Integrated Timing Analysis & Verification of Component-based Distributed Real-time Systems

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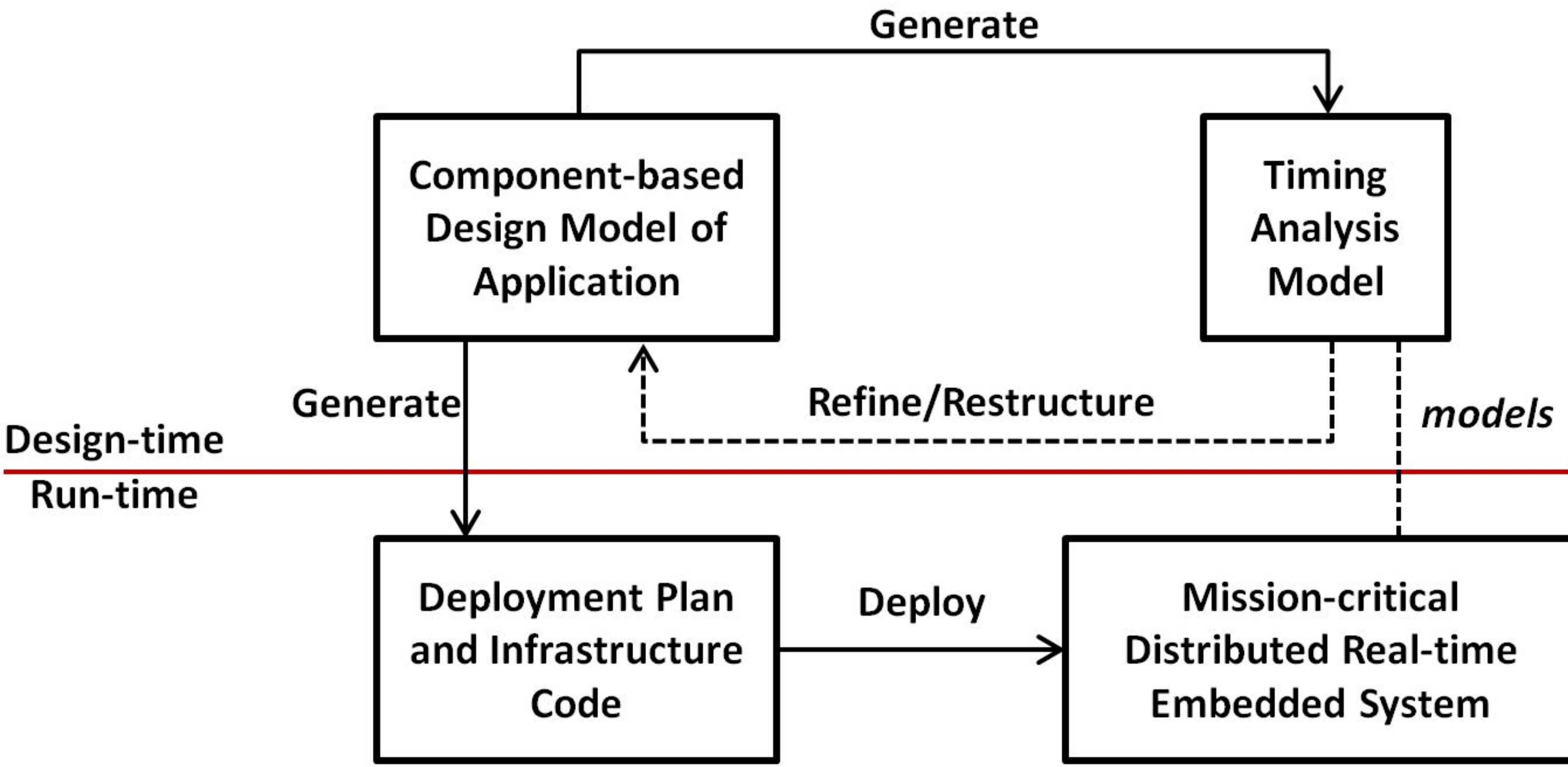
Distributed Real-time Systems

- Avionics, Locomotive control, Industrial Control and Automation
  - Utilizing dependable and predictable software is critical
- Functionality of DRE systems requires large and complex software designs
- Model-driven Development & Component-based Software Engineering
  - Assemble tested components that implement services - Reusability
- Heterogeneous concerns: Strict timing requirements, resilience to faults
- Design-time modeling and analysis methods are a requirement
  - Subscribing to MDD, we design systems by constructing models - We can use these models for analysis

- *https://en.wikipedia.org/wiki/Space_Shuttle_orbiter*
- *https://en.wikipedia.org/wiki/History_of_robots*

Verification-driven Workflow



Analysis Goal: Ensure that a component-based DRE system meets its temporal specifications

Fundamentals

Real-time Systems

- Definition
  - Real-time systems (RT-Systems) are computational systems that offer an assurance of timeliness of service provision
  - Systems whose correctness depends on functional as well as temporal aspects
- Evaluation
  - Timeliness of applications - The execution times of all application tasks must meet individual deadlines
- Distributed real-time systems are characterized by a set of computational nodes that interact by exchanging messages

Timing Analysis of Real-Time Systems

- Assume an ideally functional real-time system
- Annotate computational tasks with timing properties
  - Worst-case Execution Time (WCET)
- Characterize the system using an Analysis Model to study the timing behavior of the entire system
- *Verification*: Prove that the implementation of the system is correct w.r.t. requirements
  - Does our product comply with regulations?
- *Validation*: Show that the implementation of the system meets user's expectations
  - Does our product meet the needs of the customer?

Analysis Challenges

- With CBSE, tried and tested components are composed to construct large and complex systems
- *Principle of Compositionality*
  - Properties of a composed system can be derived from the properties of its components and connections
- *Challenge*
  - Ensure the correct and timely operation of a system consisting of a composed set of interacting components
- *Timing Analysis Requirements*
  - Verify the timing properties of each component
  - Analyze the temporal behavior of a component assembly

Related Research

General Methodologies

- *Testing and Evaluation*
  - Black box and White box Testing
  - Manual and Automatic test input generation
  - Simulation-based Testing
- *Static Code Analysis*
  - Sophisticated methods to analyze executable code
  - Language restrictions and skillset requirements
- *Formal Analysis Methods* - Check correctness with mathematical rigor
  - *Theorem Proving*
    - Requires human intervention and expertise
  - *Model Checking*
    - Requires precise specification of properties to be examined
    - Less suitable for data intensive applications

State Space Analysis

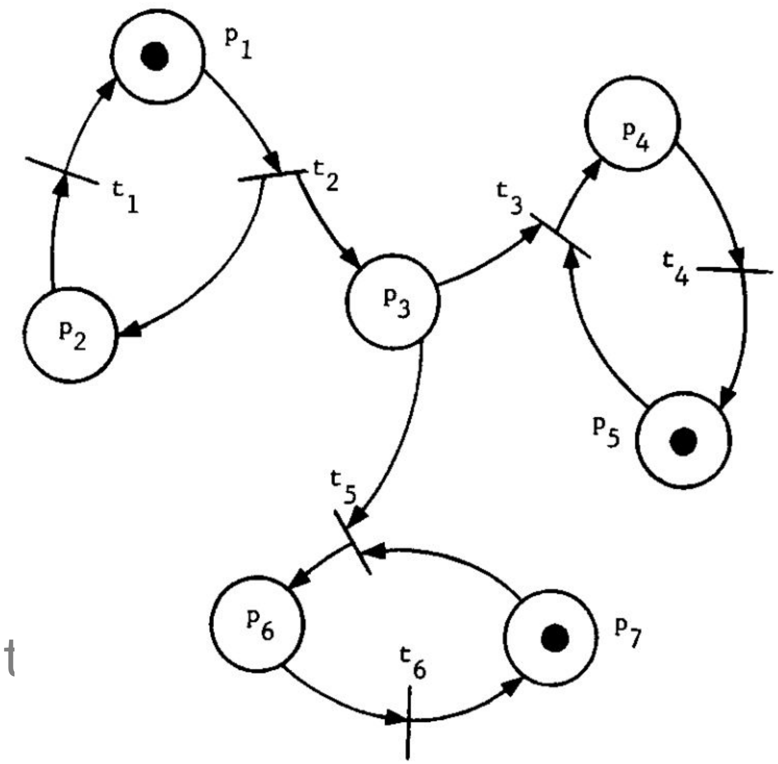
- Suitable for automatic analysis and verification of the behavior of the system
- We construct a structure that consists of all states that a system can reach, and all transitions that system can make between these states - *state space*
- State Space Explosion
  - Size of the state space tends to grow exponentially in the number of its processes and variables
  - Methods have been developed to reduce the number of required states for answering analysis questions
- The user may ask various queries on the state space and obtain various statistics on the state space

Some Timing Analysis Tools and Frameworks

- Cheddar Real-Time Scheduling Framework *[Singhoff et al., 2004]*
  - Ada framework based on real-time scheduling theory
  - Scheduling simulation and feasibility tests
    - Compute schedules and look for task constraint properties in the computed schedule
    - Classic real-time schedulers - RMS, EDF etc.
- UPPAAL *[Bengtsson et al., 1996]*
  - RT systems modeled as a network of Timed Automata
    - Finite state machines extended with clock variables
    - Clocks are real-valued and progress synchronously
  - Can formulate schedulability analysis problems that UPPAAL can check with its model checker

Petri Net-based Analysis

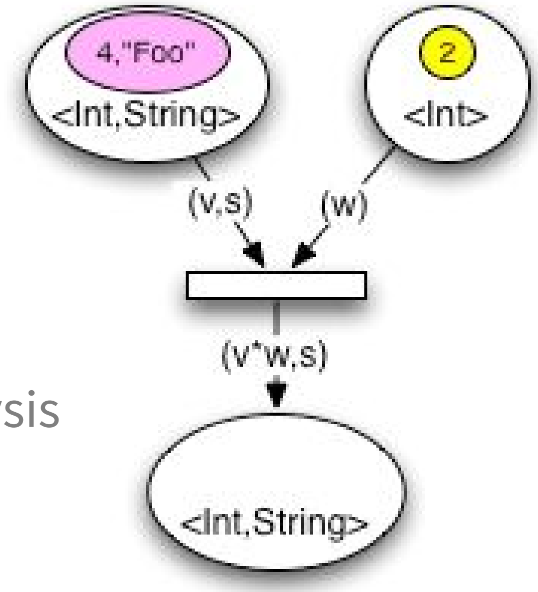
- Formal model of information flow
- Places
  - Places contain tokens
  - Input Places and Output Places
- Transitions
  - Transitions represent events
  - Firing rules - input places with tokens
- Petri net Execution - Token Movement
- Modeling Dynamic System Behaviors
  - Concurrency, Synchronization and Resource Sharing



J. L. Peterson. Petri nets. ACM Computing Surveys (CSUR), 9(3):223–252, 1977.

High-level Petri Nets

- Timed Petri Nets
  - Occurrence times associated with transitions
  - Tokens are removed from input places at the beginning of the occurrence period and deposited to output places at the end of this period
- Colored Petri Nets
  - Tokens can be complex typed data structures
  - Richer constraints on transitions
  - Compact hierarchical description
  - CPN Tools for simulation and state space analysis *[Ratzer et al., 2003]*



http://scienceblogs.com/goodmath/2007/10/10/colored-petri-nets/

Analyzing AADL Models with Petri nets

- *[Renault et al., ISORC 2009]* Translate AADL models to Petri nets
    - subnet generated for each AADL *thread* - Nets become intractable for large applications - does not scale well for large process sets
    - Tightly bound to AADL modeling concepts
- *[Renault et al., RSP 2009]* Timed Petri net to model thread lifecycle
    - State of AADL threads - modeled using places
    - Lifecycle over the states - handled by transitions
    - Observer places to monitor Petri net execution
        - Detect property violations and operation completion
    - Only considers periodic threads with fixed execution time
    - No preemptive scheduling

Modeling and Analysis Suite

- *[Gonzalez et al., 2001]* Timing analysis integration for fixed priority scheduled systems - Single processor and distributed systems
- Event-driven model with complex dependence patterns
- No model checking or formal verification
- MAST events are periodic, sporadic or bursty
  - Does not model the nature of the event itself e.g. blocking behavior
- Provision to model schedulable entities and processing resources
  - No explicit provision to model hierarchical schedulers - primitive support now in MAST 2

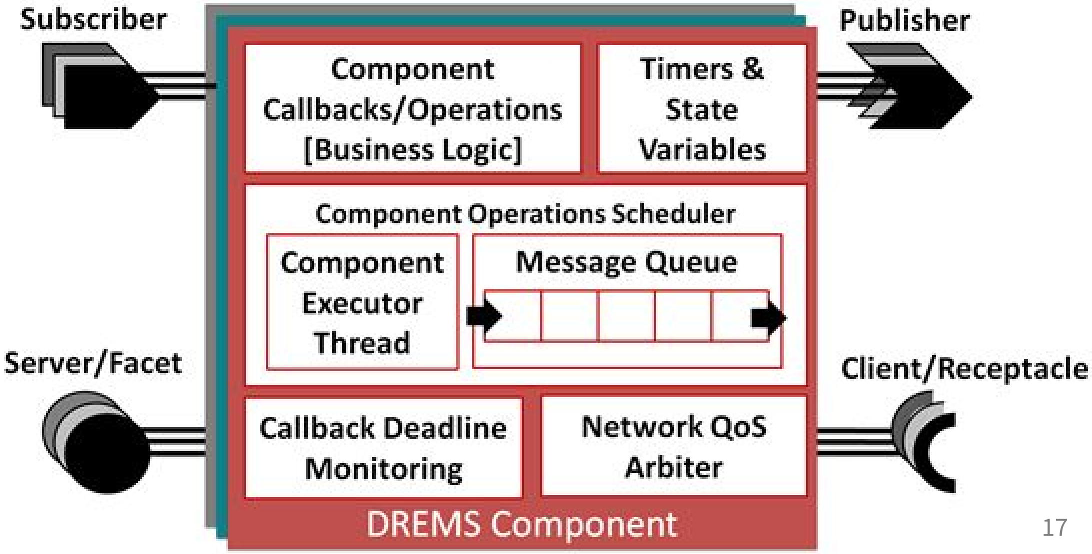
Design Model: DREMS

[Levendovszky et al., 2014]

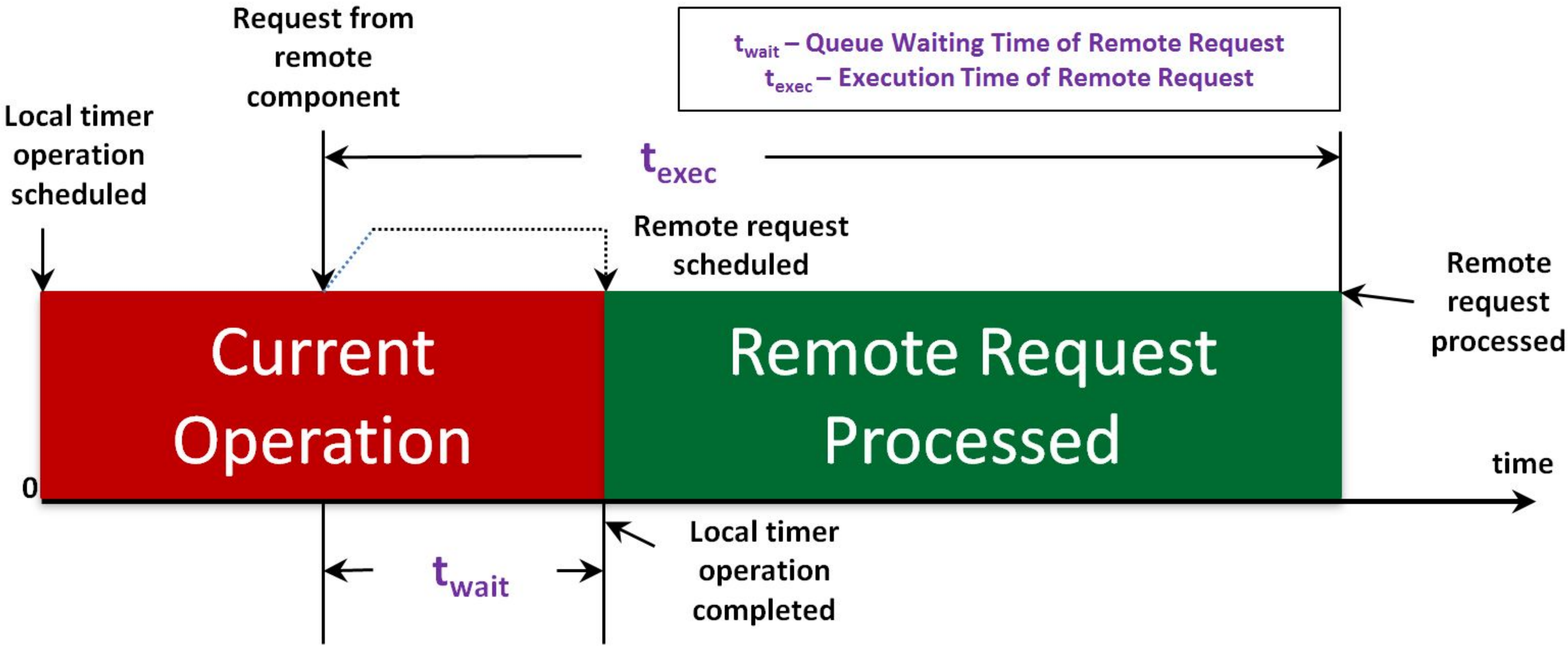
Distributed Real-Time Managed Systems

- Design, Implementation, and Operation of DRE systems
- Model-driven development
- Component-based Software Engineering Principles
    - Varied and generic interaction patterns
    - Precise component execution semantics
- Robust runtime platform
- Managing mixed-criticality real-time applications
- Enforces strict timing requirements

http://www.wired.com/images_blogs/dangerroom/2013/05/System-F6-Satellite_formation_landscape.jpg



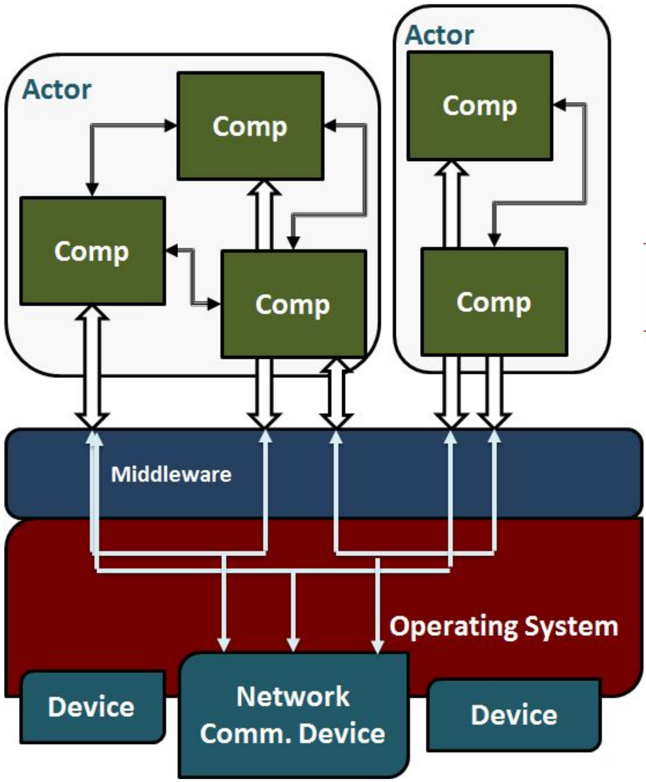
Component Model - Execution Semantics

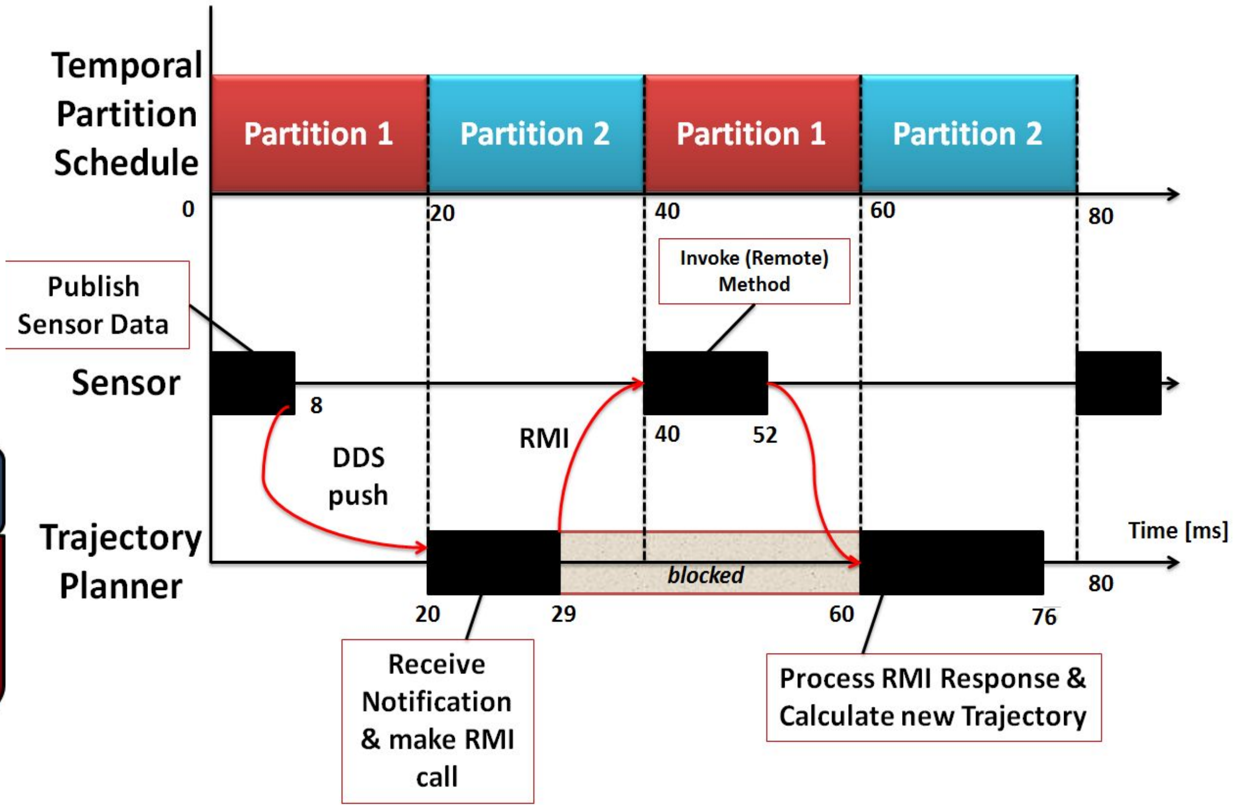


- A single component executor thread executes operation requests scheduled in the message queue
- Operation scheduling is non-preemptive i.e. the next request is processed only when the current operation is completed

DREMS OS - Temporal Partition Scheduler

- ARINC-653 style temporal and spatial partitioning
- DREMS components are grouped into uniquely identifiable processes - *actors*
- Each actor is assigned to a temporal partition
    - Periodic fixed intervals of the CPU's time
- Temporal isolation is achieved between threads in different partitions





Problem Statement

- We have DREMS-style component-based applications distributed and deployed on a cluster of embedded devices
- Analysis Assumptions
  - Design Model: Component Definitions, assembly, temporal partitioning, deployment model etc.
  - Each component operation executes a sequence of computational steps (of finite duration)
  - Known worst-case estimated time taken by step
- Temporal Behavior of the composed system must meet end-to-end timing requirements
  - Deadlines, Trigger-to-Response times etc.

Research Plan:
Design-time Timing Analysis of Component-based DRE Systems

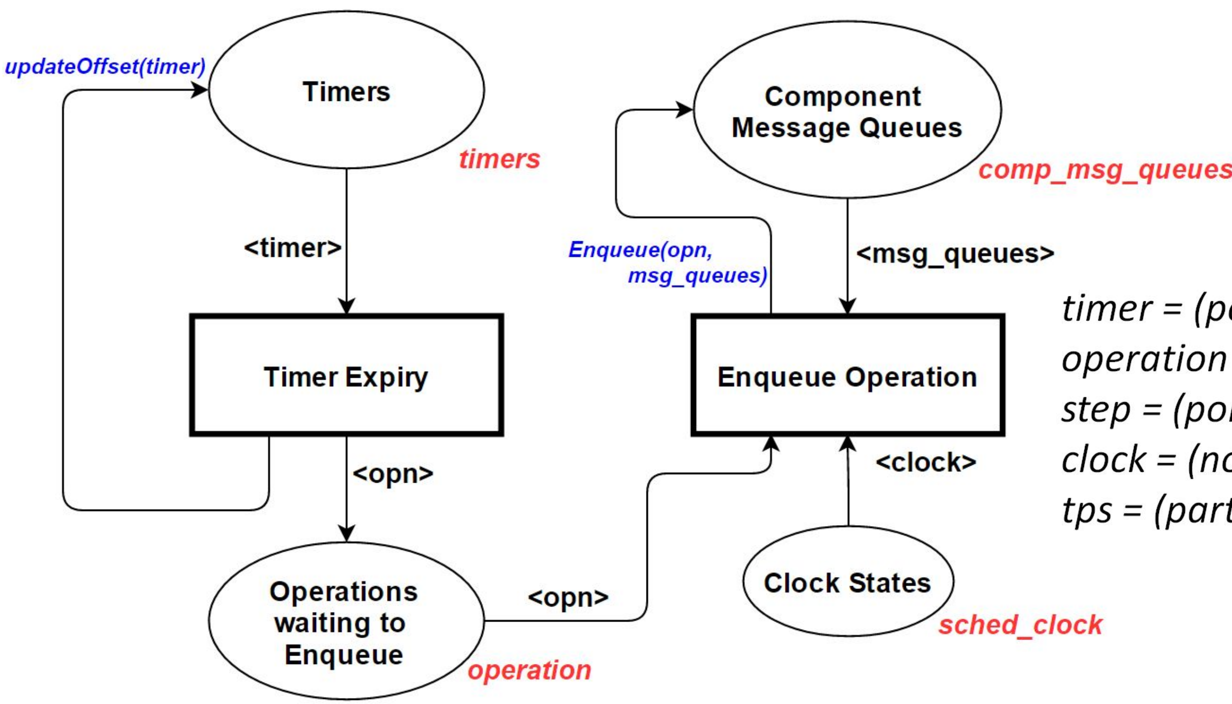
Preliminary Results and Proposed Work

Colored Petri Net-based Timing Analysis

- Challenge
  - How to design and construct an extensible, scalable timing analysis model for component-based DRE systems?
- Approach
  - Design and implement a CPN-based timing analysis model
    - Capture structure and behavior of component assembly
    - Capture business logic of component operations (steps)
    - Capture timing properties of steps in each operations
- Preliminary Results
  - Developed an extensible CPN analysis model
  - Performed bounded *state space analysis* on a variety of DREMS scenarios
    - Detect timing violations e.g. deadline miss, deadlocks etc.
    - Estimate worst-case trigger to response times
    - Estimate processor utilization
    - Estimate partial thread execution orderings
  - Implemented a DREMS *model interpreter* that generates our CPN analysis model from the design model

Colored Petri Net-based Timing Analysis

- Places manage application state
- Transitions represent events
- When transitions fire:
  - Tokens in input places are consumed/modified
  - Output places receive tokens - postconditions of the triggered event
- Output arc inscriptions are able to operate on the consumed tokens



timer = (period, offset, operation)
operation = (opn_name, priority, deadline, steps)
step = (port_name, unblk_list, duration)
clock = (node_name, clock_value, tps)
tps = (partition_name, period, duration, offset)

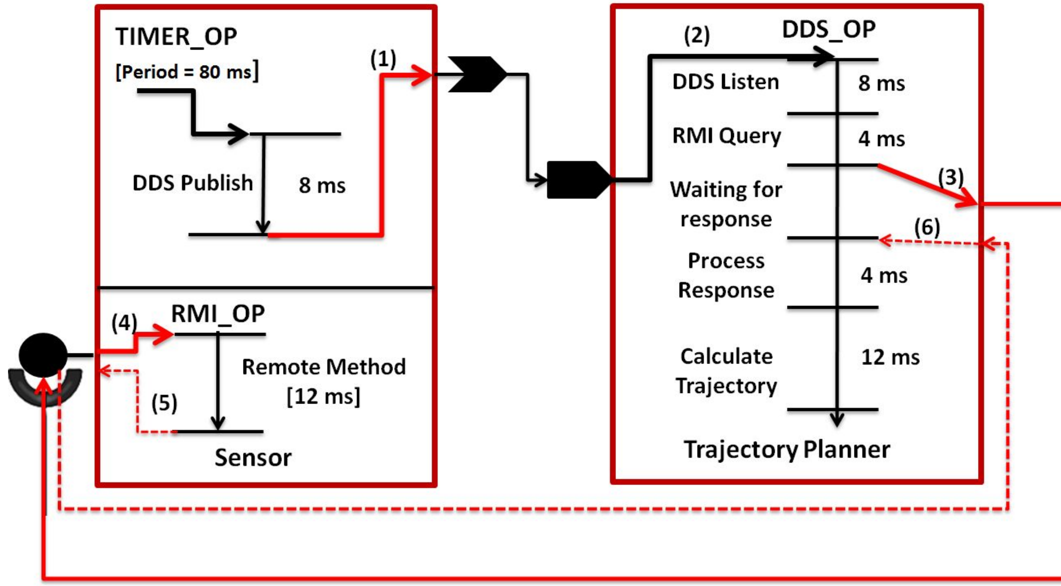
Modeling Component Operations

- Challenge
  - Operation Business logic: Piece of code executed when a component operation is scheduled
  - This code directly affects the behavior of components
  - It is not sufficient to annotate models of component operations with a single WCET - Need a finer grain model of temporal behavior
- Approach
  - Component Operations are modeled and represented as a sequence of timed steps - each step is annotated with a WCET
- Preliminary Results
  - Designed a modeling grammar to represent the business logic of component operations
  - Relevant ports and timers in every component are annotated with operation business logic models
  - When the design model is parsed, these BL models are translated into *CPN tokens* and generated into distinct places in our analysis model

Modeling Component Operations

```
// Trajectory Planner - Subscriber Operation
do DDS_OP {
   LOCAL 12;
   RMI Fetch_Sensor_Data.server_operation;
   LOCAL 16;
}
```

ANTLR-based business logic model is translated into CPN tokens



(* Generated CPN Token for Trajectory Planner Subscriber Operation *)

```
1`[{opn={opname="DDS_OP", op_node="Sat1", op_comp="Trajectory_Planner",
        op_pn="Part2", op_prio=60, op_dl=50, op_st=0, op_dv=false,
        op_steps=[{port_type="Local", port_name="Local", unblk_list=[], induced=false, call_st=0,
                        call_et=0, call_exec_t=0, call_dur=12},
                  {port_type="RMI_Receptacle", port_name="Fetch_Sensor_Data", unblk_list=[],
                        induced=false, call_st=0, call_et=0, call_exec_t=0, call_dur=0},
                  {port_type="Local", port_name="Local", unblk_list=[], induced=false,
                        call_st=0, call_et=0, call_exec_t=0, call_dur=16}]}}]
```

Modeling and Analysis Improvements

- Challenge - Alleviate state space explosion - Caused by:
  - Our model of time
  - Our model of Distributed Deployment
- Approach
  - Modify our timing analysis execution by introducing dynamic time progression (time jumps)
  - Remodel distributed deployments - use ordered lists instead of unordered sets
- Preliminary Results
  - CPN execution progresses at a much faster rate
    - Reduces number of states recorded in the state space
  - Reduces the number of transition firings with regards to distributed deployments
      - from C! to 1 for C computing nodes
      - Can support a larger number of computing nodes with improved scalability

Investigating Advanced State Space Analysis

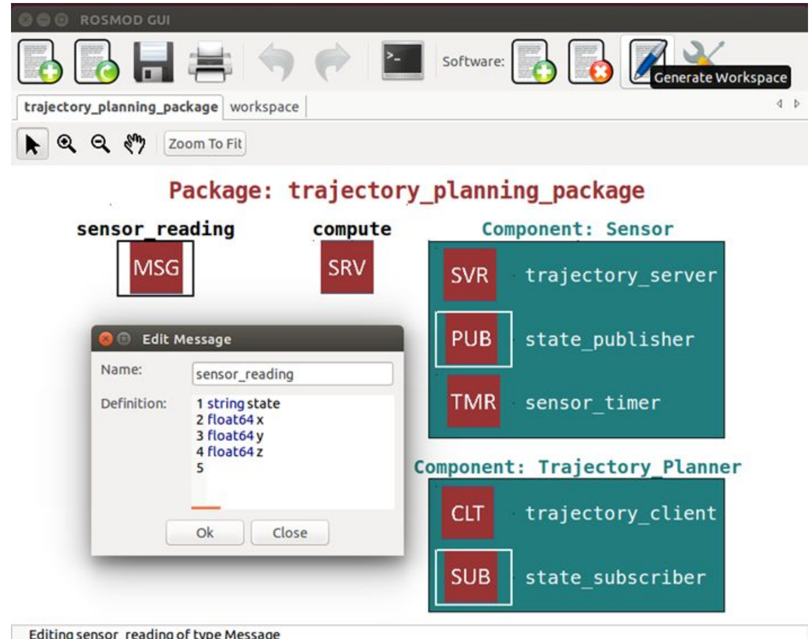
- Challenge
  - How to improve the efficiency and speed of state space generation and leverage advanced analysis and memory management techniques
- Approach
  - ASAP CPN Analysis Tool - Integrate our CPN analysis model with ASAP platform and apply advanced analysis methods
- Preliminary Results
  - Combat State Space Explosion - Sweep-line method
  - Safety Properties, Deadlock, Liveness, Boundedness, …
  - On-the-fly efficient verification of system constraints
  - Time taken to generate state space is greatly reduced by applying ASAP memory optimization, hashing methods, and on-the-fly checking

State Space Exploration Time (seconds)

Model	States	CPN Tools	ASAP	Speed-up
50 component DREMS sample	124K	846	211	4.01
100 component DREMS sample	485K	2,160	576	3.75

Experimental Validation

- Challenge
  - How to validate theoretical results obtained from our CPN analysis methodology?
- Approach
  - RCPS Testbed for Validation
  - Execute components individually with RT priority
  - Obtain worst-case *pure execution time* of operations
    - Low-overhead logging to hook into middleware
  - Construct business logic models and generate CPN
  - Analyze and Verify
  - Compare CPN results with real-system execution



Analysis of Long-running Operations (LRO)

- Challenge
  - How to integrate and support AI-style long-running operations with DREMS?
  - Our DREMS component model implements a non-preemptive operations scheduler - LRO can disrupt the execution of highly critical operations
  - How to model the execution semantics of LRO?
- Approach
  - We assume known fixed-interval LRO cancellation *checkpoints*
  - We also assume that the LRO e.g. path-planning search algorithm reaches a safe state at each checkpoint before cancelling LRO
  - This way, a higher-priority operation waiting in the component message queue would cause LRO cancellation before its own execution
  - This requires the introduction of new concepts to our operation steps e.g. checkpointing steps

Analysis of Cyber-Physical Systems (CPS)

- Challenge
  - How to support the analysis of component-based applications interacting with a physical environment e.g. UAV swarms?
    - Physics Simulation
  - How to model component interactions with simulation interface?
  - How to validate our theoretical analysis results?
- Approach
  - We will model and analyze a variety of interaction patterns between ‘I/O components’ and CPS sensors/actuators
    - Sensors are modeled as periodic data pumps
    - Actuator interfaces are modeled as non-blocking fixed-time operations
  - Analysis results will be evaluated against prototype CPS deployments in our RCPS testbed

Summary and Schedule

- We have proposed an extensible, scalable CPN-based timing analysis methodology for component-based DRE systems
  - Precise model of component execution semantics
  - Tool support for advanced analysis and verification
  - Interesting potential extensions and scope
- We have presented some remaining work in this topic and outlined our plans for completion

TASKS	PROPOSED TIMELINE
Thorough Experimental Validation	**10/2015 - 11/2015**
Analysis of Long-Running Operations	**10/2015 - 12/2015**
Modeling and Analysis of CPS deployments	**11/2015 - 02/2016**
Dissertation Writing	**10/2015 - 03/2016**

Publications

- **P. S. Kumar**, A. Dubey, and G. Karsai. Colored petri net-based modeling and formal analysis of component-based applications. In 11th Workshop on Model Driven Engineering, Verification and Validation MoDeVVa 2014, page 79, 2014
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- AWAITING REVIEW:
  - W. Emfinger, **P. Kumar**, A. Dubey, G. Karsai. Towards Assurances in Self-Adaptive, Dynamic, Distributed Real-time Embedded Systems. In Software Engineering for Self-Adaptive Systems: Assurances, 2015.

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- ***[Renault et al., ISORC 2009]*** From aadl architectural models to petri nets: Checking model viability. In Object/Component/Service-Oriented Real-Time Distributed Computing, 2009. ISORC ’09. IEEE International Symposium on, pages 313–320, March 2009.
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