Discovery of Design Methodologies for the Integration of Multi-disciplinary Design Problems

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Contents

• The problem

• Why is a solution important?

• We have a solution!

• How did we get the solution?

• The approach

• Contributions and Conclusions
Purpose of a Ph.D. Dissertation

• In General
  • Advancing Frontiers of Knowledge

• In Engineering
  • New Knowledge for the Benefit of Humans
Helping Designers

a team of designers wishing to find faster and less expensive ways to do design

They need integration:

- Common Goals
- Communication
- Resolving Conflicts
- Sharing Resources
The Questions the Team of Designers Face

- What design methods to use?
- In what order?
- When to stop to exchange their designs?
- How to evaluate their designs?
- How to cooperate?
- How to do things concurrently?

How to do the design?

... and NOT:

What is the design?
• **Product versus Process**
  
  • **Destination versus Journey**

• **Better Product** versus **Better Process**

  **Better City**
  - lower cost of living
  - better school system
  - lower crime rate

  **Better Journey**
  - faster
  - less expensive
  - better roads

• **Better Design Methodology**

  • Better Route for the Journey:

    Route 9 or Mass Pike make a Trip to Boston
• Why Need for New and Better Methodologies?
  • Why Need for New and Better Products?

• Need for Continuous Improvement
  • Need for Rapid Incorporation of New Technologies
  • Need for Shorter Time-to-market
  • Need for less Expensive Process
  • Need for Integration
  • Need for Concurrency
What can the team rely on?

- Experience
- Engineering Judgement

... what else?

Is there currently a method or a tool that the team could use to generate better methodologies?

- Systematically
- Incorporating Integration
- Incorporating New Technologies

... 

The answer is: NO!

especially for multi-disciplinary designs:

- multiple points-of-view: conflicts
- multiple languages: no communication

...
What can we do to:

- generate methodologies for the design team
- get a Ph.D.

An Answer:

anticipate the design process : Goal

How to anticipate the future?

by Simulating the design process : Approach
Barriers

• Departmentalization
• Built-in Disciplinary Goals
• Disciplinary Design in Large Segments
• Counter-Intuitive Behavior
• Evolving Knowledge
• “Tragedy of the Commons”
• Highly Focused Disciplinary Knowledge
• Multifaceted Interactions
Design of a Robot

Dynamics

Kinematics

Computer

Mechanics

Electronics

Controls
Design of a 2-DOF Robot

- Disciplinary Design Knowledge
  - Kinematic
  - Structural Mechanics
  - Dynamics
  - Controls
Example: Design a 2-DOF Robot that:

1 - Covers the following points:

2 - can carry a load of 1.0 kg;
3 - has a settling time of 1.0 sec;
4 - has an overshoot of 10%;
5 - deflection of the tip is less than 0.001 of the sum of its link lengths;
6 - gains of its controllers are less than 100.

What methodology would you use for designing this type of robot?
**Methodology:**

**IF:**

**Requirements:**
- workspace: “small-M”,
- workload: easy,
- settling time: tough,
- maximum overshoot: tough;

and ...

**Constraints:**
- deflection of the tip: tight,
- gain of the controller: tight.

**THEN** do the following ...
Methodology

- **choose** the location of the base of the robot: “left or below midway of the workspace length”
- **choose** the material: “steel stainless AISI 302 annealed”
- **select** the shape of the cross section of the link: “hollow round”
- **choose** the structural safety factor: “3”
  - **do** the design and proceed to the next step
- **choose** the link 2 to link 1 length ratio: “0.5”
  - **do** the design and proceed to the next step
- **pick** the configuration of the arm: “left-handed”
- **select** the ratio of the cross section dimension of the link to minimum required by stress analysis: ”4”—if it fails select “3”
  - **do** the design and proceed to the next step
- **find** the accessible region: use Equation 2-4
- **find** the deflection of the tip: use Equation 2-14
- **choose** the type of controller: “PD”
  - **do** the design and finish the process.
Why ‘this’ methodology?

Anticipation shows that this is the fastest and a well integrated way to design.

How was it generated?

By Simulating what a team of designers would do.

How was the design process simulated?

By implementing a knowledge-based model of the design process in the form of a multi-agent computer program.
Approach: Knowledge-based Design

Knowledge

Use

Methodologies

Kinematics Design Methods

Structural Design Methods

Dynamics Design Methods

Control Design Methods

Design Project 1

Design Project 2

Design Project m

Design Methodology for Projects of Type 1

Design Methodology for Projects of Type 2

Generalizing: Inductive Learning

Use of Design Methods
Implementation: Multi-agent Systems

• Agent:
  • a self-contained problem solving system
  • an abstraction tool for managing complexity
  • autonomous
  • reactive
  • pro-active
  • social behavior

• Multi-agent Systems:
  • composed of multiple interacting agents
  • distributed
  • modeling and implementing social interactions
  • parallelism
**Multi-agent Design System: Architecture**

[Diagram of multi-agent design system with roles and connections labeled.]
Implementation in Java
Software Development Challenges

- Design
  - incremental approach
  - message sequence charts
- Large Scale
  - packages
  - classes
  - inner classes
- Code
  - 30,000 lines
- Platforms
  - SUN Ultra 5 Workstation
  - Digital Alpha Workstation
- Concurrency
  - multi‐threading
  - synchronization
  - cycles of consistency
- Communication
  - message passing
  - KQML
- Run Time
  - few seconds: easy requirements and loose constraints
  - few hours: tough requirements and tight constraints
## Design Projects

### Range of Values for the Constraints and Requirements

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Requirements</th>
<th>Constraints</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum ratio of deflection</td>
<td>workspace</td>
<td>maximum proportional gain1</td>
<td>(“small-M”, “small-L”, “big-M”, “big-L”)</td>
</tr>
<tr>
<td>of tip to sum of link lengths</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>maximum proportional gain1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>maximum proportional gain1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>maximum proportional gain1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Indexing Projects</th>
<th></th>
<th>Indexing Projects</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>d/L ratio</td>
<td>gain 1</td>
<td>workspace</td>
<td>workload</td>
</tr>
<tr>
<td>0.01</td>
<td>1000</td>
<td>“small-M”</td>
<td>1.0</td>
</tr>
<tr>
<td>0.01</td>
<td>1000</td>
<td>“small-M”</td>
<td>1.0</td>
</tr>
<tr>
<td>0.01</td>
<td>1000</td>
<td>“small-L”</td>
<td>1.0</td>
</tr>
<tr>
<td>0.001</td>
<td>100</td>
<td>“small-M”</td>
<td>1.0</td>
</tr>
<tr>
<td>0.001</td>
<td>100</td>
<td>“big-L”</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Different Workspace Used as Requirements
Example: Project 732

Constraints:

\[
0 < \text{link1\_length} < \text{workspace\_rectangle\_length} \\
0 < \text{link2\_length} < \text{link1\_length} \\
0 < \text{link1\_cross\_section\_dimension} < 0.1 \times \text{link1\_length} \\
0 < \text{tip\_deflection} < 0.001 \times (\text{sum of link lengths}) \\
0 < \text{accessible\_region\_area} < 1.0 \times \text{workspace\_rectangle\_area} \\
0 < \text{proportional\_gain1} < 100 \\
0.05 \times \text{section\_dimension} < \text{link1\_cross\_section\_thickness} < 0.25 \times \text{section\_dimension}
\]

Requirements:

workspace = \{(0.5, 0.25), (0.75, 0.5), (1.0, 0.75), (1.25, 1.0), (1.5, 0.75), (1.75, 1.0), (2.0, 0.75), (2.25, 0.5), (2.5, 0.25)\} m
workload = 1.0 kg
settling\_time = 1.0 sec
maximum\_overshoot = 10%
Discovering Dependencies: Project 732

Design Parameters:
1. workspace
2. workload
3. settling_time
4. maximum_overshoot
5. base_location
6. material_name
7. material_mass_density
8. material_yield_stress
9. material_elasticity_modulus
10. structural_safety_factor
11. link_cross_sectional_shape
12. link1_length
13. link2_length
14. theta1_min
15. theta1_max
16. theta2_min
17. theta2_max
18. link1_cross_section_dimension
19. link2_cross_section_dimension
20. link1_cross_section_thickness
21. link2_cross_section_thickness
22. accessible_region_area
23. tip_deflection
24. proportional_gain1
25. derivative_gain1
26. proportional_gain2
27. derivative_gain2

Design Requirements
Design Path: Project 732

Path Trace: Project 732

Design Approaches

<table>
<thead>
<tr>
<th>Designer Agent</th>
<th>Design Approach</th>
<th>Approach Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>K_1</td>
<td>base_at_left_below_midway_workspace_length</td>
<td>0</td>
</tr>
<tr>
<td>S_2</td>
<td>steel_stainless_AISI_302_annealed</td>
<td>0</td>
</tr>
<tr>
<td>S_3</td>
<td>safety_factor_3</td>
<td>0</td>
</tr>
<tr>
<td>S_4</td>
<td>hollow_round</td>
<td>0</td>
</tr>
<tr>
<td>K_2</td>
<td>link_lengths_ratio_0.5</td>
<td>0</td>
</tr>
<tr>
<td>K_3</td>
<td>theta1_is_alpha1_minus_alpha2</td>
<td>0</td>
</tr>
<tr>
<td>S_1</td>
<td>dimension_min_ratio_3</td>
<td>1</td>
</tr>
<tr>
<td>K_4</td>
<td>default</td>
<td>0</td>
</tr>
<tr>
<td>S_5</td>
<td>default</td>
<td>0</td>
</tr>
<tr>
<td>C_1</td>
<td>default</td>
<td>0</td>
</tr>
</tbody>
</table>

Chosen Design Approach

Not Chosen Design Approaches

Number of Possible Paths = $6 \times 2 \times 4 \times 2 \times 3 \times 2 \times 4 \times 1 \times 1 \times 1 = 2304$
## Clustering Design Projects that Followed the Same Trace

### Projects that Followed Trace 1

<table>
<thead>
<tr>
<th>Projects in the Cluster</th>
<th>Constraint on Deflection</th>
<th>Constraint on Gain 1</th>
<th>Workspace</th>
<th>Workload (kg)</th>
<th>Settling Time (sec)</th>
<th>Maximum Overshoot (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 to 24</td>
<td>0.01</td>
<td>1000</td>
<td>small-M</td>
<td>2</td>
<td>(3</td>
<td>2</td>
</tr>
<tr>
<td>121, 126, 132, 134, 139, 146 to 148, 151 to 152, 159 to 160, 163 to 164, 171 to 172, 175 to 176</td>
<td>0.01</td>
<td>1000</td>
<td>big-M</td>
<td>(1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>246, 252, 254 to 256, 259 to 260</td>
<td>0.01</td>
<td>100</td>
<td>small-M</td>
<td>(1</td>
<td>2)</td>
<td>(3</td>
</tr>
<tr>
<td>364</td>
<td>0.01</td>
<td>100</td>
<td>big-M</td>
<td>1</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>493 to 504</td>
<td>0.001</td>
<td>1000</td>
<td>small-M</td>
<td>2</td>
<td>(3</td>
<td>2</td>
</tr>
<tr>
<td>614, 619, 626 to 628, 631 to 632, 639 to 640, 643 to 644, 651 to 652, 655 to 656</td>
<td>0.001</td>
<td>1000</td>
<td>big-M</td>
<td>(2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>726, 732, 734 to 736, 739 to 740</td>
<td>0.001</td>
<td>100</td>
<td>small-M</td>
<td>(1</td>
<td>2)</td>
<td>(3</td>
</tr>
</tbody>
</table>
Mapping Problems to Designs via Traces

Problem Space (960)  Trace Space (2304)  Design Product Space (2211840)

Trace 1
Frequency of Successful Traces

![Frequency of Successful Traces](image)
Frequency of Traces

- Total number of traces with non-zero frequency = 87
- Number of traces with successful design = 84
- Number of traces with unsuccessful design = 4
Distribution of Traces versus Projects
Correlation between Requirements and Approaches

all traces generated for the "Small−M" workspace

all traces in which Designer−K−1 used "base−at−left−below−midway−workspace−length" approach

all traces in which Designer−K−1 used "minimize−link−lengths−summation" approach
Correlation between Clusters of Problems and Clusters of Traces

Cluster of Problems

(270)

Cluster of Traces

(9)

Traces:
0, 1, 2, 769, 770, 1536, 1537, 1538, 1922

Design Product Space
(270)
Discovery of Design Methodologies for the Integration of Multi-disciplinary Design Problems

Cirrus Shakeri
**METHODOLOGY 1-0:**

**IF**
- constraints on deflection and the gain are loose,
- workspace is of type “small-M”;

**THEN**
**IF**
- requirement on the workload is easy, i.e., less than 1.0 kg;

**THEN**
- for designers use their first or default approaches.

**ELSE IF**
- requirement on the workload is in the range of 2.0 kg;

**THEN**
- use a dimension for the cross section that is not more than 3 times the minimum required dimension by stress criteria.

**ELSE IF**
- constraints on deflection and the gain are both tight, and
- requirements on workload is rather “easy”;

**THEN**
**IF**
- workspace is of type “small-M”;

**THEN**
- use a dimension ratio for the cross section equal to 4 —*if it fails* reduce the ratio to 3,
  - for all other designers use their first approaches.
The Outcome

• An Approach to Discover Design Methodologies
  • Type of Design
  • Knowledge Acquisition
  • Small Design Methods
  • Design Approaches
  • Designer Agents
  • Multi-agent Design System
  • Design Experiments
  • Experiments
  • Analysis of Traces
  • Generate Methodologies
Evaluation

• Return in Investment
• Type of Design
• Scalable
• Automated Extraction of Methodologies
• Quality of the Methodologies
• Quality of the Design

Contributions

• Theoretical
• Experimental
• Implementation
• Robot Design
Summary

- **Problem:** Lack of Systematic Approaches for Integration
- **Approach:** Knowledge-based Simulation
- **Implementation:** Multi-agent System
- **Results:** Promising

Final Conclusion

Computers can help to discover superior methodologies for design problems.


**Future Work**

- Other types of design problems
- Other multi-disciplinary domains
- Rules for simplification of the process
- Evaluation of the methodologies
- Scaling up
- Enrich the design methodologies
- Biased methodologies: “Design for X”
- Change the order of approaches
- Convert the tool to a sensitivity analysis tool
- Introduce new types of design approaches
- Close the feedback loop around the system
- Adaptive Mesh Generation in the Problem Space
- Trade-off between the design quality and correct traces

**Extensions**

- Exploratory Tool in Complex Systems
- Supply Chain Management
- Shop Floor Job Scheduling