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Automated Planning for Supporting Human Robot Collaboration in Assembly Cells

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Manufacturing Automation

- Processes are highly automated
  - CNC machining, laser cutting, 3D printing, injection molding
- Assembly
  - Significant automation in mass production setting
  - Significant manual labor in small batch manufacturing

Assembly Automation Challenges

- Assembly Consists of
  - Localizing, Grasping, Transporting, Attaching, Ungrasping
- Sensing Limitation
- Dexterity Limitations
- Planning Challenges
  - Constraint extraction
  - Sequencing
  - Tool selection
  - Motion planning
- Assembly automation is very challenging in small batch production

Research Focus: Assembly Automation

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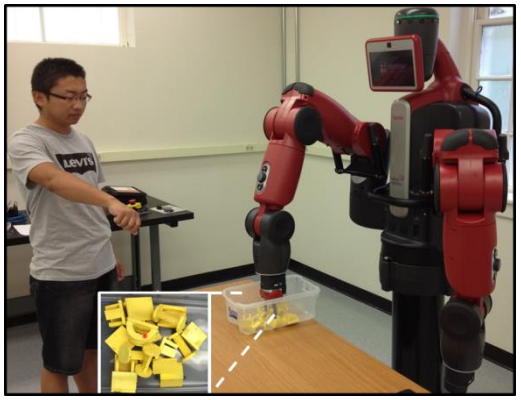
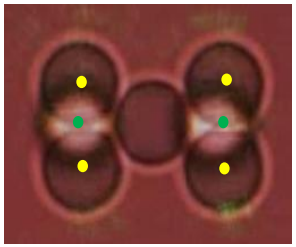
Assembly at Macroscale: Human Robot Collaboration



Assembly at Mesoscale: In-Mold Assembly

Assembly at Microscale: Optical Micromanipulation



Eliminating Assembly: Layered Manufacturing

Traditional Role of Industrial Robots in Manufacturing

- Mass Production
  - Assembly
  - Welding
  - Painting
  - Loading and unloading machines
- Lines are operated for months at a time without change
  - Tasks are highly repetitive and do not require human intervention
  - Setup times are small compared to line operation times
  - Robots separated from humans

(Image Source: ATACO Steel Products)

Small and Medium Manufacturers in US

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- The National Association of Manufacturers (NAM) defines
  - Small manufacturers as companies with 500 or fewer employees
  - Medium-sized manufacturers as companies with 2,500 or fewer employees
- NAM estimates that that US has close to 300,000 Small and Medium Manufacturers (SMM)
- SMM represents a very important segment of manufacturing sector in the US

Why SMMs Do Not Use Robots?

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- Industrial robots are costly
- Industrial robots are unable to do tasks that are labor intensive because, they
  - Lack dexterity and perception
  - Unable to operate in confined spaces
- Industrial robots take a long time to program
  - Significant expertise is needed to use robots
- Industrial robots are not considered safe for operating in the close proximity of humans
  - Tasks need to be decomposed to ensure separation between humans and robots

(Image Source: www.avplastics.co.uk)

Human Robot Collaboration in Assembly Tasks

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- Humans have certain strengths
  - Perception
  - Dexterity
  - Ability to cope with contingencies
- Robots have certain strengths
  - Accuracy
  - Speed
  - Endurance
  - Ability to apply large force

New opportunities for deploying robots in small and medium batch manufacturing

Hybrid Assembly Cells

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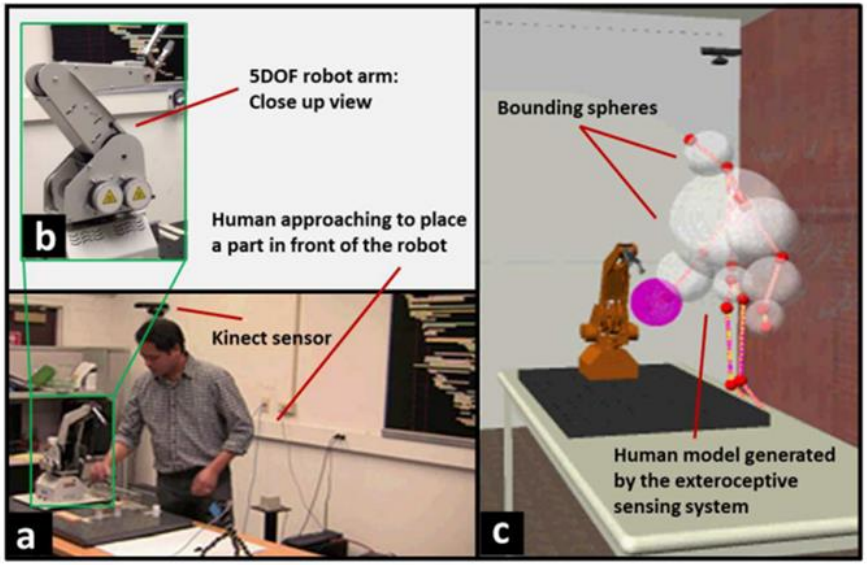
- Humans and robots safely and efficiently collaborate on assembly operations
  - Humans are tracked in the cells
  - Robots can take preventive measures to avoid collisions with humans
  - Parts are tracked in the assembly cell to detect errors and generate instructions to correct errors
  - Real-time planning capability to generate instructions for humans and robots



Planning for Hybrid Cell Operation

- Cell Level Planning
  - Sequence planning for complex assemblies
  - Planning for human robot collaboration in bin picking
- Human Operations
  - Automated Instruction generation for human operators
- Robotic Operations
  - Learning from demonstrations
  - Robot instructing humans on part placement
- Ensuring Human Safety
- Recovering from Errors

Planning for Complex Assemblies

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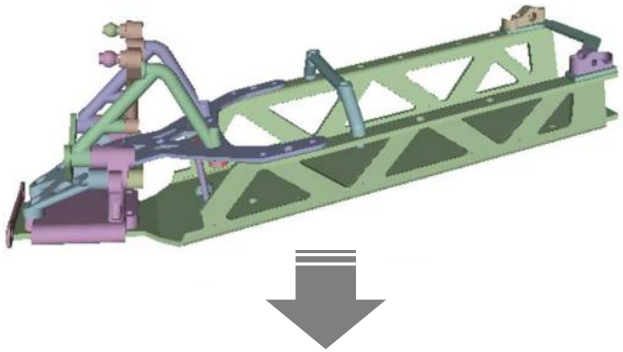
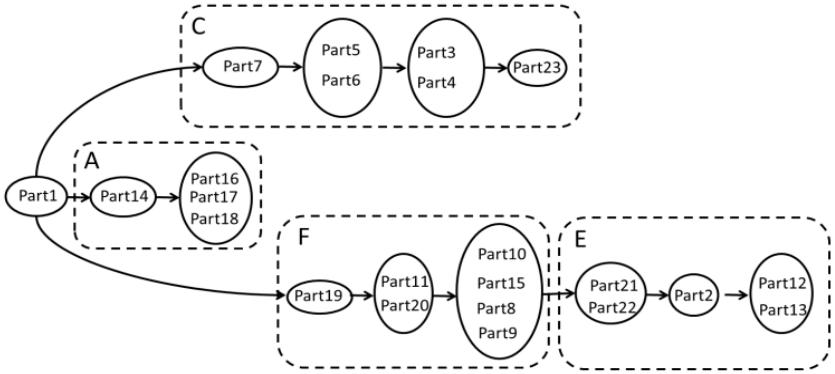
- Spatial clustering to automatically detect part interaction clusters
- Motion planning to assess operation feasibility
- Combining above two methods into assembly-by-disassembly approach to generate improved assembly precedence constraints





Morato, C., Kaipa, K.N., and Gupta, S.K. (2013). Improving assembly precedence constraint generation by utilizing motion planning and part interaction clusters, *Computer-Aided Design*, 45 (11): 1349-1364.

Morato, C., Kaipa, K.N., and Gupta, S.K. Assembly sequence planning by using multiple random trees based motion planning. *ASME Computers and Information in Engineering Conference* (IDETC/CIE 2012), Chicago, Illinois, USA, August 12-15, 2012.

Planning for Complex Assemblies (Contd.)

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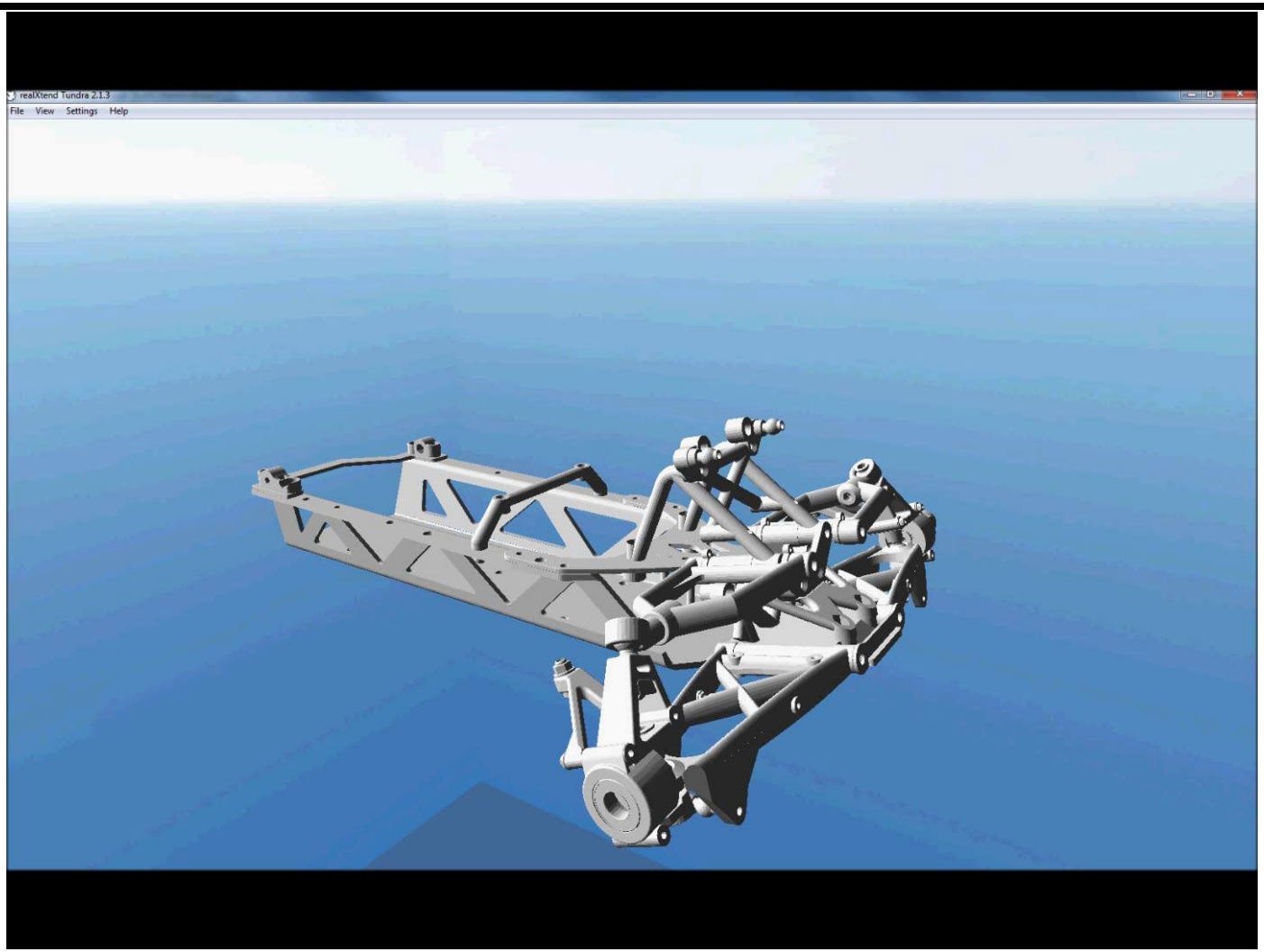

Automated Instruction Generation for Human Operators

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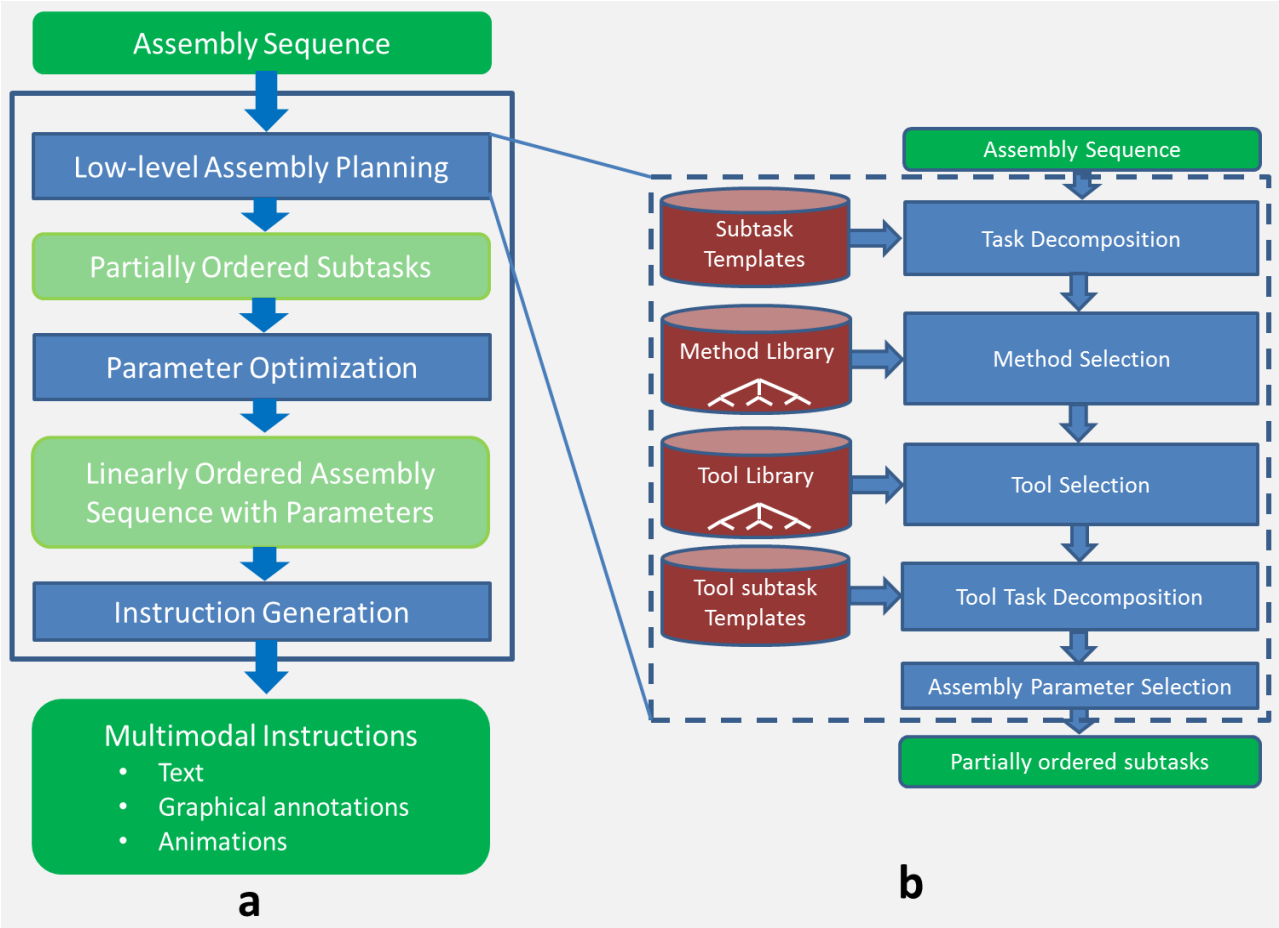
- Input
  - Assembly sequence
- Output
  - Text, graphical annotations, and 3D animations
- Part identification instructions
- Voice-based interface to control instruction display



Kaipa, K.N., Morato, C., Zhao, B., and Gupta, S.K. Instruction generation for assembly operations performed by humans. *ASME Computers and Information in Engineering Conference* (IDETC/CIE 2012), Chicago, Illinois, USA, August 12-15, 2012.

VIDEO

https://www.youtube.com/watch?v=wW98epD0vQk&feature=youtu.be

Robot Instructing Humans on Part Placement

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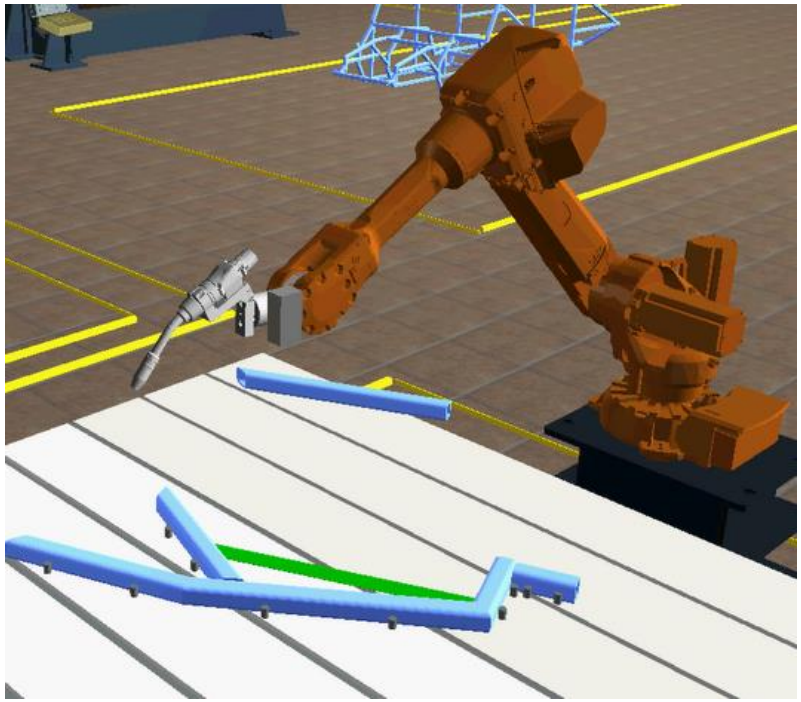
- Robot equipped with augmented reality guides human where to place parts by casting markers in desired postures
- Part position and orientation used to control relative postures of markers
- Same information also fed to robot's laser projector that casts similar shapes at appropriate places on assembly table



Eliminates need for manual measuring or calibration equipment required for component placement

Video

https://www.youtube.com/watch?v=UdliOqzE2G8

Planning for Human Robot Collaboration in Bin Picking

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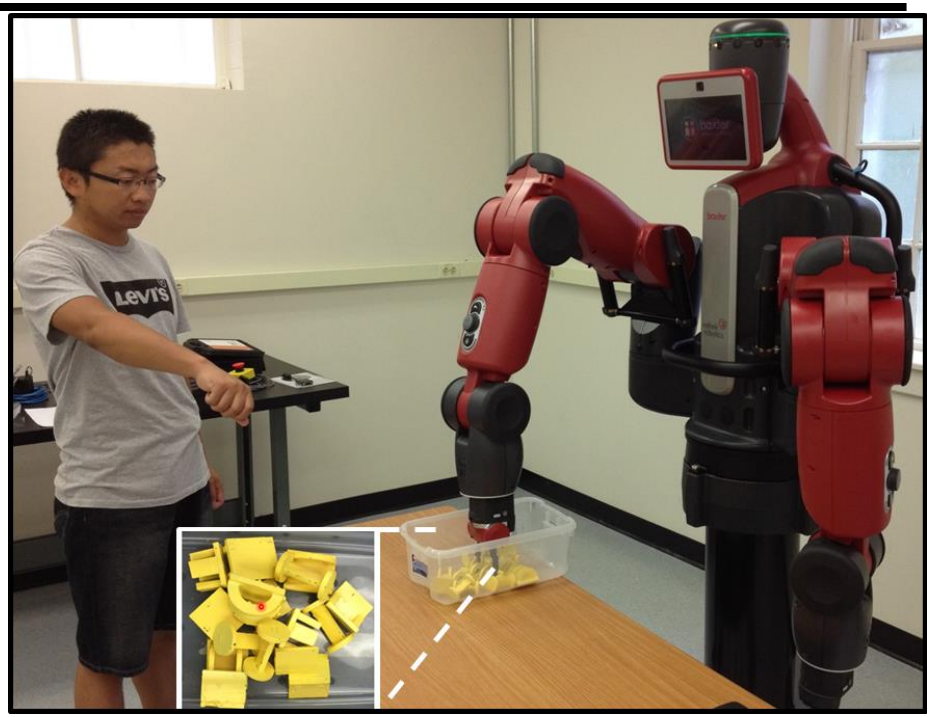
- Mixed bin-picking precedes assembly in many low volume production scenarios
- Challenges
  - Random part postures, overlaps, occlusions, background clutter, shadows, poorly lit conditions
- Approach



  - Robot does bin-picking and assembles each part to build the product
  - Human assists robot in critical situations by (1) resolving perception and/or grasping problems encountered during bin-picking and (2) performing dexterous manipulation required during assembly

Planning for Human Robot Collaboration in Bin Picking (Contd.)

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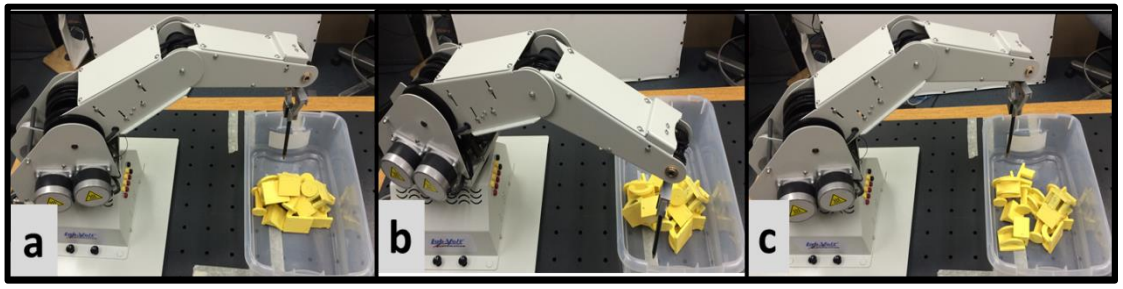
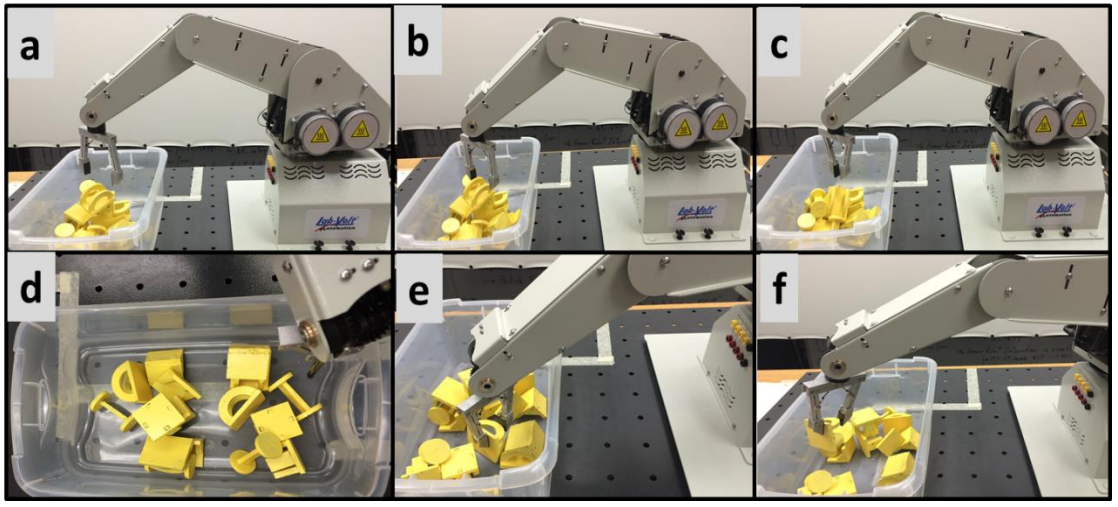
- Scenario 1
  - Human shines laser on a part
  - Robot picks up the indicated part
- Scenario 2
  - Robot de-cluttering
- Scenario 3
  - (a-c) Robot fails to grasp the part
  - (d) Robot de-clutters in response to human's command
  - (e)-(f) Robot successfully picks up the part





Learning from Failed Demonstrations

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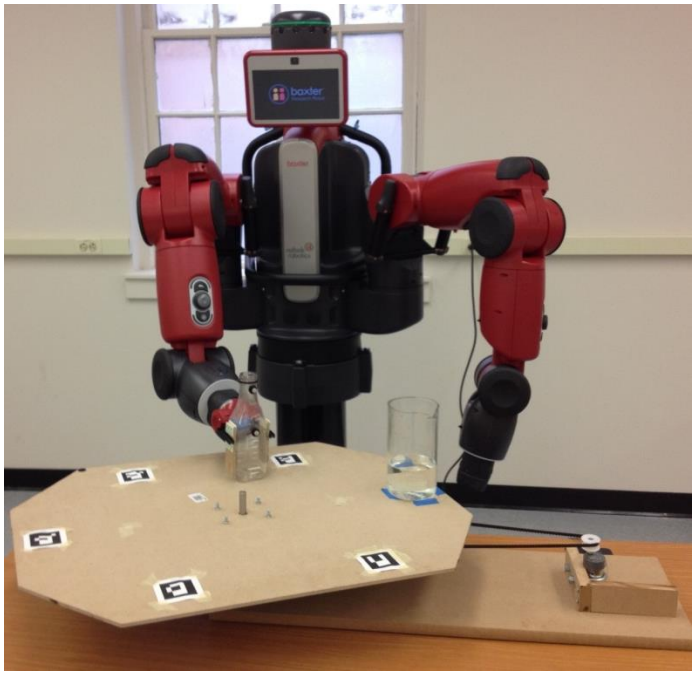
- Approach allows learning from successful human demonstrations, errors made by humans, and how humans recovered from these errors in subsequent trials



- SVM based classifiers and iterative search to generate initial task parameters for robot

- If robot fails, simple rules are learned to refine them by capturing how humans change parameters to transition from failure to success

Video

https://www.youtube.com/watch?v=ydnjS__8Ooc

Planning for Ensuring Human Safety

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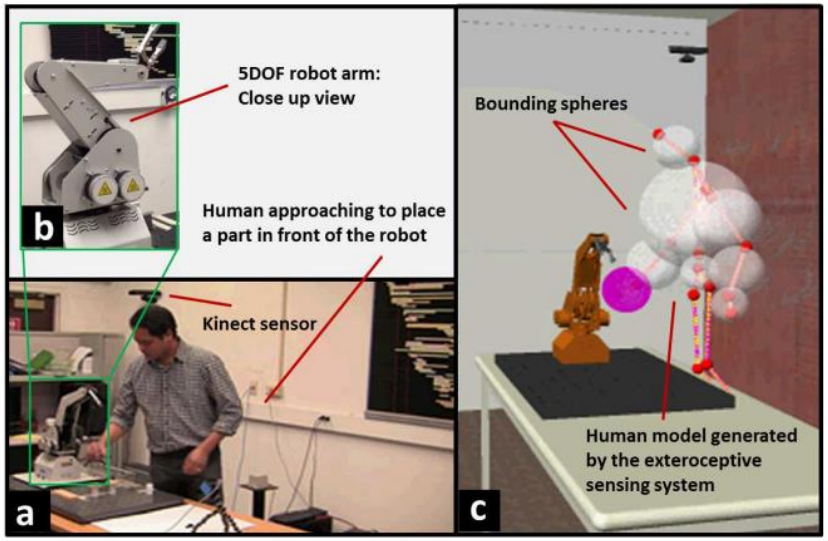
- Real-time replication of human and robot movements inside a physics-based simulation of the work cell
- Multiple Kinects based system to track and model human
- Roll-out strategy
  - forward-simulate robot's trajectory and create temporal set of its postures for next few seconds
  - Check whether any of these postures collide(s) with human model
- Pause robot's motion whenever imminent collision detected



Morato, C., Kaipa, K.N., Zhao, B., and Gupta, S.K. (2014). Toward safe human robot collaboration by using multiple Kinects based real-time human tracking. *Journal of Computing and Information Science in Engineering*, 14(1):011006-011006-9.

Video

https://www.youtube.com/watch?v=X68F9p8DMLg

Planning for Recovering from Errors

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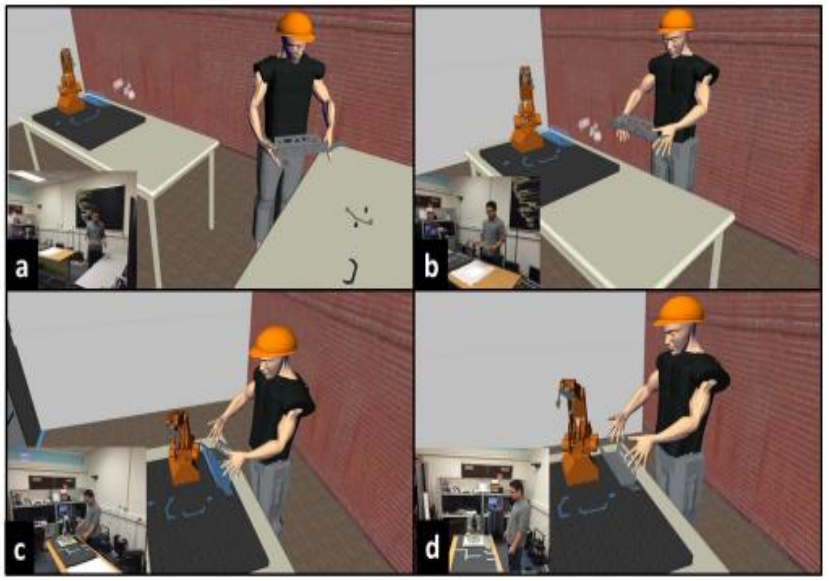
- System state monitoring and re-planning enable contingency handling
- Ability to handle contingencies in different regimes
  - Deviations that leads to process errors
  - Deviations that leads to improvements in the assembly speed or output quality
  - Deviation that leads to adjustment in the assembly sequence



- Design permits human to make adjustments to assembly sequence in real-time with little delays to assembly cell output

Morato, C., Kaipa, K.N., Liu, J., and Gupta, S.K. A framework for hybrid cells that support safe and efficient human-robot collaboration in assembly operations. *ASME Computers and Information in Engineering Conference* (IDETC/CIE 2014), Buffalo, New York, USA, August 17-20, 2014 (to appear)

Planning for Recovering from Errors (Contd.)

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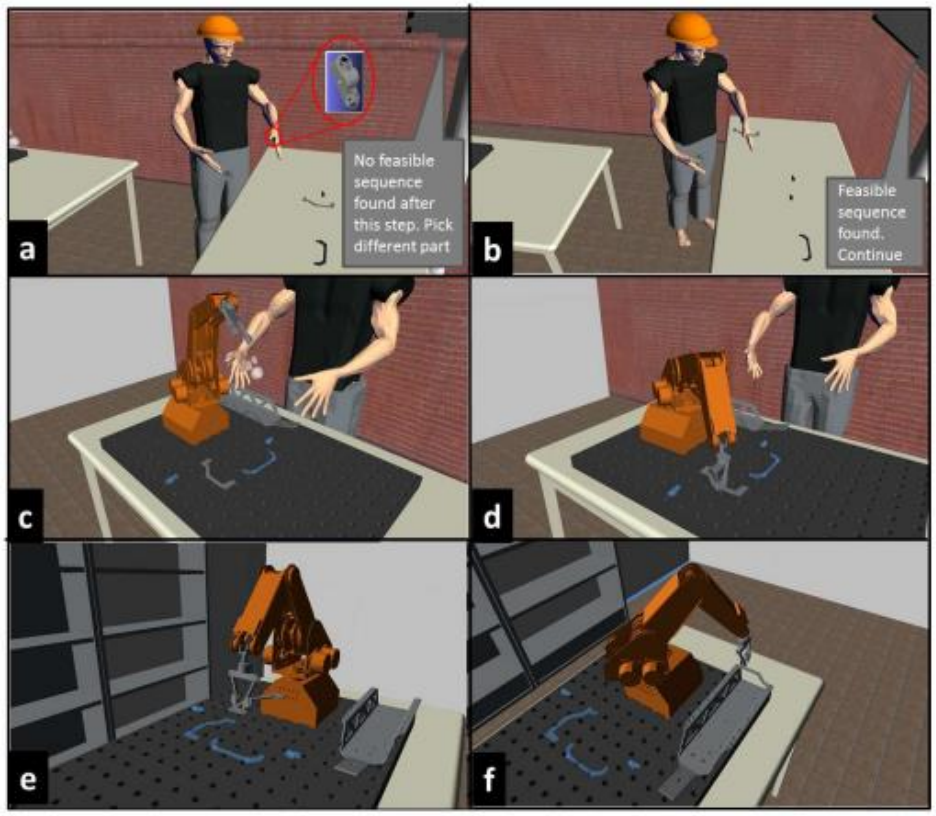
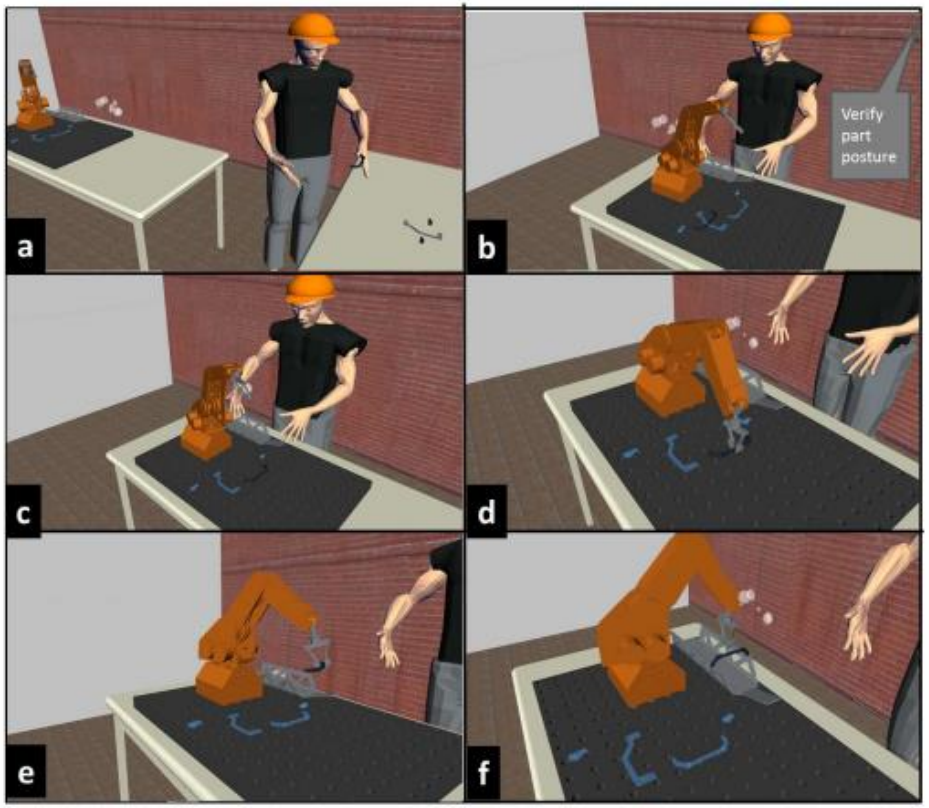
- Illustration 1
  - Warning generation and replanning when human picks "wrong" part



- Illustration 2
  - Warning generation when human places part in wrong location



Conclusions

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- Hybrid cells can potentially enable use of robots in low volume production assembly operations
- Many new types of planning challenges need to be addressed to enable safe and efficient robot and robot collaborations in assembly operations
- We have developed many component technologies to enable safe and efficient human robot collaboration on assembly tasks

Questions?