A Programming Model for Heterogeneous CPS from the Physical Point of View

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Short Resume

- Since March 2020 research assistant at the Operating Systems Group of the TUC
- 2016–2020 tutor for research and teaching
- 2013–2020 student of Applied Informatics and Automotive Software Engineering
- Research focused on programming models for CPS
CPS

- Connect digital and physical world
- Multitude of heterogeneous sensors and actuators
- Observing through sensors
- Influencing through actuators
Running Example — Robot Soccer

- Heterogeneous players
- **Physical objects:** players, ball, goal
- **Sensors:** observing ball and players
- **Actuators:** influencing ball and players
- Distribution, Coordination, ...
Challenges

- Distribution and heterogeneity
- Currently: digital point of view
- Impact on physical environment often not clear
- Disconnection between programmer’s view and environment
- Programming is error-prone and complex
- We need **abstractions**!
Abstractions

- Physical point of view
  - clear physical semantics
- Program physical objects
  - Which properties?
  - Influences on them
  - Desired change
- Sensor and actuator virtualization
  - Which devices achieve above is not relevant
- Systemic view
Motivation

Programming Models

- Describe programmer’s view on the system
- Allow to hide system features through transparency
- Allow to access them through awareness
- Describe translation of program description into actions
State of the Art — Physical Modeling

- Approaches for taking physical point of view
- Physical modeling languages (Modelica, Simulink, etc.)
- Description of physical processes
- Code generation for utilizing sensors/actuators
- No virtualization or distribution transparency

Our Approach — The Programmer’s View

- Developer programs physical objects
- Attributes for properties
  - What has to be measured?
- Methods for behaviour
  - How may it be influenced?
- Virtualization
  - Measurements matter, not sensors
  - Influences matter, not actuators
- Inheritance for similar properties and behaviour

```java
Ball extends MovingObject {
  ...
}
```
Physical Objects — Attributes

- Describe physical properties (shape, velocity, mass, …)
- Constitute state of the object
- Measured by sensors
- Influenced by actuators

```java
constructor() {
    this.mass = Mass(0.3[kg]);
    this.position = Position(?[m], ?[m], ?[m]);
    ...
}
```
Physical Objects — Methods

- Change of physical properties based on physical actions or internal dynamics $\rightarrow$ change of state

- Actuator inputs as parameters

- Possibly from different actuators

- Requirements on actuators to provide inputs

Require(Act(v) == Act(m) && Act(v).pos == this.pos)

```java
method get_kicked(Velocity v, Mass m) {
    this.v = ...;
}
```
The Programmer’s View – Physical System

- So far: physical object state and behaviour description
- Bundle of properties and behaviours of objects
- Constraints for describing target state of physical system

```cpp
target defense() {
    abs(player, opponent) <= 1.0[m];
    abs(player, ball) <= 0.5[m];
    ...}
```
The Programmer’s View — Recap

- Physical system of interest is group of physical objects
- OOP for describing physical objects
- **Attributes**: measured by sensors, constitute state
- **Methods**: change of state, based on possible acuator inputs and internal dynamics
- **Constraints** for describing target state space of system
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Runtime Environment

```java
class Ball {
    ...
}
```

Sensor Measurements
Actuator Control

Interpreter

CS

O
C
RTE – Interpreter

- Interpreter creates property specifications from attributes
  - What has to be measured?

- Creates state space equations from methods
  - How can it be influenced?
  - How does system evolve?
RTE – Observer

- Distributed observer (O) module observes physical objects of interest

- **Input:**
  - Property descriptions (1)
  - Sensor measurements (2)

- **Output:**
  - Class instances of observed objects (3)
RTE – Constraint Solver

- Constraint solver (CS) solves state equations (1) for inputs to reach target state

- **Input:**
  - Measured object properties (2)
  - Available actuator influences (3)
  - Target state constraints and state equations (1)

- **Output:**
  - Required actuator influences (4)
RTE – Controller

- **Distributed controller (C) module for coordinating actuators**

- **Input:**
  - Required actuator influences (1)

- **Output:**
  - Available actuator influences (2)
  - Actuator control (3)

```java
class Ball {
    ...
}
```

![Diagram of RTE - Controller with class Ball and connections to CS and C]
Conclusion

▶ Provided conceptual programming model
▶ Allows description of desired behaviour of physical objects
▶ Physical impact on environment made explicit
▶ Sensor and actuator virtualization
▶ RTE for supporting programmer’s view
Next Steps – Observer

- Sensor model for generic specification of sensors
- Allows mapping of available sensors to object properties
- Sensor fusion based on physical system description
- Data distribution and aggregation
Thank you!
State Equation

Method $m$, Class $c$, State $\vec{x}$, Actuator Input $\vec{u}$, System $\Sigma$:

$$\vec{x}'_{c,m}(t) = f_m(\vec{x}_c, \vec{u}_m, t) \xrightarrow{\text{linear}} \vec{x}'_{c,m}(t) = A_m \vec{x}_c + B_m \vec{u}_m(t)$$ (1)

$$\vec{x}'_c(t) = \sum_{m \in M} \vec{x}'_{c,m}(t) = \sum_{m \in M} (A_m \vec{x}_c + B_m \vec{u}_m(t))$$ (2)

$$\vec{x}_\Sigma(t) = [\vec{x}_c^0 \quad \vec{x}_c^1 \quad \ldots \quad \vec{x}_c^n]^T(t)$$ (3)