Multi-Objective Optimization in Industrial Robot Design and Robotic Cell Design

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Presentation Outline

- Objectives to this presentation
- Introduction to industrial robot manipulator (design and use)
- Optimal robot cell design: Research background
- Optimal robotic cell design: Research results and modeFrontier experiences
- Future work
- Conclusions
Objective of This Presentation

- Promoting practical use of optimization – Significance of modeFrontier
- Argument using examples in industrial robotics
  - Optimal robot cell design
  - Robot drive-train design optimization
- Outline future work
Introduction to Industrial Robotics

ABB Robots
Introduction to Industrial Robotics

Terminology

- Arm house
- Upper arm
- Lower arm
- Wrist
- Tool flange
- Stand
- Base
- Axis 1
- Axis 2
- Axis 3
- Axis 4
- Axis 5
- Axis 6

ABB IRB4600 robot
Introduction to Industrial Robotics
Drive-Train of Industrial Robots

- Gearboxes as speed reducers
- AC Servo motors with integrated brakes and position sensors as actuators
- Design issues
  - Motor torque levels
  - Gearbox torque levels
  - Motor speed levels

Gearbox and gear wheels

Electric motors

Pictures courtesy ABB and
http://legacy.elizabethtown.kctcs.edu/
Motion simulation tool employs a virtual control of ABB industrial robots

Inputs to the motion simulation tool are
- Robot parameter file
- Robot cycle/program file defining tasks to be conducted by the robot

Outputs from the motion simulation tool are
- Cycle time
- Torques and speeds on motor and gearbox sides
- Other system information for robot use
Introduction to Industrial Robotics
Robot Performance May be Modified/Adapted by

- Changing the position of tasks to be conducted by a robot in its workspace
- Changing the drive-train setup parameters
Research Background
Performance Dependent on Robot Task Placement - Physical Meaning

Inhomogeneous performance
Typical pick-and-place robot cycle
ABB robot motion simulator
Performance depends on the placement position of the robot cycle

<table>
<thead>
<tr>
<th>Positions</th>
<th>Normalized cycle time</th>
<th>Normalized lifetime</th>
<th>Normalized motor power consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pos0</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Pos1</td>
<td>1.02</td>
<td>1.01</td>
<td>0.98</td>
</tr>
<tr>
<td>Pos2</td>
<td>0.94</td>
<td>1.00</td>
<td>1.24</td>
</tr>
<tr>
<td>Pos3</td>
<td>1.01</td>
<td>1.03</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Research Background
Performance Dependent on Robot Task Placement - modeFrontier Workflow

- DOE sequence (Uniform Latin Hypercube with 18 values)
- Variations in 3 task placement position parameters
Research Background
Performance Dependent on Robot Task Placement - Results

- Results normalized based on original task placement position parameters
- Parameter variation ranges
  \( \Delta X \in (-0.1m, 0.1m) \)
  \( \Delta Y \in (-0.1m, 0.1m) \)
  \( \Delta Z \in (-0.2m, 0.5m) \)

- Resulted variation in cycle time by 9.5%
- Resulted variation in lifetime by 9%
- Resulted variation in Total motor power consumption by 26%
Research Background
Performance Dependent on Drive-Train Setup Parameters - Physical Meaning

- Three main axes studied
- Motor torques, motor speeds, and gearbox torques of the three main axes, in total 9 design variables used in the study
- Typical pick-and-place cycle
- ABB robot motion simulator

<table>
<thead>
<tr>
<th>Axis-1</th>
<th>Motor torque</th>
<th>Motor speed</th>
<th>Gearbox torque</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T_motor_1</td>
<td>Spd_1</td>
<td>T_gear_1</td>
</tr>
<tr>
<td>Axis-2</td>
<td>T_motor_2</td>
<td>Spd_2</td>
<td>T_gear_2</td>
</tr>
<tr>
<td>Axis-3</td>
<td>T_motor_3</td>
<td>Spd_3</td>
<td>T_gear_3</td>
</tr>
</tbody>
</table>
Research Background
Performance Dependent on Drive-Train Setup Parameters - Workflow

- DOE sequence (Uniform Latin Hypercube with 54 values)
- Variations in 9 drive-train parameters
Research Background
Performance Dependent on Drive-Train Setup Parameters - Results

- Results normalized based on original drive-train setup parameters
- Parameter variation ranges $\varepsilon (0.9, 1.2)$

![Graphs showing normalized cycle time, lifetime, and total motor power consumption variations]

- Resulted variation in cycle time by 6.5%
- Resulted variation in lifetime by 85%
- Resulted variation in Total motor power consumption by 22.5%
Research Background
Technical Challenges for a Robotic Cell Designer

- How to search in the design space to explore/optimize the trade-offs among
  - Cycle time performance
  - Component lifetime performance
  - Energy efficiency
Research Results

- Optimal design of robotic working cell. More details may be refer to
Two Optimization Problem Formulations

- Task placement optimization
  \[ \mathbf{DV} = [\Delta X, \Delta Y, \Delta Z]^T \]

- Combined Optimization (Optimizing both drive-train and task placement)
  \[ \mathbf{DV} = [\Delta X, \Delta Y, \Delta Z, DV_1, DV_2, \ldots, DV_n]^T \]

- Multi-objective optimization problem formulation 1
  - Min(Normalized cycle time) &
  - Min(Normalized total motor power consumption)

- Multi-objective optimization problem formulation 2
  - Min(Normalized cycle time) &
  - Min(1 / Normalized lifetime)
Research Results

Optimal Task Placement (minimize cycle time and power consumption) - Workflow

- 3 Design variables
- 2 objective functions
  - Min(cycle time)
  - Min(power consumption)
- Uniform Latin Hypercube DOE (12 values)
- MOGA-II (20 generations)
Research Results
Optimal Task Placement (minimize cycle time and power consumption) - Results

- Simulation time: 29 min
- Function evaluations: 240
- Color bubbles show good Pareto front optimization convergence
- Pareto front explores relation between cycle time performance and power consumption
  - Improved cycle time performance always results in increased power consumption
Research Results
Combined Optimization (minimize cycle time and power consumption) - Workflow

- 12 Design variables
- 2 objective functions
  - Min(Norm cycle time)
  - Min(Norm power consumption)
- Uniform Latin Hypercube DOE (48 values)
- MOGA-II (20 generations)
Research Results
Combined Optimization (minimize cycle time and power consumption) - Results

- Simulation time: 3h 15m
- Function evaluations: 960
- Color bubbles show good Pareto front optimization convergence
- Pareto front explores relation between cycle time performance and power consumption
  - A 5% energy saving may be achieved without lose of cycle time performance (Region A)
  - A 8% cycle time improvement results in 25% increase of power consumption (Region B)
Research Results
Combined Optimization (minimize cycle time and power consumption) – Parallel Coordinates

“Parallel Coordinates” plots help to understand design trade-offs and design solutions in an interactive manner

Figure shows one example on achieving 10% cycle time improvement results in 30% increase in power consumption
Research Results
(minimize cycle time and power consumption) - Result Summary

Optimal task placement

Combined optimization

- Results sets A-A’ (with no cycle time improvement)
  - Combined optimization explores a energy saving by 5% (Solution set A in right figure)
  - Task placement optimization explores no energy saving (Solution set A’ in left figure)

- Results sets B-B’ (with 4% cycle time improvement)
  - Combined optimization explores an increase in energy consumption of 7% (Solution set B in right figure)
  - Task placement optimization explores an increase in energy consumption of 9% (Solution set B’ in left figure)
Research Results
(minimize cycle time and maximize lifetime) - Result Summary

- Results sets A-A’ (with 4% cycle time improvement)
  - Combined optimization explores a lifetime improvement of more than 40% (Solution set A in right figure)
  - Task placement optimization explores a lifetime improvement of about 15% (Solution set A’ in left figure)

- Results sets B-B’ (with 9% cycle time improvement)
  - Combined optimization explores a lifetime lose of about 10% (Solution set B in right figure)
  - Task placement optimization explores no such solution (Solution set B’ in left figure)
Future Work

- Multi-objective optimization in robot drive-train design
  - Explore the trade-off between time performance and cost
  - Explore the trade-off between light-weight design and energy efficiency design
- Multi-objective optimization in robot family design optimization
  - CAD tool integration
  - Mixed variable design optimization
  - To explore trade-off among time performance, module reuse, and direct material cost
Each optimization iteration involves the following engineering simulations:
Geometry manipulation in CAD tool; kinematics; and Robot dynamics including
1) time performance, 2) structure forces, and 3) lifetime of drive-train
Conclusions

Technical conclusions

- Task placement positions have significant impacts on robot performance
- Combined drive-train and task placement optimization explores better trade-offs between time performance and lifetime and between time performance and power consumption
- Multi-objective optimization explores good insight for designers in robotic cell design

General conclusions

- modeFrontier has contributed to our understanding of the robotic cell design optimization problems
- We see increasing need in multi-objective optimizations in industrial robotic cell design, industrial robot design, and robot family design