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

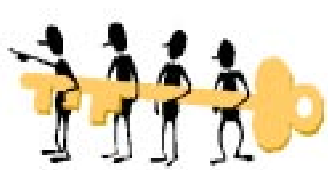
Purpose of a Ph.D. Dissertation

- In General
  - Advancing Frontiers of Knowledge
- In Engineering
  - New Knowledge for the Benefit of Humans

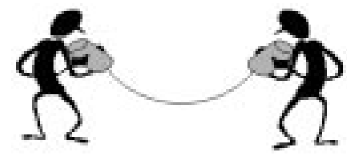
Helping Designers

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

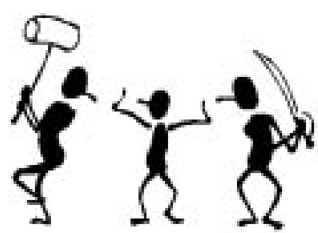
They need integration:



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*

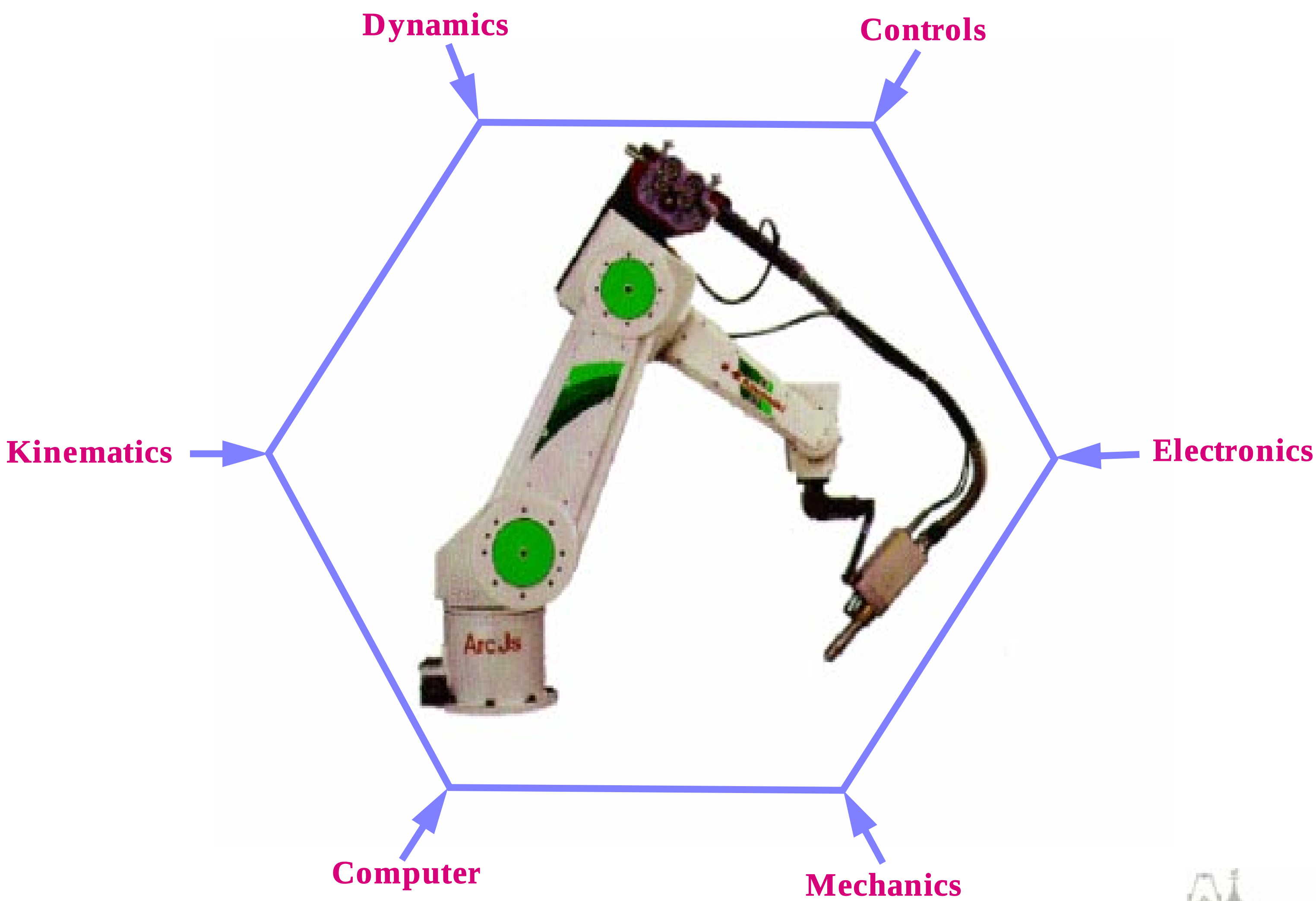
How to anticipate the future?

by Simulating the design process *: Approach*

Barriers

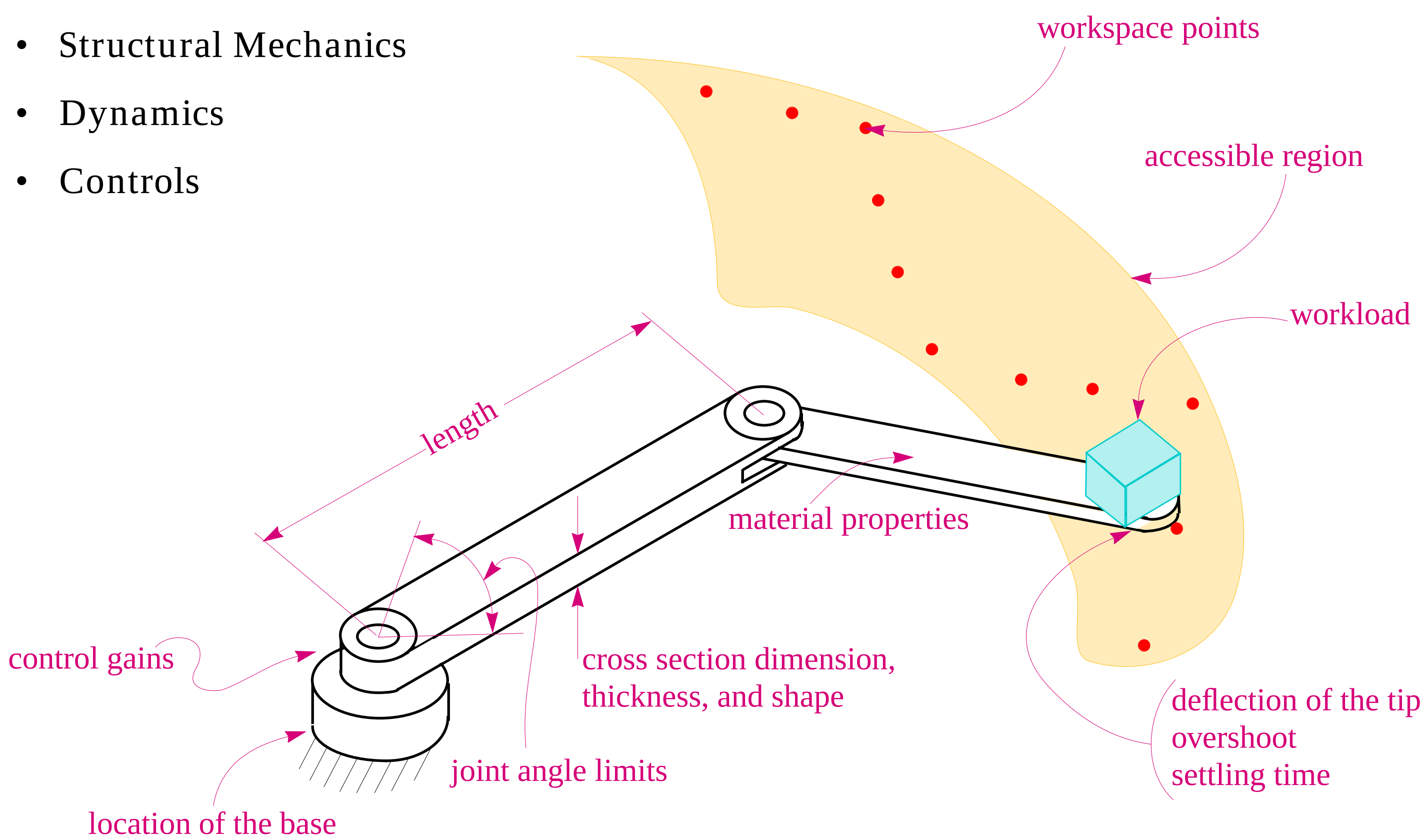
- Departmentalization
- Built-in Disciplinary Goals
- Disciplinary Design in Large Segments
- Counter-Intuitive Behavior
- Evolving Knowledge
- “Tragedy of the Commons”
- Highly Focused Disciplinary Knowledge
- Multifaceted Interactions

Design of a Robot



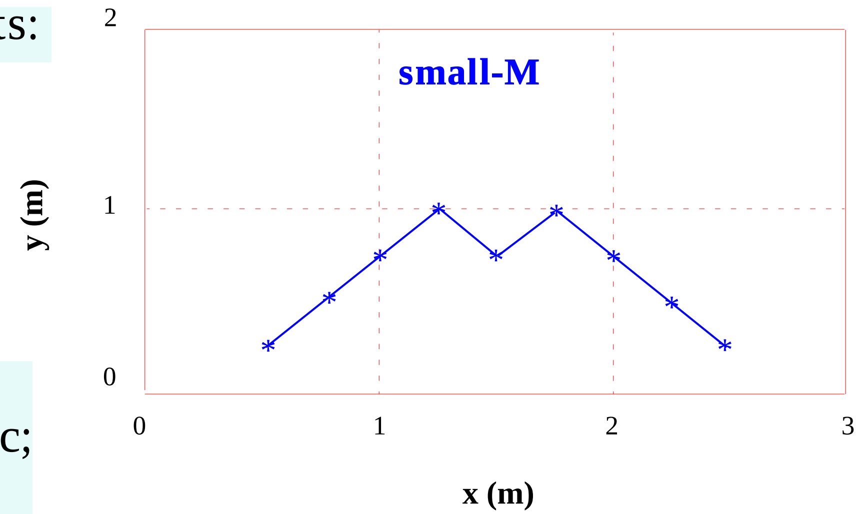
Design of a 2-DOF Robot

- 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.

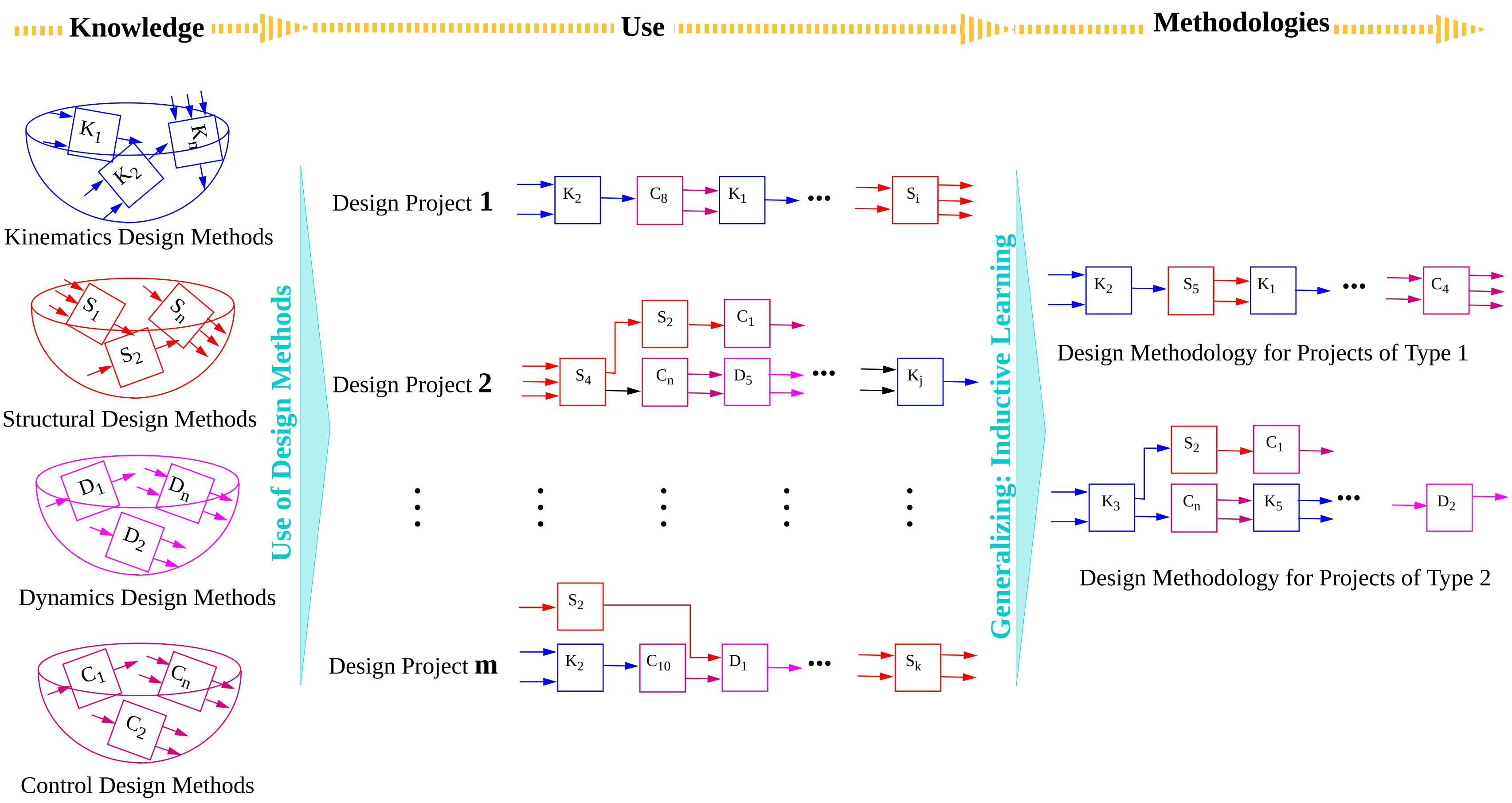
How was it generated?

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

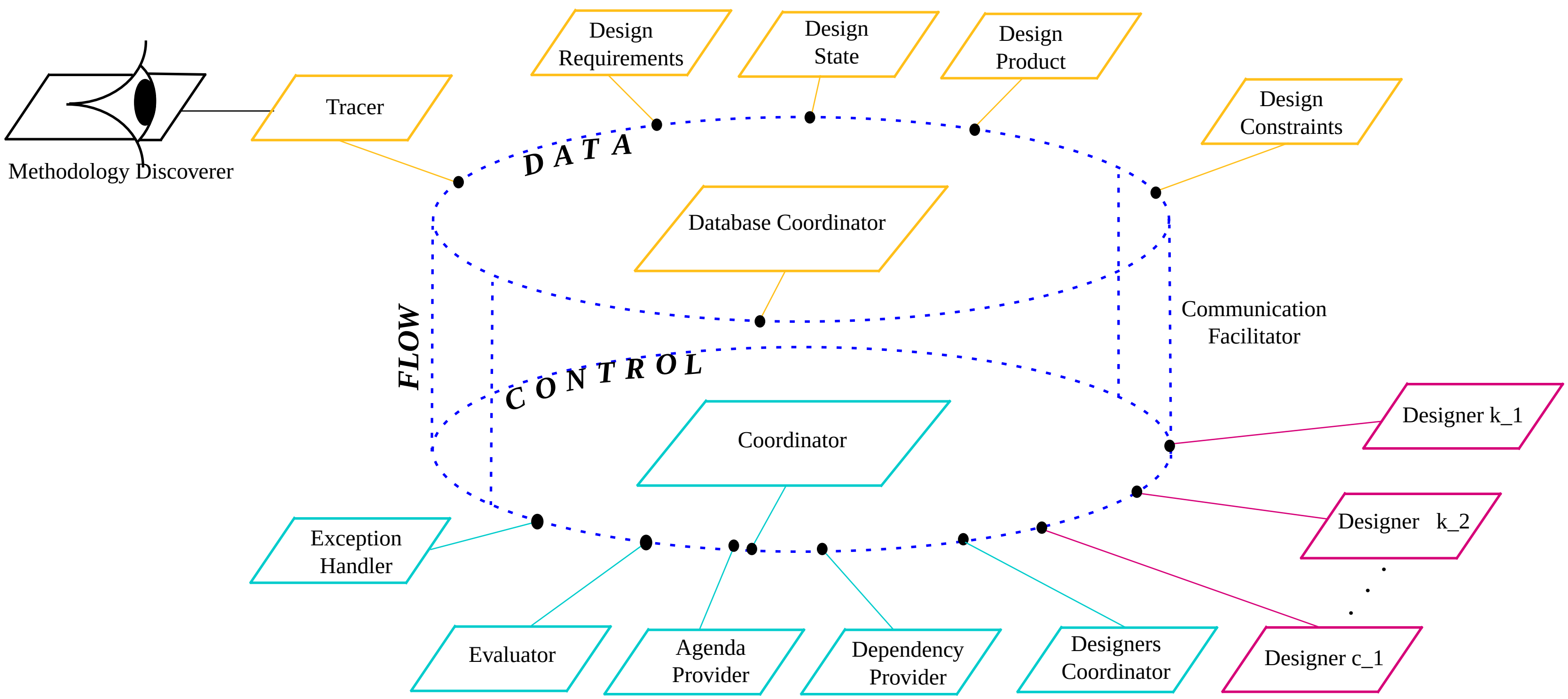


Implementation: Multi-agent Systems

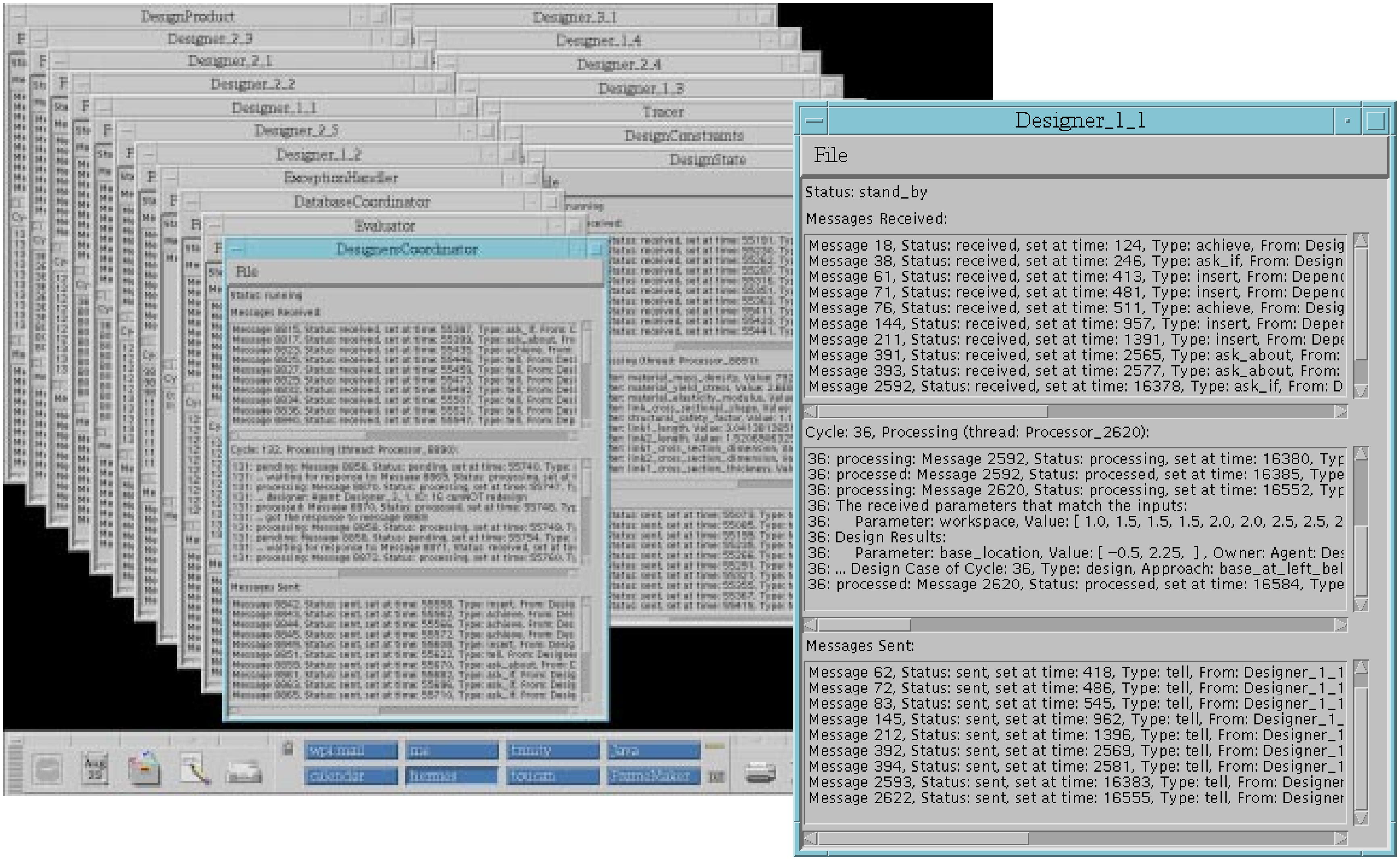
- Agent:
    - a self-contained problem solving system
    - an abstraction tool for managing complexity
    - autonomous
    - reactive
    - pro-active
    - social behavior

- Multi-agent Systems:
    - composed of multiple interacting agents
    - distributed
    - modeling and implementing social interactions
    - parallelism

Multi-agent Design System: Architecture



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

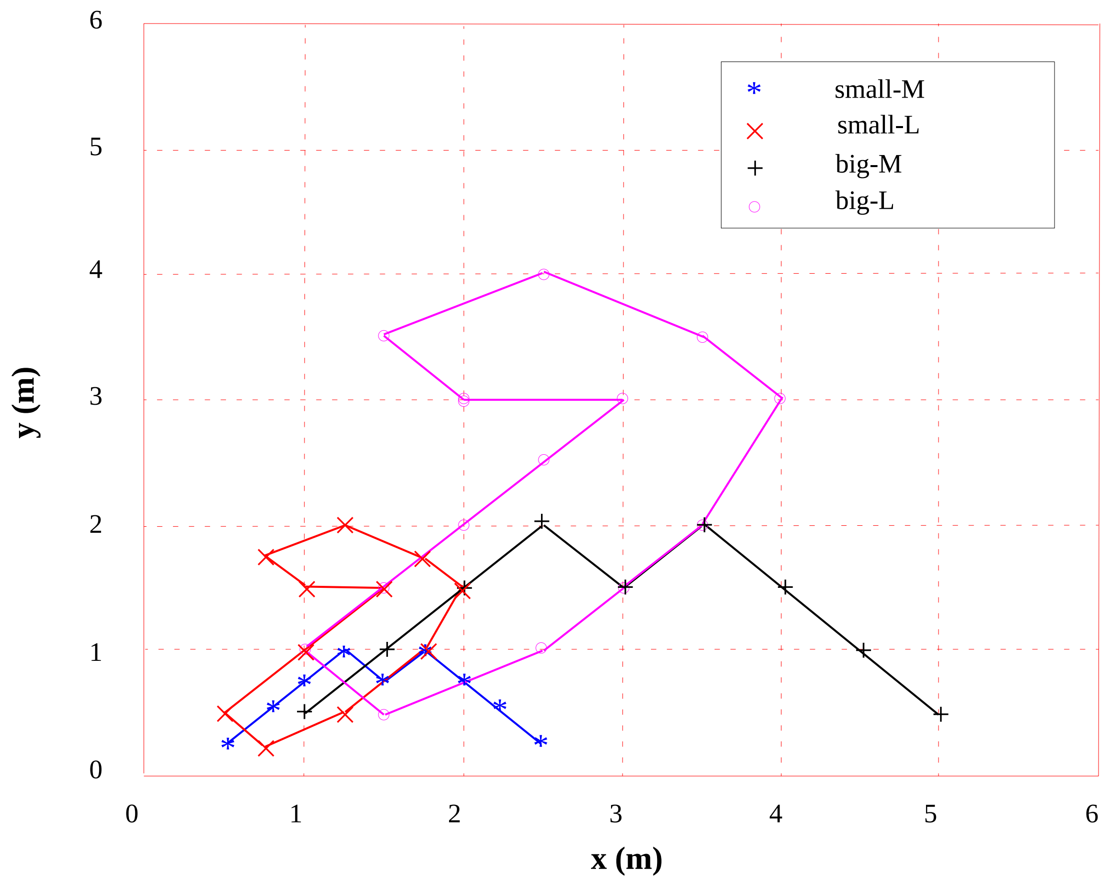
Range of Values for the Constraints and Requirements

Constraints	maximum ratio of deflection of tip to sum of link lengths	{0.01, 0.001}
	maximum proportional gain1	{1000, 100}
Requirements	workspace	{“small-M”, “small-L”, “big-M”, “big-L”}
	workload (kg)	{1.0, 2.0, 3.0, 4.0, 5.0}
	settling time (sec)	{3.0, 2.0, 1.0}
	maximum overshoot (%)	{50, 40, 20, 10}

Indexing Projects

d/L ratio	gain 1	workspace	workload	settling time	overshoot	Project Index
0.01	1000	“small-M”	1.0	3.0	50	1
0.01	1000	“small-M”	1.0	3.0	40	2
			....			
0.01	1000	“small-L”	1.0	3.0	50	61
			....			
0.001	100	“small-M”	1.0	1.0	10	732
			....			
0.001	100	“big-L”	5.0	1.0	10	960

Different Workspace Used as Requirements



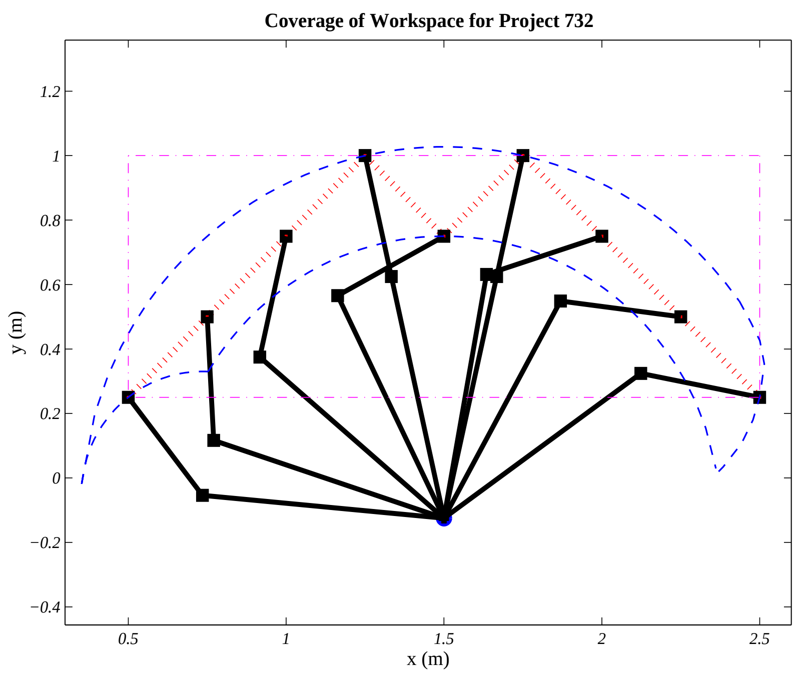
Example: Project 732

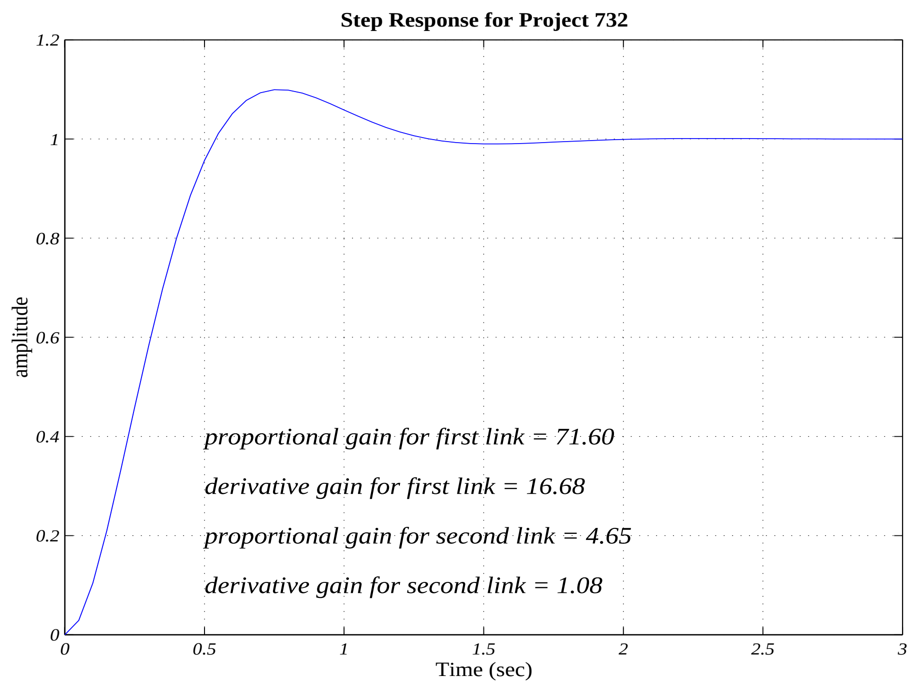
Constraints:

0 < link1_length < workspace_rectangle_length
0 < link2_length < link1_length
0 < link1_cross_section_dimension < 0.1 * link1_length
0 < tip_deflection < 0.001 * (sum of link lengths)
0 < accessible_region_area < 1.0 * workspace_rectangle_area
0 < proportional_gain1 < 100
0.05 * section_dimension < link1_cross_section_thickness < 0.25 * section_dimension
...

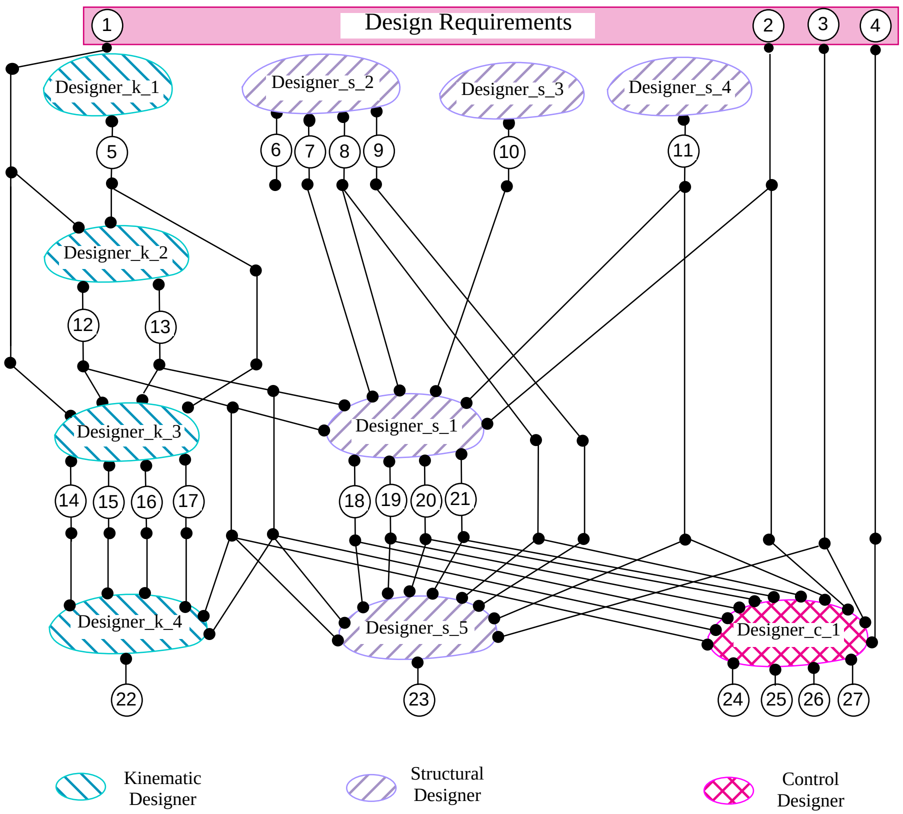
Requirements:

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%





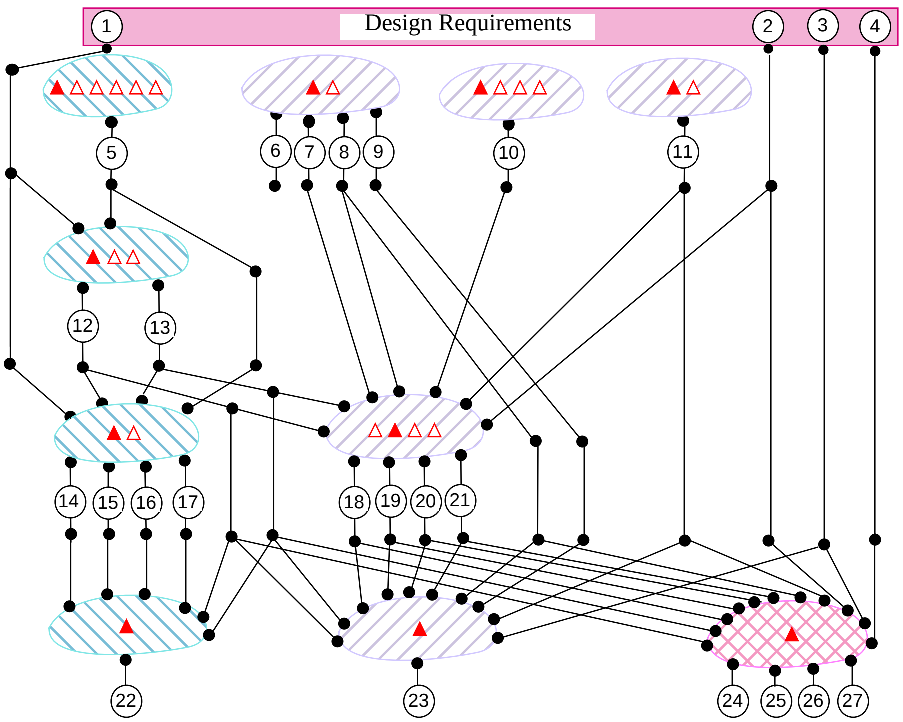
Discovering Dependencies: Project 732



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 Path: Project 732



▲ **Chosen Design Approach**

△ **Not Chosen Design Approaches**

Path Trace: Project 732

Design Approaches

Designer Agent	Design Approach	Approach Index
K_1	base_at_left_below_midway_workspace_length	0
S_2	steel_stainless_AISI_302_annealed	0
S_3	safety_factor_3	0
S_4	hollow_round	0
K_2	link_lengths_ratio_0.5	0
K_3	theta1_is_alpha1_minus_alpha2	0
S_1	dimention_min_ratio_3	1
K_4	default	0
S_5	default	0
C_1	default	0

Trace Index: 1

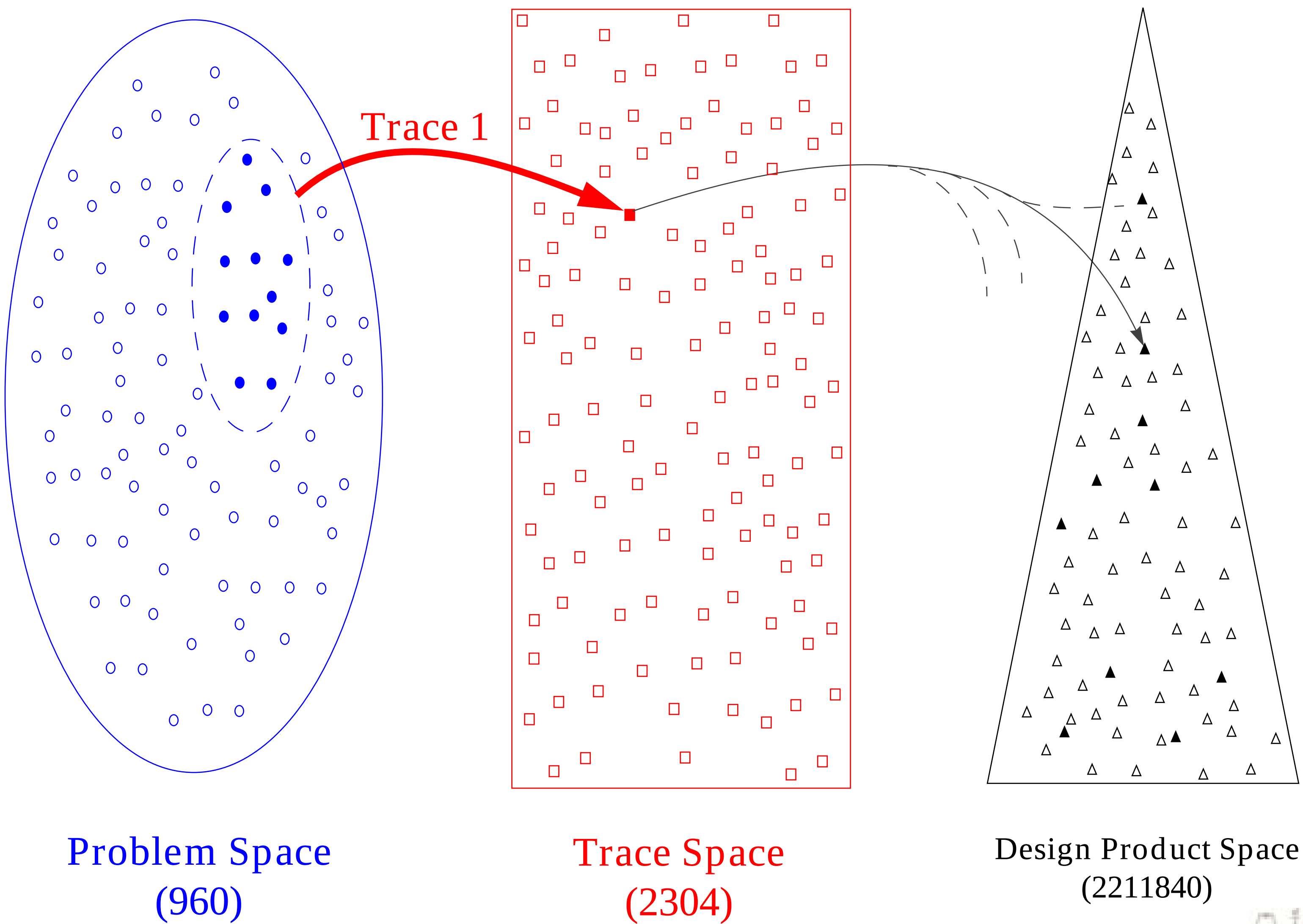
Number of Possible Paths $= 6 \times 2 \times 4 \times 2 \times 3 \times 2 \times 4 \times 1 \times 1 \times 1 = 2304$

Clustering Design Projects that Followed the Same Trace

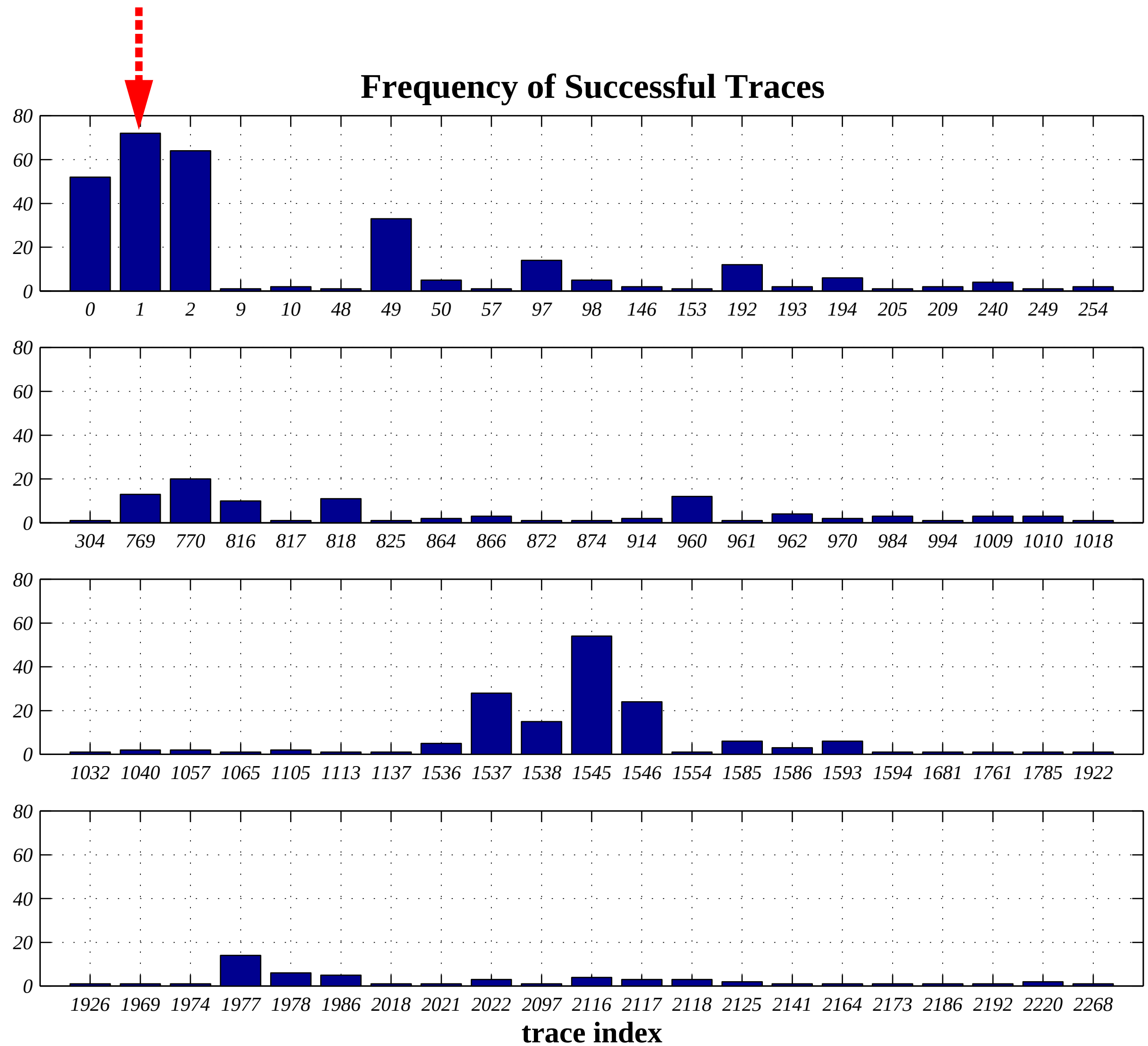
Projects that Followed Trace 1

Projects in the Cluster	Constraint on Deflection	Constraint on Gain 1	Workspace	Workload (kg)	Settling Time (sec)	Maximum Overshoot (%)
13 to 24	0.01	1000	small-M	2	(3 | 2 | 1)	(50 | 40 | 20 | 10)
121, 126, 132, 134, 139, 146 to 148, 151 to 152, 159 to 160, 163 to 164, 171 to 172, 175 to 176	0.01	1000	big-M	(1 | 2 | 3 | 4 | 5)	(3 | 2 | 1)	(50 | 40 | 20 | 10)
246, 252, 254 to 256, 259 to 260	0.01	100	small-M	(1 | 2)	(3 | 2 | 1)	(40 | 20 | 10)
364	0.01	100	big-M	1	3	10
493 to 504	0.001	1000	small-M	2	(3 | 2 | 1)	(50 | 40 | 20 | 10)
614, 619, 626 to 628, 631 to 632, 639 to 640, 643 to 644, 651 to 652, 655 to 656	0.001	1000	big-M	(2 | 3 | 4 | 5)	(3 | 2)	(40 | 20 | 10)
726, 732, 734 to 736, 739 to 740	0.001	100	small-M	(**1** | 2)	(3 | 2 | **1**)	(40 | 20 | **10**)

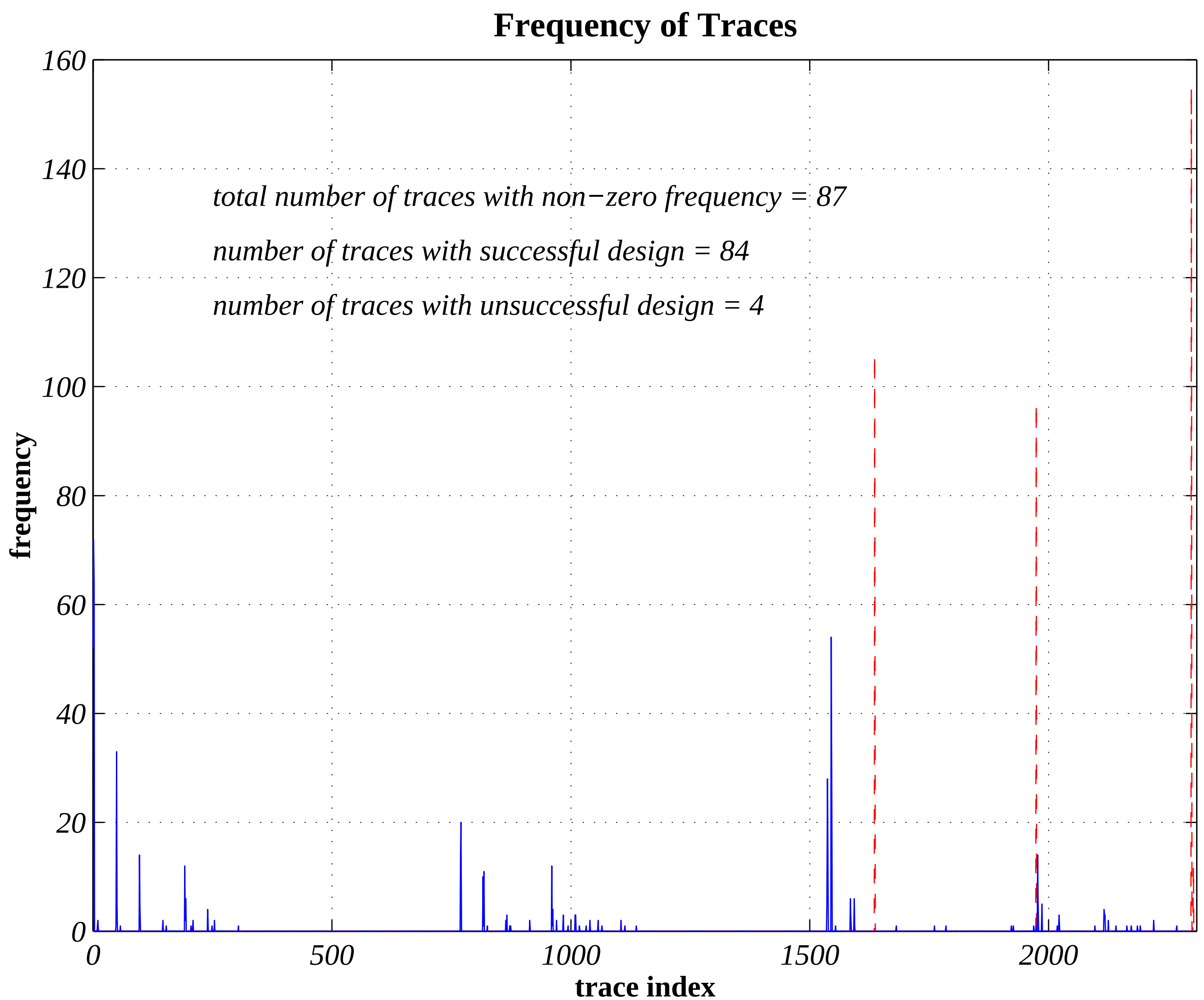
Mapping Problems to Designs via Traces



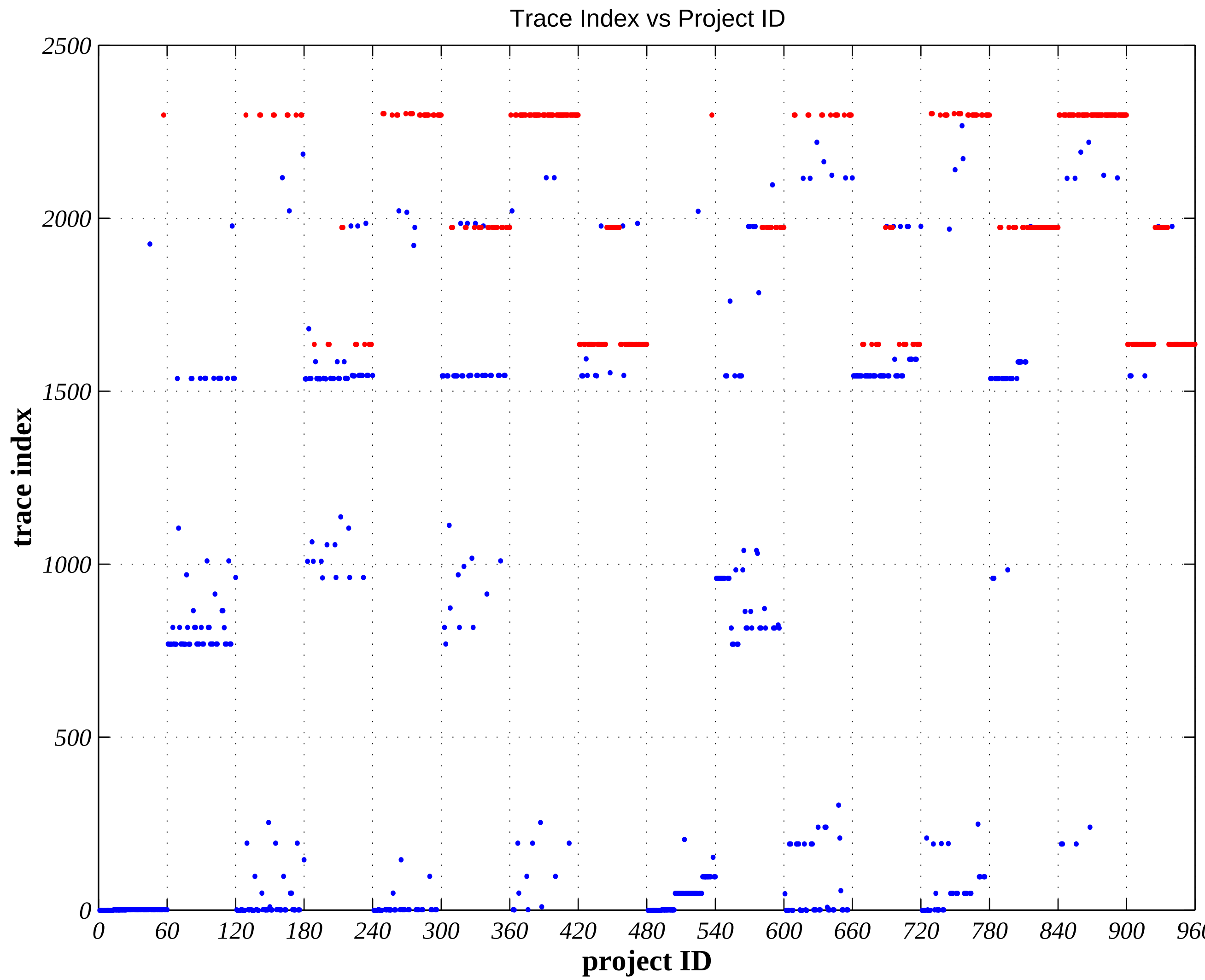
Frequency of Successful Traces



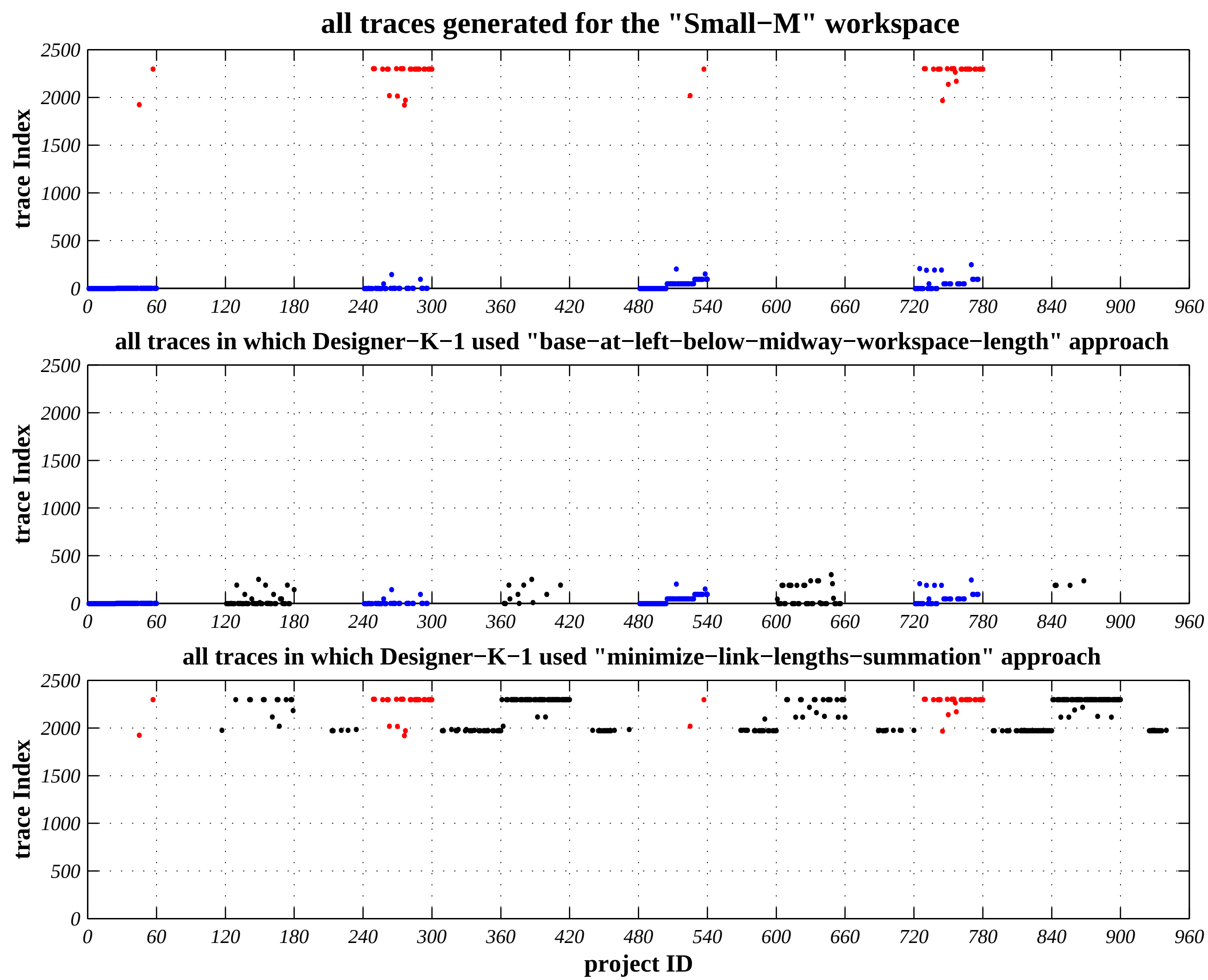
Frequency of Traces



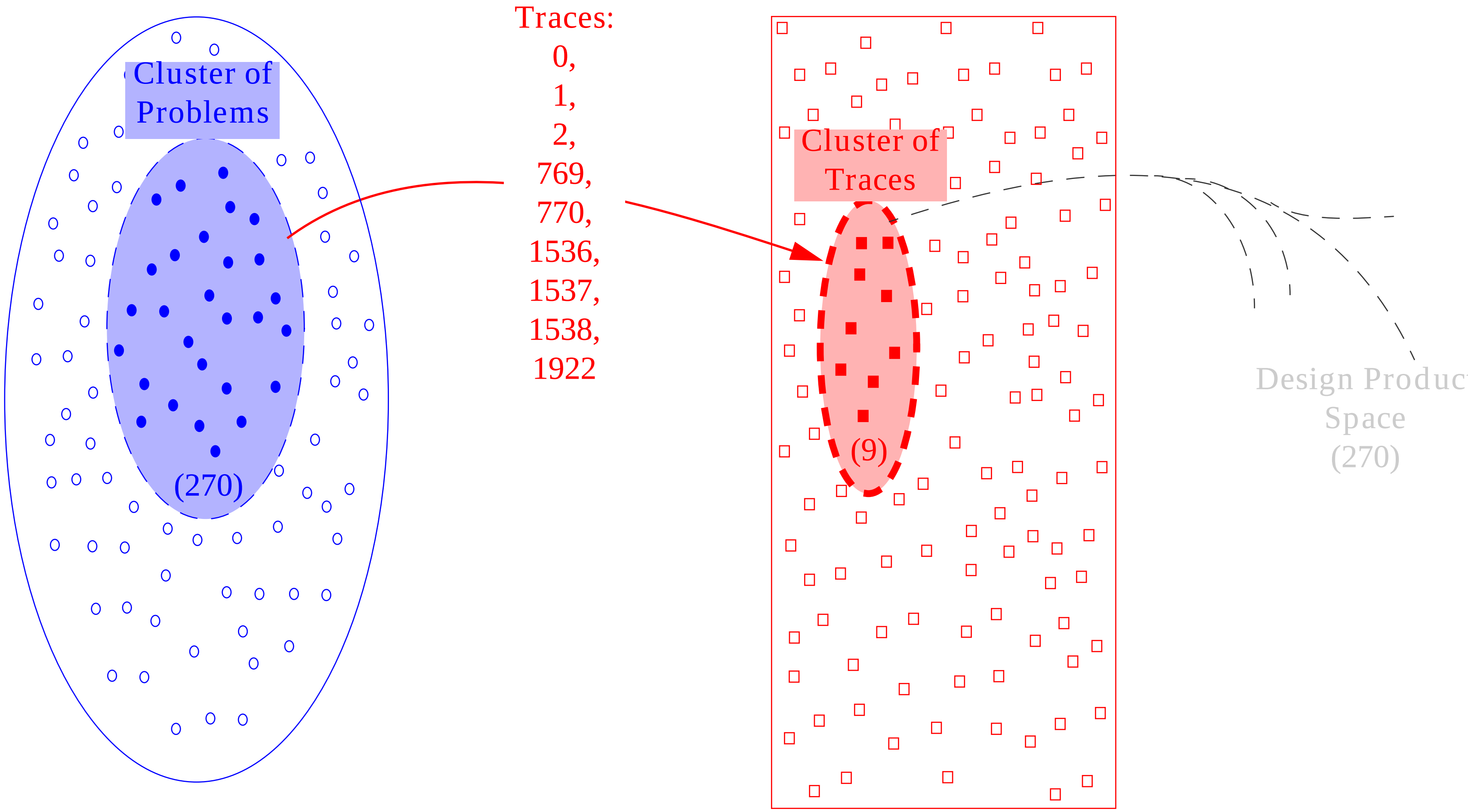
Distribution of Traces versus Projects

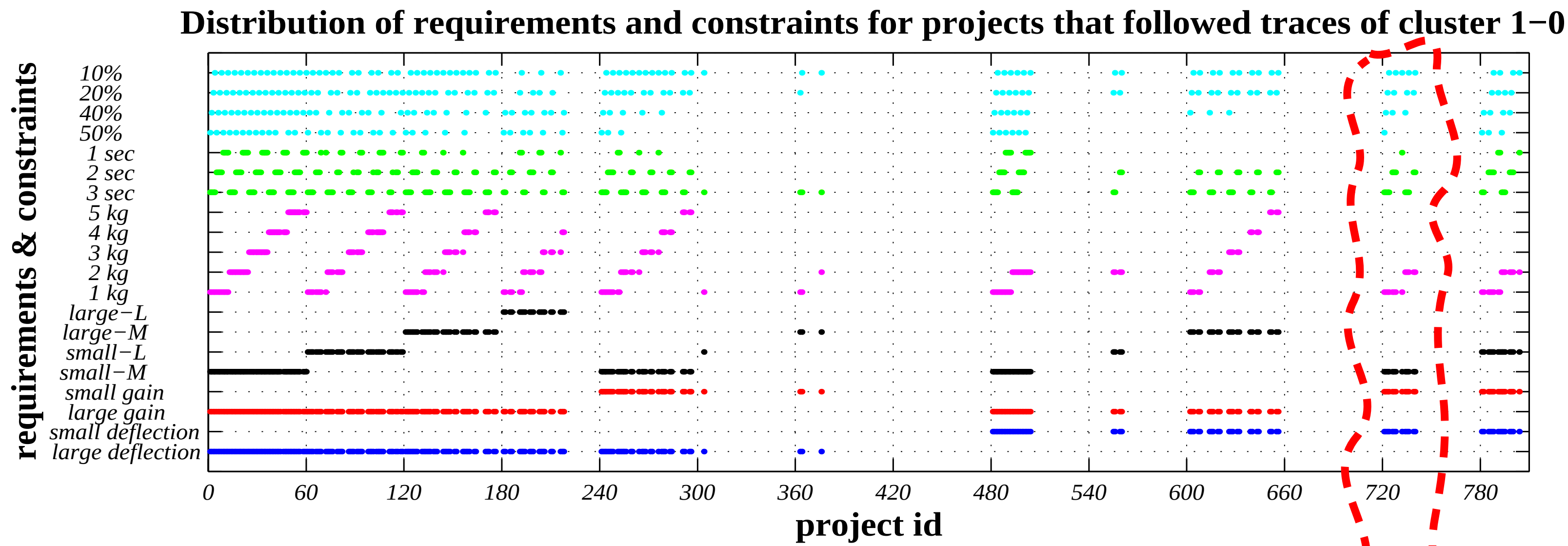


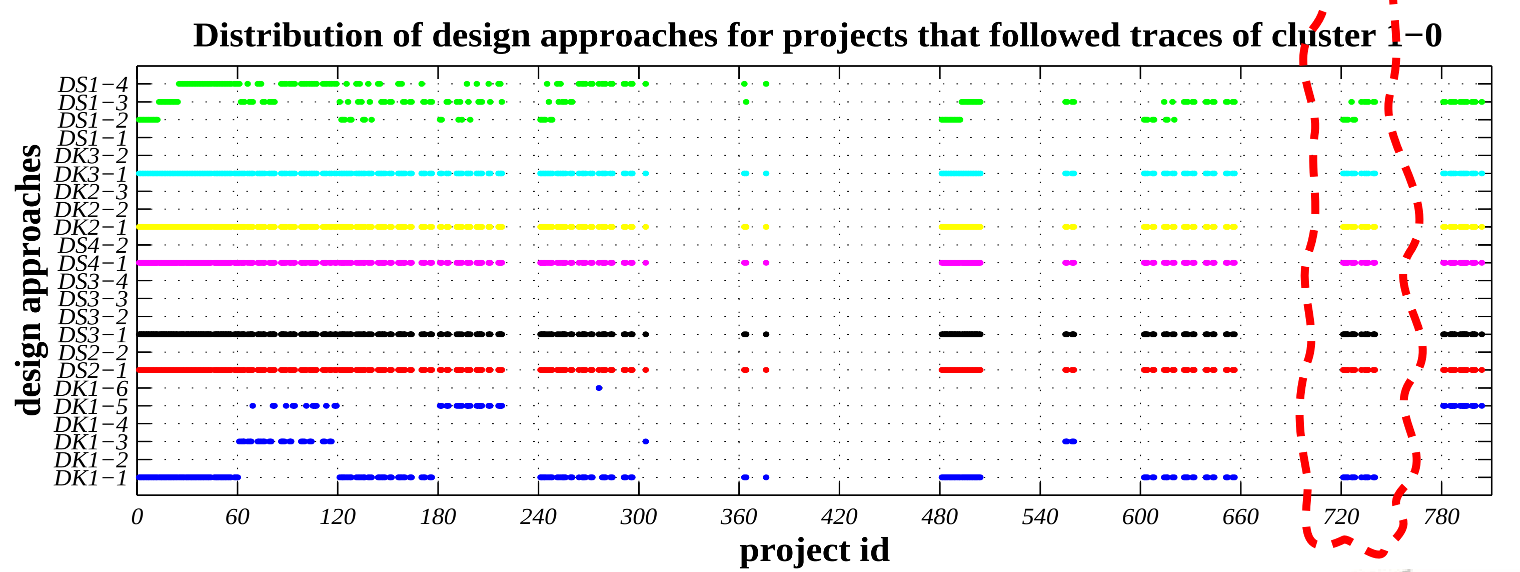
Correlation between Requirements and Approaches



Correlation between Clusters of Problems and Clusters of Traces




Distribution of requirements and constraints for projects that followed traces of cluster 1−0
requirements & constraints
10%
20%
40%
50%
1 sec
2 sec
3 sec
5 kg
4 kg
3 kg
2 kg
1 kg
large−L
large−M
small−L
small−M
small gain
large gain
small deflection
large deflection
0
60
120
180
240
300
360
420
480
540
600
660
720
780
project id


Distribution of design approaches for projects that followed traces of cluster 1−0
design approaches
DS1−4
DS1−3
DS1−2
DS1−1
DK3−2
DK3−1
DK2−3
DK2−2
DK2−1
DS4−2
DS4−1
DS3−4
DS3−3
DS3−2
DS3−1
DS2−2
DS2−1
DK1−6
DK1−5
DK1−4
DK1−3
DK1−2
DK1−1
0
60
120
180
240
300
360
420
480
540
600
660
720
780
project id

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