Heterogeneous Modeling and Design in Ptolemy II

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with material courtesy of Edward Lee and the Ptolemy group

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Ptolemy II A Software Laboratory

Ptolemy II

- Java based
- Graphical modeling and simulation environment
- Multiple "models of computation"
- Hierarchical & heterogeneous models
- Code generator
- Actor language

Outline

- Introduction
- Ptolemy II basics
- A motivating example
- Research Issues
- Summary

Embedded Systems

- Computers not thought of as computers
- Increasingly complex designs
  - networked, fail safe, etc
- Development speed
  - time to market
- Bugs, bugs, bugs
  - hard to correct a released product
  - don't want to reboot your toaster

What is So Different With Embedded Software?

- Interaction with physical processes
  - sensors, actuators, processes
- Critical properties are not all functional
  - real-time, fault recovery, power, security, robustness
- Heterogeneous
  - hardware/software, mixed architectures
- Concurrent
  - interaction with multiple processes
- Reactive
  - operating at the speed of the environment

Component Technology

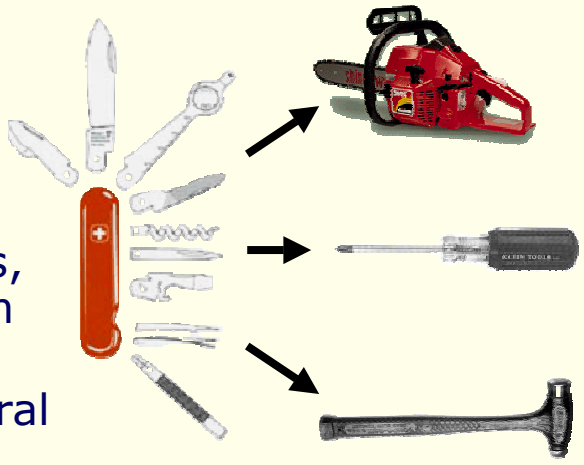
- Examples: Java beans, VB-components, etc
- Rationale
  - Encapsulation
  - Reuse
  - Divide complexity
- Successful in many areas
- Problems with concurrent components
  - Threads are not components
  - Priorities are global parameters
- Difficult to design embedded systems component with state-of-the art technology

Multipurpose tools

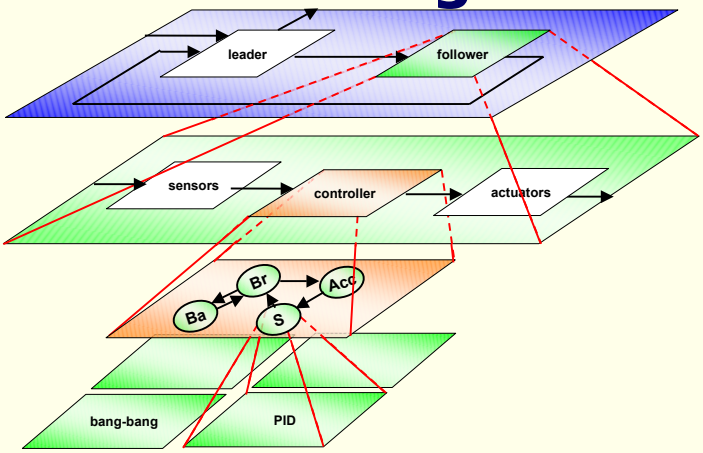
- Express almost anything, guarantee almost nothing
- You only need to know *one* programming language
  - Quick starts, but sometimes slower endings
- Programmers+language, a lifelong marriage
- Examples:
  - Java
  - C/C++ with RTOS, ADA, Modula-2
  - RMA & EDF scheduling

Sharpen your tools

- Use problem specific tools
  - Constrain the solutions
- Choice of tools, a major design decision
- Combine several tools



Hierarchical, Heterogeneous Modeling and Design



Ptolemy Background

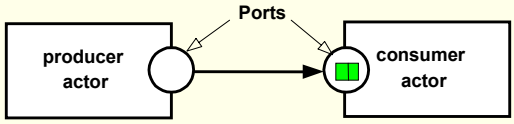
- Initially a signal processing tool
- Gabriel (Lisp) 1985-1990
- Ptolemy Classic (C++) 1990-1997
- Ptolemy II (Java) 1996-

Claudius Ptolemy

Edward A. Lee

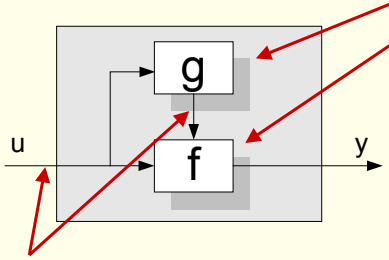
Ptolemy II Basics

- A model is a a set of interconnected *actors* and one *director*
- Actor
  - Input & output *ports*, states, & parameters
  - *Atomic* or *composite*
  - Communicates using *tokens*
  - When it is *fired* it produces and consumes tokens



Component Interaction Semantics

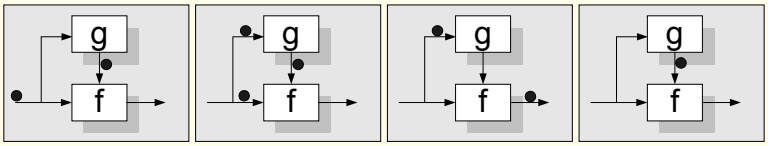
Are actors active? passive?
How is the flow of control determined?



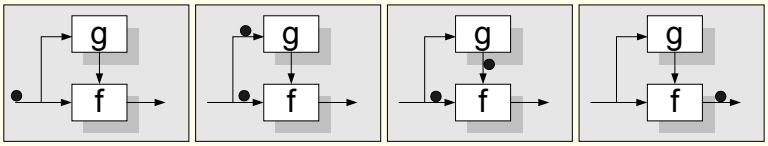
Are communications timed? synchronized? buffered?
How is the communications mediated?

Interaction Semantics
3 Different Interpretations

- Continuous time: $y(t)=f(g(u(t), u(t))$
- Discrete time : {f, g} $\Rightarrow y(k)=f(g(u(k-1)), u(k))$



- Discrete time : {g, f} $\Rightarrow y(k)=f(g(u(k), u(k))$

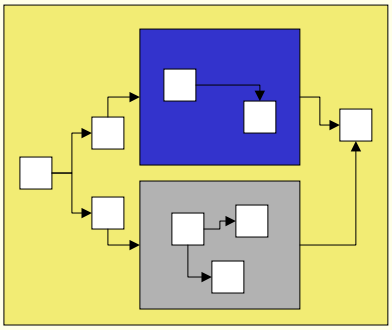


Ptolemy II Basics

- Director
  - Manages the data flow and the scheduling of the actors
  - The director fires the actors
- Receiver
  - Defines the semantics of the port buffers
- Models of Computation
  - Define the interaction semantics
  - Implemented in Ptolemy II by a *domain*
    - Director + Receiver

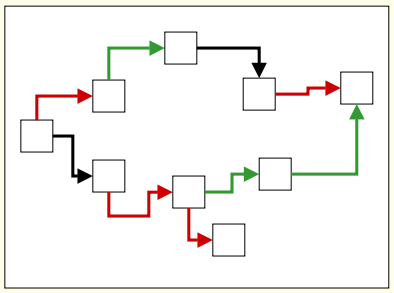
Hierarchical Heterogeneity vs. Amorphous Heterogeneity

Hierarchical



Color is a domain, which defines both the flow of control and interaction protocols.

Amorphous



Color is a communication protocol only, which interacts in unpredictable ways with the flow of control.

Available Domains

- CSP – concurrent threads with rendezvous
- CT – continuous-time modeling
- DE – discrete-event systems
- DT – discrete time
- PN – process networks
- PN' – Petri nets
- SDF – synchronous dataflow
- SR – synchronous/reactive
- GR – Graphics, 3D animations

Each is realized as a director and a receiver class in Ptolemy II

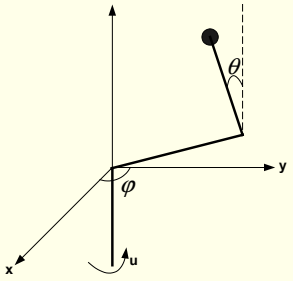
Examples of Actors+Ports Software Architectures

- Simulink (The MathWorks)
- Labview (National Instruments)
- Port-based objects (CMU/U of Maryland)
- SPW, signal processing worksystem (Cadence)
- System studio (Synopsys)
- ROOM, real-time object-oriented modeling (Rational)
- Polis & Metropolis (UC Berkeley)
- VHDL, Verilog, SystemC (Various)
- …

An Example: Controlling the Furuta Pendulum

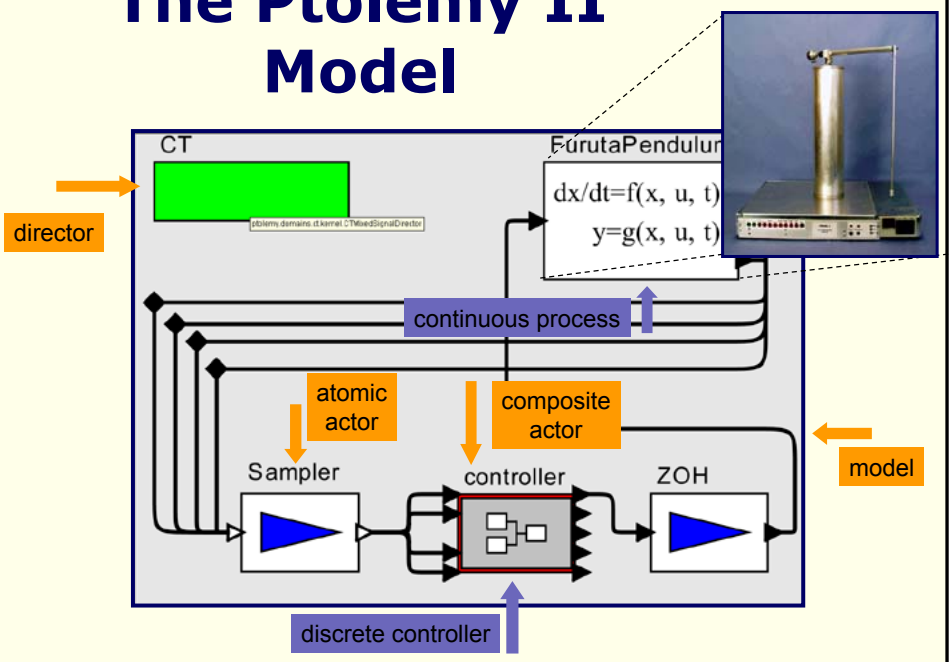
- Classic control problem
- Swing up the pendulum and then keep it in the upright position

The Example System



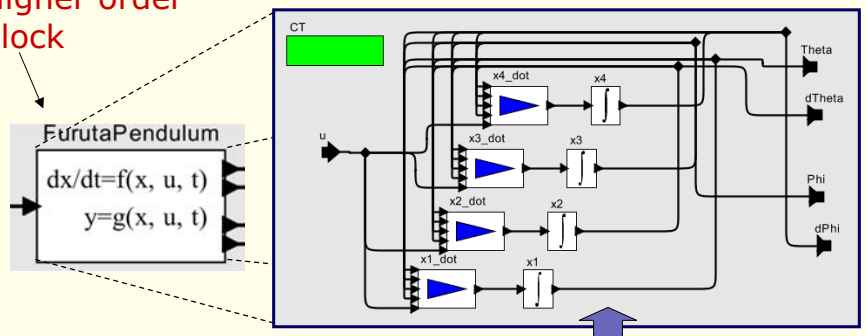
- Four states (all measurable)
  - the pendulum angle θ,
  - and its velocity $\dot{\theta}$
  - the arm angle ϕ,
  - and its velocity $\dot{\phi}$
- Input signal u is the torque on the arm
- Starts in the downright position
- Use three subcontrollers:
  - to swing it up (energy based approach)
  - to catch it (linear state feedback)
  - to stabilize it (linear state feedback)

The Ptolemy II Model



Pendulum dynamics in CT – Continuous Time

Higher order block



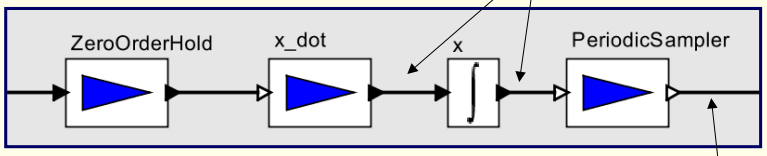
$$\left(J_p + Ml^2\right)\ddot{\theta} - Mrl\ddot{\phi}\sin\theta\cos\theta + Mrl\dot{\phi}^2\cos\theta - gl\left(M + \tfrac{m}{2}\right)\sin\theta = 0$$

$$Mrl\ddot{\theta}\cos\theta - Mrl\dot{\theta}^2\sin\theta + 2\left(J_p + ml^2\right)\dot{\theta}\dot{\phi}\sin\theta\cos\theta$$

$$+\left(J + mr^2 + Mr^2 + (Jp + ml^2)\sin^2\theta\right)\ddot{\phi} = u$$

CT Domain

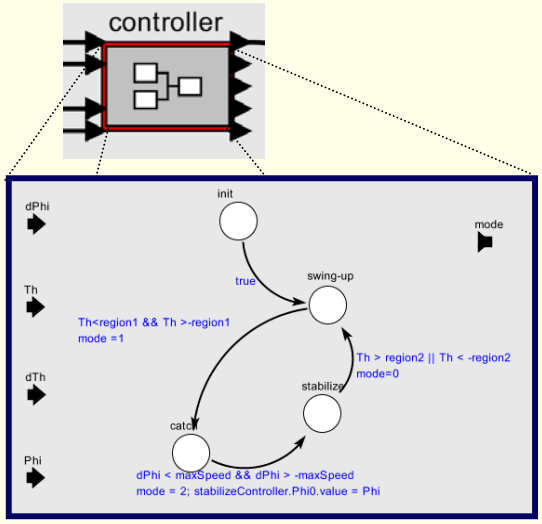
- The CT domain models components
  - interacting by continuous signals
  - described by ODE
  - network of integrators



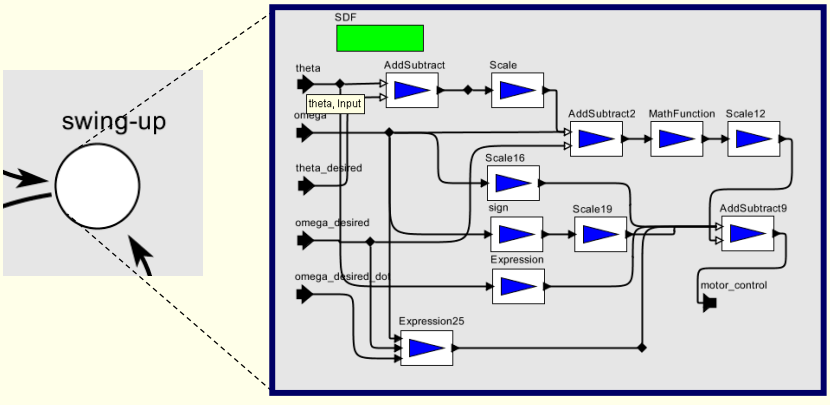
- Strengths
  - Accurate model for many physical systems
  - Established and mature simulation techniques
- Weaknesses
  - Covers a narrow application domain
  - Relatively expensive to simulate
  - Difficult to implement in software

Controller Logic in FSM - Finite State Machine

- States
  - initial
  - refinements
- Transitions
  - Guards
  - Assignments
- Natural way to express modal behavior
- Verification



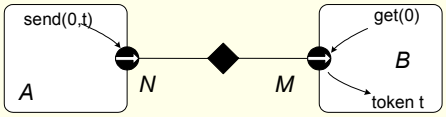
Subcontrollers in SDF - Synchronous Data flow



SDF Domain

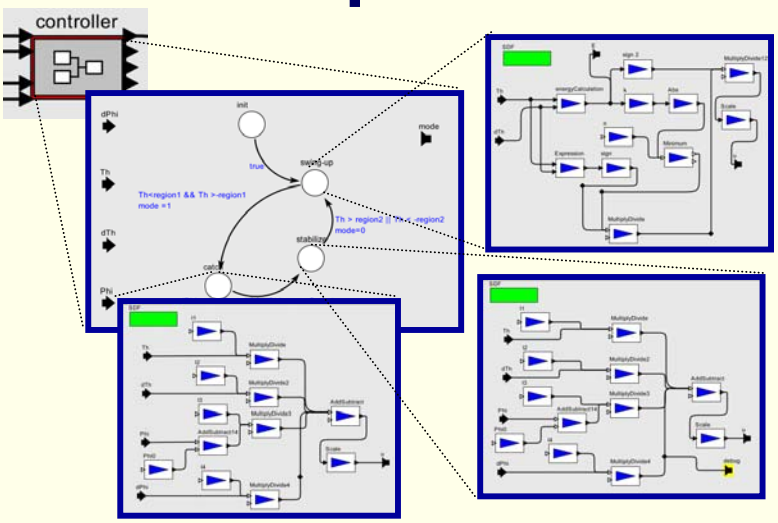
- Requires constant consumption and productions rates
- Balance equations:

  $F_A N = F_B M$



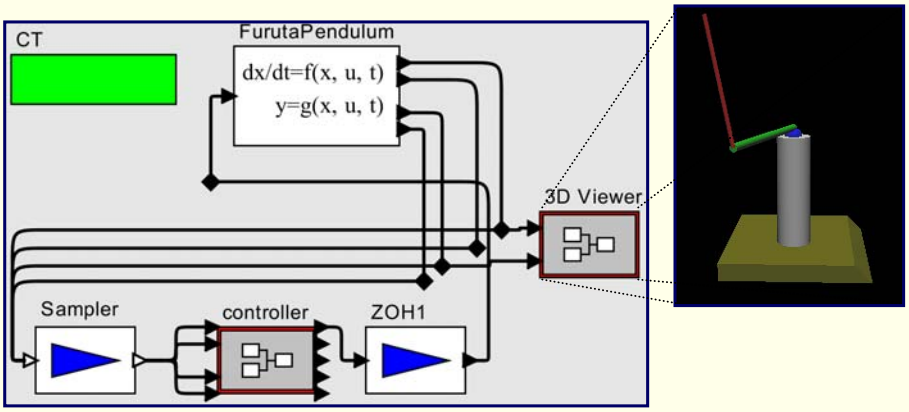
- Is statically schedulable
- Decidable resource requirements
- *Adding appropriate restrictions, increases freedom*

The Complete Controller

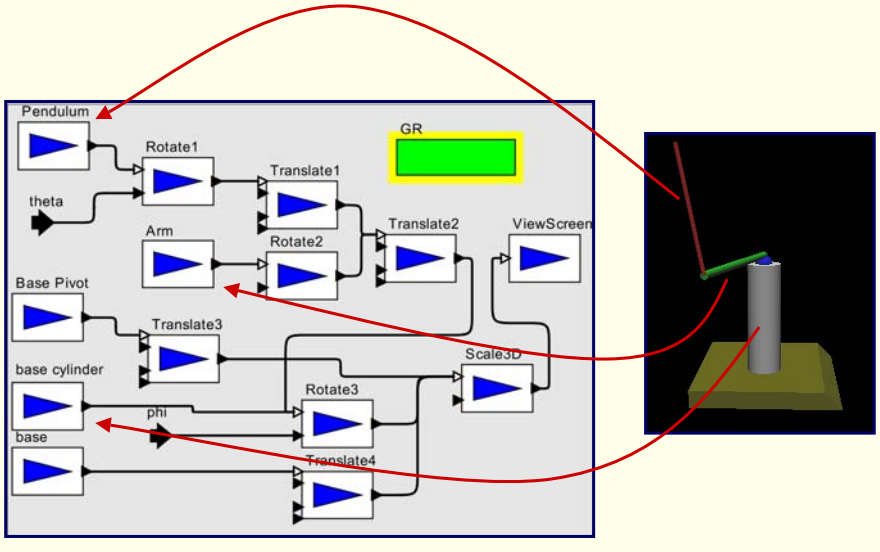


Hierarchical and heterogeneous

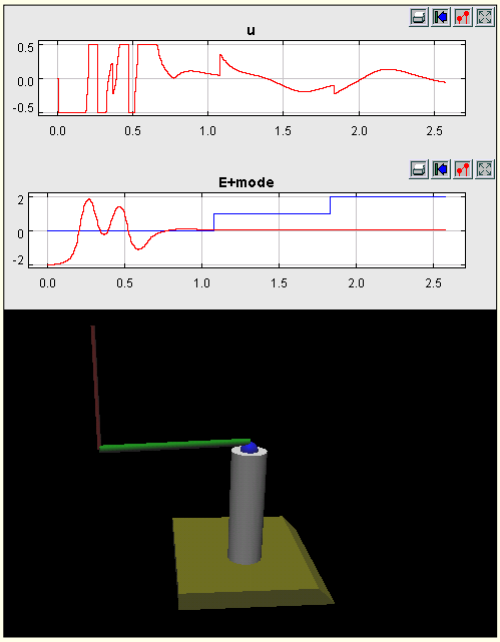
3D Visualization in GR - Graphics Domain



GR Domain



Execution [demo]



Current Research Issues

- The *Caltrop* actor language
  - Find a more concise actor description
- Code generation
  - Compile hierarchical model
- System level types
  - Go beyond data type checking
  - Extend into dynamic behavior

Summary

- Domain semantics defines
  - flow of control across actors
  - communication protocols between actors
  - implemented with directors & receivers
- Actors define:
  - functionality of components
- Hierarchy:
  - Aggregation not just syntactical
  - Composite actors are opaque, i.e. they look like atomic actors
  - Multiple domains may be used in the same model

Conclusion

- Embedded system components
- Realized in the Ptolemy II framework
- Modeling, simulation & code generation
- More information
  - Edward Lee "What's Ahead for Embedded Computing?", IEEE Computer, Sept. 2000
  - **http://ptolemy.eecs.berkeley.edu**
- Thanks to: Edward Lee, Yuhong Xiong, Jie Liu, Jörn Janneck, Steve Neuendorffer, Xiaojun Liu

THE
END