Vision and Force Guided Robot Assisted Assembly

Smarter Robots in Manufacturing through Modeling, Sensing, Control, and Learning

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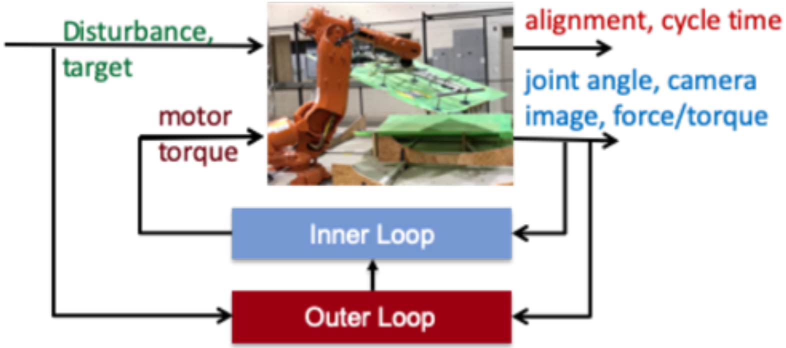
Outline

- Attributes and Challenges in Industrial Robot Control
- Case Studies
    - Composites Panel Assembly
    - Robotic Satellite Servicing
    - Assistive Robot
- Robotics Software
- Robotics education

Industrial Robot Control

Attributes

- Outer Loop Control
- Semi-structured
- Crowded workspace: Human workers, other robots and machineries
- Process interruptions



Challenges/Requirements

- Speed
- Precision
- Model imprecision
- Variable operation conditions
- Extensible architecture
- Load flexibility
- Joint flexibility
- Outer Loop Dynamics (delay, nonlinearities)
- Redundancy resolution
- Interruption recovery

Industrial Robot Control

Challenges/Requirements	Potential Solutions
• Speed	🡐 Local optimization
• Precision	🡐 Sensor based control
• Model imprecision	🡐 Robust control
• Variable conditions	🡐 Robust control
• Extensible architecture	🡐 State machine, hybrid control
• Load flexibility	🡐 Control design, notch filter
• Joint flexibility	🡐 Control design, notch filter
• Outer loop dynamics	🡐 Predictive compensation
• Redundancy resolution	🡐 Secondary control objectives
• Interruption recovery	🡐 Error detection and mitigation

Control Needs

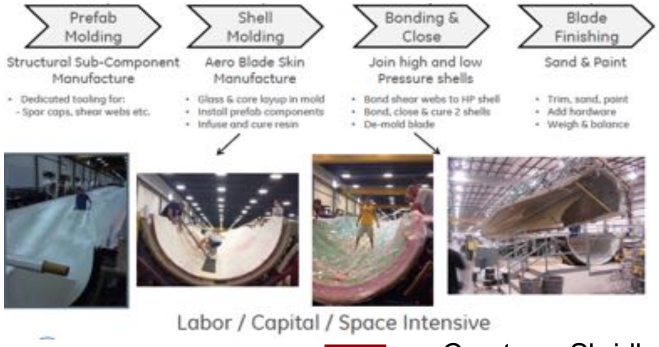
- Faster motion planner
- More *intuitive* robot paths
- Robustness to lighting, calibration..
- Co-simulation
- Human predictive modeling
- ….

Case Study: Composites Panel Assembly

Motivation

- Manufacturing of large composite structures a time consuming, labor intensive process
- Challenges: Large, heavy, curved loads, structural flexibility, high precision alignment requirement

Joint project with GE GRC, funded by ARM



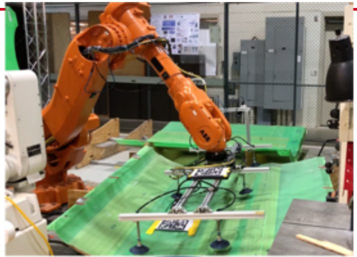
Courtesy: Shridhar Nath (GE GRC)

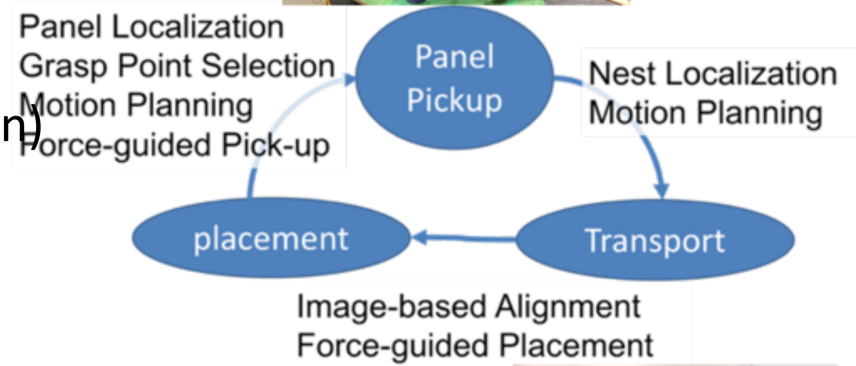
Demonstration Testbed

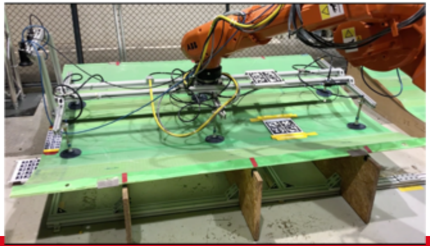
Performance Metrics: Cycle Time, Alignment Tolerance, Damage avoidance (vibration, placement force)

- Speed (motion, planning)
- Precision (alignment, force)
- Model imprecision (CAD, camera calibration)
- Variable conditions (lighting)
- Extensible architecture (robot-agnostic)
- Load flexibility (panel vibration)
- Joint flexibility
- Outer loop dynamics (nonlinearity)
- Redundancy resolution
- Interruption recovery (error, user)

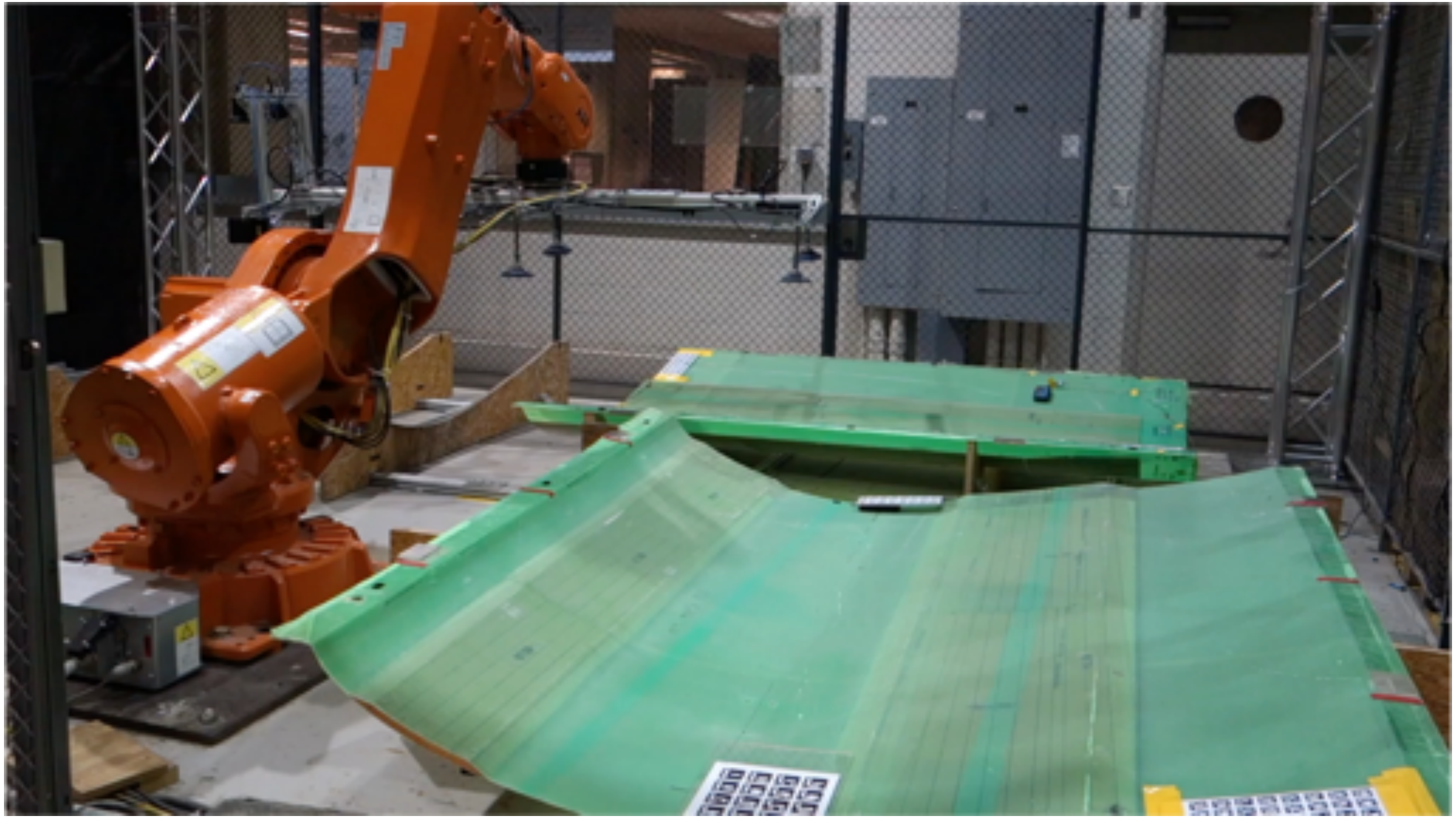
ARM
ADVANCED ROBOTICS FOR MANUFACTURING





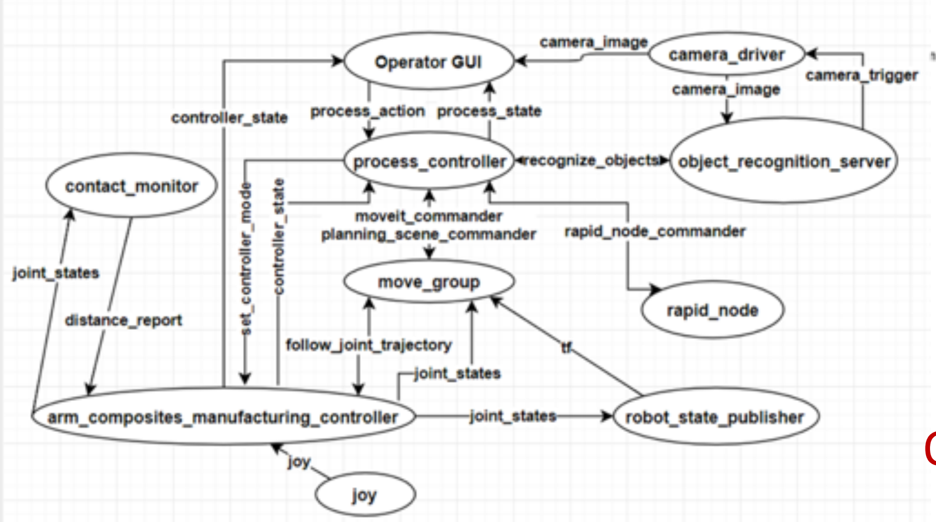


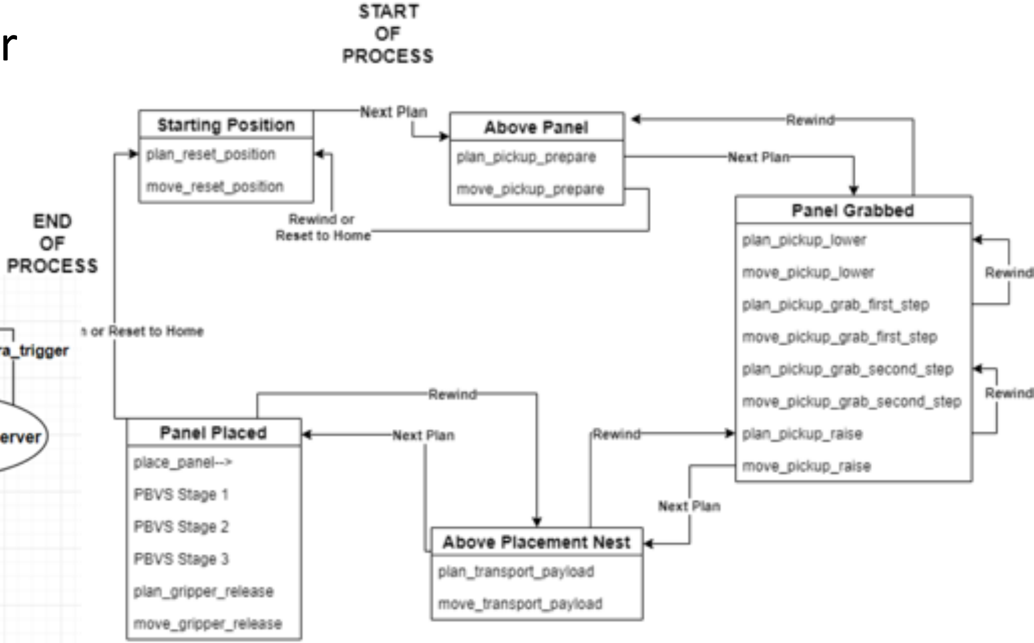
Experiment



Process and Software Architecture

- Bidirectional process flow for operator intervention and diagnostics
- ROS implementation





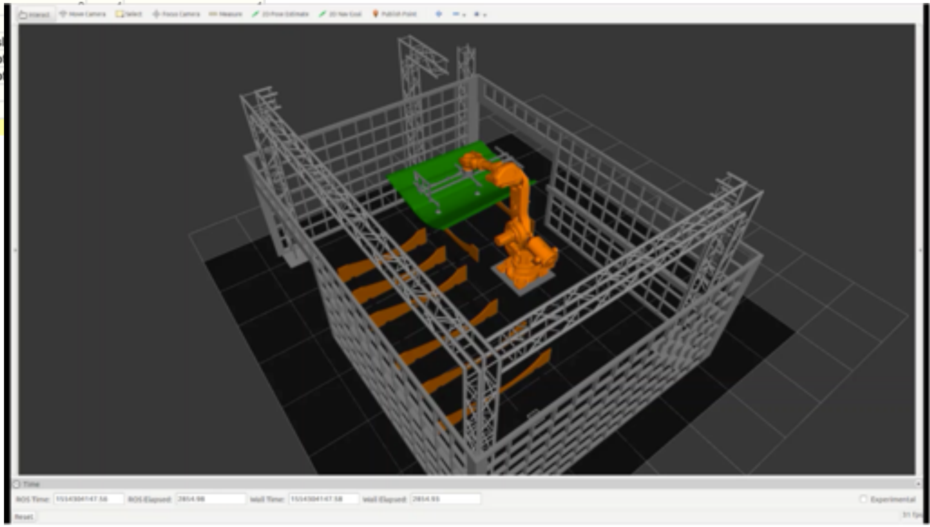
Opportunity: Hybrid control analysis

Motion Planning

Global optimization with fixed environment

- MoveIt! (TRRT)
- TrajOpt + Tesseract (SwRI)

#	Planners	Trial 1		Trial 2	
		Good Path	Bad Path	Good Path	Bad Path
1	BFMTkConfigDefault	2	3		
2	BKPIECEkConfigDefault	5	0	4	1
3	BiESTkConfigDefault	4	1		
4	BiTRRTkConfigDefault	4	1 no motion plan found		
5	ESTkConfigDefault	4	1 no motion plan found		
6	FMTkConfigDefault	5	0	4	1 no motion plan found
7	KPIECEkConfigDefault	5	0	4	1 no motion plan found
8	LBKPIECEkConfigDefault	0	5		
9	LBTRRTkConfigDefault	4	1		
10	LazyPRMkConfigDefault	4	1		
11	LazyPRMstarkConfigDefault	4	1		
12	PDSTkConfigDefault	4	1 no motion plan found		
13	PRMkConfigDefault	4	1		
14	PRMstarkConfigDefault	4	1		
15	ProjESTkConfigDefault	5	0	5	0
16	RRTConnectkConfigDefault	5			
17	RRTkConfigDefault	3			
18	RRTstarkConfigDefault	very sl			
19	SBLkConfigDefault	4	1 no mot		
20	SPARSkConfigDefault	4	1 no mot		
21	SPARStwokConfigDefault	5			
22	STRIDEkConfigDefault	5			
23	TRRTkConfigDefault	5			



Local Solution: Quadratic Programming with human guidance

$$\min_{\dot{q},\alpha_r,\alpha_p} ||J\dot{q} - \alpha v_d||^2 + \epsilon_r(\alpha_r - 1)^2 + \epsilon_p(\alpha_p - 1)^2$$

$$h_I(q) \geq \eta > 0 \Rightarrow \nabla h_I(q)\dot{q} \geq \sigma(h_I(q))$$

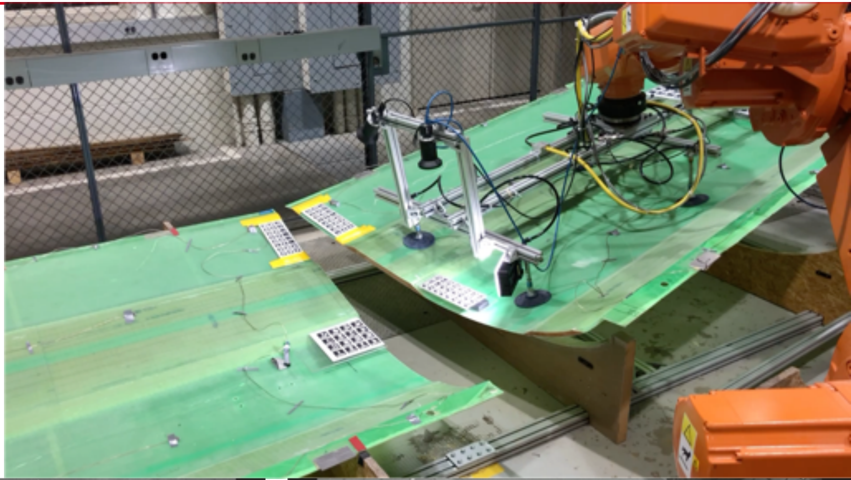
$$\dot{q}_{\min} \leq \dot{q} \leq \dot{q}_{\max}$$

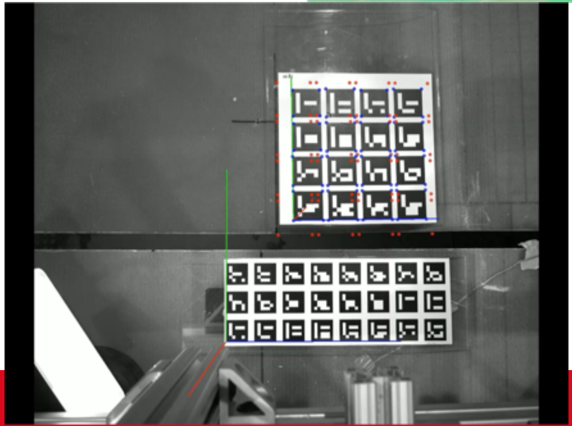
Opportunity: User directed optimal control, model predictive control

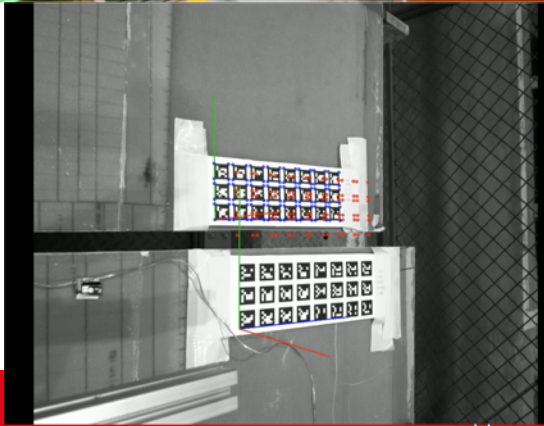
Vision Guided Motion

- Placement (gripper cameras): PBVS vs. IBVS
  - PBVS pose-based vs IBVS image-based error
  - Servoing: Jacobian vs. Inverse kinematics
  - Reduce dependence on calibration accuracy
  - Single tag/camera vs. Two-tag/two-camera

  Trade-off between orientation accuracy and camera accuracy. Best experimental combination: .75 overhead + .25 side cameras







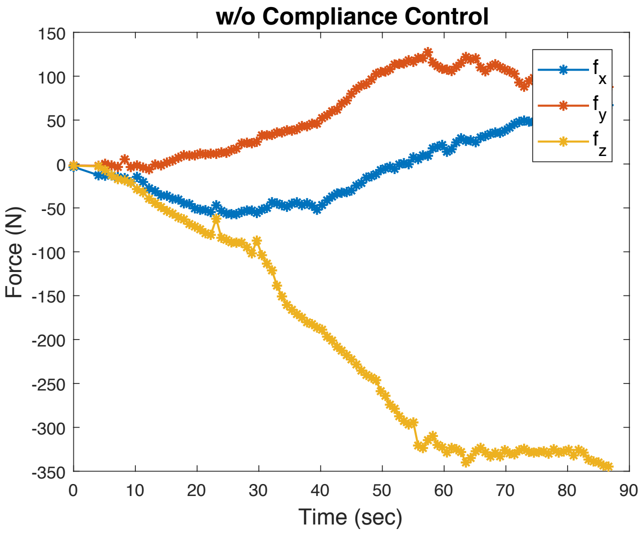
Opportunity: Sensor-fusion, integrated lighting control, visual design

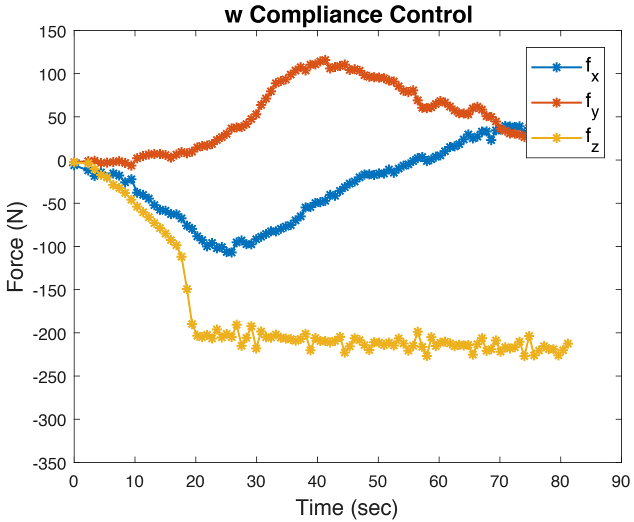
Force Guided Motion

- Placement: compliance force control (generalized damper) as part of QP control

$$\begin{bmatrix} \omega_T \\ v_T \end{bmatrix} = \begin{bmatrix} \omega_m \\ v_m \end{bmatrix} - K \begin{bmatrix} \tau - \tau_d \\ f - f_d \end{bmatrix}$$

$$\min_{\dot{q}, \alpha_R, \alpha_P} \left\| J(q)\dot{q} - \begin{bmatrix} \alpha_R \omega_T \\ \alpha_P v_T \end{bmatrix} \right\|^2 + \epsilon_R(\alpha_R - 1)^2 + \epsilon_P(\alpha_P - 1)^2$$

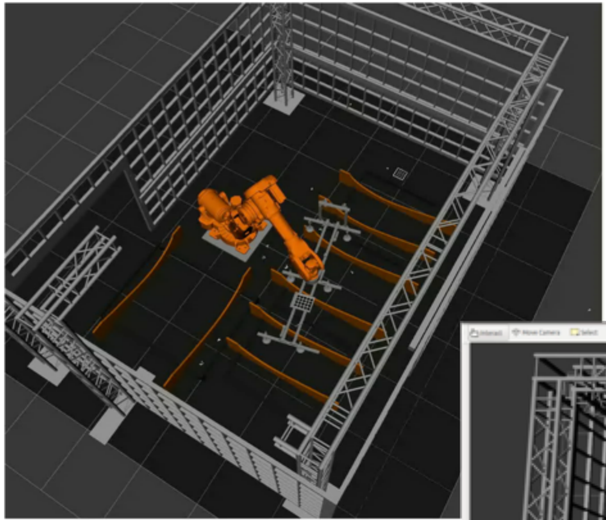




Opportunity: Multi-contact flexible load assembly/compliance control

Human Tracking, Safe Teleoperation

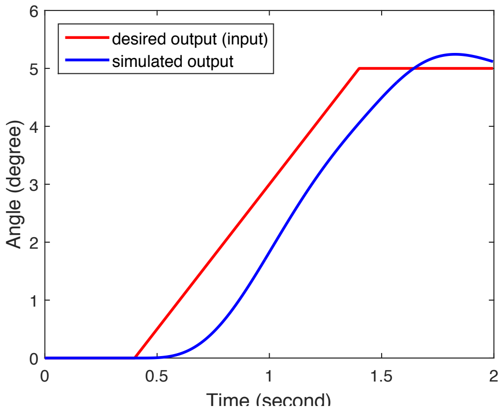
- Multiple point cloud sensor for human tracking, object identification
- User teleoperation without collision
- Distance calc: 10Hz



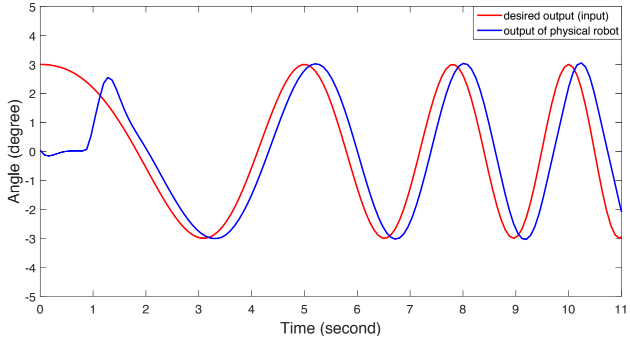
Opportunity:
Guaranteed safe robot motion with predictive control

Iterative and Neural Learning Control

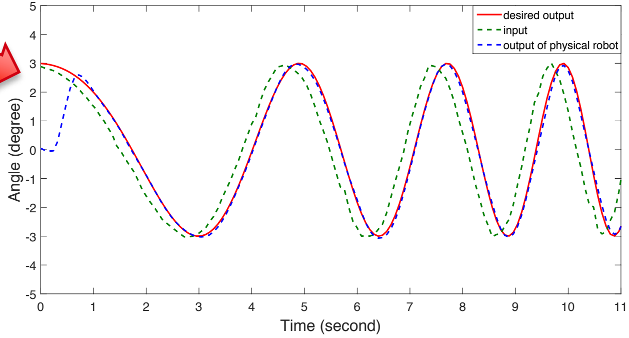
- Robot/load dynamics
- Iterative improvement over tracking error
- Simulation-based learning
- Encoding in neural network

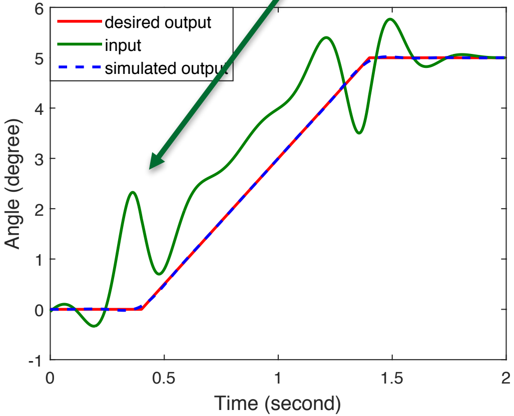


Strictly proper system ➔ Non-causal input



Noncausal NN FF compensation



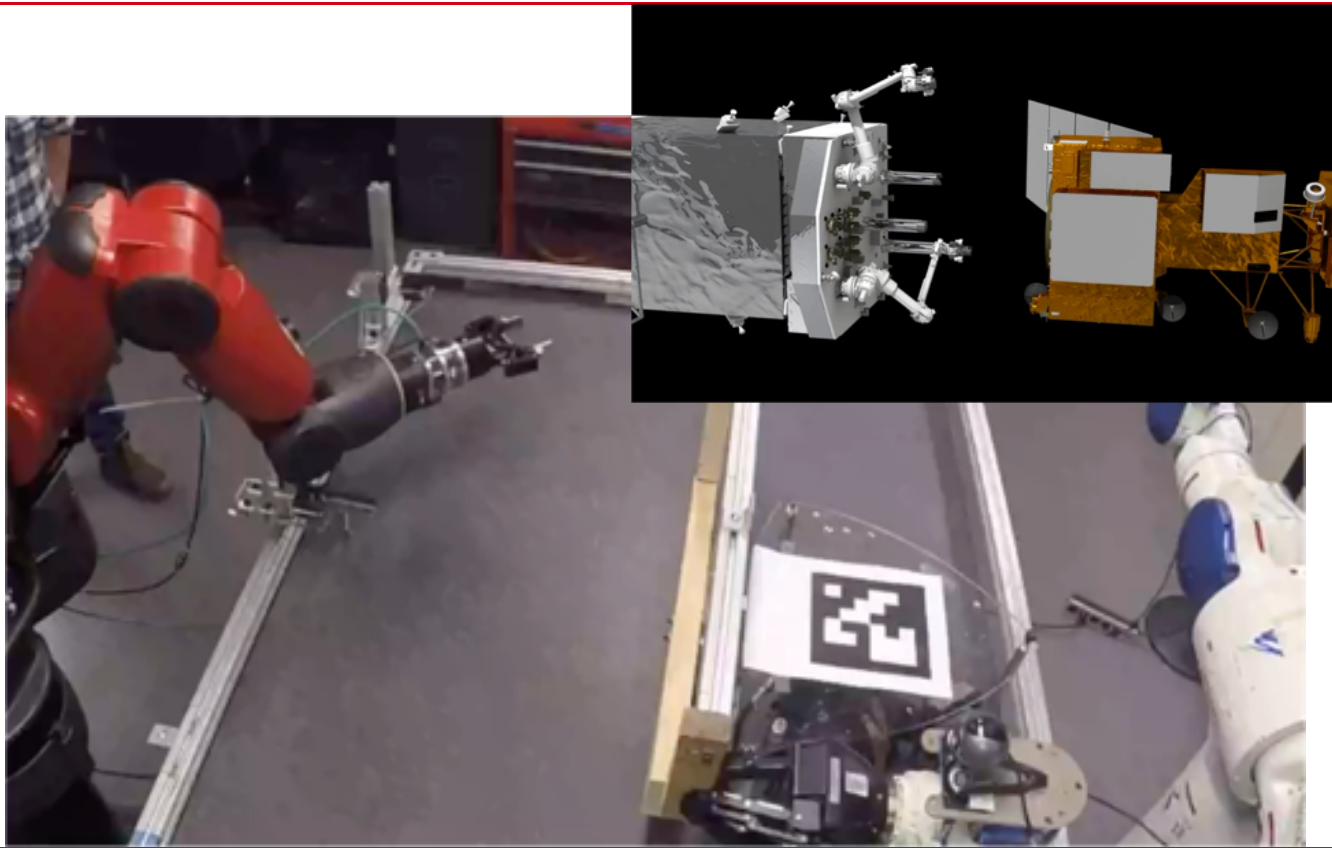


Opportunity: Neuro-adaptive control for nonlinear dynamical system

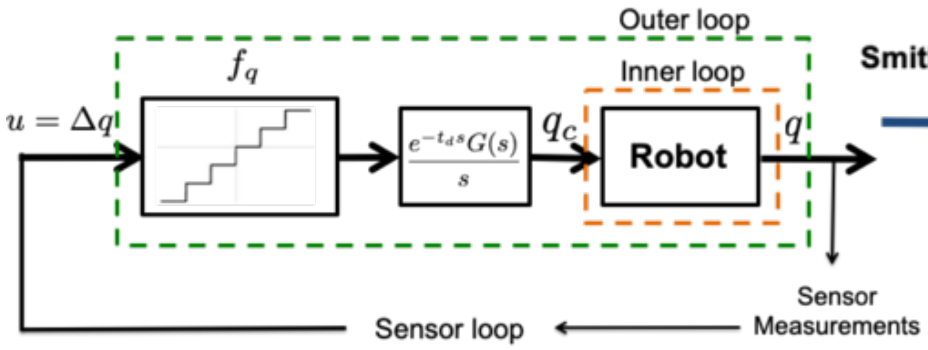
Robot Satellite Servicing

Restore-L Mission

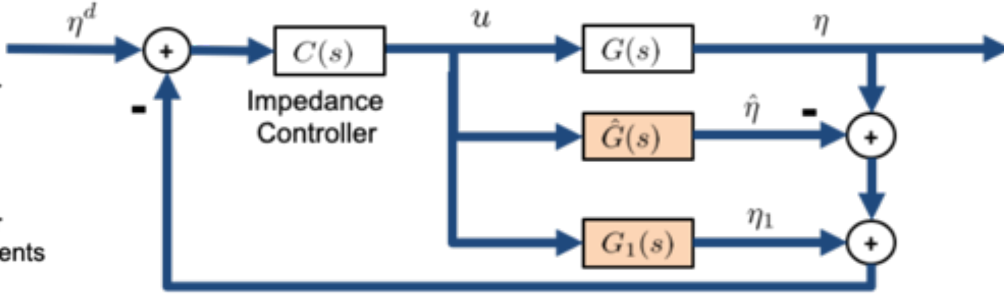
- Joint flexibility → bounded snap traj
- High-inertia load transport
- Compliance force control in 0-g
- Ground simulation



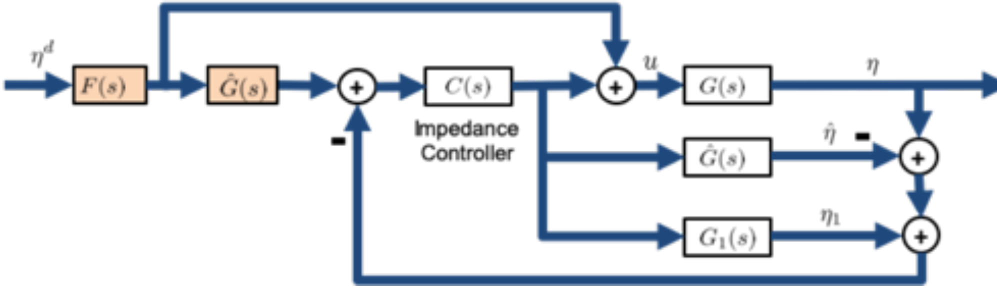
Impedance Control with Delay Compensation



Smith Predictor

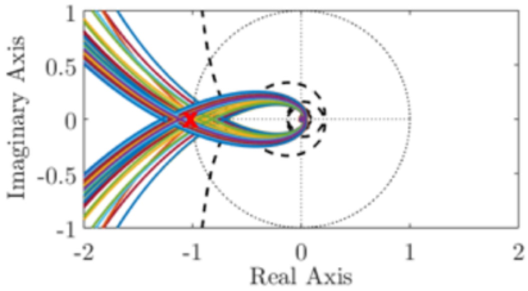


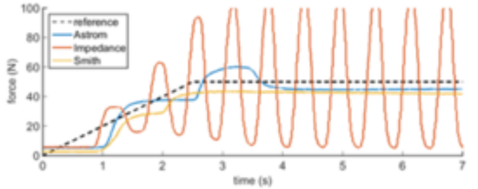
Astrom-Smith Predictor



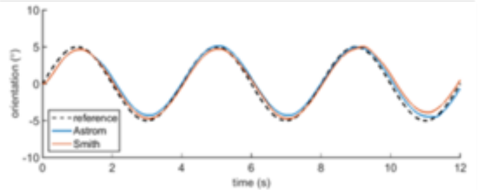
Stability and Nonlinearity

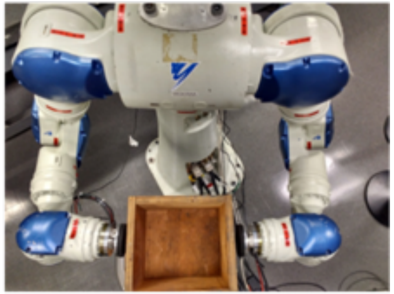
Impedance Controller



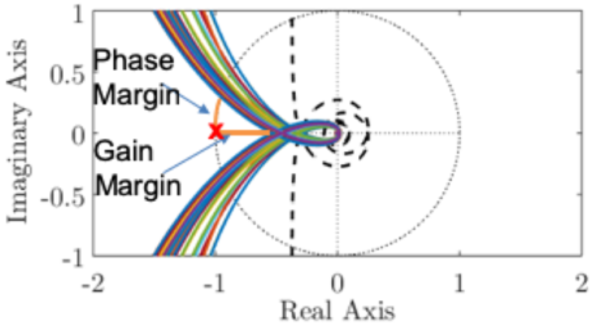


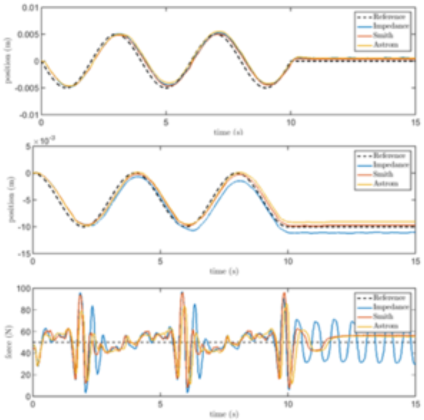
$\beta = 5000$ Rotation about Y





Smith Predictor





Assistive Robot

Human-robot collaboration

Redundancy resolution

Robot Software

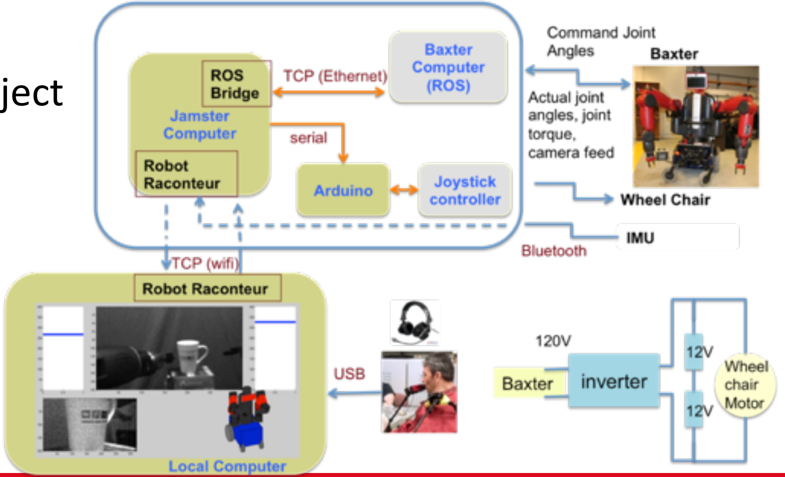
Middleware for distributed communication and control:

- Smart Grid (DOE): Volttron message bus
- Robotics: Robot Operating System (ROS, ROS 2.0)
- Industrial Internet (GE/RTI): Data Distribution Service (DDS)
- Robot Raconteur (Wason Tech, RPI)

Point-to-point (client-service)
Data vs. Object

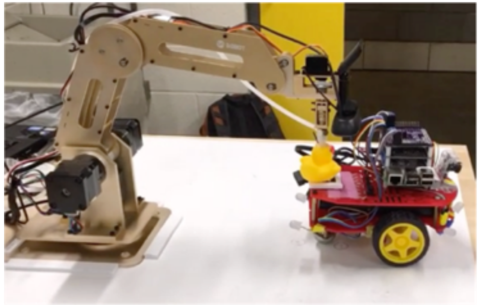
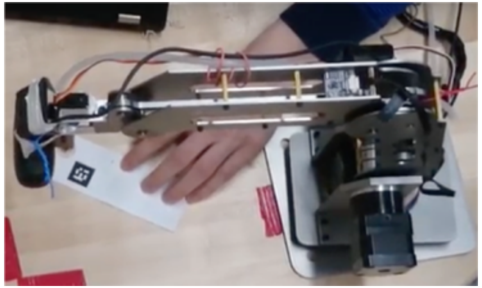
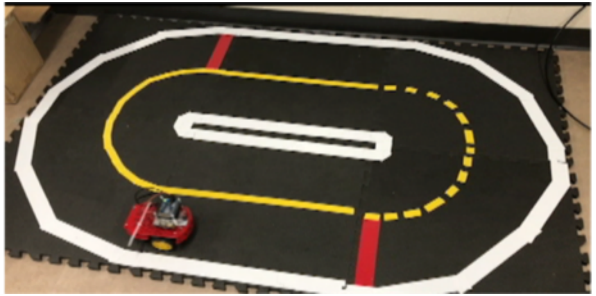
Distributed architecture: No master node
Object oriented: Client-service model
Ease of connection: no *a priori* info on data type and object
Plug-and-Play: Automatic node discovery
Security: user name and session authentication
Interoperability: ROS bridge, MATLAB, LabView
Compatible OS: Windows, Linux, MacOS
Embedded platform: Raspberry Pi, Arduino

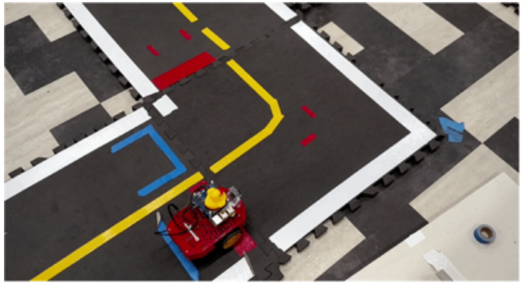
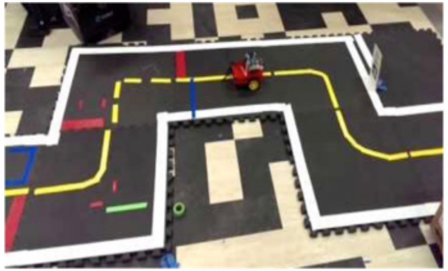
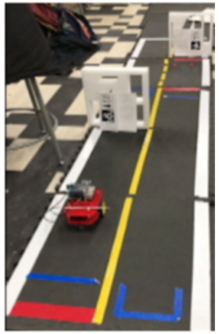
Open source, free download at robotraconteur.com



Robot Education

- Duckietown, Dobot, …

Summary

- Opportunities for control community to advance robots in manufacturing
- Model-based optimization + sensor-based feedback control + data-driven learning ➔ Improved manufacturing processes
- Numerous challenging manufacturing applications: surface modification, composites lay-up, robotic welding

Acknowledgment

- Robot assisted composites panel assembly: Shridhar Nath, Mark Vermilyea (GE), John Wason (Wason Technology), Matt Robinson, Levi Armstrong (SwRI), Glenn Saunders, William Lawler, Yuan-Chih Peng, Shuyang Chen, Dev Jivani, Rich Radke (RPI)

  Supported by ARM Institute and NYSTAR: ARM-17-QS-F-01 Robot Assistant for Composite Manufacturing

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- Assistive Robot: Dan Kruse (SRI Robotics), Lu Lu (NJIT) (Tufts University, Craig Nielsen Foundation)

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