Do Search-Based Approaches Improve the Design of Self-Adaptive Systems?
A Controlled Experiment

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Agenda

- Context & motivation
- Our search-based architectural design approach
- The quasi-experiment
- Contributions of this paper
- Final remarks
Context & Motivation

- The need for self-adaptive systems (SAS):
  - Dynamic and uncertain operating environments
  - Stringent requirements for scalability, dependability, energy-efficiency, and performance
  - Incomplete/partial requirements
  - Problem/design space complexity approaching the limits of human capability
  - Rapidly varying workloads and data characteristics
  - Some problems are inherently self-adaptive or self-organizing (e.g.: robots motion coordination, particles/swarm optimization, etc)
Context & Motivation

- MAPE-K Reference Architecture [1]

Context & Motivation

• Current challenges:
  – Intricate problem space
  • How to effectively elicit the adaptation requirements?

Goals:
• Type (regulation, tracking, disturbance rejection, optimization)
• Evolution (static, dynamic)
• Duration (persistent, temporary)
• Multiplicity (single, multiple)
• Dependency (independent, complementary, conflicting)
• Flexibility (rigid, constrained, unconstrained)

Change:
• Source (internal, external)
• Anticipation (foreseen, foreseeable, unforeseen)
• Frequency (rare, frequent)
• Type (functional, non-functional, technological)
Context & Motivation

- Current challenges:
  - Intricate problem space
  - How to effectively elicit the adaptation requirements?
  - Large and complex solution space
Context & Motivation

- Current challenges:
  - Intricate problem space
  - How to effectively elicit the adaptation requirements?
  - Large and complex solution space

- Type (parametric, structural)
- Mechanism (signaling, frameworks, profiling, etc)
- Uncertainty handling (redundancy, filtering, smoothing)
Context & Motivation

- Current challenges:
  - Intricate problem space
    - How to effectively elicit the adaptation requirements?
  - Large and complex solution space

- Mechanism (symptoms databases, policies, queue networks, game theory, etc)
- System/Environment representation (ad-hoc, models)
Context & Motivation

• Current challenges:
  – Intricate problem space
    • How to effectively elicit the adaptation requirements?
  – Large and complex solution space

  • Actuation law (intelligent agents, control theory, search-based, etc)
  • Cardinality (single, utility functions, parent-front)
  • Type (static, dynamic)
Context & Motivation

• Current challenges:
  – Intricate problem space
  • How to effectively elicit the adaptation requirements?
  – Large and complex solution space

- Type (parametric, structural)
- Mechanism (function pointers, aspect weaving, metaobjects, middleware-based)
- Timeliness (best-effort, guaranteed)
Context & Motivation

• Current challenges:
  – Intricate problem space
    • How to effectively elicit the adaptation requirements?
  – Large and complex solution space
    • How to come up with an effective managing system architecture for the adaptation requirements at hand?
    • How to judiciously evaluate all available design alternatives?
    • How to make well-informed decisions about quality attributes trade-offs?
  – Consequences:
    • Lack of organized design knowledge for routine use
    • False intuition, design bias, and sub-optimal architectures
Our Search-Based Design Approach – DuSE

• Research questions

To which extent may SAS design knowledge be systematically represented for routine use?

How to support well-informed decision making regarding quality attribute trade-offs between alternative architectures for SAS?
Our Search-Based Design Approach – DuSE

- We combine the use of ...
  - Metamodeling and Domain-Specific Languages (DSL)
  - Structured Architecture Design Spaces
  - Multi-Objective Optimization

- … in order to …
  - Enable a more disciplined and automated “handbook” of SAS design
  - Provide a solid basis for choosing between architectures which exhibit different quality attributes
Our Search-Based Design Approach – DuSE

- Initial System Model
  - Annotated with corresponding UML Profile

- Domain-Specific Design Dimensions + Quality Metrics
  - Specified using the DuSE language

- Domain-Specific Design space

- Domain-Specific Supporting UML Profile

- Generic Architecture Optimization Engine

- Pareto-front of Candidate Architectures

Our Search-Based Design Approach – DuSE

- Domain independent
- Metamodel dependent
- Design space navigation engine
- Optimization engine (NSGA-II)

Our Search-Based Design Approach – DuSE

Our Search-Based Design Approach – SA:DuSE

- **SA:DuSE**
  - A particular DuSE instance which captures the most prominent design dimensions of SASs

- **Evaluation dimensions:**
  - Is SAS design indeed a multi-objective problem?
  - To which extent the quality of Pareto-optimal architectures are indeed observed in real prototypes?
  - Do search-based approaches improve the design of SAS?
The Quasi-Experiment

- Analyze the design of SAS
- For the purpose of evaluating the search-based design approach we propose and a design process based on architecture styles catalogs
- With respect to the effectiveness and complexity of resulting architectures, as well as the method's potential for leveraging the acquisition of distilled design knowledge by novice architects
- From the point of view of researchers
- In the context of graduate students endowing systems with self-adaptation capabilities
The Quasi-Experiment

- **Quasi-experiment:**
  - Blocked subject-object study with a paired comparison design

- **Subjects:**
  - 24 students of a graduate program in Distributed and Ubiquitous Computing

- **Experiment objects:**
  - Two UML models representing the managed system (web server and MapReduce distributed architecture)

- **Experiment tests:**
  - Design a managing system architecture for both objects
  - Answer a questionnaire on quality attribute trade-offs in SAS
The Quasi-Experiment

- **Independent variable:**
  - Design method
    - Search-based approach
    - Style-based approach

- **Dependent variables:**
  - Effectiveness of resulting SAS architectures
  - Complexity of resulting SAS architectures
  - The method's potential for leveraging the acquisition of distilled SAS design knowledge by novice architects

- **Experiment website:**
  - http://wiki.ifba.edu.br/tr-ce012014
## The Quasi-Experiment

### Experiment timetable

<table>
<thead>
<tr>
<th>Part</th>
<th>Day</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lectures</td>
<td>1</td>
<td>Self-Adaptive Systems Foundations (motivation, MAPE-K reference architecture, current approaches, challenges)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Feedback Control Introduction (control goals, control properties, fixed gain SISO approaches)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Feedback Control (MIMO and adaptive approaches)</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Self-Adaptive Systems - Case Studies</td>
</tr>
<tr>
<td>Exam and</td>
<td>5</td>
<td>First hour: discussion</td>
</tr>
<tr>
<td>Training</td>
<td></td>
<td>Next 3h: Pen and paper exam</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>First hour: exam discussion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Next 3h: Training (DuSE-MT and architectural styles catalog)</td>
</tr>
<tr>
<td>Experiment</td>
<td>7</td>
<td>First 110min: Tests #1 and #2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Next 110min: Tests #3 and #4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Next 20min: Tests #5 and #6 (questionnaire)</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>First 110min: Tests #7 and #8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Next 110min: Tests #9 and #10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Next 20min: Tests #11 and #12 (questionnaire)</td>
</tr>
</tbody>
</table>
The Quasi-Experiment

- Experiment tests

<table>
<thead>
<tr>
<th>#Test</th>
<th>Object</th>
<th>Treatment</th>
<th>Subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Web Server</td>
<td>Style-Based Approach</td>
<td>Group 1</td>
</tr>
<tr>
<td>2</td>
<td>MapReduce Architecture</td>
<td>Search-Based Approach</td>
<td>Group 2</td>
</tr>
<tr>
<td>3</td>
<td>MapReduce Architecture</td>
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<td>Group 1</td>
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<td>Web Server</td>
<td>Search-Based Approach</td>
<td>Group 2</td>
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<tr>
<td>5</td>
<td>Questionnaire</td>
<td>Style-Based Approach</td>
<td>Group 1</td>
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<tr>
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<td>Questionnaire</td>
<td>Search-Based Approach</td>
<td>Group 2</td>
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<td>11</td>
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<td>12</td>
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<td>Style-Based Approach</td>
<td>Group 2</td>
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</tbody>
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The Quasi-Experiment

- Experiment objects
The Quasi-Experiment

- Measuring effectiveness (Generational Distance)

\[ GD = \left( \frac{\sum_{i=1}^{\left| P^*_i \right|} d_{i}^{P^*}}{|Q|} \right)^{1/p} \]

where

\[ d_{i}^{2} = \min_{k=1}^{M} \sum_{m=1}^{M} (f_{m}^{(i)} - f_{m}^{(k)})^2 \]

The Quasi-Experiment

- Measuring complexity (Component Point)

\[
CC_c = IFCI_c + ITCI_c = \frac{IFC_c}{n_c} + \frac{ITC_c}{m_c}
\]

\[
IFC_c = \sum_{j=1}^{2} \sum_{k=1}^{3} I_{jk} \times W_{jk}
\]

\[
ITC_c = \sum_{i=1}^{p} \sum_{j=1}^{q} \left( IF_{ij} \times \sum_{k=1}^{r} CM_{ijk} \right)
\]

\[
CM_{ijk}(D, L) = L + \sum_{n=1}^{m} CM(DT_n, L + 1)
\]

The Quasi-Experiment

- Measuring the acquisition of distilled design knowledge:
  - Questionnaire with 10 multiple choice questions
  - Questions related to quality attributes trade-offs in the SAS domain
  - Questionnaire answered at the end of each experimentation day
  - Normalized grades assigned to each student/day
The Quasi-Experiment

- Hypotheses formulation

**H$_0^1$** - there is no difference in design effectiveness between a feedback control loop design created using the style-based approach (RA) and a feedback control loop design created using the search-based approach (IA)

\[ H_0^1 : \mu_{GD_{RA}} = \mu_{GD_{IA}} \]
\[ H_1^1 : \mu_{GD_{RA}} > \mu_{GD_{IA}} \]

**H$_0^2$** - there is no difference in design complexity between a feedback control loop design created using the RA and a feedback control loop design created using the IA

\[ H_0^2 : \mu_{AC_{RA}} = \mu_{AC_{IA}} \]
\[ H_1^2 : \mu_{AC_{RA}} > \mu_{AC_{IA}} \]

**H$_0^3$** - there is no difference in the acquisition of distilled design knowledge between a feedback control loop design created using the RA and a feedback control loop design created using the IA

\[ H_0^3 : \mu_{QG_{RA}} = \mu_{QG_{IA}} \]
\[ H_1^3 : \mu_{QG_{RA}} < \mu_{QG_{IA}} \]
The Quasi-Experiment

- Descriptive statistics

<table>
<thead>
<tr>
<th></th>
<th>Generational Distance (GD)</th>
<th>Architecture Complexity (AC)</th>
<th>Questionnaire Grade (QG)</th>
</tr>
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<tbody>
<tr>
<td><strong>mean(μ)</strong></td>
<td><strong>median</strong></td>
<td><strong>std. dev.</strong></td>
<td></td>
</tr>
<tr>
<td>Search-Based Approach (IA)</td>
<td>2.40</td>
<td>2.45</td>
<td>1.08</td>
</tr>
<tr>
<td>Style-Based Approach (RA)</td>
<td>2.59</td>
<td>2.41</td>
<td>1.03</td>
</tr>
<tr>
<td>Difference (IA–RA)</td>
<td>-0.19</td>
<td>-0.62</td>
<td>1.32</td>
</tr>
</tbody>
</table>

|                          | **mean(μ)**                  | **median**                  | **std. dev.**            |
| Search-Based Approach (IA)| 6.46                        | 6.65                        | 2.77                     |
| Style-Based Approach (RA)| 7.02                        | 7.05                        | 2.70                     |
| Difference (IA–RA)        | -0.57                       | -1.90                       | 3.47                     |

|                          | **mean(μ)**                  | **median**                  | **std. dev.**            |
| Search-Based Approach (IA)| 6.85                        | 7.00                        | 1.43                     |
| Style-Based Approach (RA)| 7.04                        | 7.25                        | 1.27                     |
| Difference (IA–RA)        | -0.19                       | -0.50                       | 1.51                     |
The Quasi-Experiment

- Assumptions of parametric tests:
  - Data is taken from an interval or ratio scale
  - Observations are independent
  - Population variances are equal between groups (homoscedasticity)
  - Measured values are normally distributed

<table>
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α=0.05
The Quasi-Experiment

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\( \alpha = 0.05 \)

Cannot reject homoscedasticity
The Quasi-Experiment

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$\alpha=0.05$
The Quasi-Experiment

- Results of the statistical tests

<table>
<thead>
<tr>
<th>$H_0^i$</th>
<th>Test</th>
<th>Criteria</th>
<th>Conclusion</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Wilcoxon Signed-Rank</td>
<td>$T(410) &gt; T_{critical}(378)$</td>
<td>Rejected</td>
</tr>
<tr>
<td>2</td>
<td>Wilcoxon Signed-Rank</td>
<td>$T(367) &gt; T_{critical}(361)$</td>
<td>Rejected</td>
</tr>
<tr>
<td>3</td>
<td>Paired t-test</td>
<td>p-value=0.5488018266</td>
<td>Not Rejected</td>
</tr>
</tbody>
</table>

$\alpha=0.05$
The Quasi-Experiment

- Threats to validity
  - Construct:
    - Inadequate preoperational explication of constructs
    - Hypothesis guessing
    - Objects representativeness
  - Internal:
    - Maturation
    - Instrumentation
  - External:
    - Students acting as subjects
  - Conclusion:
    - Experiment holders creating the experiment objects
Contributions of this paper

- To the best of our knowledge, SA:DuSE is the first effort in applying search-based approaches in the SAS domain.
- To the best of our knowledge, this is the second controlled experiment in the SAS domain (the first one is [8]).
- We got some empirical evidence about the benefit of search-based approaches when designing SASs.
- The potential for leveraging knowledge acquisition still deserves further investigation.

Final Remarks

- A lot of research towards principled and systematic design of self-adaptive systems
- Effectiveness of systematic design spaces in capturing intricate solution spaces
  - However, qualitative approaches may be used to address another facets of architectural design
- Future work:
  - SA:DuSE expansion (NSGA-III)
  - More investigation on real prototypes
  - From design spaces to design theories
Thanks ! Questions ?

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