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

Jessica Leu, Yujiao Cheng, Xinghao Zhu, Shiyu Jin, Liting Sun, Changliu Liu*, and Masayoshi Tomizuka

Graduate Student, Graduate Student, Graduate Student, Graduate Student, Postdoc, Professor, Professor (PI)

Department of Mechanical Engineering, UC Berkeley, CA, USA.

* Currently with Robotics Institute, Carnegie Mellon University, Pittsburgh, PA, USA.

http://msc.berkeley.edu

CHALLENGES AND OVERVIEW

Moving robots out of cages and deploying 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 [1].

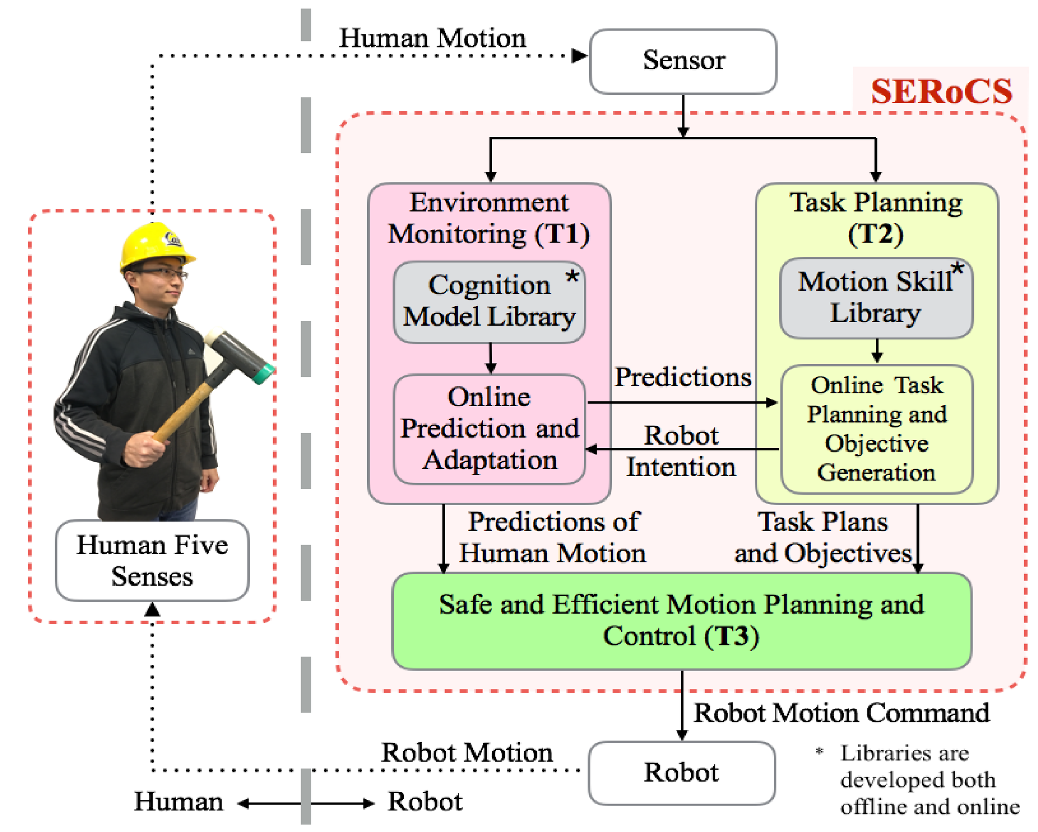
Objective: to establish a set of design principles of safe and efficient robot collaboration systems (SERoCS) for the next generation co-robots.

Task 1. Environment Monitoring with Human Motion Prediction

Task 2. Task Planning and Skill Library

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

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



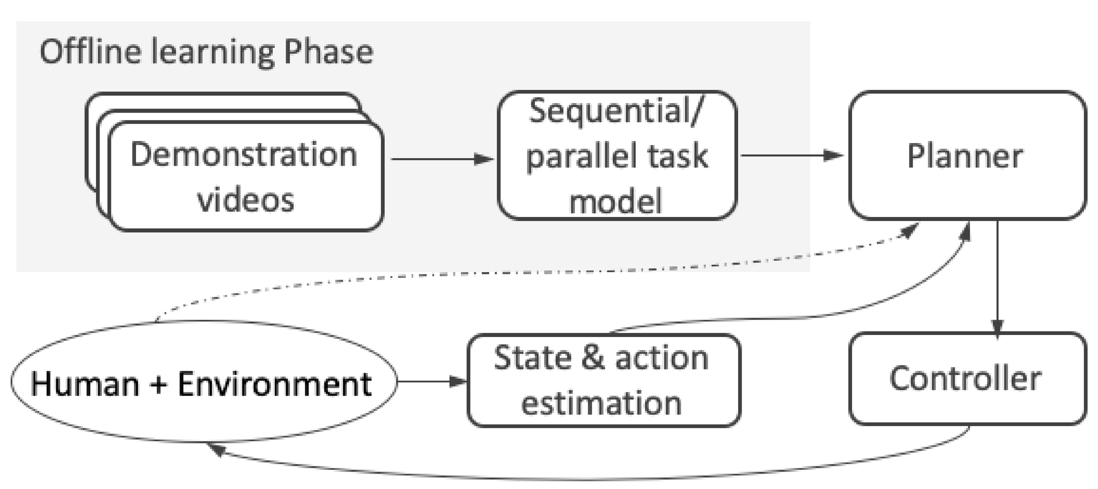
SCIENTIFIC IMPACTS

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 for the co-robot system have been proposed. A demo of SERoCS system is presented.

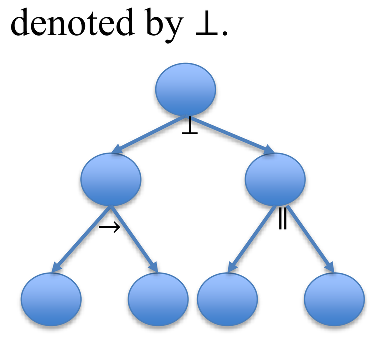
SOLUTIONS

Task 2. Task planning [2]



- Constructing the task model

❖ Sequential nodes: their child nodes must be executed in the order from left to right, which is denoted by the operator →.
❖ Parallel nodes: their child nodes can be executed in parallel, which is denoted by ‖.
❖ Independent nodes: their child nodes can be executed in any orders, which is denoted by ⊥.



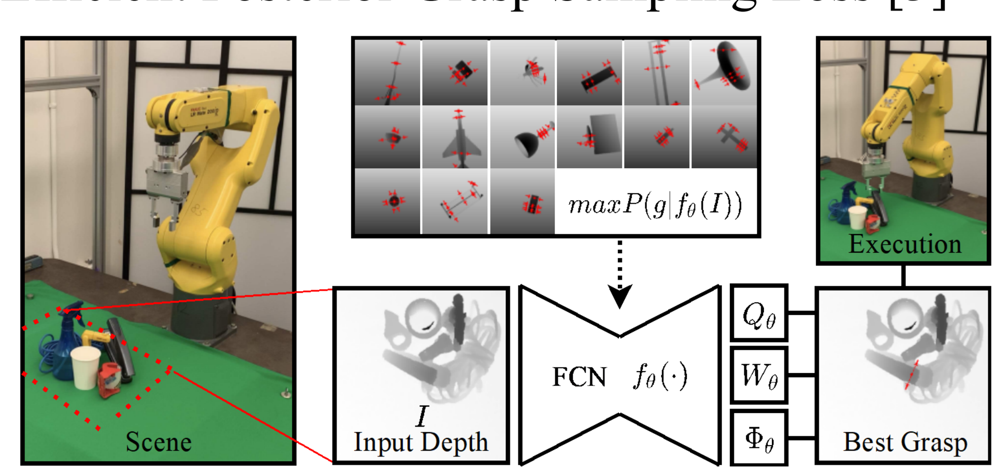
- Optimization-based task planning with task context

$$\begin{aligned} \min_{x_h, x_r} \quad & t \\ \text{s.t.} \quad & x_h^T t_1 + t_o \leq t \\ & x_r^T t_2 \leq t \\ & x_h + x_r = \mathbf{1} \\ & x_h, x_r \in \{0,1\}^k \\ & x_{h\{C-C_h\}} = 0 \\ & x_{r\{C-C_r\}} = 0 \end{aligned}$$

t: completion time
x_r: assignment for the robot
x_h : assignment for the human
t_0 : the time human takes to complete the current action
t_1 : the time human takes to complete the assigned actions
t_2 : the time robot takes to complete the assigned actions
C: capability set
C_h: human's capability set
C_r: robot's capability set

Task 2. Skill Library For Grasping

- Learn to Grasp with Less Supervision: A Data-Efficient Posterior Grasp Sampling Loss [3]



- Grasp models f_θ are trained to recover ground-truth grasp distributions with limited observations, such that
- Results demonstrate 8x more data-efficient than previous works with similar physical grasping success rate at 91.8%.

$$\theta = \underset{\theta}{\operatorname{argmin}}\ \mathcal{L}(\tilde{G}, f_\theta(I))$$

where

$$\mathcal{L}(\tilde{G}, f_\theta(I)) = \sum_{i=1}^{k} -\log P(\tilde{p}_i | f_\theta(I)) + \text{MSE}(\hat{\phi}_i, \tilde{\phi}_i) + \text{MSE}(\hat{w}_i, \tilde{w}_i)$$

$\tilde{G}$ is a set of success grasp labels; $\widetilde{\phi_i}$, $\widetilde{w_i}$ are success grasp labels at pixel $\widetilde{p_i}$; $\widehat{\phi_i}$, $\widehat{w_i}$ are predicted grasp at the same place

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

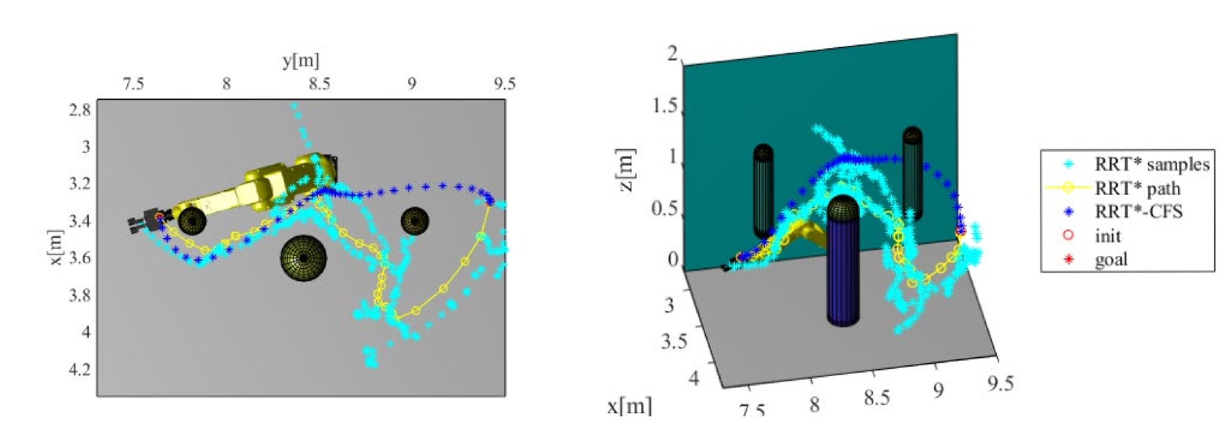
Motion planning algorithm: RRT*-CFS [4]

- Combining optimization-based algorithms and sample-based algorithms for better overall optimality while maintain convergence guarantee.
- The RRT*-CFS motion planner has stochasticity to avoid bad local optima and inherits the CFS properties of convergence.

Algorithm 1 RRT*-CFS

```
procedure RRT*-CFS(θ_0, θ_goal, n_samples, O)
  while ! ∃ θ^RRT do
    θ^RRT ← Multi_thread_RRT*(θ_0, θ_goal, n_samples, O)   ▷ Get the shortest RRT* path among all threads.
  x^0 ← generate_reference(θ^RRT)   ▷ Generat the initial reference x^0 for CFS based on θ^RRT.
  while Stop criterion is not satisfied do   ▷ k = 0, 1, 2, ...
    χ^(k) = ∩_{j=1}^{n} {x : h_j(x^(k)) + ∇^T h_j(x^(k))(x − x^(k)) ≥ 0}
    x^(k+1) = arg min_{x ∈ χ^(k)} f(x).
  return x^(k+1)
```

- Planning results

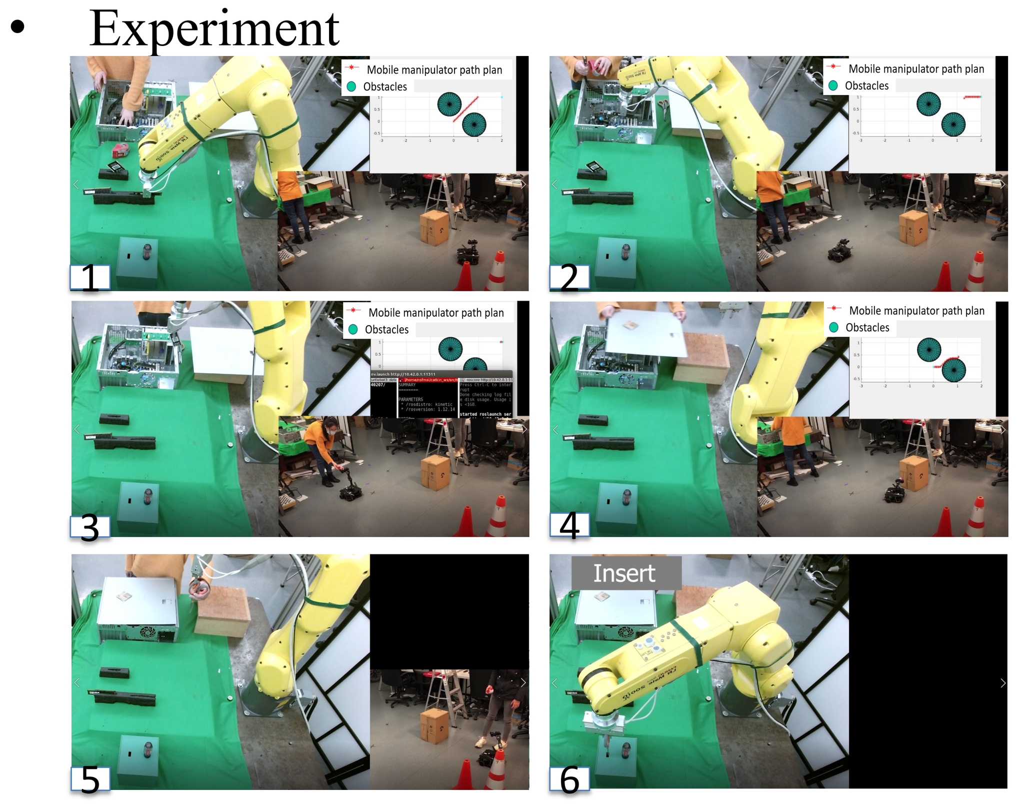


Task 4. Evaluation and Experiment

- Task

	Human worker	Manipulator	Mobile Manipulator
Computer assembly	Install CPU (1) Bundle wires (2)	Install memory card (1) Put tag on the case (3)	Approach worker (1,2)
Tool sharing	Handover Tape (3)		Receive Tape (3)
Tool storing	Handover Scissors (5)	Insert scissors into the toolbox (5,6)	

- Experiment



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] Y. Cheng, L. Sun, & M. Tomizuka. “Human-Aware Robot Task Planning Based on a Hierarchical Task Model.” IEEE Robotics and Automation Letters, 6(2), 1136-1143. (2021)
[3] X. Zhu, Y Zhou, Y Fan, L Sun, and M. Tomizuka, "Learn to Grasp with Less Supervision: A Data-Efficient Posterior Grasp Sampling Loss", in Proc. IEEE Robotics and Automation Letters (RA-L), submitted, Feb. 2021.
[4] J. Leu, G. Zhang, L. Sun, and M. Tomizuka. “Ecient robot motion planning via sampling and Optimization." in Proc. American Control Conference (ACC 2021), May 2021.
[5] J. Leu, L. Sun, and M. Tomizuka, \Motion planning for mobile manipulators with physical contact in uncertain environment," in Proc. 2021 IEEEInternational Conference on Robotics and Automation (ICRA), submitted, Oct. 2021.

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