Programming Dynamic Reconfigurable Systems with DR-BIP

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**Dynamic architectures**

- **Architectures** are organization principles, recipes for composing components in order to build complex systems meeting given properties.

- **Dynamic architectures** have the ability to adapt so as to meet given properties depending on a changing environment.
Autonomous systems are very important in modern applications

- e.g. transportation, robotics, mobile, resilient, self-* systems
- are reactive, that is, they continuously interact with their environment
- consist of interacting components that provide basic functionality
- exhibit dynamicity in different forms understood as the change of the coordination structure and the number and type of components involved

Is there a possible classification proposing basic types of coordination changes whose combination encompasses any other kind of dynamic coordination?

1. We study a rigorous modeling methodology and develop a framework for the description of dynamic architectures
2. We show that the framework encompasses various dynamic coordination mechanisms
**Dynamic architecture for autonomous systems**

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1. We study a rigorous modeling methodology and develop a framework for the description of dynamic architectures
2. We show that the framework encompasses various dynamic coordination mechanisms
Dynamic architectures - a classification

Endogenous vs., Exogenous

- *Endogenous*: the coordination mechanisms are *integrated* in the description of components, as in programming languages that use synchronization primitives, function calls etc.

- *Exogenous*: respects a strict *separation* between coordination and internal behavior i.e., components have interface *ports* to which coordination mechanisms are attached.

Declarative vs., Imperative

- *Imperative*: the coordination mechanisms are *explicitly* built from elementary mechanisms e.g. semaphores, function call, connectors

- *Declarative*: using logics to specify the coordination mechanisms like interaction or configuration logic, etc - Usually coordination mechanisms are constraints that must be met.

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Dynamic architectures - beyond parametric architectures

Static architectures: static coordination
- a fixed number of component instances and interactions
- e.g., a Master/Slave architecture with 2 masters and 5 slaves

Parametric architectures: parametric coordination rules
- arbitrary number of instances of types of components
- e.g., a parameterized Ring architecture involving $N$ components

Beyond parametric architectures: dynamic coordination
- dynamic, self organizing systems adapting their structure to achieve some goal
- e.g., a pipeline may be configured into a ring and then into a star architecture
- e.g., robots or autonomous agents may adopt various coordination schemes

Our framework: express dynamic architectures as a set of architectural motifs, each motif being governed by proper coordination rules
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Our framework: express dynamic architectures as a set of *architectural motifs*, each motif being governed by proper coordination rules
Outline

1 Introduction

2 DR-BIP - Dynamic Reconfigurable BIP
   - Components and Interactions
   - Motifs for Dynamic Architectures
   - Motif-based Systems

3 Programming Dynamic Reconfigurable Systems
   - Dynamic Token Ring System
   - Dynamic Multicore Task System
   - Automated Highway Traffic System
   - Self-organized Robot Colonies

4 Conclusion
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4. Conclusion
Component-based systems = layered composition of

- **Behavior**, atomic functional units (automata, code)
- **Interactions**, cooperation between actions of behavior
- **Priorities**, scheduling between interactions

**Model-based and component-based design**

- providing support for validation and performance analysis
- providing support for implementation on given platforms
BIP: atomic components

**extended finite state machines**

- a set of *control locations* e.g., c0, c1, ...
- a set of *variables* e.g., s, y
- a set of interface *ports* e.g., report, store
  - attached with variables
- a set of *labelled transitions*
  - port e.g., store
  - *guard* condition e.g., true
  - *assignments* to variables e.g., s:=f(y)
- ...

**Example:** an “Event-Creator” component
BIP: multiparty interactions

composition using \( n \)-ary multiparty interactions

- sets of ports which are *synchronized* at execution
e.g., \((c_1\text{.invite}, r_1\text{.receive}, r_2\text{.receive}), (r_1\text{.push}, c_1\text{.store}), \ldots\)
- guard and assignment of variables from different components

---

operational semantics of a system

atomic execution of enabled interactions
The concept of motif in DR-BIP

- a set of component instances $B$
  - parameterized using a logical map $H = (N, E)$ and an addressing / deployment function $D : B \rightarrow N$
- a set of parameterized interaction rules
- a set of parameterized reconfiguration rules
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- A set of *component instances* \( B \)
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- A set of parameterized *interaction rules*
- A set of parameterized *reconfiguration rules*
The concept of motif: interaction rules

- component's interactions parameterized by the motif content $B$, $H$, $D$

  \[
  \text{sync-rule-name(formal-args)} \equiv \text{when rule-constraint sync interaction-ports} \quad [\text{interaction-guard } \rightarrow \text{interaction-action}]^+
  \]

- an interaction defined for every matching of an interaction rule

- the architectural motif defines a regular BIP system
The concept of motif: interaction rules

**Interaction rules**

\[ \text{sync-inout}(x_1, x_2 : C) \equiv \]
\[ \text{when } D(x_1) \mapsto D(x_2) \]
\[ \text{sync } x_1.\text{out } x_2.\text{in} \]

**Behavior B**

\[ b_1 \quad b_2 \quad b_3 \]

**Deployment D**

**Map H**

**Reconfiguration rules**
The concept of motif: interaction rules

Interaction rules

\[ \text{sync-inout}(x_1, x_2 : C) \equiv \]
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\(b_1\) \(b_2\) \(b_3\)

Deployment D

Map H

Reconfiguration rules

set of interactions between components defined by the interaction rule
The concept of motif: interaction rules

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**Behavior**

\[
b_1 \quad b_2 \quad b_3
\]

**Deployment**

\[
D
\]

**Map**

\[
H
\]

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**Behavior B**

\[ b_1 \quad b_2 \quad b'_2 \quad b_3 \quad b'_3 \]

**Deployment D**

\[ \text{set of interactions between components defined by the interaction rule} \]
The concept of motif: reconfiguration rules

- reconfiguration actions parameterized by the motif content $B$, $H$, $D$
  
  \[
  \text{do-rule-name(formal-args)} \equiv \\
  \text{when rule-constraint} \\
  \text{do reconfiguration-action}^+ 
  \]

- a potential reconfiguration action defined for every matching of a reconfiguration rule

- the execution of reconfiguration actions is atomic
The concept of motif: reconfiguration rules

```
Reconfiguration rules

do-insert() ≡ when |B| ≤ 10
  do x := B.create(C, idle),
  n := H.extend(), D(x) := n
```

`define different forms of architecture dynamism through updates of component instances, map and/or deployment`
The concept of motif: reconfiguration rules

**Interaction rules**

**Behavior B**

- $b_1$
- $b_2$
- $b_3$
- $b_4$

**Deployment D**

**Map H**

**Reconfiguration rules**

- do-insert() ≡ when $|B| \leq 10$
- do $x := B.create(C, \text{idle})$
- $n := H.extend()$, $D(x) := n$

**define different forms of architecture dynamism through updates of component instances, map and/or deployment**
The concept of motif: reconfiguration rules

define different forms of architecture dynamism through updates of component instances, map and/or deployment
The concept of motif-based system

- a set of *components instances*
- organized according to one or more *architectural motifs*
  - an instance may belong to several motifs
- a set of parameterized *inter-motif reconfiguration rules*
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- a set of parameterized inter-motif reconfiguration rules
Inter-motif reconfiguration rules

- Global reconfiguration actions parameterized by the system content
- Define architecture dynamism at system level through joint execution of
  - *intra-motif reconfiguration* actions
  - Component instance *migration* from a motif to another
  - Architectural motif *creation* and *deletion*
Motif-based systems: operational semantics

- Operational semantics is defined incrementally for components, motifs and systems.

- A motif-based system state is a couple \((m, b)\) including motifs configuration \(m\) and behaviour / component states \(b\).

- Separation of concerns between interaction and configuration steps:
  - Interactions \(\alpha\) preserve motifs configuration i.e., architecture.
  - Reconfiguration \(\rho\) preserve component states.
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Exercises

1. Dynamic Token Ring System
   - component creation/deletion, motif reconfiguration

2. Dynamic Multicore Task System
   - component creation/deletion, component migration

3. Automated Highway Traffic System
   - Bergenhem, Approaches for facilities layer protocols for platooning, 2015
   - component migration, motif creation/deletion, inter-motif reconfiguration

4. Self-organized Robot Colonies
   - Dorigo et al, Teamwork in self-organized robot colonies, 2008
   - component migration, inter-motif reconfiguration
Dynamic token ring system

- a token-passing ring system consisting of identical component instances
- the token is send / received through synchronization with the corresponding neighbor
- new component instances are allowed to enter and existing instances to leave the ring at any time
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Dynamic token ring system

The **Ring** motif

- The map is a cyclic graph with additional update primitives
- Components are deployed 1-to-1 into map nodes
- Interaction rules

\[
\text{sync-ring-inout}(x_1, x_2 : \text{C}) \equiv \\
\quad \text{when } D(x_1) \mapsto D(x_2) \text{ sync } x_1.\text{out } x_2.\text{in}
\]

Reconfiguration rules

\[
\begin{align*}
\text{do-ring-insert()} & \equiv \\
& \quad \text{do } x := \text{B.create(C, idle)}, \\
& \quad n := \text{H.extend()}, D(x) := n
\end{align*}
\]

\[
\begin{align*}
\text{do-ring-remove}(x : \text{C}) & \equiv \\
& \quad \text{when } |\text{B}| \geq 3 \land x.\text{idle} \\
& \quad \text{do } n := D(x), \text{B.delete(x), H.remove(n)}
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Dynamic multicore task system

- $n \times n$ multicore grid, $n$ fixed
- every core runs several tasks
- *tasks can migrate such that to balance the load amongst cores*
- *new tasks created, completed tasks removed*
Dynamic multicore task system

- $n \times n$ multicore grid
  - The **Processor** motif captures the static architecture
  - Grid-like map and 1-to-1 deployment of core components onto map locations

- Every core runs several tasks
  - The **CoreTask** motif captures the current task allocation
  - Map and deployment are not relevant
Dynamic multicore task system

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- **every core runs several tasks**
  - the **CoreTask** motif captures the current task allocation
  - map and deployment are not relevant
Dynamic multicore task system

- *tasks can migrate such that to balance the load amongst cores*
- inter-motif reconfiguration rule

\[
do-migrate(y_1, y_2 : \text{CoreTask}, y_3 : \text{Processor}, x_1, x_2 : \text{Core}, x_3 : \text{Task}) \equiv \\
\text{when } \langle y_1 : x_1 \in B \rangle \land \langle y_2 : x_2 \in B \rangle \land \\
\langle y_3 : D(x_1) \leftrightarrow D(x_2) \rangle \land \\
|y_1.B| > |y_2.B| + K \land x_3 \in y_1.B \\
do \ y_2.migrate(x_3), \ y_1.delete(x_3)
\]

- new tasks created, completed tasks removed, etc
- additional reconfiguration rules within the CoreTask motifs
Dynamic multicore task system

- tasks can migrate such that to balance the load amongst cores
- inter-motif reconfiguration rule

\[
\text{do-migrate}(y_1, y_2 : \text{CoreTask}, y_3 : \text{Processor}, \ x_1, x_2 : \text{Core}, x_3 : \text{Task}) \equiv \\
\text{when } \langle y_1 : x_1 \in B \rangle \land \langle y_2 : x_2 \in B \rangle \land \\
\langle y_3 : D(x_1) \mapsto D(x_2) \rangle \land \\
|y_1.B| > |y_2.B| + K \land x_3 \in y_1.B \\
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- tasks can migrate such that to balance the load amongst cores
- inter-motif reconfiguration rule

```
do-migrate(y_1, y_2 : CoreTask, y_3 : Processor, x_1, x_2 : Core, x_3 : Task) ≡
    when ⟨ y_1 : x_1 ∈ B ⟩ ∧ ⟨ y_2 : x_2 ∈ B ⟩ ∧
        ⟨ y_3 : D(x_1) ↦ D(x_2) ⟩ ∧
        |y_1.B| > |y_2.B| + K ∧ x_3 ∈ y_1.B
    do y_2.migrate(x_3), y_1.delete(x_3)
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Dynamic multicore task system

- **tasks can migrate such that to balance the load amongst cores**
- **inter-motif reconfiguration rule**

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do\text{-migrate}(y_1, y_2 : \text{CoreTask}, y_3 : \text{Processor}, x_1, x_2 : \text{Core}, x_3 : \text{Task}) \equiv \\
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(y_3 : D(x_1) \leftrightarrow D(x_2)) \land \\
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- **new tasks created, completed tasks removed, etc**
  - additional reconfiguration rules within the **CoreTask** motifs
Dynamic multicore task system

Simulation results of a $3 \times 3$ dynamic multicore task system for 3000 steps (new tasks are created at $c_{11}$, completed tasks are removed at $c_{33}$)
Automated highway traffic system

- a single-lane one-way road
- an arbitrary number of autonomous homogeneous self-driving cars are moving in the same direction, at different cruising speeds
- cars are organized into *platoons* i.e. groups of cars cruising at the same speed and closely following a leader car
- platoons may dynamically merge or split
  - a merge takes place if two platoons are close enough
  - a split takes place when an arbitrary car requests to leave the platoon

[ C. Bergenhem, *Approaches for facilities layer protocols for platooning*, 18th IEEE International Conference on Intelligent Transportation Systems, ITSC 2015 ]
the behavior of Car components

includes both platoon leader and follower functionality
Automated highway traffic system

- The **Road** motif captures the movement of *all* cars

\[
\ldots \quad c_{i+1} \quad c_{i+2} \quad \ldots \quad c_j \quad c_{j+1} \quad c_{j+2} \quad \ldots \quad c_k \quad \ldots
\]

- Single move interaction involving all cars

\[
\text{sync-road-move}(X : \text{Car}) \equiv \text{when } X = \text{B sync } X.\text{move}
\]
Automated highway traffic system

- The **Road** motif captures the movement of *all* cars

\[
\text{sync-road-move}(X : \text{Car}) \equiv \text{when } X=B \text{ sync } X.\text{move}
\]
the **Platoon** motif captures the coordination in *one* platoon

interactions for synchronizing speed and notifying split maneuver

$$\text{sync-platoon-speed}(x : \text{Car}, X : \text{Car}) \equiv \text{when } X = B \setminus x \land D(x) = H.\text{head}$$

$$\text{sync} x.\text{setSpeed} X.\text{getSpeed} \text{ do } X.v = x.v$$

$$\text{sync-platoon-split}(x_1, x_2 : \text{Car}) \equiv \text{when } D(x_1) = H.\text{head} \land x_1 \neq x_2$$

$$\text{sync} x_1.\text{ack\_split} x_2.\text{split}$$
Automated highway traffic system

- Platoons merge and split dynamically ...

- inter-motif reconfiguration rules for merging

```
do-platoon-merge(\(y_1, y_2: \text{Platoon}, x_1, x_2: \text{Car}\)) \equiv
\text{when } \langle y_1 : D(x_1) = H.\text{tail} \rangle \land \langle y_2 : D(x_2) = H.\text{head} \rangle \land |x_1.\text{pos} - x_2.\text{pos}| < K
\text{do } B := y_1.B \cup y_2.B, H := \text{append}(y_2.H, y_1.H), D := y_1.D \cup y_2.D,
\text{create}(P, (B, H, D)), \text{delete}(y_1), \text{delete}(y_2)
```
Automated highway traffic system

- Platoons merge and split dynamically...

- Inter-motif reconfiguration rules for splitting

```haskell
do-platoon-split(y : Platoon, x : Car) ≡
   do ⟨y : H := H.sublist(0, D(x)), B₁ := D⁻¹(H₁), D₁ := D.restrict(H₁),
       H₂ := H.sublist(D(x), H.length), B₂ := D⁻¹(H₂), D₂ := D.restrict(H₂)⟩,
       create(P, (B₁, H₁, D₁)), create(P, (B₂, H₂, D₂)), delete(y)
```
Automated highway traffic system

Simulation results of the highway traffic with 200 cars along 2000 steps (the yellow rectangle designates some fixed car)
Self-organized robot colonies

- a number of identical robots are randomly deployed on a field and have a mission to locate an object (the prey) and to bring it near another object (the nest)
- the robots know neither the position of the nest nor the position of the prey; they have limited communication and sensing capabilities
Self-organized robot colonies


1. the robots self-organize into an *exploration path* starting at the nest
   - the first robot detecting the nest initiates the path, i.e. stops moving and displays a specific status
   - any robot that detects the path, begins moving along the path towards its tail, explores a bit further its neighborhood and gets connected

2. the robots push the prey back to the nest along the *exploration path*
   - additional robots converge near the prey
   - when enough robots have converged, they start pushing the prey along the path towards the nest
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2. the robots push the prey back to the nest along the *exploration path*
   - additional robots converge near the prey
   - when enough robots have converged, they start pushing the prey along the path towards the nest
Self-organized robot colonies

- The **Arena** pattern contains all the components (robots, nest, prey)

![Arena diagram]

- No particular map/deployment structure
- Defines a global *tick* interaction for modeling synchronous time progress
- All robots move i.e. update their position at every tick

\[
\text{sync-arena-tick}(X: \text{Robot}) \equiv \text{when } X = \text{B.Robot } \text{sync } X.\text{tick}
\]
Self-organized robot colonies

- The **Neighborhood** pattern represents the visibility range for a given robot.

- Inter-motif reconfiguration rules keep the neighborhood updated.

```
do-neighborhood-enter(\(y_1\) : Neighborhood, \(y_2\) : Arena, \(x_1, x_2\) : Robot) \equiv
  \text{when } \langle y_1 : D(x_1) = H.\text{center} \land x_2 \notin B \rangle \land \langle y_2 : x_2 \in B \rangle \land \text{dist}(x_1, x_2) \leq R_{\text{min}}
  \text{do } y_1.\text{migrate}(x_2), \langle y_1 : n := H.\text{extend}(), D(x_2) := n \rangle

do-neighborhood-leave(\(y_1\) : Neighborhood, \(x_1, x_2\) : Robot) \equiv
  \text{when } \langle y_1 : D(x_1) = H.\text{center} \land x_2 \in B \rangle \land x_1 \neq x_2 \land \text{dist}(x_1, x_2) \geq R_{\text{max}}
  \text{do } \langle y_1 : n := D(x_2), B.\text{delete}(x_2), H.\text{remove}(n) \rangle
```
Self-organized robot colonies

- The **Chain** pattern represents the *exploration path* constructed dynamically.

```
\[ \text{do-chain-connect}(y_1 : \text{Chain}, \ y_2 : \text{Neighborhood}, \ x_1, \ x_2 : \text{Robot}) \equiv \\
\quad \text{when } \langle y_1 : D(x_1) = H.\text{tail} \land x_2 \not\in B \rangle \land \langle y_2 : D(x_1) = H.\text{center} \land x_2 \in B \rangle \\
\quad \text{do } y_1.\text{migrate}(x_2), \langle y_1 : n = H.\text{extend}(), \ D(x_2) := n \rangle \\
\text{do-chain-disconnect}(y_1 : \text{Chain}, \ x_1 : \text{Robot}) \equiv \\
\quad \text{when } \langle y_1 : D(x_1) = H.\text{tail} \rangle \land \langle y_1 : x_1.\text{timeout} = \text{true} \rangle \\
\quad \text{do } \langle y_1 : n := D(x_1), \ B.\text{delete}(x_1), \ H.\text{remove}(n) \rangle \\
\]```

- Inter-motif reconfiguration let every robot join/leave the chain.
Self-organized robot colonies

- Overall view of the motif-based system

- Dynamic architecture and behaviour fully defined as the superposition of **Arena**, **Neighborhood(s)** and **Chain** motifs
Outline

1 Introduction

2 DR-BIP – Dynamic Reconfigurable BIP
   - Components and Interactions
   - Motifs for Dynamic Architectures
   - Motif-based Systems

3 Programming Dynamic Reconfigurable Systems
   - Dynamic Token Ring System
   - Dynamic Multicore Task System
   - Automated Highway Traffic System
   - Self-organized Robot Colonies

4 Conclusion
Conclusion

DR-BIP provides architectural motifs:

- an *exogeneous framework* for dynamic architectures
  - based on elementary structuring concepts of *map* and *deployment*
  - fully *declarative* for interaction definition
  - mixed declarative/imperative for reconfiguration

- three basic types of architectural dynamism
  - behavior dynamism: component *instances creation* and *deletion*
  - deployment dynamism: *mobility* of component instances along map
  - map dynamism: map updates according to specific primitives

- operational semantics
  - built on operational semantics for static BIP systems
  - prototype implementation available
Future Work

Towards automated verification of DR-BIP models

- **correctness of parametric interacting systems**
  - extract parametric interaction invariants for static systems with arbitrary (yet fixed) number of components
  - combine with component invariants and prove system level properties
  - *e.g.*, show that the dynamic ring system is deadlock-free regardless the number of components

- **correctness of reconfiguration operations**
  - prove that architectural properties are preserved by statements changing components, the map and the deployment
  - *e.g.*, show that the ring property is preserved by every reconfiguration, that is, an architectural invariant

Beyond simulation, implementation for existing middleware platforms *e.g.*, OSGi
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Beyond simulation,
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Thank you for your attention!

Questions?

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