HUMAN-ROBOT COLLABORATION IN MANUFACTURING: TRUST-BASED ROBOT CONTROL, DECISION-MAKING, AND MOTION PLANNING

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Robot Assisted Manufacturing: Challenges and Opportunities

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Interdisciplinary &
Intelligence Research

I2R Research Overview & Motivation

Computational Trust Models

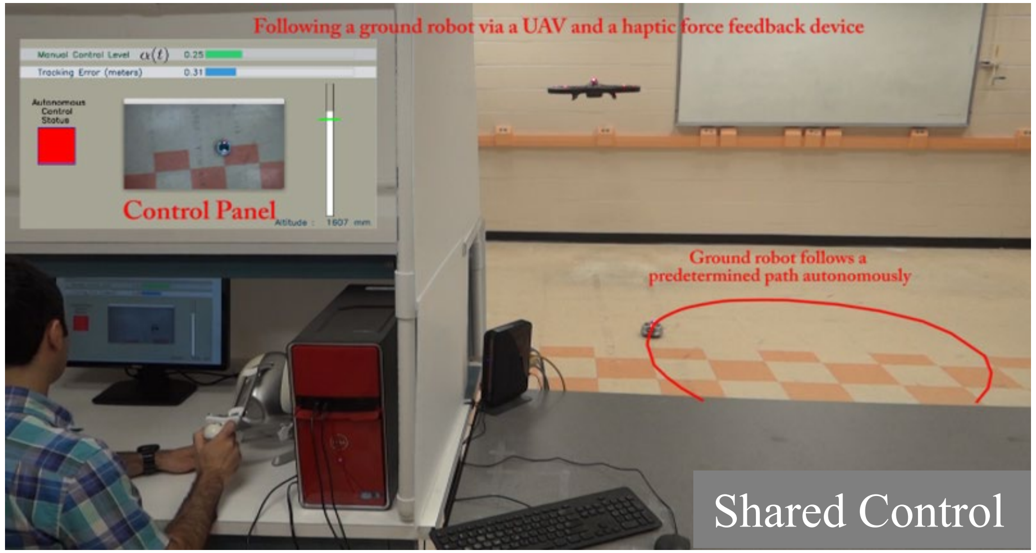
Trust-based Human-Robot Collaborative Pick and Place (PnP)

Trust-based Robot-Human Handover

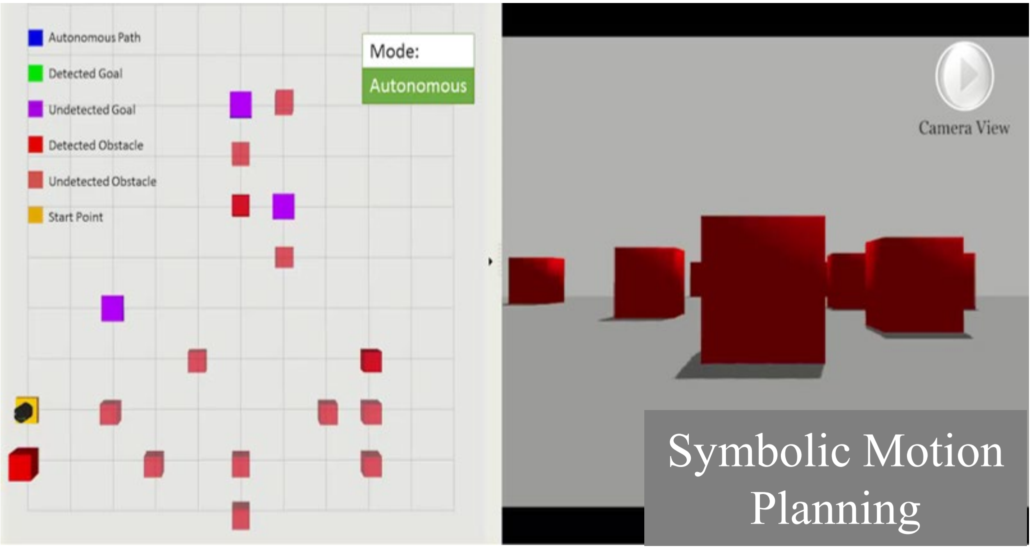
Trust-based Human-Robot Co-Manipulation

Robotics Education & Conclusion

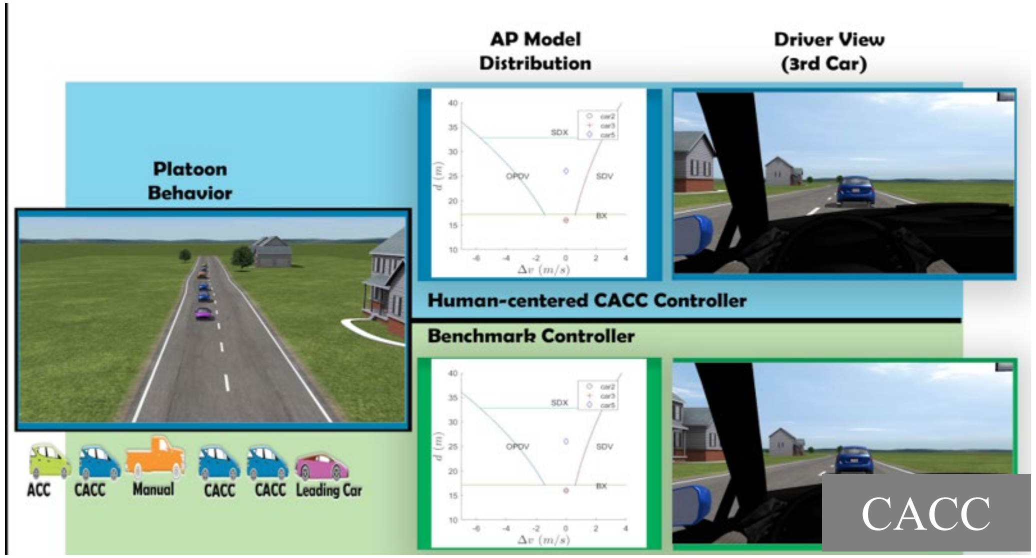
I2R Research Overview



[Fu et. al., JGCD 18; Saeidi et. al., RAL 18, IROS 17; Saeidi et. al., T-Ro 17; Saeidi et. al., ACC 16]



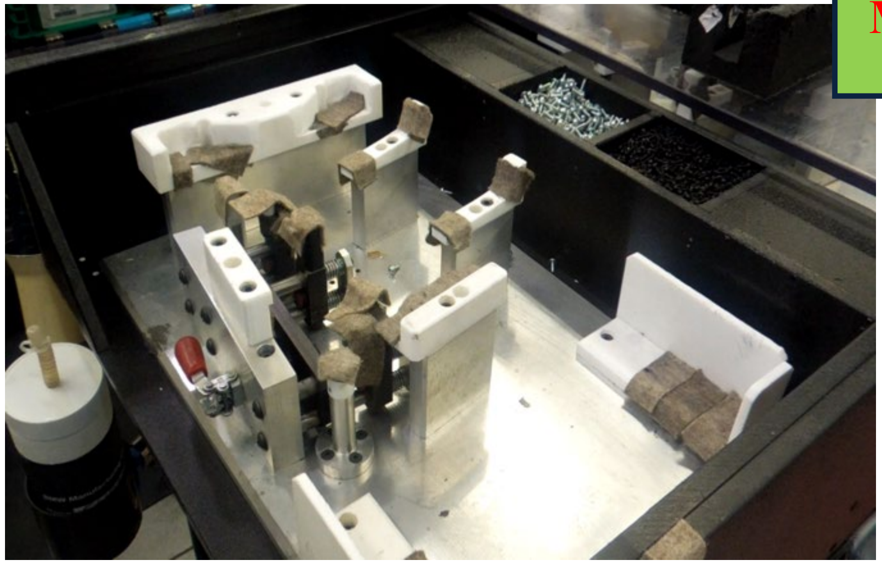
[Zheng & Wang, ACC 19 [ThC01]; Wang et. al., TiiS 18; Mahani & Wang, DSCC 18; Spencer et. al., IROS 16]



[Wang et. al., JCAV 19; Sarker et. al., ITS 19; Li & Wang, ITS 17; Dey et. al., ITS 16]

[Rahman & Wang, Mechatronics, 18; Sadr & Wang, TASE 17; Sadr et. al., CASE 16; M. Rahman et. al. CASE 16a]

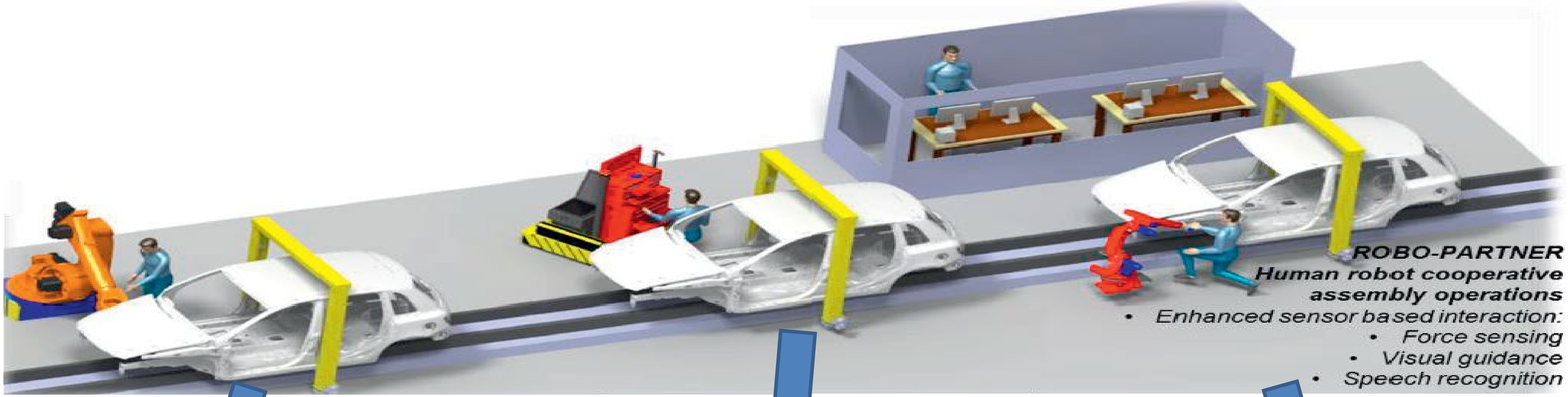
Human-Robot Collaboration (HRC) in Manufacturing



Hybrid
Manufacturing Cell

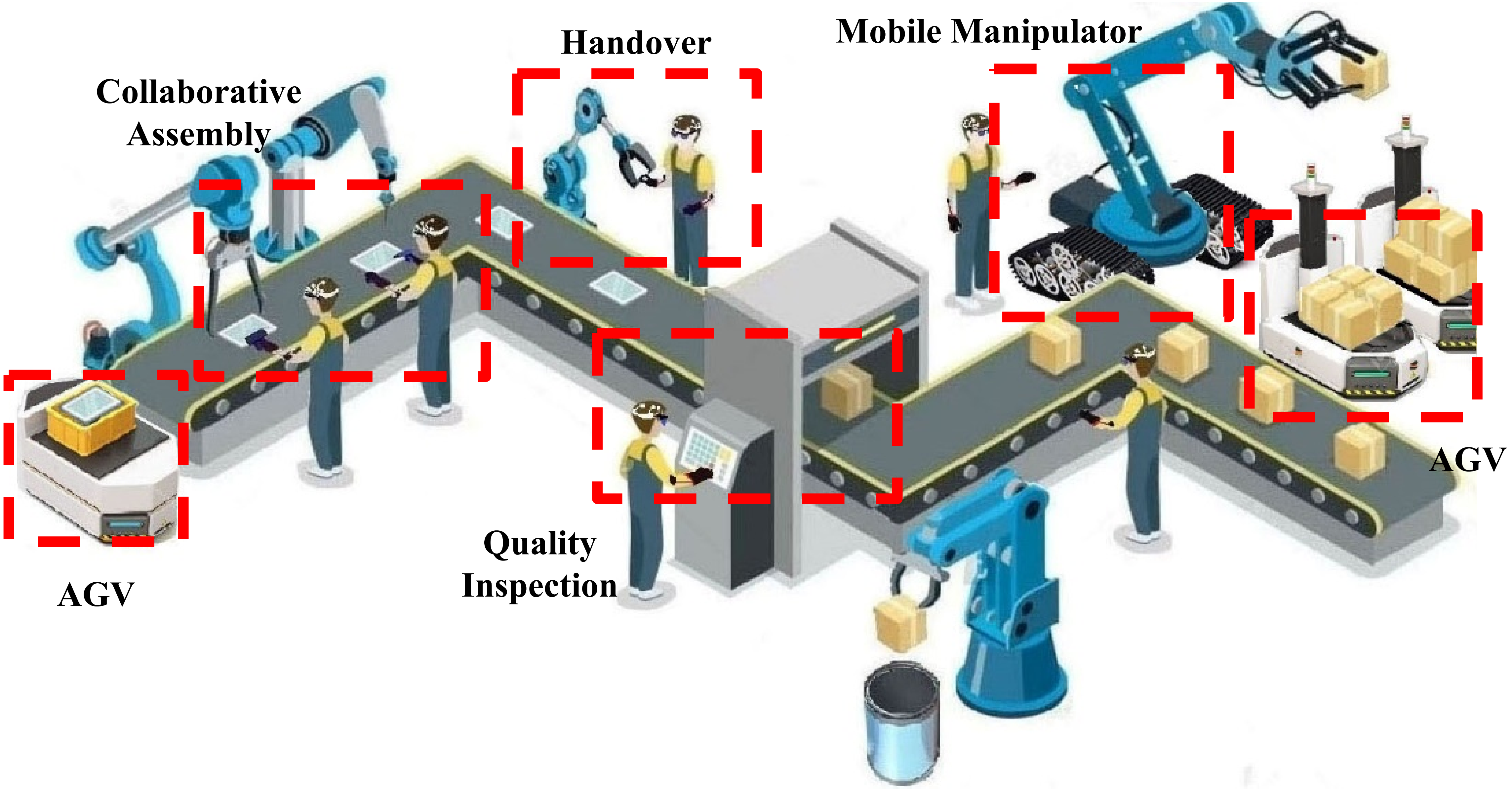
*Photo & Video Courtesy: BMW, Spartanburg, SC

Human-Robot Collaboration (HRC) in Manufacturing



*ROBO-PARTNER by Michalos et. al., 2014 - CIRP Conference on Assembly S&T

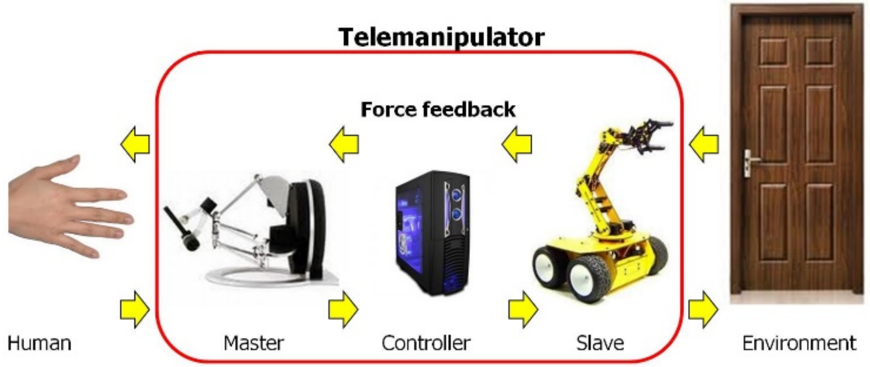
Human-Robot Collaboration (HRC) in Manufacturing

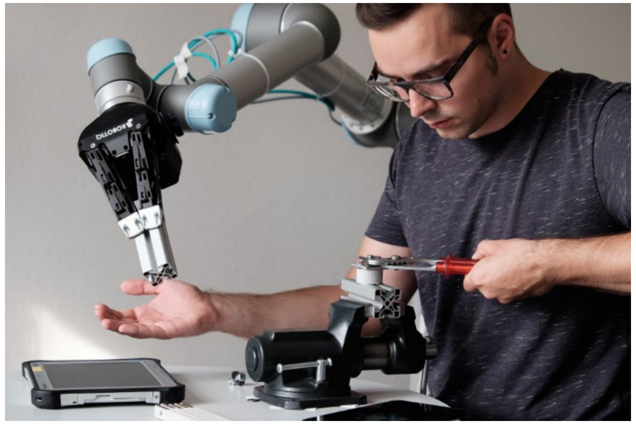


Why is Trust Important?

- 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.

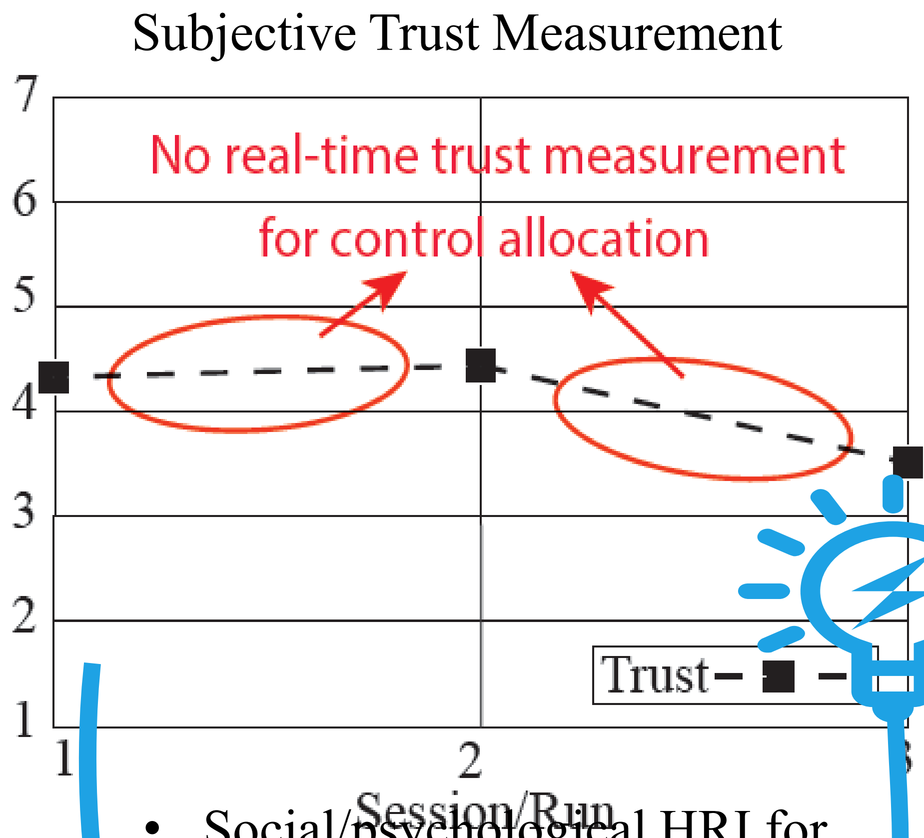




Background & Motivation - Trust

Trust

- Central enabl
  allocation of
- Qualitative n
- Little insight
  performance



HRI

- HMI design
- Lack understanding of the dynamic interaction for real-time robotic operations in complex and uncertain environments
- Lack system-level performance guarantees
- HRI in multi-robot systems
- Beyond safety and optimality? Human intent

- Social/psychological HRI for real-time robotic operations
- Quantitative analysis
- Control theory, decision theory, robot motion planning, and human factors analysis

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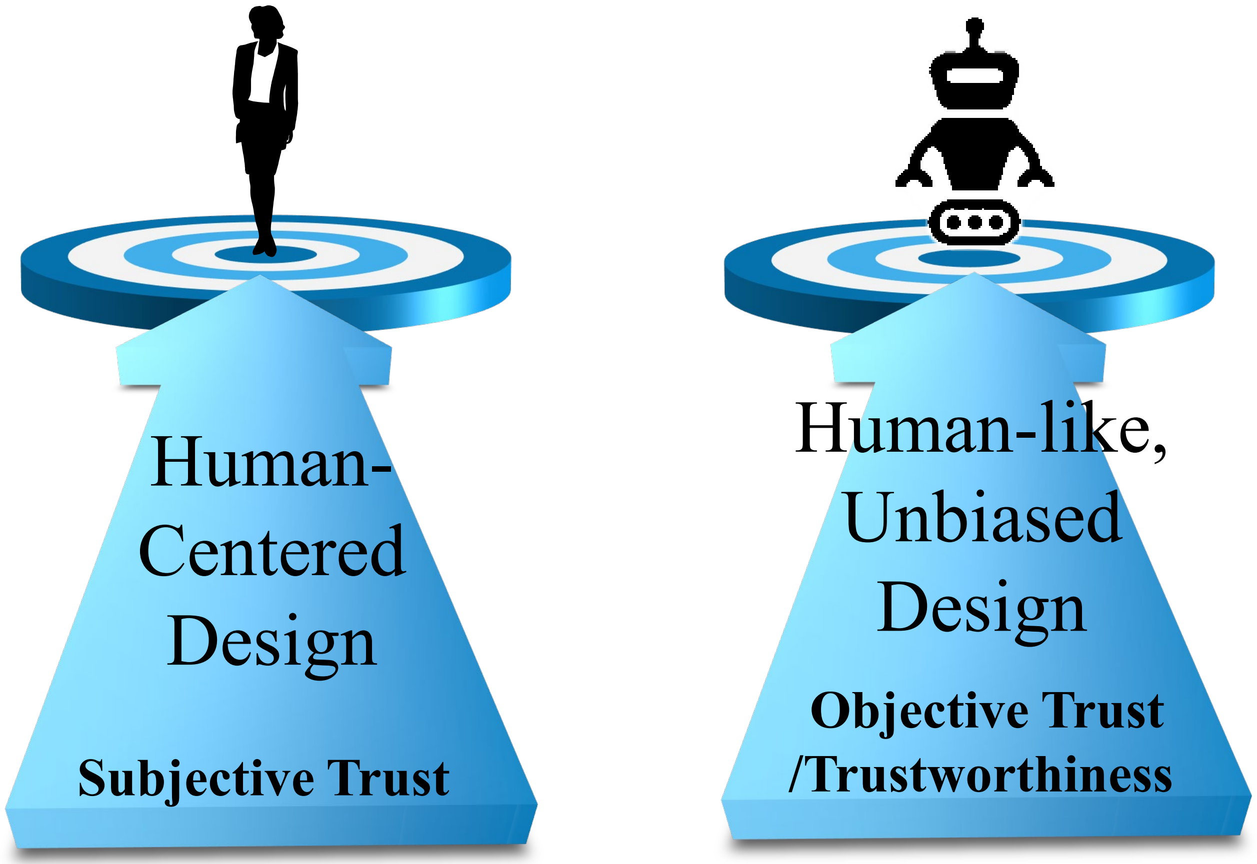
Computational Trust Models

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]



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

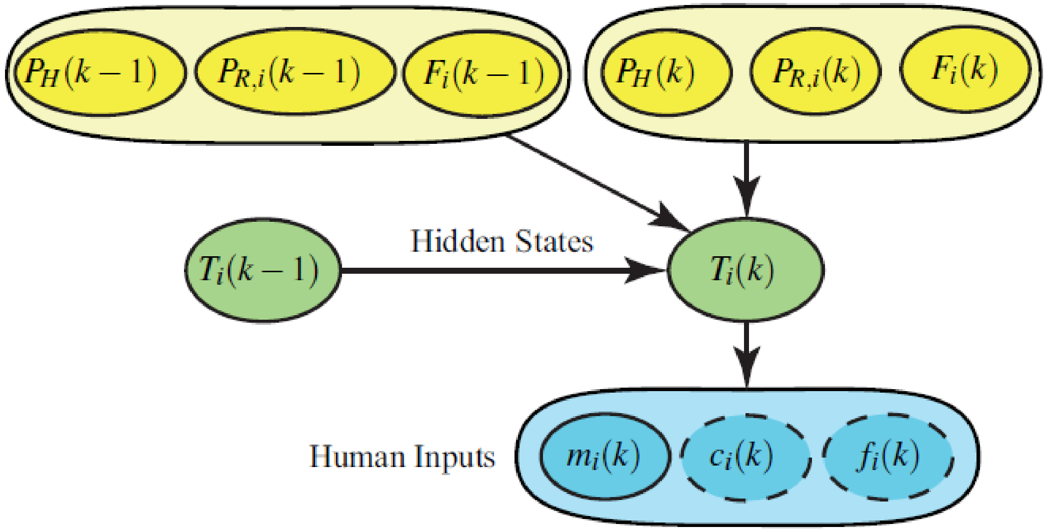
  [Wang et. al. ACC 2015, CPS 2015; Wang & Zhang ed., Spring 2017; Mizanoor & Wang, Mechatronics, 2018]

- RoboTrust for multi-robot systems

  [Saeidi et. al., IROS 2017]

DBN Trust Models

[Wang et. al., ACM TiiS, 2018]



Trust belief

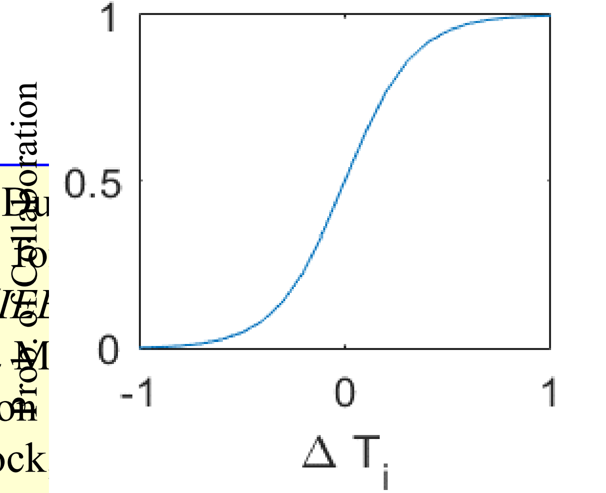
$$\mathrm{Prob}(T_i(t)|P_{R,i}(1:t),P_H(1:t),F_i(1:t),m_i(1:t),c_i(1:t),f_i(1:t),T_i(0))$$

$$= bel(T_i(t)) = \frac{\int \overline{bel}(T_i(t),T_i(t-1))\mathrm{d}T_i(t-1)}{\int\int \overline{bel}(T_i(t),T_i(t-1))\mathrm{d}T_i(t-1)\mathrm{d}T_i(t)}$$

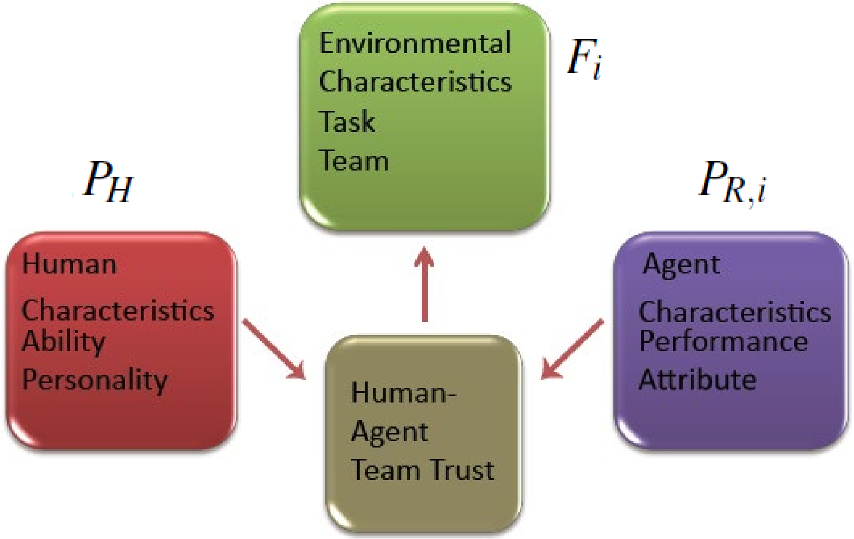
$$\overline{bel}(T_i(t),T_i(t-1))$$
$$= \mathrm{Prob}(m_i(t)|T_i(t),T_i(t-1))\mathrm{Prob}(c_i(t)|T_i(t),T_i(t-1))\mathrm{Prob}(f_i(t)|T_i(t))\cdot$$
$$\mathrm{Prob}(T_i(t)|T_i(t-1),P_{R,i}(t),P_{R,i}(t-1),P_H(t),P_H(t-1),F_i(t),F_i(t-1))bel(T_i(t-1))$$

$$\mathrm{Prob}(m_i(t)=1|T_i(t),T_i(t-1)) = (1+exp(-(\omega_1 T_i(t)-\omega_2 T_i(t-1))))^{-1}$$

Autonomy Allocation



Main Factors



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- Lee & M… …d allocation of function… …*gonomics*, 1992.
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- Hoff & Bashir, "Trust in Automation: Integrating Empirical Evidence on Factors that Influence Trust", *Human Factors*, 2014

$$\mathrm{Prob}(T_i(t)|T_i(t-1),P_{R,i}(t),P_{R,i}(t-1),P_H(t),P_H(t-1),F_i(t),F_i(t-1))$$
$$= \mathcal{N}(T_i(t);\bar{T}_i(t),\sigma_i(t))$$

where $\bar{T}_i(t) = A\,T_i(t-1)+B_1P_{R,i}(t)-B_2P_{R,i}(t-1)+C_1P_H(t)-C_2P_H(t-1)$
$+D_1F_i(t)-D_2F_i(t-1).$

Time-series trust model

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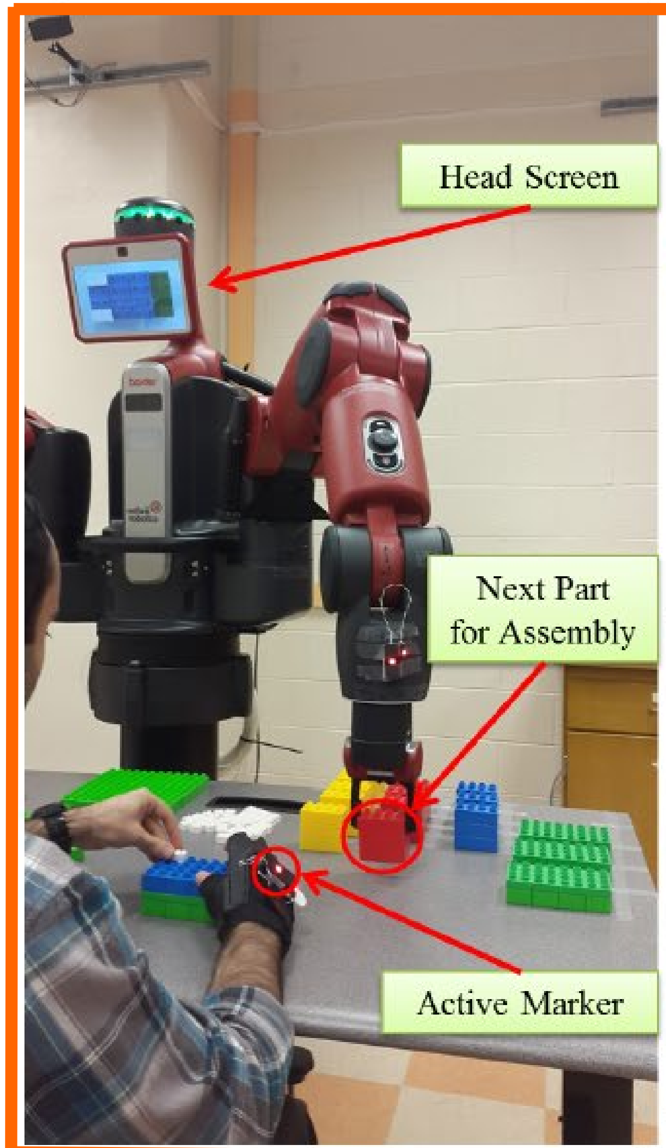
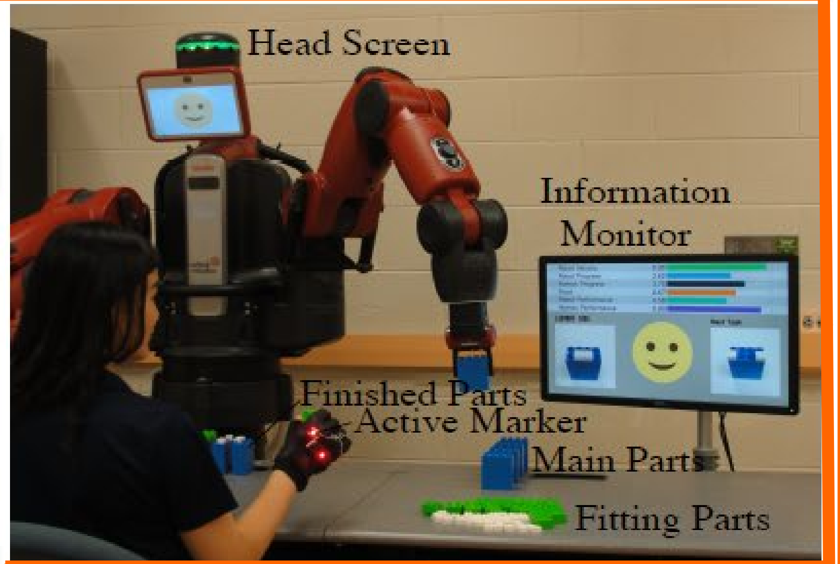
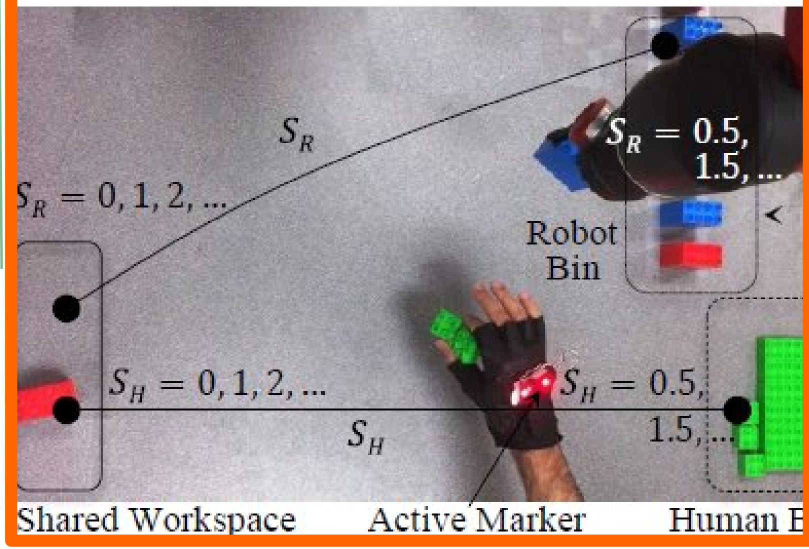
Conclusion

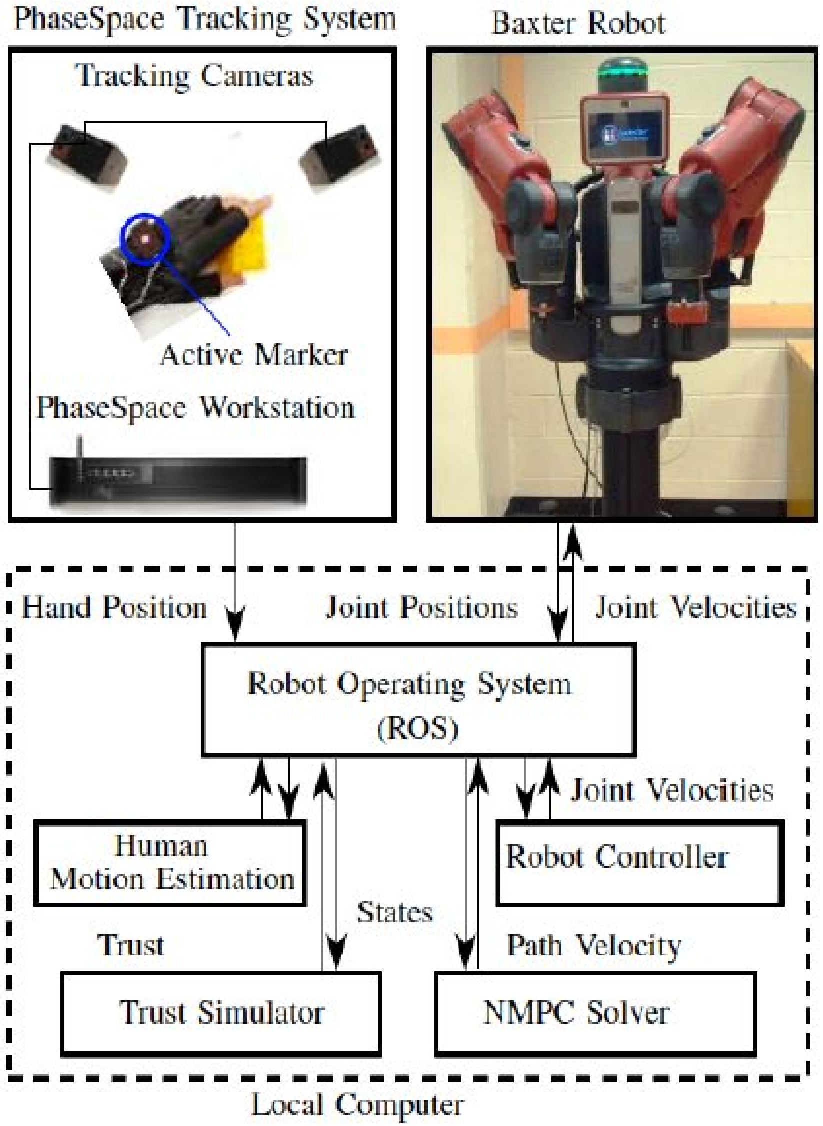
Trust-based Robot Speed Control in HRC Assembly in Manufacturing

[Sadrfaridpour et. al. CASE, 2016, Best student paper winner; IEEE TASE, 2017; Mizanoor & Wang, Mechatronics, 2018]





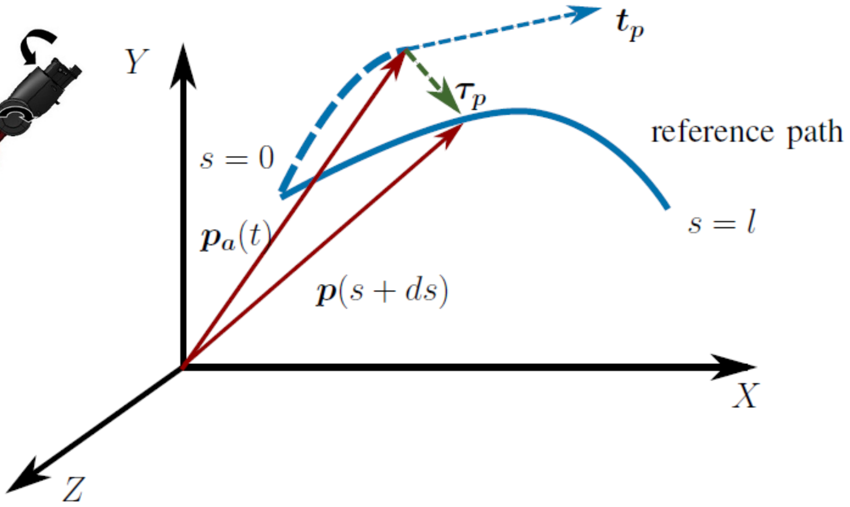




Trust-based Robot Speed Control In HRC Assembly in Manufacturing

[Sadrfaridpour et. al. CASE, 2016, Best student paper winner; IEEE TASE, 2017]

Moving Robot along a Given Path



$$\dot{q} = J^*(q)\{v[\rho_1 t(s) + \rho_2 \tau] + K[t(s) - f_t(q)]\}$$

Speed along the path

Compensation along reference trajectory

Closed-loop inverse kinematics (CLIK) for control accuracy

$$J^*(q) = \left(J(q)J^T(q) + \lambda^2 I\right)^{-1} J^T(q)$$

Damped least-square technique for singularity avoidance

Estimating Human Arm Kinematics

$$v_h(k+1) = \theta^T \Phi(k)$$

$$\Phi(k) = \begin{bmatrix} [-v_h(k) \quad \ldots \quad -v_h(k+1-n)]^T \\ [p_h(k) \quad \ldots \quad p_h(k-m)]^T \end{bmatrix}$$

Human arm kinematics

Estimation of human kinematics

$$\hat{v}_h(k+1) = \hat{\theta}^T(k)\Phi(k)$$

$$J(k) = \sum_{i=1}^{k} \left[v_h(i) - \hat{\theta}^T(k)\Phi(i-1)\right]^2$$

$$\hat{\theta}(k+1) = \hat{\theta}(k) + K(k)(v_h(k+1) - \hat{\theta}^T(k)\Phi(k))$$

$$K(k) = \frac{F(k)\Phi(k)}{1 + \Phi^T(k)F(k)\Phi(k)}$$

$$F(k+1) = (I - K(k)\Phi^T(k))F(k)$$

Recursive Least Square (RLS) estimate

$\|\hat{\theta}(k) - \hat{\theta}(k-1)\| \le \epsilon$ Termination Condition

Trust-based Robot Speed Control In HRC Assembly in Manufacturing

[Sadrfaridpour et. al. CASE, 2016, Best student paper winner; IEEE TASE, 2017]

MPC for Robot Speed Control in HRC Assembly

$$\min_{v(0),\ldots,v(N-1)} \sum_{k=1}^{N} \{ \|S_R(k) - S_H(k)\|_Q + \|v(i) - v_{\max}\|_R + \|T(i) - T_{\max}\|_W \},$$

Subject to

$$S_R(k+1) = \frac{v(k)T_s}{2rl_i\|\boldsymbol{t_p}(s(k))\|} + S_R(k),\ 0 \leqslant v(k) \leqslant v_{\max},$$

$$S_H(k+1) = \frac{\hat{\boldsymbol{i}}_{\boldsymbol{h}}(k)(\boldsymbol{p_h}(k) - \boldsymbol{p_0}(k))}{2hl_h} + \frac{c_h}{2h}$$

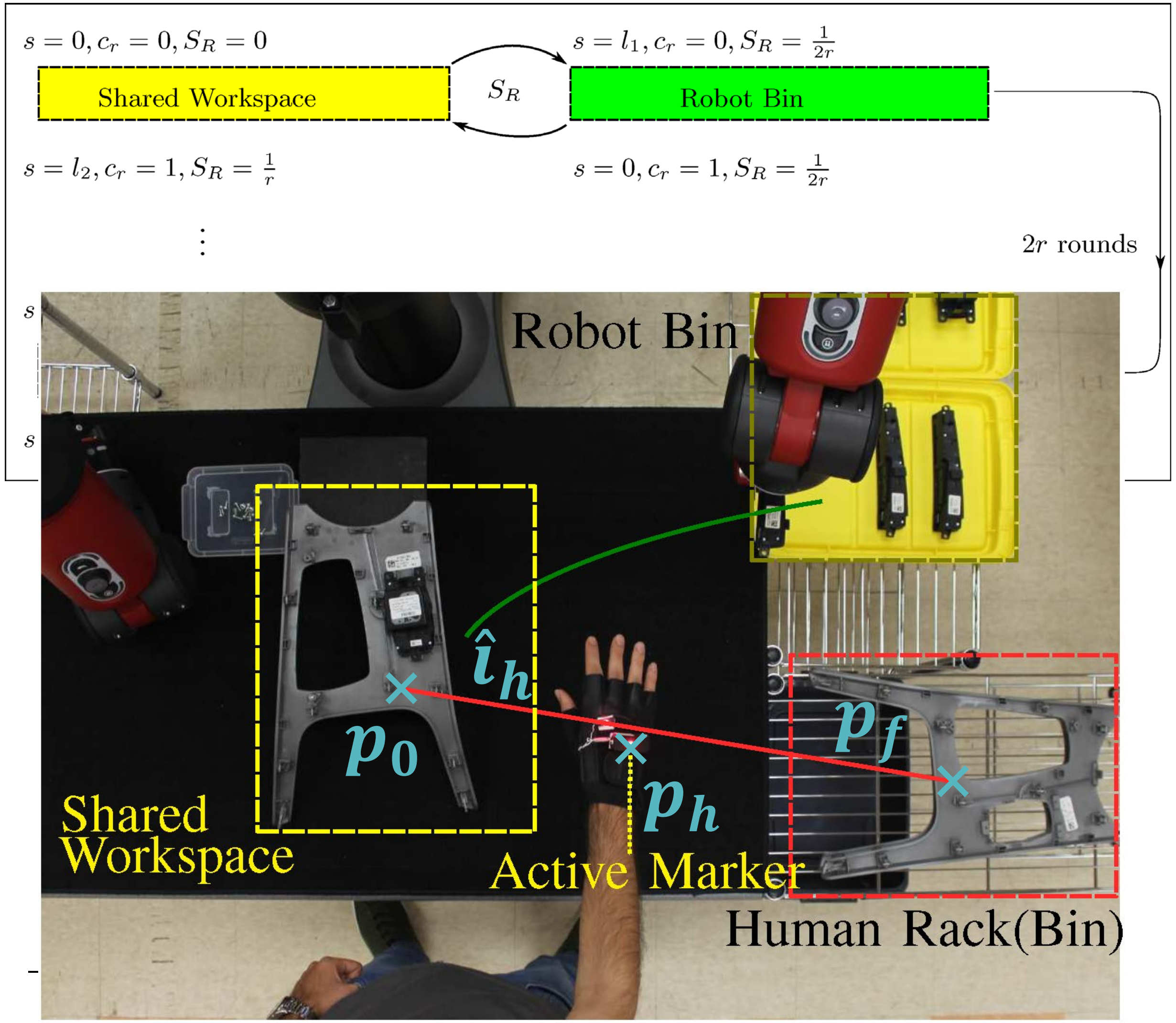
Time-series trust model

$$T(k) = aT(k-1) + bP_R(k-1) + cP_H(k-1),$$

$$P_R(k+1) = P_{R,\max} - w_3\,|v(k) - v_{ref}(S_R(k))| - w_4|S_R(k) - S_H(k)|,$$

$$P_H(k+1) = P_{H,\max} - w_1 \left| \frac{\hat{\boldsymbol{i}}_{\boldsymbol{h}} \boldsymbol{v_h}(k)}{v_{\max}} - v_{ref}(S_H(k)) \right| - w_2(S_R(k) - S_H(k))H(S_R(k) - S_H(k)),$$

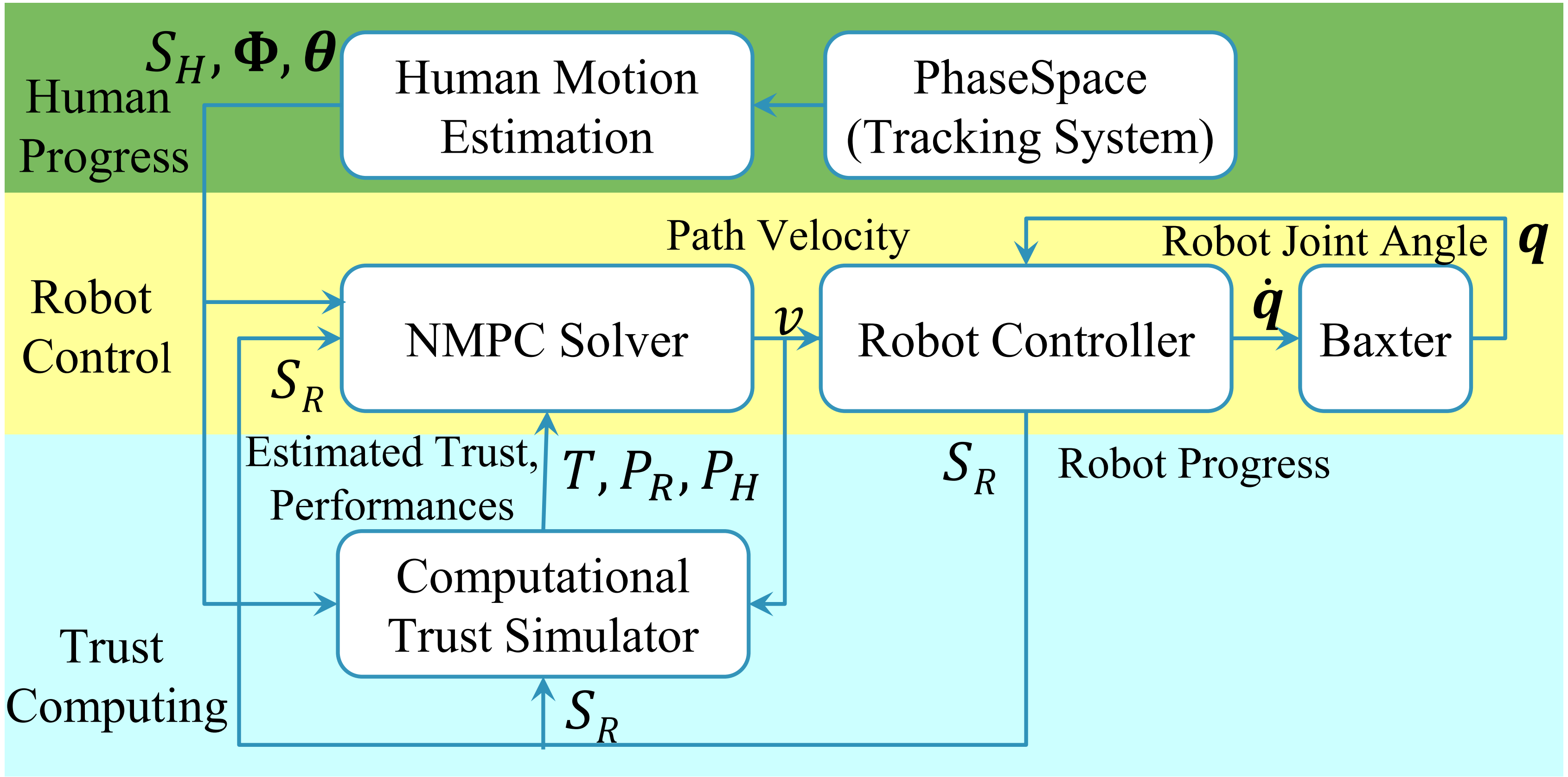
$$T(i) > T_{\min}$$



Trust-based Robot Speed Control In HRC Assembly in Manufacturing

[Sadrfaridpour et. al. CASE, 2016, Best student paper winner; IEEE TASE, 2017]

Block Diagram of the Integrated HRC Framework



+

(a) Happy Face

(b) Worried Face

(c) Bored Face

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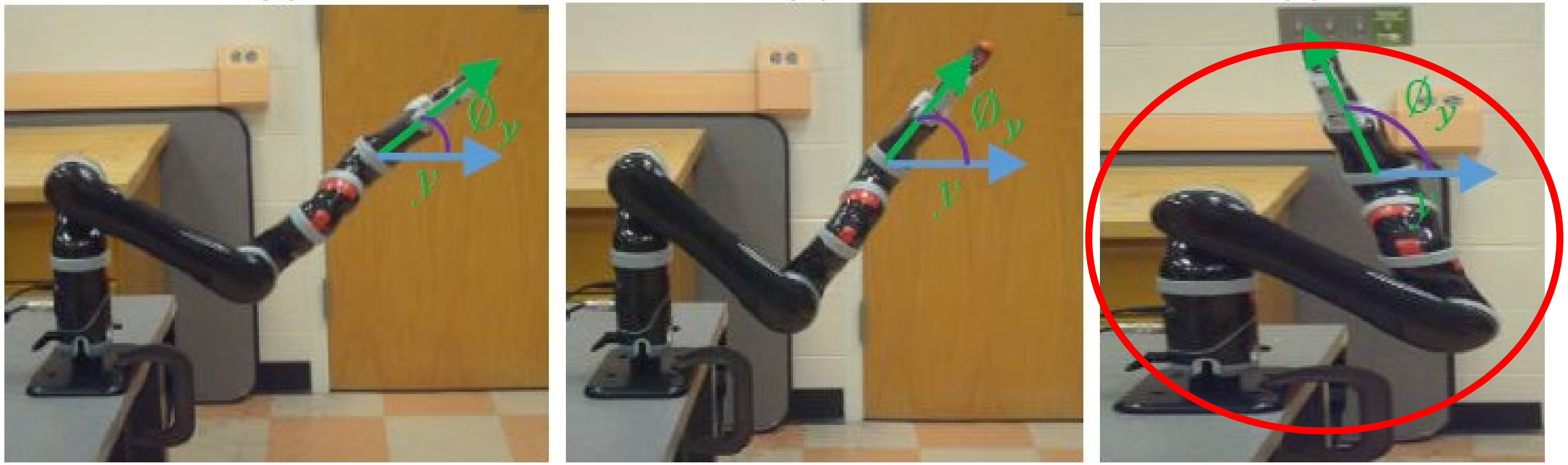
Robotics Education & Conclusion

Trust-based Robot Handover in Collaborative Assembly

[I. Walker et. al. MSCI 2015; M. Rahman et. al. CASE 2016a] (Collaborative work with Dr. Mizanoor Rahman, Ian Walker, Laine Mears, Richard Pak, and Laine Mears)

- High trust
- Maximal impact force
- Default handover



- Low trust
- Minimal impact force
- Extremely cautious handover

- Robot to human trust decreases → more cautious handover (“braced” configuration)

Trust-based Robot Handover in Collaborative Assembly

[I. Walker et. al. MSCI 2015; M. Rahman et. al. CASE 2016a]

Instantaneous velocity increment due to impact, $\Delta\dot{\boldsymbol{q}}$,

$$\Delta\dot{\boldsymbol{q}} = \boldsymbol{M}^{-1}(\boldsymbol{q})\boldsymbol{J}^{\boldsymbol{T}}(\boldsymbol{q})\boldsymbol{F}$$

Force acting at the robot end-effector tip (tool), $\boldsymbol{F}$,

$$\boldsymbol{F} = \boldsymbol{J}^{\dagger^T}(\boldsymbol{q})\boldsymbol{M}(\boldsymbol{q})\Delta\dot{\boldsymbol{q}}$$

Minimizing the impact force using redundancy

$$\dot{\boldsymbol{q}} = \boldsymbol{J}^{\dagger}(\boldsymbol{q})\dot{\boldsymbol{x}}_M + \alpha[\boldsymbol{I} - \boldsymbol{J}^{\dagger}(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q})](\nabla\boldsymbol{F})^T$$

Robot Joint Control

$\boldsymbol{x_M}$: modified task-space trajectory

Replacing $\nabla\boldsymbol{F}$

$$\dot{\boldsymbol{q}} = \boldsymbol{J}^{\dagger}(\boldsymbol{q})\dot{\boldsymbol{x}}_M - k_1[\boldsymbol{I} - \boldsymbol{J}^{\dagger}(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q})]\boldsymbol{H}(\boldsymbol{q} - \boldsymbol{q}_r)$$

$\boldsymbol{q_r}$: final arm configuration where $\nabla\boldsymbol{F}$ has minimal value

Impact Force

$\boldsymbol{H}$: a positive definite matrix, here $\boldsymbol{H} = \boldsymbol{I}$

Final trust-based handover stratrgy:

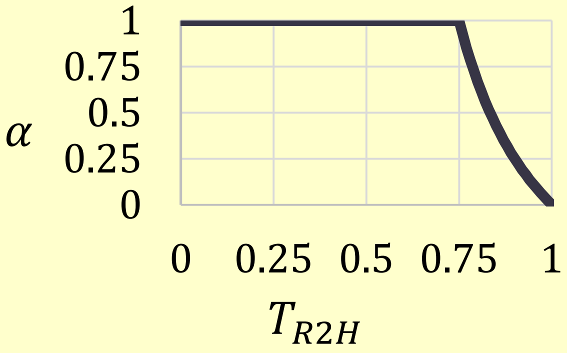
$$\dot{\boldsymbol{q}} = \boldsymbol{J}^{+}(\boldsymbol{q})\dot{\boldsymbol{x}}_M + \alpha[\boldsymbol{I} - \boldsymbol{J}^{+}(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q})](\boldsymbol{q}_r - \boldsymbol{q})$$

The potential impact force in y direction, $\boldsymbol{F_y}$,

$$\boldsymbol{F}_y = (\mu\boldsymbol{n}(\boldsymbol{q})\boldsymbol{n}_y)\boldsymbol{F}$$

Modifying α based on trust value

$$\alpha = \begin{cases} \frac{T_{max}-T_{R2H}}{T_{R2H}-T_{min}} : & T_{R2H} > \frac{T_{max}+T_{min}}{2} \\ 1 : & \text{otherwise} \end{cases}$$



Trust-based Scaling

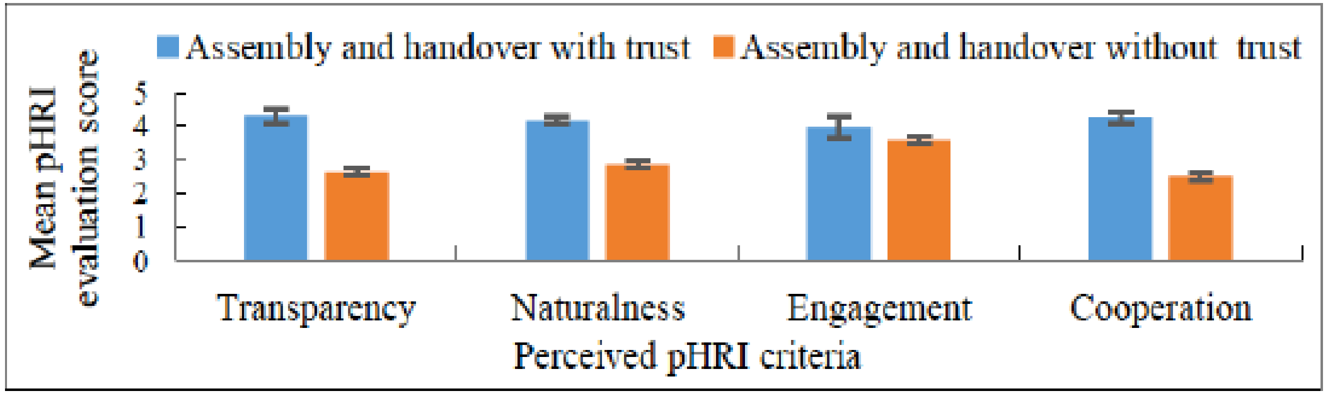
Trust-based Robot Handover in Collaborative Assembly

[I. Walker et. al. MSCI 2015; M. Rahman et. al. CASE 2016a]

- Objective:
  - To evaluate the impact of trust-based handover motion strategy on HRI, handover and assembly performance, and safety.
- The independent variable:
  - The handover scheme
- The dependent variables:
  - HRI
  - Handover success rate
  - Handover and assembly efficiency
  - Safety
- Experiment Protocols:
  - Assembly with trust-based handover
  - Assembly without trust-based handover

Evaluation criteria	Evaluation results for assembly and handover	
	With trust	Without trust
Handover safety (%)	100	80
Handover success rate (%)	100	70
Mean handover efficiency (%)	95.89 (1.53)	97.76 (2.33)
Mean assembly efficiency (%)	98.36 (2.19)	91.63 (1.97)

Comparison of performance



Comparison of perceived pHRI

Evaluation criteria	Evaluation results for assembly and handover	
	With trust	Without trust
Mean mental workload	29.13 (1.27)	54.76 (2.91)
Mean human trust in robot	4.32 (0.44)	3.14 (0.26)

Comparison of perceived cHRI

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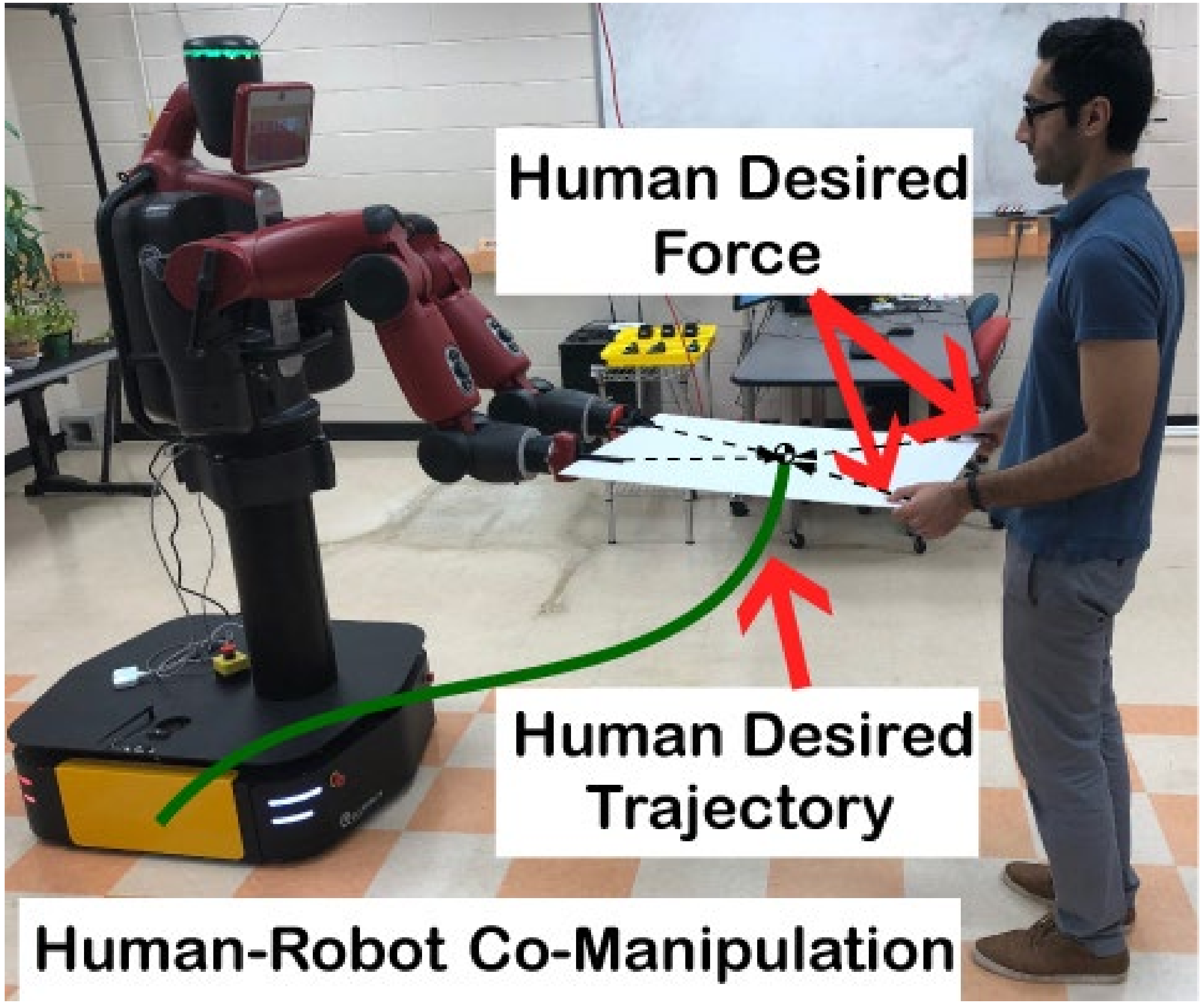
- **Robotics Education & Conclusion**

Trust-Based Human-Robot Co-Manipulation



Trust-Based Impedance Control Strategy for Human-Robot Co-Manipulation

[Sadrfaridpour et. al. DSCC, 2018]

Motion Objective for Object

$$\lim_{t\to\infty} \boldsymbol{x}(t) \to \boldsymbol{x}^d(t)$$

Force Objective for Manipulators

$$\lim_{t\to\infty} \boldsymbol{h}(t) \to \boldsymbol{h}^d(t)$$

Object equation of motion

$$\boldsymbol{M}_o\ddot{\boldsymbol{x}} + \boldsymbol{C}_o(\boldsymbol{x},\dot{\boldsymbol{x}}) = \boldsymbol{h}_e + \boldsymbol{h}_{ext}$$

Desired behavior (impedance control)

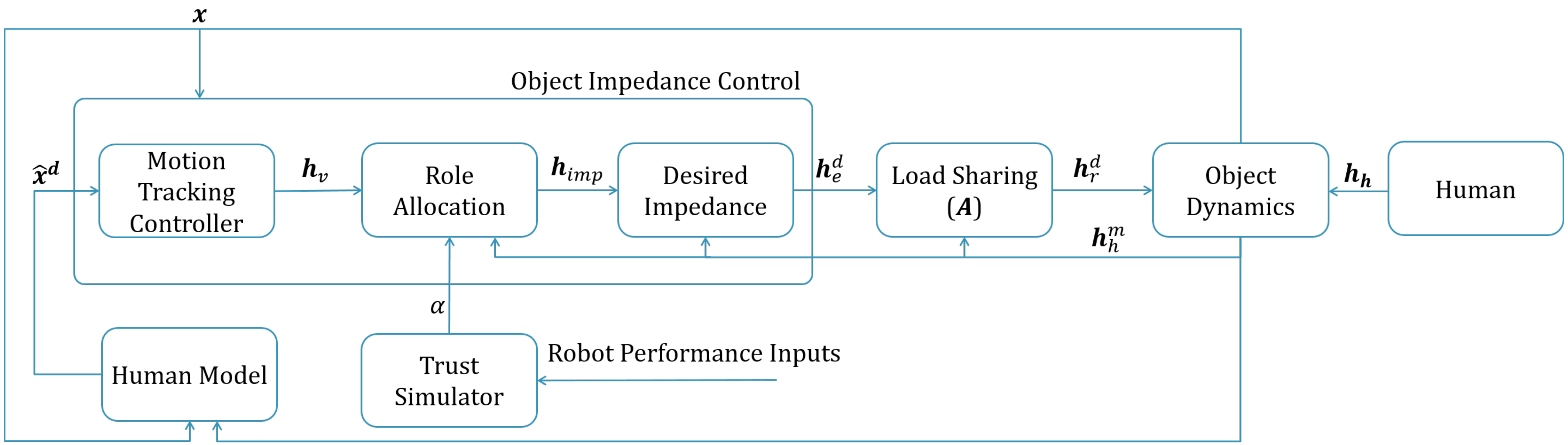
$$\boldsymbol{M}_v\ddot{\boldsymbol{x}}(t) + \boldsymbol{D}_v\dot{\boldsymbol{x}}(t) = \boldsymbol{h}_h(t) + \alpha(t)\boldsymbol{h}_v(t)$$

$$\boldsymbol{h}_v = \boldsymbol{K}_D\dot{\boldsymbol{e}} + \boldsymbol{K}_P\boldsymbol{e}, \qquad \boldsymbol{e} = \boldsymbol{x}^d - \boldsymbol{x}$$

$$\boldsymbol{h}_e^d = \boldsymbol{C}_o - \boldsymbol{h}_{ext} + \boldsymbol{M}_o\boldsymbol{M}_v^{-1}[\alpha\boldsymbol{h}_v + \boldsymbol{h}_h - \boldsymbol{D}_v\dot{\boldsymbol{x}}]$$

The role allocation parameter $\alpha(t) \in [0,1]$

$$\alpha(t) = E(bel_f(t))$$



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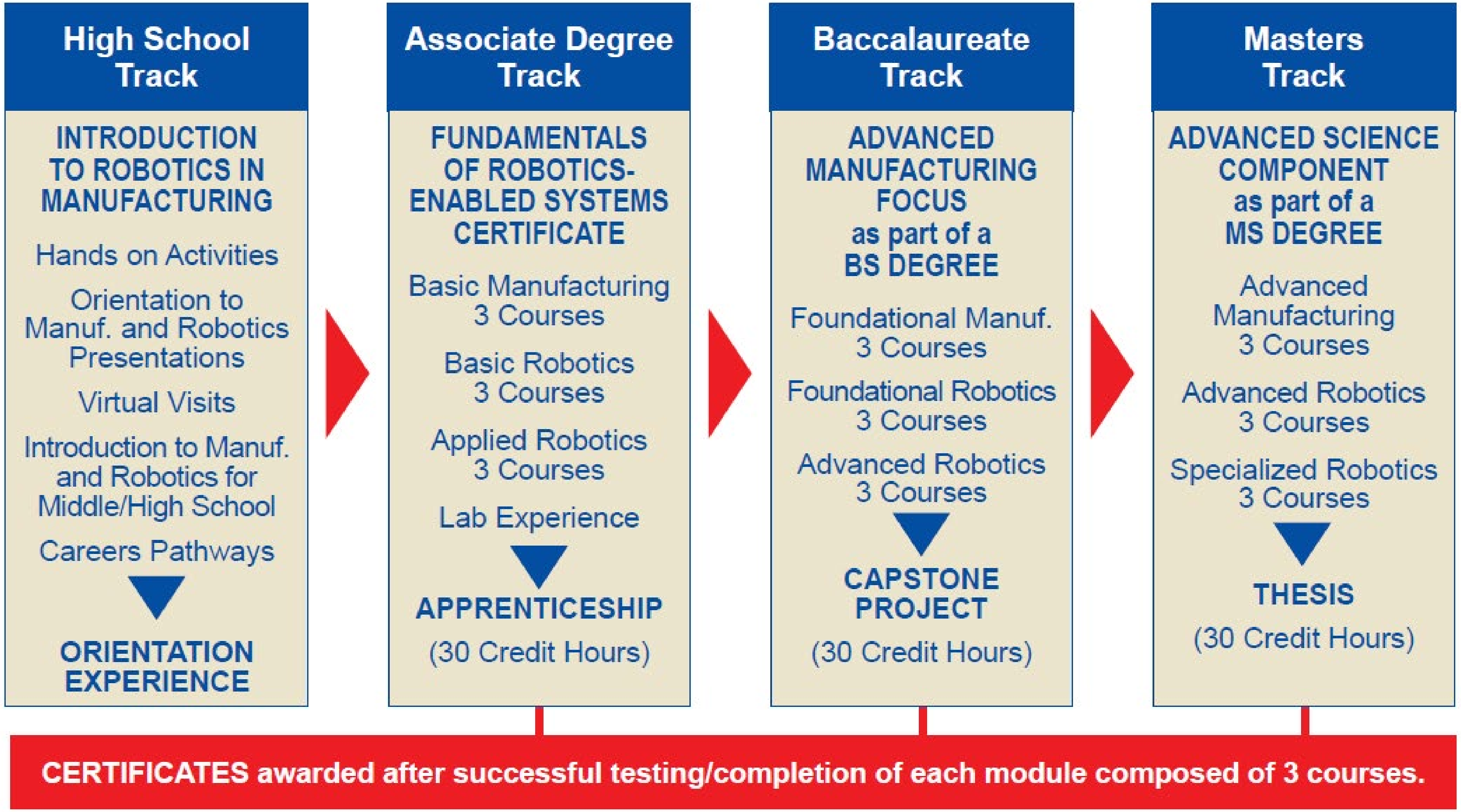
Robotics Education & Conclusion

Robotics Education

TIME FOR ROBOTICS

Lead PI: Dr. Anand Gramopadhye

- TIME for Robotics – Technology in Manufacturing Education for Robotics



Conclusion

- Computational trust models to quantify and predict human-robot trust with psychological insights and human subject data
- Trust-based human-robot collaborative PnP task for assembly manufacturing (pHRI, sHRI)
- Trust-based robot-human handover task
- Trust-based human-robot cooperative manipulation
- Robot experiments and human subject tests suggest that robot controls integrating trust analysis outperform non-trust based strategies in terms of HRI and team performance
- Robotics education for manufacturing workforce

Interdisciplinary and Intelligent Research (I2R) Lab


Dr. Hamed Saeidi


Dr. Rahman Mizanoor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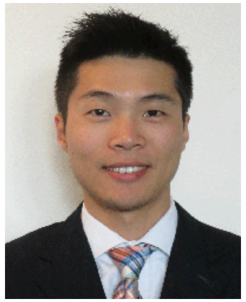
Mr. Zhanrui Liao


Ms. Qiuchen Wang


Mr. Jonathan Todd


Mr. James Svacha


Mr. Longsheng Jiang


Mr. Maziar Mahani


Mr. Fangjian Li


Mr. Huanfei Zheng


Mr. Evan Sand


Ms. Gloria Zhang


Mr. Brandon Delspina


Mr. Chong Tian


Mr. Aaysuh Rai

Question?
Comments?

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