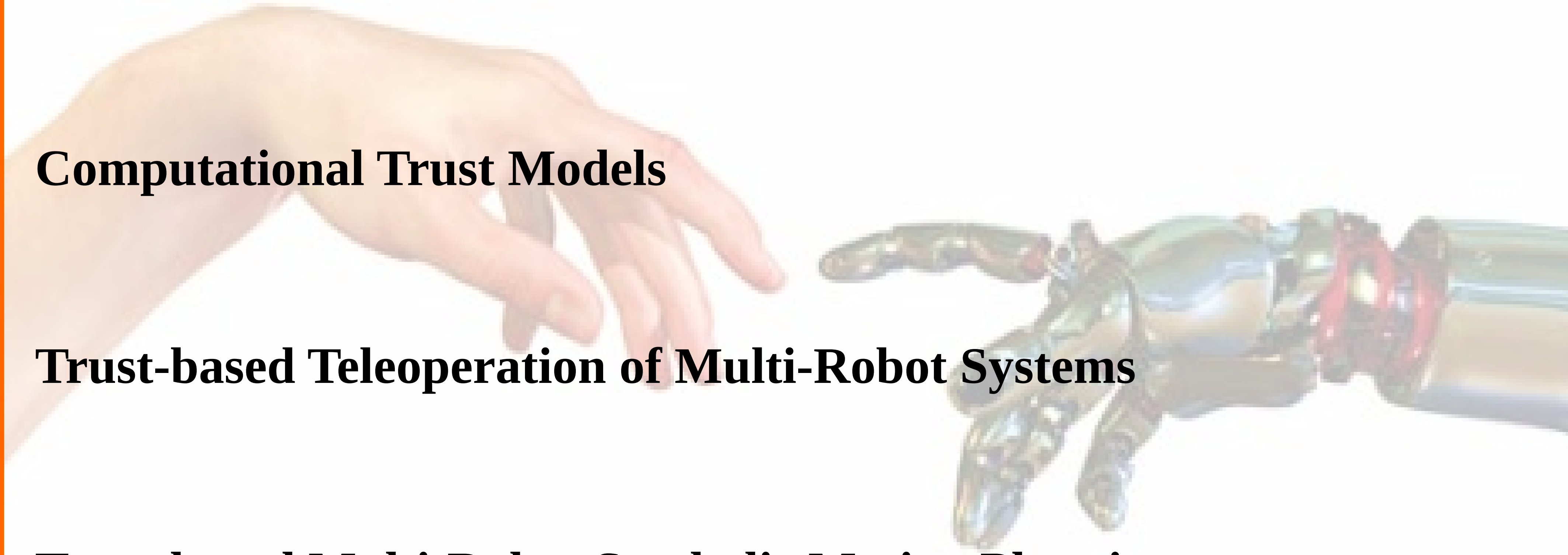
$$\delta_{i_k}(t) = \begin{cases} 1 & \text{if slave } i \text{ is the leader} \\ 0 & \text{otherwise} \end{cases}$$

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

input $r_{s_k}(t)$

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

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



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Conclusions

Trust-based Multi-Robot Symbolic Motion Planning

Linear Temporal Logic (LTL)

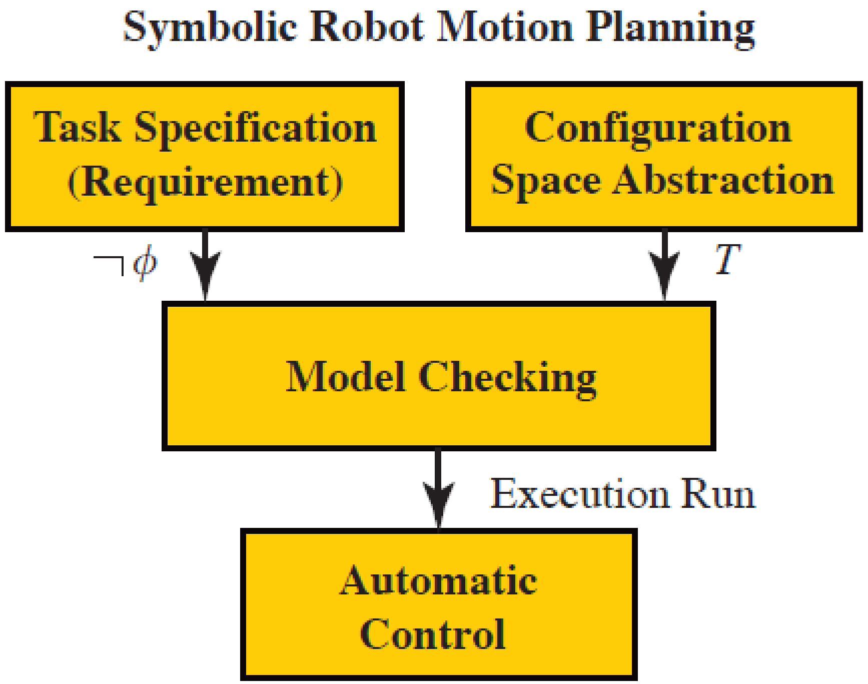
- ***Propositional Operators***: negation ¬ , conjunction ∧, disjunction ∨, implication →, equivalence ↔
- ***Temporal Operators***: until U, always □, eventually ◊
- ***Expressive Motion Tasks***: Reachability (liveliness) $\Diamond\pi_1$, obstacle avoidance and safety $\Box\neg\pi_2$, convergence (stability) $\Diamond\Box\pi_1$, sequencing and temporal ordering

Labeled Transition System (LTS)

A transition system is a tuple $T = (S, S_0, Act, \delta, \Pi, L)$, where S is a set of states, S_0 is a set of initial states, Act is a set of actions, δ is a transition relation, Π is the set of atomic propositions, and L is a labeling function.

Model Checking

Checking whether T satisfies $\emptyset$ over Π is called model checking. A model checker will return true if the formula is satisfied. If no such run can be found, the model checker returns a counterexample.



Symbolic Robot Motion Planning

Task Specification (Requirement)

Configuration Space Abstraction

$\neg\phi$

T

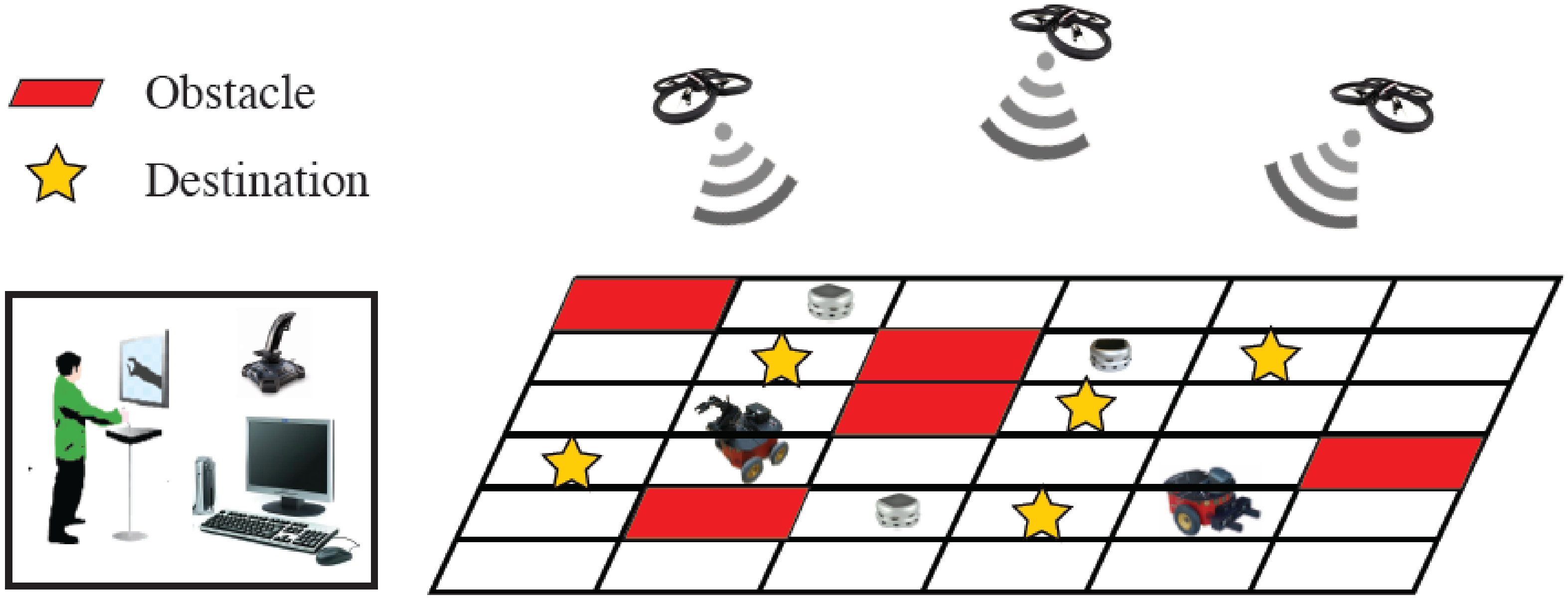
Model Checking

Execution Run

Automatic Control

Trust-based Multi-Robot Symbolic Motion Planning

[Spencer et. al., IROS 2016; Mahani and Wang, DSCC 2016; Wang et. al., ACM TiiS 2017]



Example High-level Specification for ISR Tasks

$$\phi = \underbrace{\bigwedge_{j\in \text{Goals}} \Diamond \pi_j \wedge \bigwedge_{j\in \text{Final Goals}} \Diamond\Box\pi_j}_{Reachability} \wedge \underbrace{\bigwedge_{j\in \text{Obs}} \Box\neg\pi_j}_{Obstacle\ Avoidance} \wedge \underbrace{\bigwedge_{i=1}^{N}(\pi_i^c \wedge \pi_i^o \rightarrow \neg\pi_i^u)}_{Robot\ Collision\ Avoidance}$$

Trust-based Multi-Robot Symbolic Motion Planning

[Spencer et. al., IROS 2016; Mahani and Wang, DSCC 2016; Wang et. al., ACM TiiS 2017]

Trust-based Decomposition

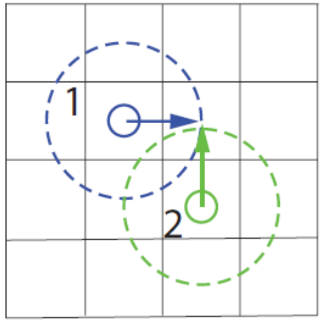
- High trust: more tasks assigned to more trusted robot
- Low trust: fewer tasks assigned to less trusted robot

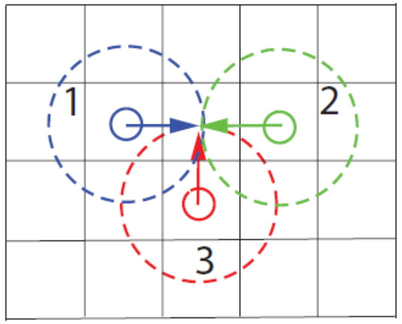
Compositional Reasoning

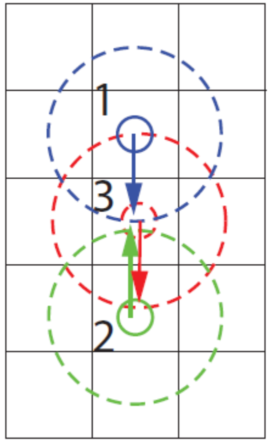
- Interleaving of transition systems
- Unconditional fairness
- AP for Comm, Obs, & Ctrl

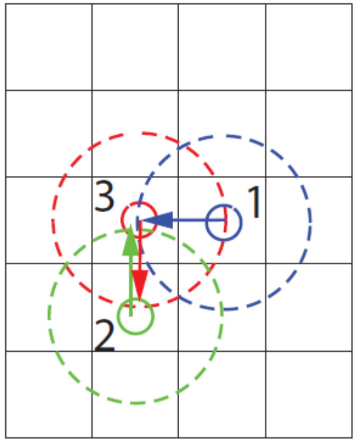
Deadlock- and Livelock- Free Algorithms

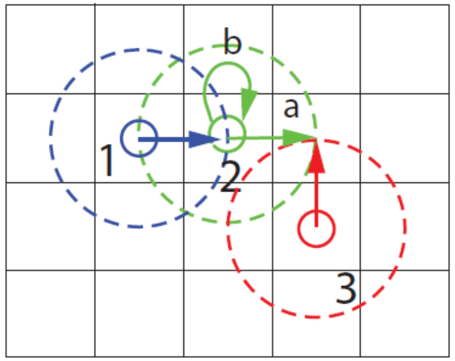
- Goal destination reachability
- Inter-robot collision avoidance
- A human-in-the-loop

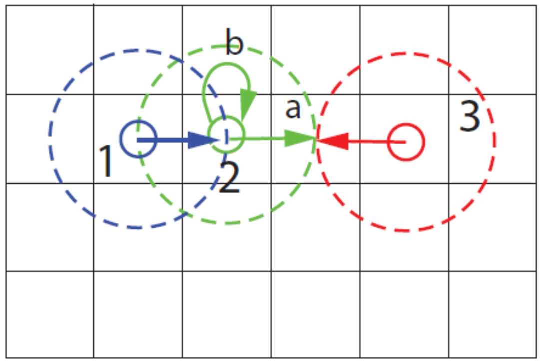


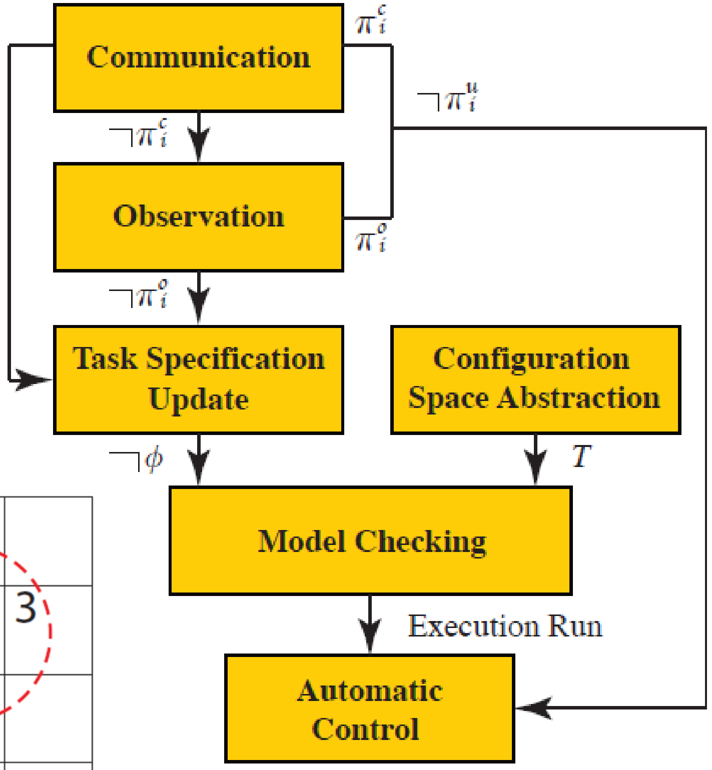












Communication

Observation

Task Specification Update

Configuration Space Abstraction

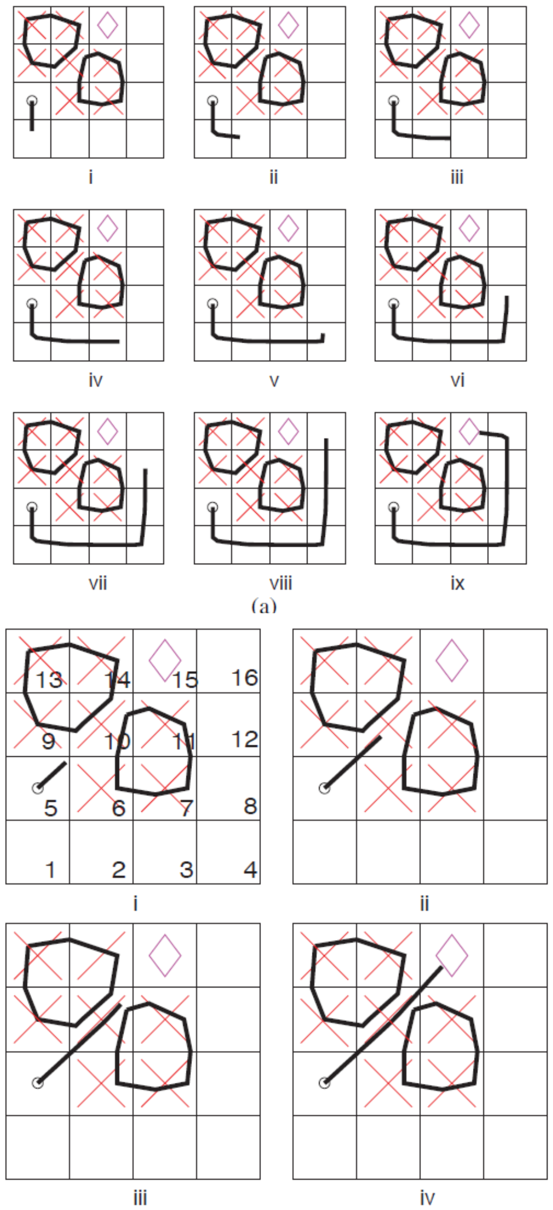
Model Checking

Automatic Control

$$\bigwedge_{i=1}^{N}(\pi_i^c \wedge \pi_i^o \rightarrow \neg\pi_i^u)$$

Trust-based Multi-Robot Symbolic Motion Planning

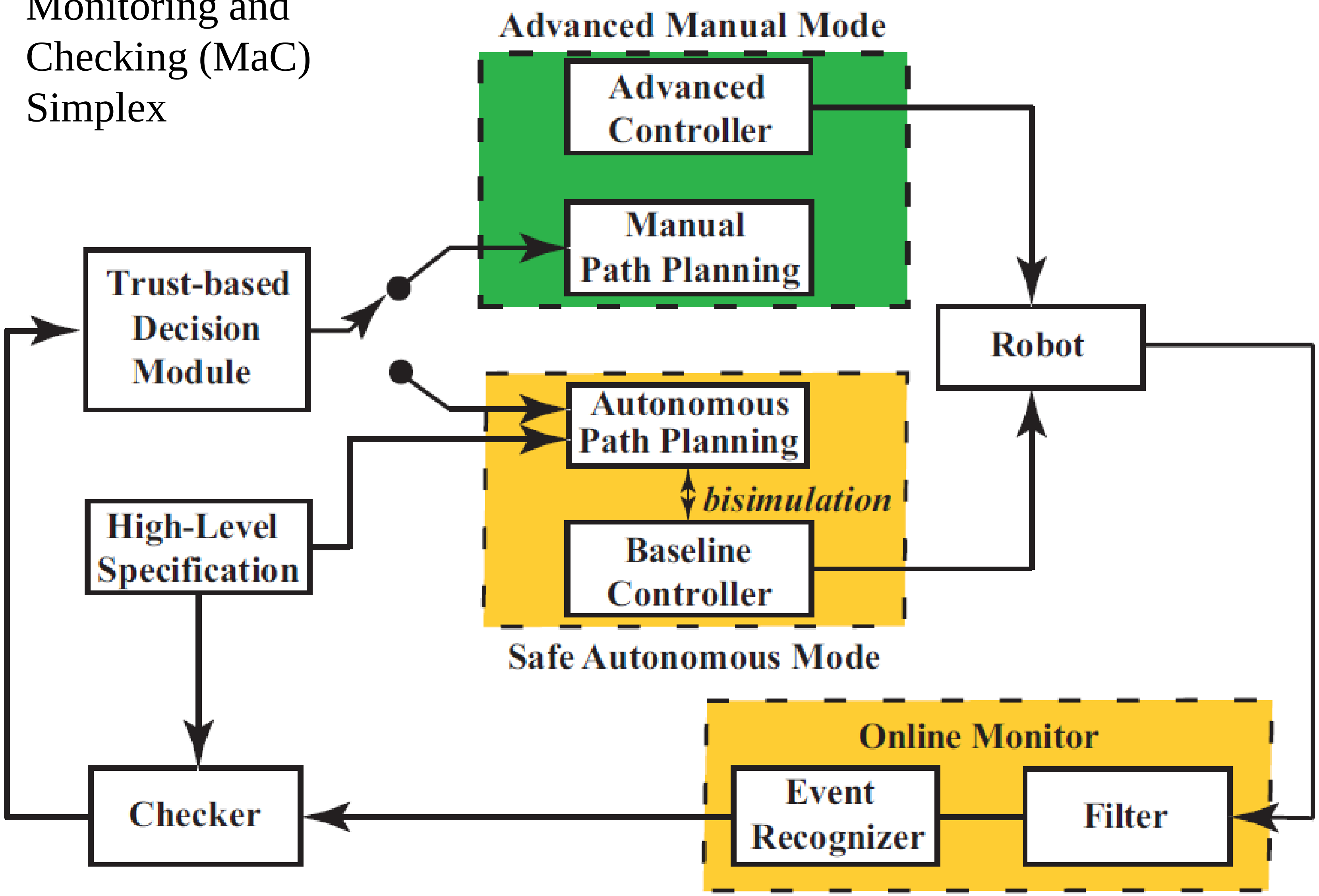
[Spencer et. al., IROS 2016; Mahani and Wang, DSCC 2016; Wang et. al., ACM TiiS 2017]



(a)

(b)

- Monitoring and Checking (MaC)
- Simplex



Advanced Manual Mode

Advanced Controller

Manual Path Planning

Trust-based Decision Module

Robot

Autonomous Path Planning

bisimulation

Baseline Controller

High-Level Specification

Safe Autonomous Mode

Online Monitor

Event Recognizer

Filter

Checker

Background and Motivation

Computational Trust Models

Trust-based Teleoperation of Multi-Robot Systems

Trust-based Multi-Robot Symbolic Motion Planning

Conclusions

Conclusions

- Computational trust models that are dynamic, quantitative, and probabilistic for real-time robotic operation
  - Human trust in robot; Robot trustworthiness; Robot trust in human; Trust propagation in multi-robot systems
- Mutual trust based bilateral teleoperation of mobile robots
  - Trust based shared control; Trust based haptic feedback; Passivity based analysis for multi-robot switches
- Trust based symbolic multi-robot motion planning with a human-in-the-loop
  - Trust based compositional reasoning for multi-robot systems; Trust based run time verification for switches between manual and autonomous motion planning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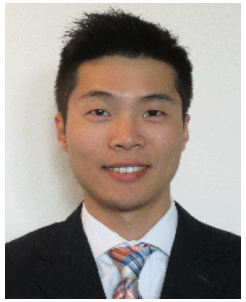
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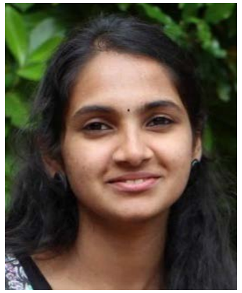
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Thank you!

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