Modeling and Analyzing Real-Time Systems in Rewriting Logic (II)

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May 4, 2010

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Context

Applications

"Concrete" Systems

Semantic Framework for Real-Time Systems

Formal Analysis for MDE Languages

Lecture Series

Last Thursday: Real-Time Maude tutorial

Today: Context and applications

Context

Applications

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Content

Context

What is it Good For?

- "Concrete" Systems
- Semantic Framework for Real-Time Systems
- Formal Analysis for MDE Languages

Summary

Context

Applications

"Concrete" Systems

Semantic Framework for Real-Time Systems

Formal Analysis for MDE Languages

Formal Analysis: Model Checking vs Theorem Proving

Model Checking

- exhaustive analysis from single initial states
- automatic
- search for subtle bugs
- cannot prove correctness

Theorem Proving

- (inductive) analysis w.r.t. all initial states
- non-trivial user interaction
- prove correctness
- typically cannot find bugs

Formal Tools: Expressiveness vs Analytic Power

Expressive formalism

- can model large and advanced systems
- formal analysis harder
- properties in general undecidable

Restricted formalism

- hard/impossible to model large and complex systems
- more optimized analysis
- properties decidable

Formal Languages and Tools for Real-Time Systems

- Timed automata
  - finite automata extended with clocks
  - restricted transition guards
  - key properties decidable
  - tools: UPPAAL, Kronos, RED
- Timed Petri nets
  - limited tool support
- Timed process algebras
- IF, TE-LOTOS, etc:
  - separate formalisms for data types, dynamic behavior, and time
  - unclear or non-existing semantics
  - based on fixed communication primitives
- MOBY/RT
  - designs specified as PLC-automata
  - translated into timed automata for model checking

Real-Time Maude in Comparison

- Expressiveness and ease of specification
  - define any computable data type
  - dynamic object creation/deletion
  - unbounded data structures
  - different forms of communication
- Simple and intuitive formalism
- "Natural" model for real-time systems
  - object-oriented real-time systems
- Properties in general undecidable

The Main Question

Are there systems where Real-Time Maude's expressiveness is needed, and where Real-Time Maude analysis yields interesting results?

Classes of Applications

- "Concrete" systems/protocols
- Semantic framework for real-time systems
- Formal analysis tool for other languages

AER/NCA

AER/NCA :

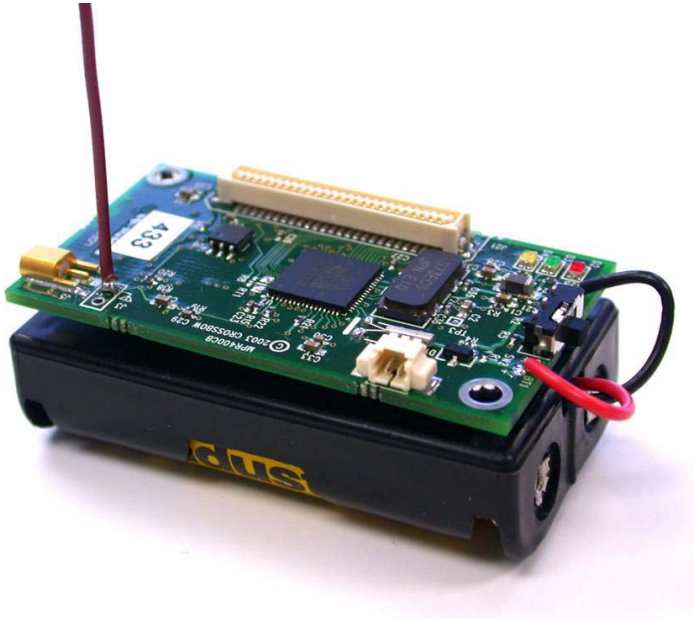
- Sophisticated multicast protocol for active networks
  - active routers buffer and repair packets
  - 50 pages of use cases
  - involves link capacity and propagation delay, packet sizes, etc.
- Easy to experiment with different sending rates, link capacities/speeds, ...
- Real-Time Maude analysis found all known design errors
- . . . and additional unknown serious design errors

CASH Scheduling Algorithm

CASH : State-of-the-art scheduling algorithm

- A job can use more or less time than allocated
- Unused execution times put in a queue for reuse
- Simulation: # elements in queue unbounded
- Modeled all possible jobs
  - analyze all possible scenarios for a given set of servers
- Search found missed hard deadline
- Extensive "Monte-Carlo simulation" did not find flaw

Density Control in Wireless Sensor Networks



- Wireless sensor network:
  - network of battery-powered nodes with sensing capabilities
  - (low-power) radio communication
  - monitor an area
- Density control:
  - extend lifetime: add redundancy
  - nodes periodically turned off to save power
    - sensing area covered by active nodes

OGDC Wireless Sensor Network Algorithm

OGDC: state-of-the-art density control algorithm

- Idea: select "best placed" node to become active next
  - minimize total overlap
- Simulated by developers using ns-2 with wireless extension
  - OGDC outperforms other algorithms

The Algorithm

Periodically:

- Some nodes become active
  - broadcast
- "Best placed" node should become active next
  - the better the location, the smaller the back-off timer
- Back-off timer expires: node becomes active and broadcasts
- Sensing area covered by active nodes: sleep!

Formal Methods Challenges

- New form of communication: radio transmission
  - broadcast to nodes within transmission range
  - OGDC definition uses transmission delay
- Time (power, timers, delays, ...)
- Geometric entities (areas, angles, distances, ...)
- Probabilistic behaviors
- Analyze performance and correctness

TTBOMK: First formal analysis of advanced WSN algorithm

Real-Time Maude Specification of OGDC (I)

- Easy to define communication model (5 equations)
- Probabilistic behaviors not supported by
  - simulation: "sample" values using pseudo-random function

Real-Time Maude Specification of OGDC (II)

Locations in a two-dimensional plane: $x \,.\, y$

```
sort Location .
op _._ : Rat Rat -> Location [ctor] .
```

Sensor nodes in OGDC:

```
class WSNode | backoffTimer : TimeInf,
               coverageArea : Bitmap,
               remainingPower : Nat,
               roundTimer : TimeInf,  ...
```

Node identified by its location:

```
subsort Location < Oid .
```

Modeling Communication in WSN

Broadcast to all nodes within transmission range

- Idea: node "sends" a `broadCast` message
- A `broadCast` message is "dissolved" into a single message to each node within range
- Message collisions not modeled

Modeling Broadcast

```
sort MsgCont .    --- Message content
msg broadcast_from_ : MsgCont Location -> Msg .
msg msg_from_to_ : MsgCont Location Location -> Msg .
```

The following equation defines the desired equivalence:

```
var C : Configuration .  var MC : MsgCont .
eq {< L : WSNode | >  (broadcast MC from L)  C} =
   {< L : WSNode | >  distributeMsg(L, MC, C)} .
```

Modeling Broadcast (cont.)

```
op distributeMsg : Location MsgCont Configuration
                   -> Configuration [frozen (3)] .

var MSG : Msg .  var O : Oid .
eq distributeMsg(L, MC, none) = none .

eq distributeMsg(L, MC, MSG C) =
    MSG distributeMsg(L, MC, C) .

eq distributeMsg(L, MC, < L' : WSNode | >  C) =
     < L' : WSNode | >  distributeMsg(L, MC, C)
     if L withinTransRangeOf L'
     then dly(msg MC from L to L', f(L, L')) else none fi .
```

Rewrite Rules

OGDC has 11 rewrite rules. One is

```
rl [startingNodePowerOn] :
   < L : WSNode | remainingPower : P, backoffTimer : 0,
                  hasVolunteered : true >
   < Random : RandomNGen | seed : M >
  =>
   < L : WSNode | remainingPower : P monus transPower,
                  backoffTimer : INF, status : on >
   < Random : RandomNGen | seed : random(M) >
   broadcast (powerOnWithDirection randomDirection(M)) from L .
```

Rewrite Rules (cont.)

Another rule is:

```
crl [recPowerOn1] :
    (msg (powerOnWithDirection D) from L' to L)
    < L : WSNode | status : undecided, neighbors : NBS,
                   bitmap : BM >
  =>
    < L : WSNode | status : off,
                   neighbors : NBS (L' starting (D >= 0)),
                   bitmap : updateBitmap(L, BM, L'),
                   backoffTimer : INF >
    if (L withinTwiceTheSensingRangeOf L')
       /\ coverageAreaCovered(updateBitmap(L, BM, L')) .
```

Real-Time Maude Simulation of OGDC

- Pseudo-random placements of nodes
  - different initial seeds give different node placements
- Measure # active nodes and coverage percentage throughout network lifetime
- Parameter values as in OGDC paper
- Simulation results:
  - ns-2 simulations: 17 to 19 active nodes for 200 – 600 nodes
  - Real-Time Maude simulations:

Total number of nodes	200	400	600
# active nodes for seed=1	32	38	45
# active nodes for seed=5	38	47	51
# active nodes for seed=97	26	46	58
# active nodes for seed=313	38	54	60
# active nodes for seed=341	37	39	61

Real-Time Maude Simulations of OGDC (II)

- But . . . ns-2 simulations ignored transmission delays
- Delays important in definition of OGDC
- Real-Time Maude simulations without delays:

Total number of nodes	200	400	600
# active nodes for seed=1	21	25	22
# active nodes for seed=5	19	20	24
# active nodes for seed=97	19	23	25
# active nodes for seed=313	21	23	21
# active nodes for seed=341	23	20	18

Flaw in OGDC

- Two nodes close/on top of each other:
  - "tie-breaker" difference in back-off timers
  - difference less than transmission delay!
- Simulation without transmission delay:
  - newly active node broadcasts and twin turns off!
- Simulation with transmission delay:
  - newly active node broadcasts, but twin turns on before message arrives!

OGDC Conclusion

Real-Time Maude simulations provide realistic performance estimates for advanced WSN algorithm

Some Other "Concrete" Applications

- LMST topology control protocol for wireless sensor networks (Katelman, Meseguer, and Hou, UIUC)
  - includes MAC contention
  - VeStA statistical model checking
- Found several bugs in embedded car software used by major car makers (Japan)
  - bugs not found by model-checking tools used in industry
- Power management algorithms for multimedia systems
- Parts of NORM multicast protocol developed by IETF

Semantic Framework for Real-Time Systems

- Real-Time Maude suitable semantic framework for real-time formalisms and languages
  - expressiveness
  - natural timed model
- Formal semantics for languages and notations
  - timed extension of the actor model
  - timed model transformations (e-Motions, MOMENT-2)
  - MDE languages for embedded systems

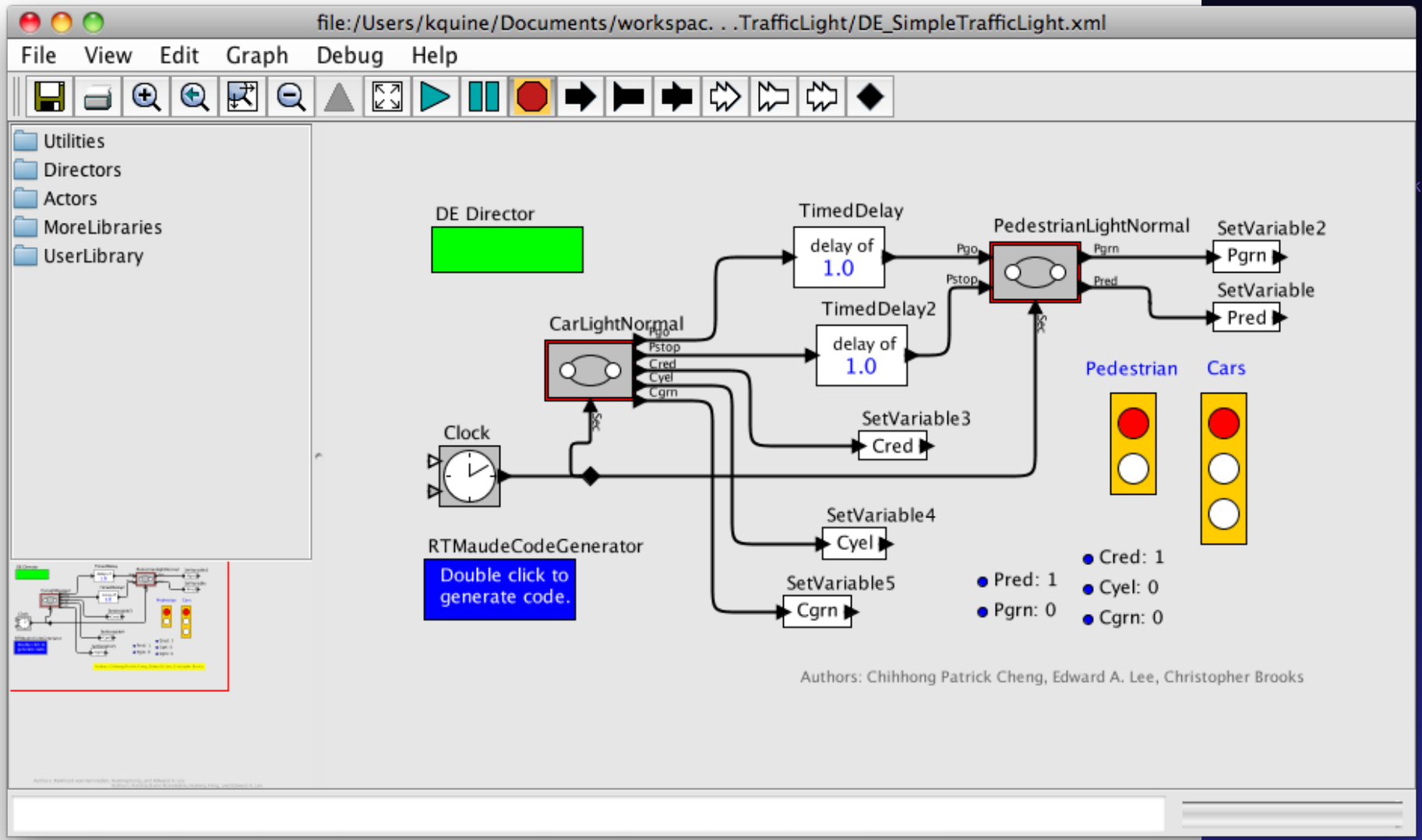
Model-driven Development

- MDE langauges for embedded systems:
  - AADL avionics standard
  - Ptolemy II
  - UML extensions
- Intuitive graphical modeling language
- Support for code generation
- Need for precise semantics and formal analysis

Enriching MDE Tools with Formal Analysis

- Define Real-Time Maude semantics of MDE language
  - Real-Time Maude's expressiveness crucial
- Use code gen infrastructure to synthesize Real-Time Maude spec from MDE model
- Define atomic propositions so that user can specify LTL properties without understanding Real-Time Maude

Analyzing Ptolemy II Models from within Ptolemy



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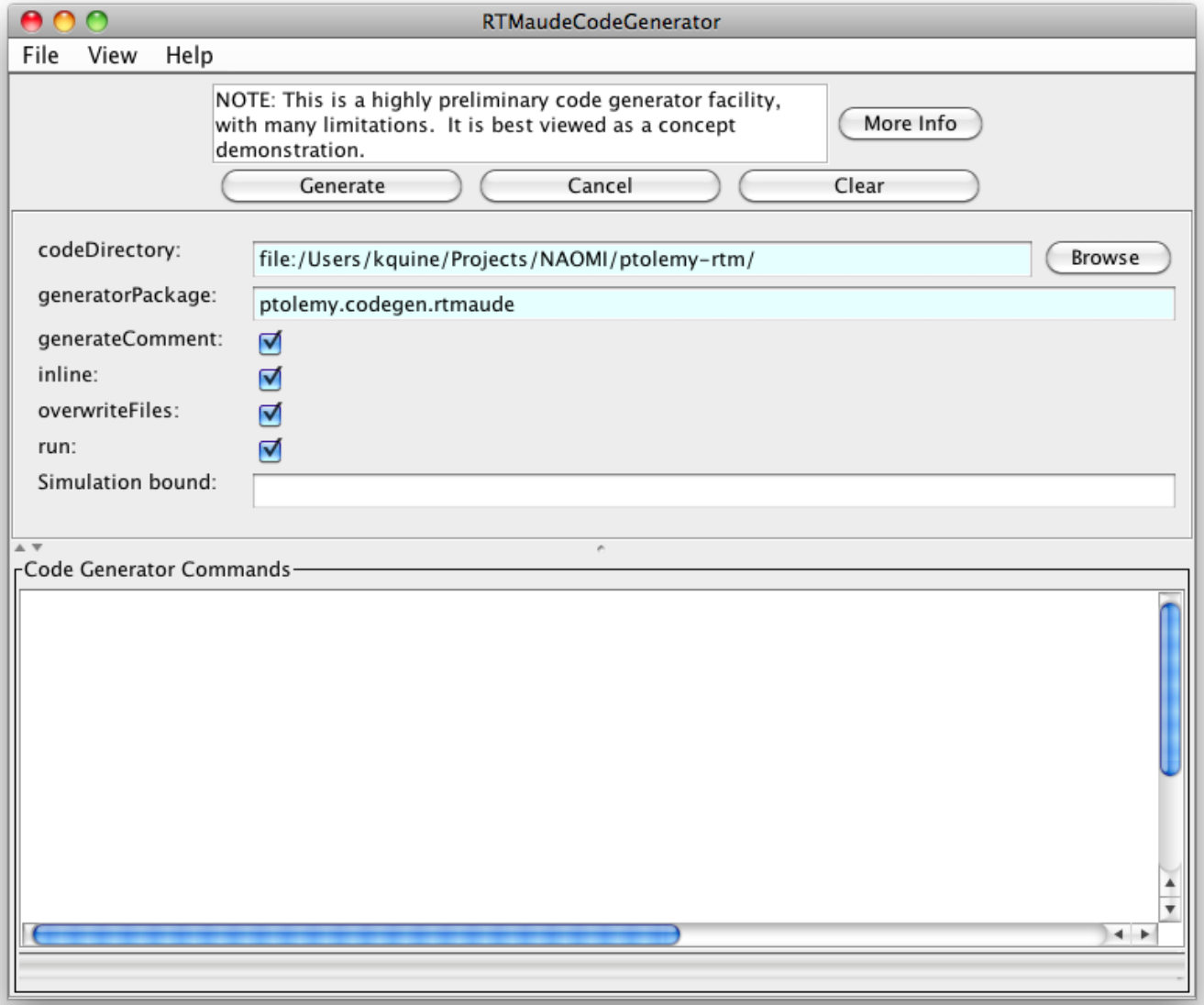

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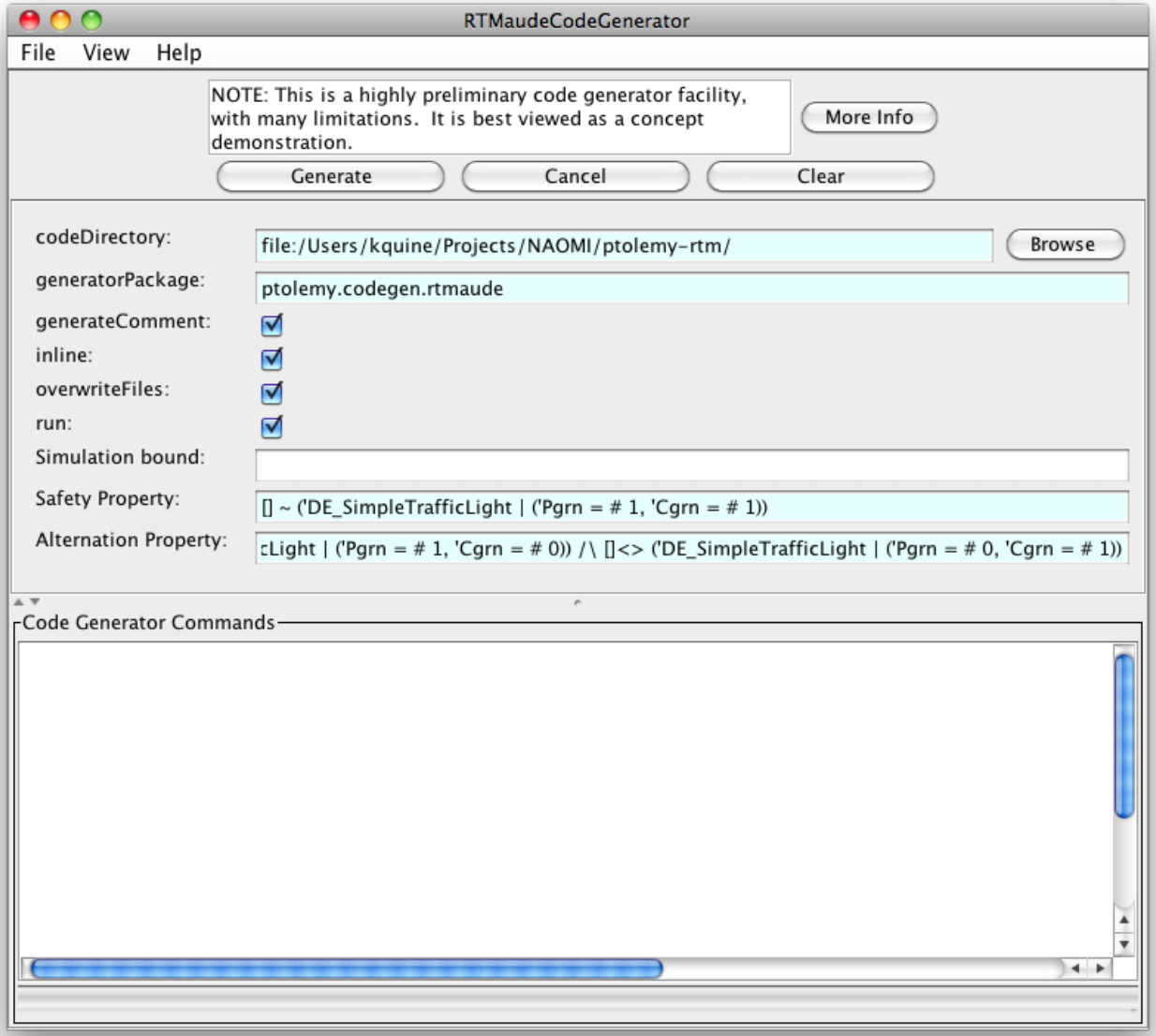

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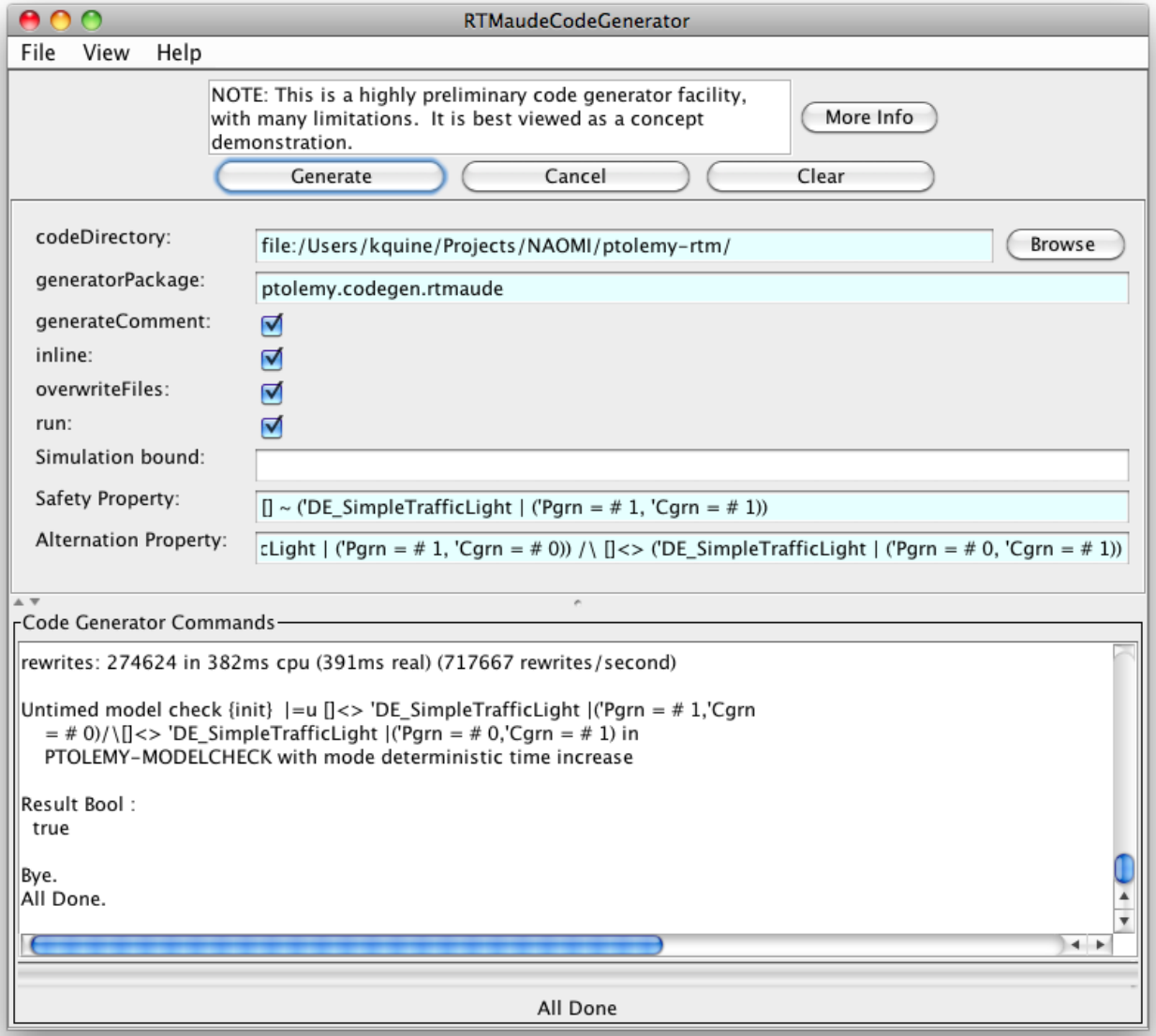

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Some Other Formal Analysis Applications

- Part of AADL avionics standard
- Handset software analysis (DoCoMo Labs)
- Real-time model transformations in MOMENT-2 and e-Motions
- Patterns for real-time systems:
  - safe operation of medical devices
  - PALS: physically asynchronous, logically synchronous

Summary

- Real-Time Maude flexible, expressive, and intuitive
- Used on state-of-the-art systems in different domains
  - value added to domain-specific analysis
- Useful both as simulation tool and model checker
  - search found error in CASH
  - simulation gives better performance estimates for OGDC than simulation tool used by WSN community
- Semantics and formal analysis capabilities for real-time MDE languages and tools
- Completeness for new classes of dense time systems