Safe and Efficient Robot Collaboration System for Next Generation Intelligent Industrial Co-Robots

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CHALLENGES AND OVERVIEW

Moving robots out of cages and employing them into flexible production lines will be an inevitable trend, and factories of the future are anticipated to be spaces where humans and robots co-exist.

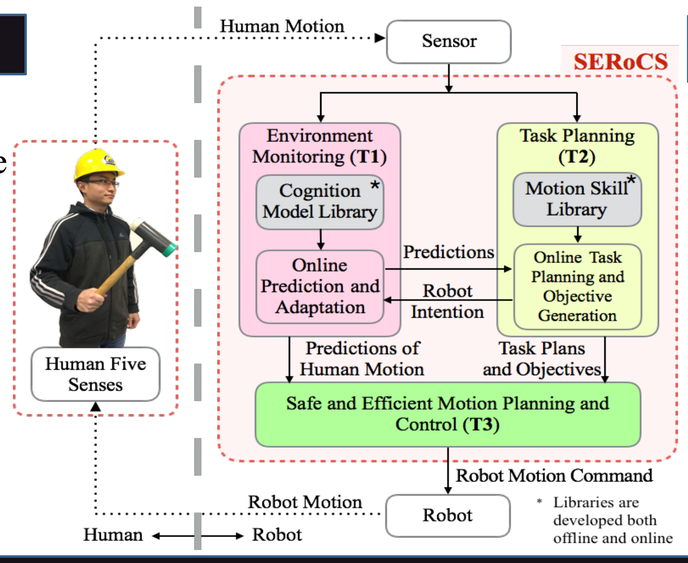
Objective: to establish a set of design principles of safe and efficient robot collaboration systems (SERoCS) for the next generation co-robots.

Task 1. Environment Monitoring with Human Motion Prediction

Task 2. Skill Library For intelligent co-robots

Task 3. Safe and Efficient Motion Planning and Control in Real Time

Task 4. Evaluation of the SERoCS by Analyses, Simulations and Experiments



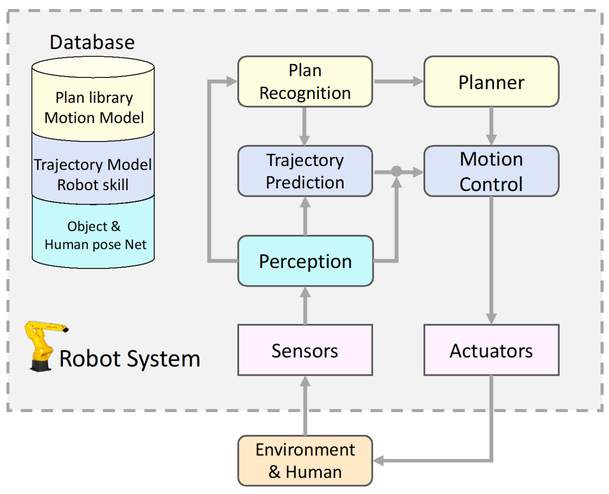
SCIENTIFIC IMPACTS

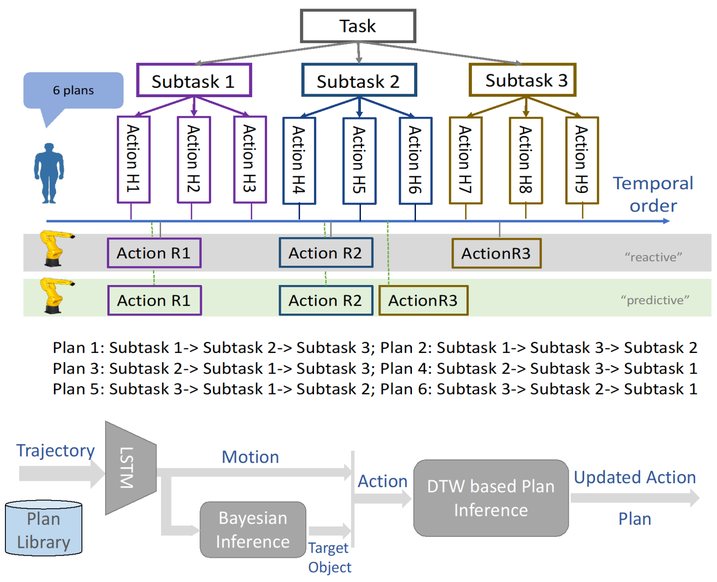
The proposed SERoCS will lead to safe and efficient human-robot collaboration as well as safe robot-robot collaboration, both of which are essential in factories of the future. The major impacts are:

- Different modules (perception, prediction, and planning) involved in Co-Robot system will be developed and open source to public to provide better solution and inspiration.
- Several Evaluation metrics and benchmark for the co-robot system have been proposed.

SOLUTIONS

Task 1. Environment Monitoring with Human Motion Prediction





Task 2. Skill Library For intelligent co-robots

- Robust cable manipulation
  - Tracking feature points

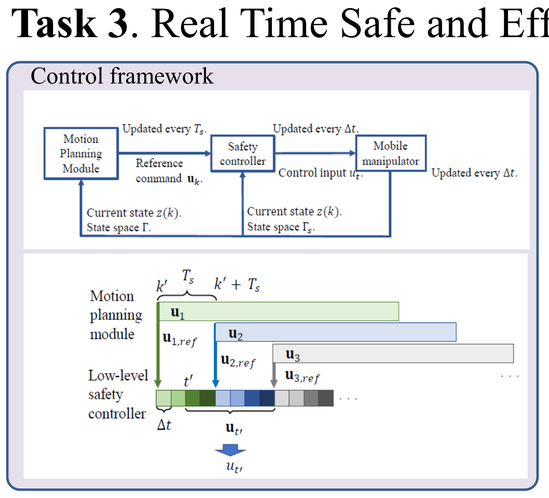
$$T^* = \arg\max_{T(\cdot)} \; Q(T(x_n), \sigma^2) - \frac{\lambda}{2}\int_{\mathbb{R}^D} \frac{|\tilde{T}(s)|^2}{\tilde{g}(s)} ds - \frac{\tau}{2}\sum_{n=1}^{N}\Big\|\sum_{i=1}^{N} S_{ni} T(x_i)\Big\|^2$$

Registration Accuracy from $\bar{X}$ to Y | Global Smoothness Regularization | Local Topology Preservation

  - Robust deformation model approximation

$$\min_{G_i(t_m)} \max_{\|\Delta\|_2 \le s} \|W[(\delta X^T(t_1:t_m) + \Delta) G_i^T(t_m) - \delta R_i^T(t_1:t_m)]\|_2^2$$

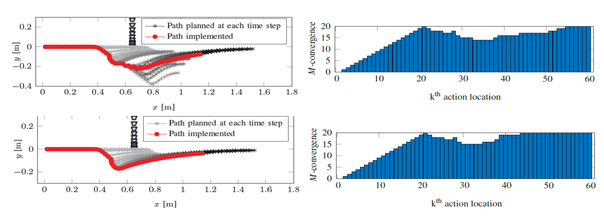
Task 3. Real Time Safe and Efficient Motion Planning and Control

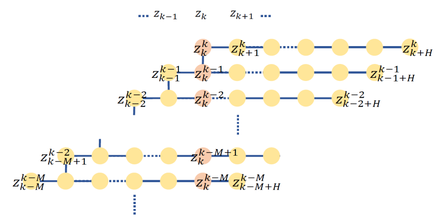


Task 4. Evaluation and Benchmarking

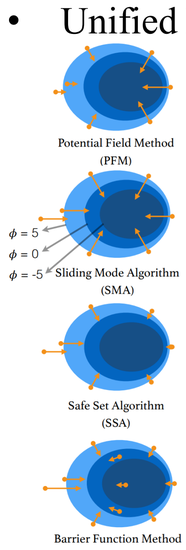
- M-Convergence (planning analysis in closed-loop)

Due to the face that the prediction of the movement of the dynamic obstacles in the environment is not perfect, the plan solved at a certain time step may be largely different from the previous plans, causing the robot to execute violent or zigzagging movements. Here we proposed a new notion, M-convergence, to serves as an indicator of the closed-loop performance, which analyzes finite local convergence (at least M steps ahead) of the open-loop trajectories toward the closed-loop trajectory.





- Unified Framework for Safe Control Algorithms

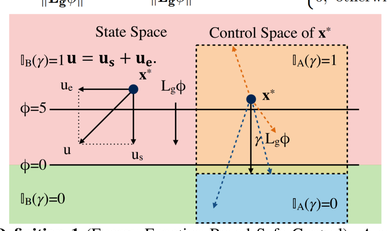


Energy function: ϕ

$$\dot{\phi}(\mathbf{x}) = \nabla\phi^\intercal(\mathbf{x})\mathbf{f}(\mathbf{x}) + \nabla\phi^\intercal(\mathbf{x})\mathbf{g}(\mathbf{x})\mathbf{u}, \quad = \mathbf{L_f}\phi + \mathbf{L_g}\phi\mathbf{u} \le \xi.$$

$$\gamma := \frac{\xi - \mathrm{L_f}\phi}{\|\mathbf{L_g}\phi\|^2}. \quad \mu := \frac{\mathbf{L_g}\phi\ \mathbf{u}_0}{\|\mathbf{L_g}\phi\|^2}.$$

$$\mathbb{I}_A(\gamma) := \begin{cases} 1, & \text{if } \mu < \gamma \\ 0, & \text{otherwise.} \end{cases} \qquad \mathbb{I}_B(\phi) := \begin{cases} 1, & \text{if } \phi \ge 0 \\ 0, & \text{otherwise.} \end{cases}$$



Definition 1 (Energy-Function-Based Safe Control). *A safe control method is called an energy-function-based safe control method if:*

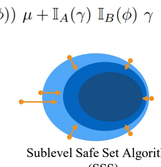
1) *it uses a scalar energy function ϕ to measure safety;*
2) *it provides safe control inputs in the following form*

$$\begin{cases} \mathbf{u}^s = \alpha\ \mathbf{L_g}\phi^\intercal \\ \mathbf{u}^c = \mathbf{u}_0^c + \beta\ \mathbf{u}_i^c \end{cases}, \qquad (19)$$

1) *for PFM:*
$$\alpha = \mu - \mathbb{I}_B(\phi)\ c_1.$$
2) *for SMA:*
$$\alpha = \mu - \mathbb{I}_B(\phi)\ c_2.$$
3) *for SSA:*
$$\alpha = (1 - \mathbb{I}_A(\gamma))\ \mathbb{I}_B(\phi))\ \mu + \mathbb{I}_A(\gamma)\ \mathbb{I}_B(\phi)\ \gamma,$$
where γ follows from (17) and $\xi = \eta$.
4) *for BFM:*
$$\alpha = (1 - \mathbb{I}_A(\gamma))\ \mu + \mathbb{I}_A(\gamma)\ \gamma$$
where γ follows from (17) and $\xi = \lambda\phi$.

Sublevel Safe Set Algorithm (SSS)

$$\begin{cases} \alpha = (1 - \mathbb{I}_A(\gamma))\ \mathbb{I}_B(\phi))\ \mu + \mathbb{I}_A(\gamma)\ \mathbb{I}_B(\phi)\ \gamma \\ \beta = 0 \\ \gamma = \frac{\xi - \mathrm{L_f}\phi}{\|\mathbf{L_g}\phi\|^2} \\ \xi = \lambda\phi \end{cases}$$

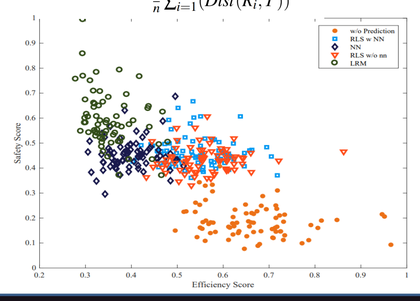


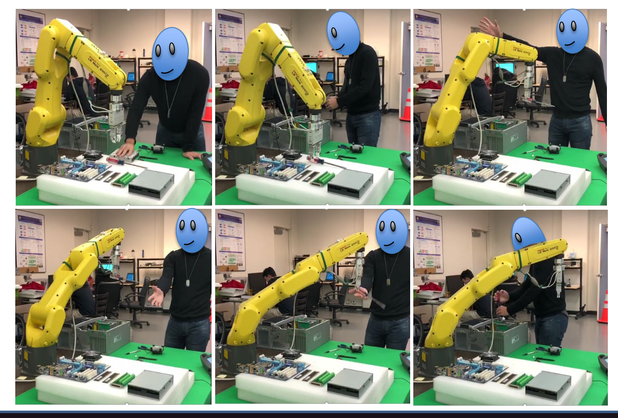
- Experimental Evaluations

To examine the relationship between Prediction and the overall co-robot system's performance, we compared several predicters to study how the performance is in terms of safety and efficiency.

$$\text{Safety} = \frac{1}{n}\sum_{i=1}^{n}(\min(Dist(H_i, R_i))),$$

$$\text{Efficiency} = \frac{\mathbb{D}_{RT}}{\frac{1}{n}\sum_{i=1}^{n}(Dist(R_i, T))},$$





BROADER IMPACTS

Society : Introducing SERoCS to factories can reduce the chances of accidents and make the best use of these robots.

Education: This project was exhibited on CalDay, the open-house of Cal. Undergraduate student researchers joined for research experience.

Potentials: This project is one of the very first that has emphasized on not only robot skills but the whole robot system including human in industrial settings. SERoCS idea may be applied to non-factory environments involving robots and human.

[1] C. Liu, T. Tang, H-C. Lin, Y. Jiao, and M. Tomizuka. "SERoCS: Safe and Efficient Robot Collaborative Systems for Next Generation Intelligent Industrial Co-Robots." arXiv:1809.08215.
[2] J. Leu and M. Tomizuka, "Motion planning for industrial mobile robots with closed-loop stability enhanced prediction," in Proc. ASME Dynamic Systems and Control Conference 2019 (DSCC 2019), presented in Oct. 2019
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[5] T. Wei, and C. Liu. "Safe Control Algorithms Using Energy Functions: A Unified Framework, Benchmark, and New Directions." *in* Proc. IEEE Conference on Decision and Control (CDC 2019).
[6] W. Zhao, et al. "Experimental Evaluation of Human Motion Prediction: Toward Safe and Efficient Human Robot Collaboration." in Proc. American Control Conference (ACC 2020).

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