Rapid Simulation Evaluation from Scenario Specifications for Command and Control Systems

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Abstract

This paper presents a technique to simulate and evaluate a system once the system scenarios are available without any simulation programming. This is different from traditional simulation where simulation code and the system specification are separately developed by human engineer and potential gaps between them might be introduced. Another significant advantage of this approach is that the scenarios specified do not need to be complete or consistent. Inconsistency and incompleteness, as well as safety, performance, and behavior problems, can be detected by the simulation via various dynamic analyses. This technique is a part of Scenario-Driven System Engineering (SDSE) that is being developed for Command-and-Control systems.

Keywords: Scenarios, ACDATE, Simulation, Scenario-Driven System Engineering, Completeness and Consistency Analysis, Safety Analysis.

1. Introduction

Future Command and Control (C2) systems need to operate within an integrated grid-based network-centric environment that allows rapid decision development and evaluation to meet the challenges of modern agile warfighting. This paper presents a Scenario-Driven System Engineering (SDSE) approach to develop, evaluate, and test C2 systems. One key component is that once system scenarios are specified, the system can be simulated without any programming and thus saves significant effort and time.

SDSE is compatible with the modern Service-Oriented Architecture (SOA) approach to develop trustworthy systems. DoD is embracing SOA in numerous projects such as the Defense Information Systems Agency GIG Enterprise Services (GES) with its component core services. The SDSE can be used to specify and analyze system behaviors in an SOA.

The core of SDSE is scenario specification and analyses. A scenario is specified using the ACDATE model:

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- Actors – An actor is either an external user, system or device, or an internal system, device, component or object;
- Conditions – A condition is a predicate used to trigger an action;
- Data – Attributes of actor, and presenting the semantic of condition, event and action
- Actions – Specified by the trigger event, guard condition, the way to change the status of actors, and sent event(s) to some actors
- Timing – A semantic statement about the relative or absolute value of time or duration
- Events – External/internal significant occurrences that may trigger action(s)

Once system behaviors are specified, various static and dynamic (via simulation) analyses can be performed on the model:

- Completeness and consistency analysis: The model can be used to identify incompleteness at compile time as well as during simulation.
- Performance evaluation: The model can be simulated to determine system performance including throughput and delay.
- Safety analysis: The model can be used to generate the event-tree model and effect-cause diagram commonly used in safety analysis;
- Behavior analysis: The model can be used to generate the state model of the system and various behavior analyses such as reachability analysis, which can be performed on the state model. Formal verification techniques such as temporal logic can be used to analyze the state model.

The SDSE is to be integrated and supported by an automated tool E2E that is currently being used in several experimental projects by US Navy.

2. ACDATE Model – An Example

This section presents an example of ACDATE modeling technique which usually contains two steps:

- Decompose the requirements into ACDATE model elements; and
- Develop system scenarios using the ACDATE model elements.

Taking a battlefield as an example, each warfighting vehicle can be treated as an *Actor*. Each actor (warfighting vehicle) may have its own *Data* such as "available fuel", and its own *Conditions* such as if there is enough fuel to continue moving for 20 miles. The given condition example is constructed on the Data 'available fuel'. An *Event* "not enough fuel" could be fired when there is not enough fuel support subsequent operations. An *Action* would be "to refill the vehicle".

A system scenario would then be specified using the ACDATE model elements: if the event "not enough fuel" occurs, the actor "warfighting vehicle" shall perform action "to refill" within the time specified by the *Timing Attribute* "within 15 minutes".

3. Scenario-Based Rapid Simulation

The key feature of the rapid simulation is automatic simulation code generation once the system scenarios are available. The simulation code has an embedded scheduler, an event queue,

a monitor, and a policy checker to track and verify the alternative system behaviors under different environments, as well as the impact from and to the environment. The simulation is discrete event simulation [1][3].

3.1 Simulation Engine Architecture

The simulation engine has two main parts: system simulator and the environment simulator. The environment simulator simulates the behavior of the environment. It can also simulate the impact of the system to its environment. Separating the system simulation and environment simulation has several significant advantages: It offers the opportunity to observe the behavior of the *system under testing* (SUT) under different loads by varying the environment simulator. Specifically, robustness, reliability and scalability of the system can be determined by generating various inputs to drive the system, e.g., generating an incorrect input can evaluate the system's robustness, and generating the input according to the operational profile will determine the system's reliability, and generating inputs of various sizes to determine the system scalability.

The simulation engine architecture is illustrated by **Figure 1**. The ACDATE model elements form an *entity pool*. The execution of each scenario, which is scheduled by the *scheduler*, will access the entity pool to read or update their internal status. Events may be emitted during the execution of a scenario, which may in turn invoke the execution of other scenarios. An *event queue* is maintained to process all the events emitted by scenarios or the environment. The scheduler will drive the *monitor* or the *policy checker* properly to track all the activities or do runtime policy verification respectively.

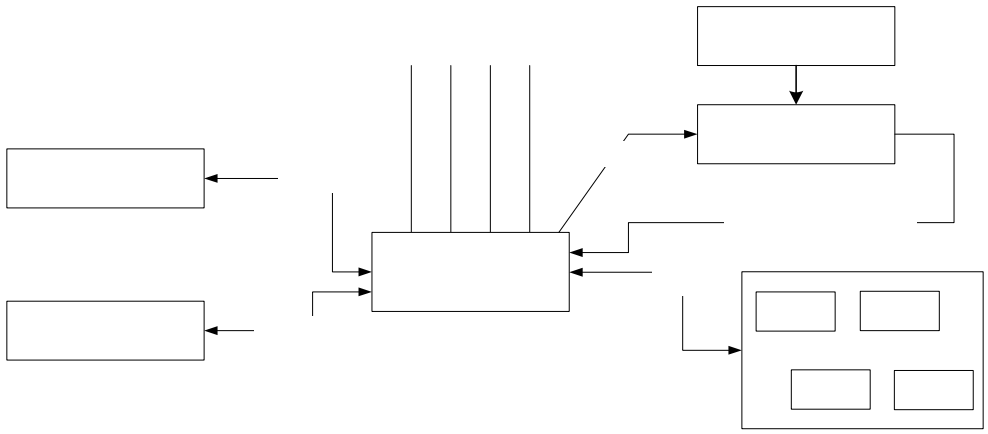

Figure 1: Scenario Based Simulation Architecture

The core of the scheduler is a virtual machine (VM) that enables fine-grained debugging capability. The execution of any scenario can be slow-played and the internal status of each entity can be set-up to any desired value to offer the opportunity to manipulate the simulation and observe rare occurrence or exceptional behaviors.

The monitor will track all the activities and the information will be used to generate the event-tree, the state diagram for each actor or the entire system. For any potential or real malfunction, the monitor or the policy checker will report warnings to indicate either there is a completeness and consistency breach or concurrency or security policy violation. The monitor will also record

the time elapsed that can be used to form the performance evaluation of each actor or the entire system.

The simulation works as follows. An event residing in the event queue, which might be emitted by the environment or the system, is picked up by the scheduler and processed. The event may trigger the execution of a scenario, which will be either concurrent with the execution of other scenarios, or occupy the VM before it finishes, due to the different scheduling policy. The execution course of the scenario may be determined by the internal status of some entities. The scheduler will read or update the corresponding internal status upon the request of the scenario. New events will be emitted on behalf of the scenario during execution, which will be appended to the end of the event queue. The new events might be communication among components inside the system or an outgoing event to the environment. Details of the execution, such as time information, action sequence, and event sequences will be recorded through the monitor, which is available to postmortem analyses. If a policy is registered into the scheduler, corresponding policy checking will be invoked by the policy checker at runtime.

3.2 Simulation Code Generation

The simulation code is generated based on the scenario specification, which includes the ACDATE definition and scenario description. Each ACDATE model element will be translated to an object with the attributes defined in the specification. Instrumentation code will be inserted to the objects to interface with the monitor and policy checker. Each scenario will be translated to a procedure that is basically a sequence of operations on the ACDATE objects or emitting events. Similarly, instrumentation code will be inserted to the procedure to interface with the scheduler, for scheduling the concurrent execution, and event queue for emitting new events. **Table 1** shows a sample simulation code that is automatically generated with instrumentation code that interfaces with the scheduler, event queue, monitor, or policy checker.

```
scenario_5 = function(co_routine_name, platform)  // a scenario
 coroutine.yield();                               // interface to scheduler
 ...
 event_4:AddDestination(1);                       // interface to monitor
 event_4:emit();                                  // interface to event queue
 ...
 data_3.value = 1000;                             // data_3:set() will be invoked and
                                                  // interface to monitor embedded there
 action_10:before_do(co_routine_name, platform);  // interface to policy checker embedded here
 action_10_dummy_func(co_routine_name, platform);
 action_10:after_do(co_routine_name, platform);
 timer[platform] = timer[platform] + unit;        // advance and record system time
 ...
```

Table 1 Sample Simulation Code

4. Simulation for Dynamic Analyses

Various dynamic analyses are enabled by simulation, e.g., completeness and consistency (C&C) analysis, performance analysis, safety analysis, and behavior analysis.

The dynamic C&C analysis complement static C&C checking [6] because some incompleteness or inconsistency can only be observed during runtime when concurrency comes

into play. The simulation will record all the potential inconsistency and incompleteness such as the simulation encounters a situation where there is no related instruction in the specification; or an action did not change the state of any actors, which may imply that the system is at an abnormal state that responses to no input. In a recent experiment with a C2 system that has around 1000 entities and 120 scenarios, it takes 3 minutes to generate and execute the simulation and it detected around 200 bugs related to incompleteness or inconsistency.

During the simulation, system time will be recorded for each action when it starts or ends, event when it is emitted or handled, and data when the value changes. The recorded time information can be used for performance analysis such as the throughput and average delay of the system.

Event sequence can be useful for safety analysis. **Figure 2** shows a sample event sequence tree which is automatically generated by simulation. The effect-cause diagram [7] can be also automatically generated by examining all the event trees related to a system to link from an effect to its possible causes. Effect-cause diagram is similar to fault tree [5] except that the elements on the diagram are analytic entries. By combining event sequence tree and effect-cause diagram, one can pinpoint which system components that failed during failure analysis.

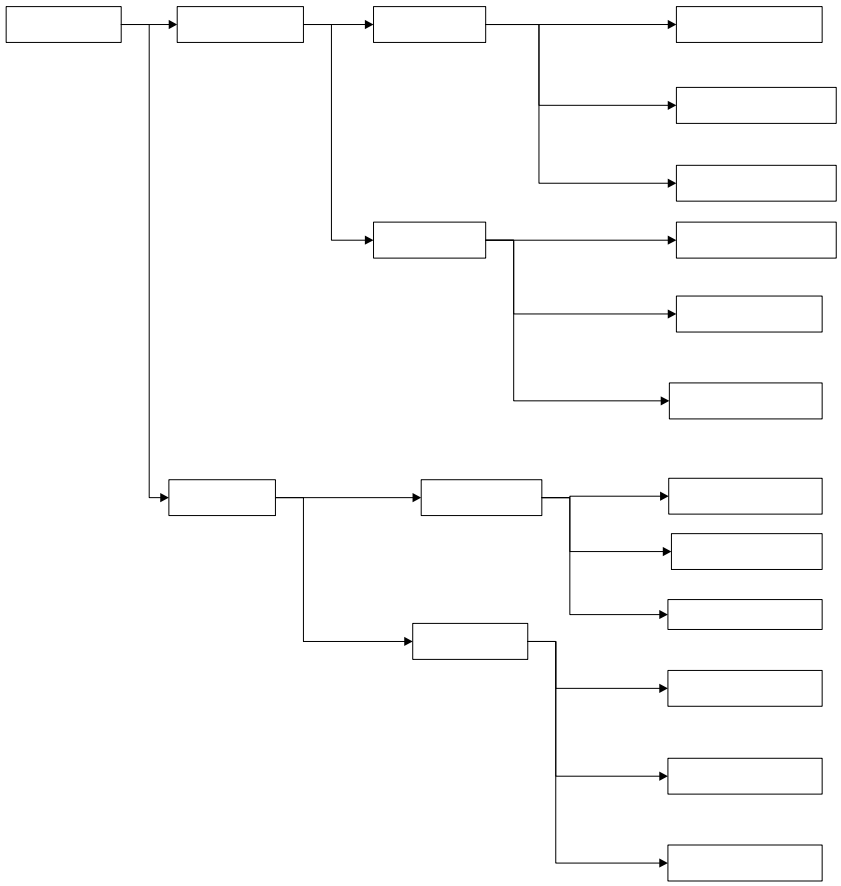

Figure 2 Sample Event Sequence Tree

Behavior analysis, such as reachability [8] analysis, is usually performed on state model. There is a natural mapping from the state model generated from the simulation (SMM) [7] to UML's Statechart [2], which can then be fed into various UML tools for further analyses. It is also possible to perform Linear Temporal Logic (LTL) analysis and model checking using SPIN [7] on the state model to detect deadlock or other malfunctions.

5. Conclusion

This paper proposes a systematic process to perform variety kinds of dynamic analyses based on scenario specification. Once system scenarios are specified, the simulation code can be automatically generated, and the system can be simulated without any additional programming. The simulation can be used to perform various dynamic analyses including C&C checking, safety analysis, and performance analysis. The SDSE is being integrated into an automated tool E2E.

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Rapid Simulation Evaluation from Scenario Specifications for Command and Control Systems

Ray Paul

DoD OSD NII

Real-Time Distributed Network-Centric Warfare

- System modeling and simulation from the system requirement important for network-centric warfare
- System modeling and simulation are usually expensive for real-time distributed network-centric warfare
- Many specification and simulation packages are available such as SDL that can model and simulate the target system from requirements. But they are often design-oriented.
- Our scenario-driven system engineering approach provides a way to perform system modeling and simulation rapidly based on system requirements.

Comparisons Between SDL and Scenario ACDATE Model

Comparison		ACDATE	SDL/TTCN
Equivalence	Essence	High-level system description	
	Approach	Requirement engineering	
Difference	Fundamental Technique	Scenario oriented	Object oriented
	Intuitive Feature	More intuitive	Less intuitive
	Code Generation	Partial code	Complete code
	Components	Actor, Condition, Data, Action, Timing, Event	Structure, Communication, Behavior, Data, Inheritance
	Simulation	Non-real code based simulation	Real code based simulation
	Testing	Test cases generation	Test script generation
	UML Relation	Class diagram, Sequence diagram	UML compatible
	MDA Support	Unavailable	Available
	Goal	Ensure no errors in requirements	Generate real time applications
	V&V Support	Convenient to support V&V	Not focus on this

SDSE and Command & Control Systems

- Future Command and Control (C2) systems need to operate within an integrated grid-based network-centric environment (GIG) that allows rapid decision development and evaluation to meet the challenges of modern agile warfighting.
- A Scenario-Driven System Engineering (SDSE) approach is proposed to develop, evaluate, and test C2 systems
- Once system scenarios are specified, the system can be simulated without any programming and thus saves significant effort and time.

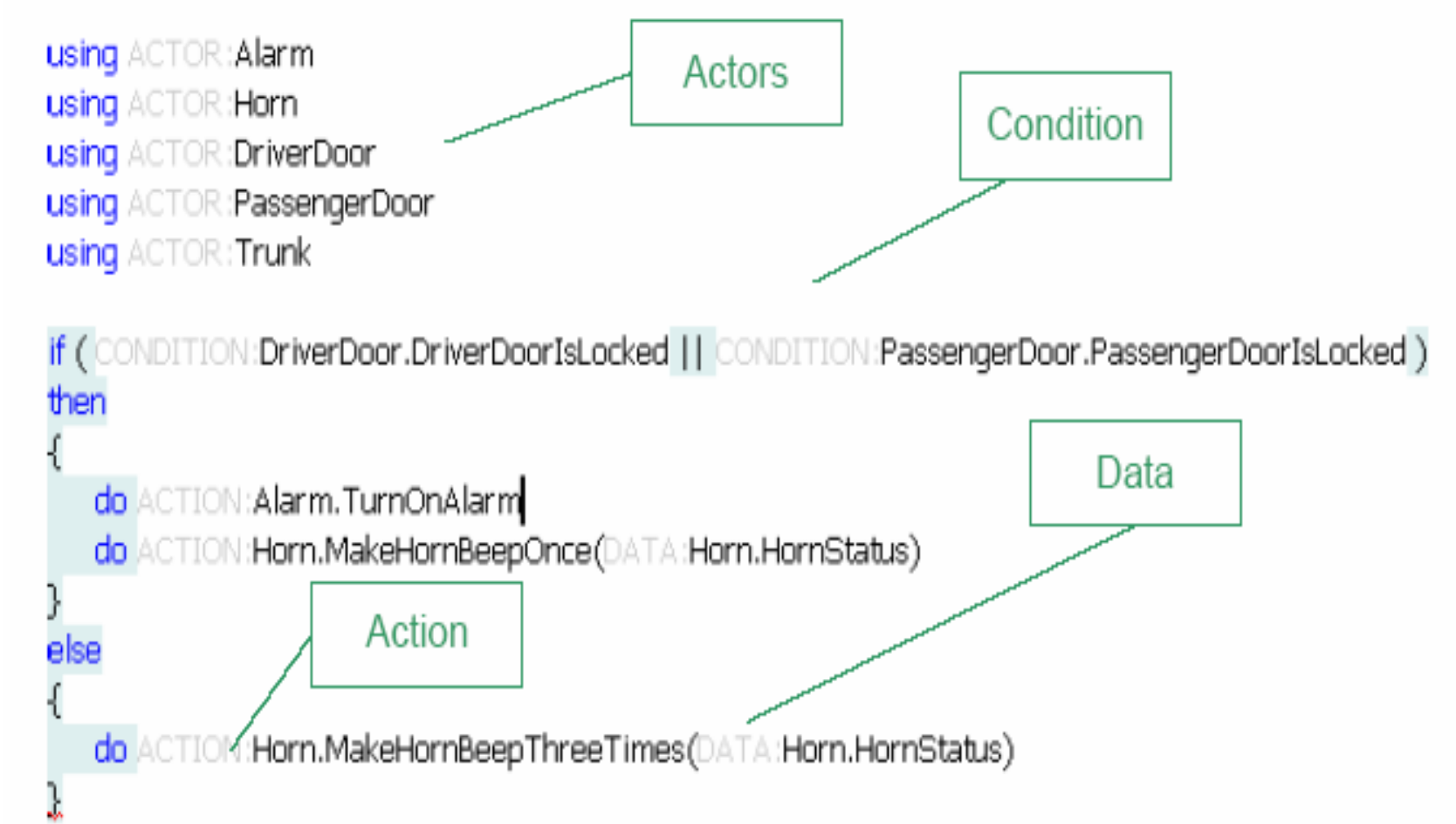
SDSE Features

- Compatible with the Service-Oriented Architecture (SOA) to develop trustworthy systems
- Can be used to specify and analyze system behaviors in an SOA.
- Core: scenario specification and analyses based on ACDATE model.

ACDATE Model

- Actors – An actor is either an external user, system or device, or an internal system, device, component or object;
- Conditions – A condition is a predicate used to trigger an action;
- Data – Attributes of actor, and presenting the semantic of condition, event and action
- Actions – Specified by the trigger event, guard condition, the way to change the status of actors, and sent event(s) to some actors
- Timing – A semantic statement about the relative or absolute value of time or duration
- Events – External/internal significant occurrences that may trigger action(s)

A Sample Scenario

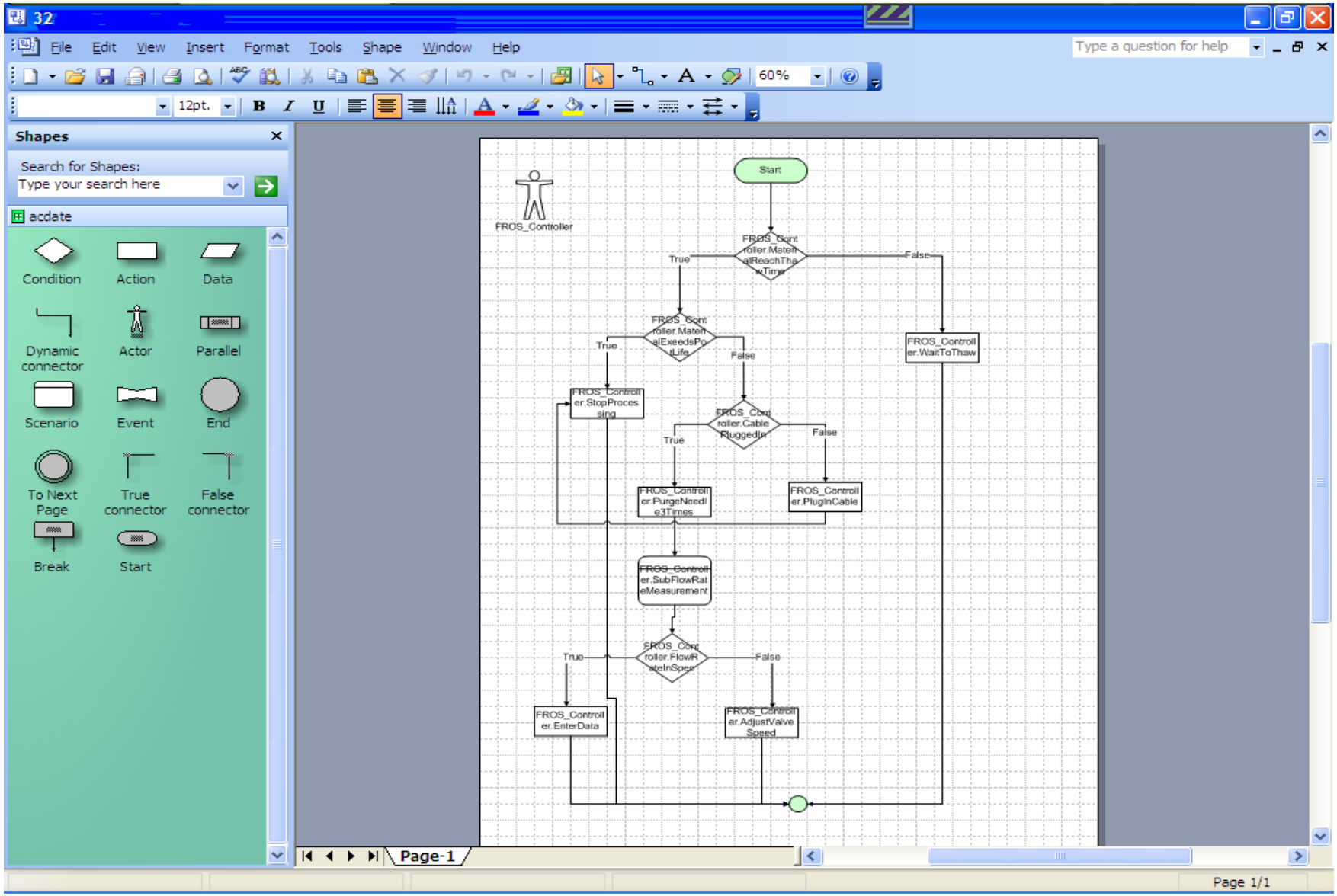


A scenario "*when driver door is locked and passenger door is locked, if remote controlled is pressed unlock, then the driver door is open*" can be specified using Scenario Specification Language as above

Analyses based on ACDATE/Scenario Model

- Based on the ACDATE/Scenario model, a variety of static and dynamic (via simulation) analyses can be performed:
  - Completeness and consistency analysis
  - Performance evaluation
  - Safety analysis
  - Behavior analysis
  - Policy specification and enforcement
- The SDSE is to be integrated and supported by an automated tool E2E that is currently being used in several experimental projects by US Navy

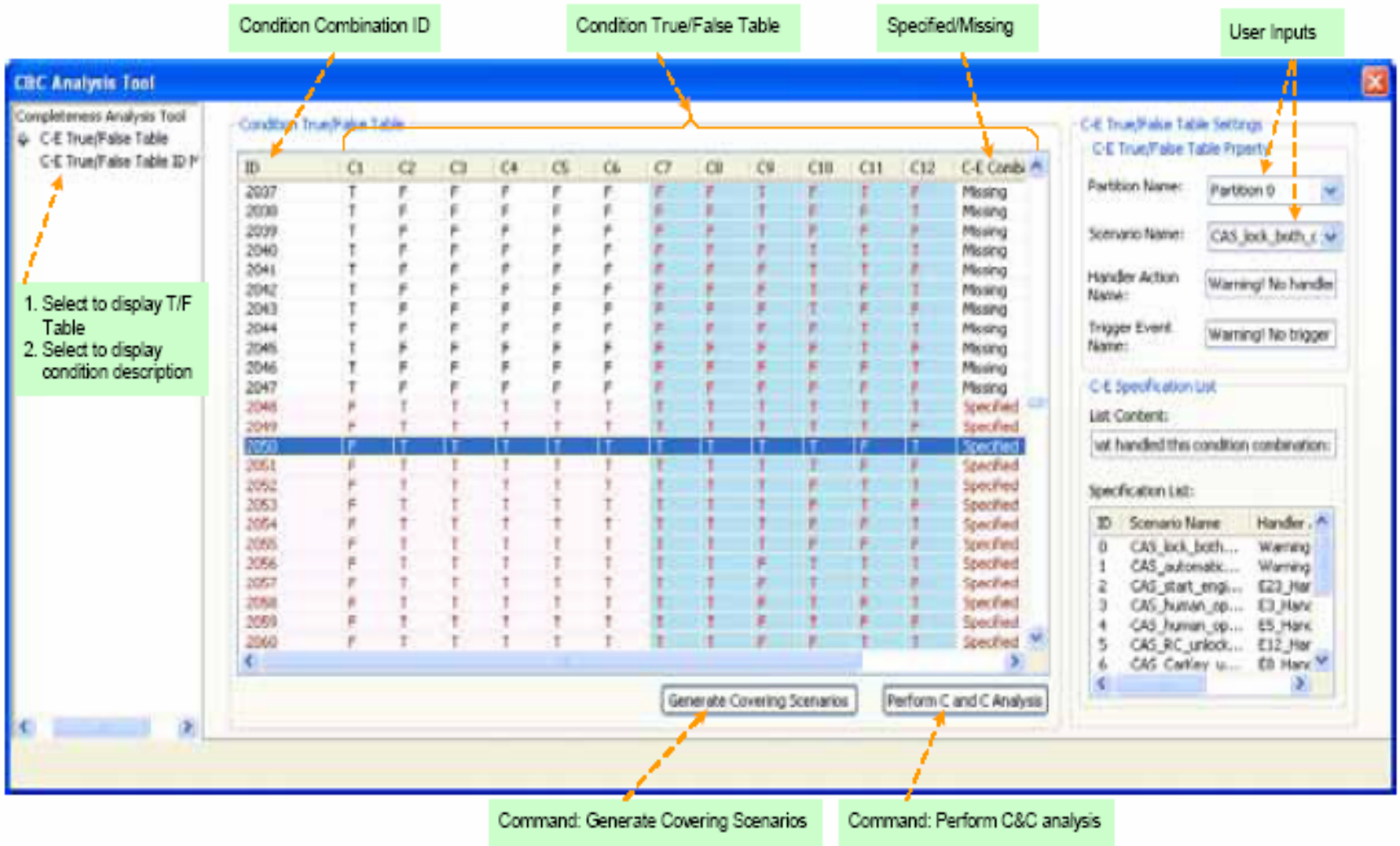
Scenario Tool Input Interface



Static C&C Analysis

- Once the system ACDATE/Scenario model is ready, one can easily using our automated tool to perform completeness and consistency analysis to see if there is any problem in system modeling
- Static C&C analysis can discover a large amount of incompleteness and inconsistency problems that are hard for engineers to detect

Static C&C Analysis Tool

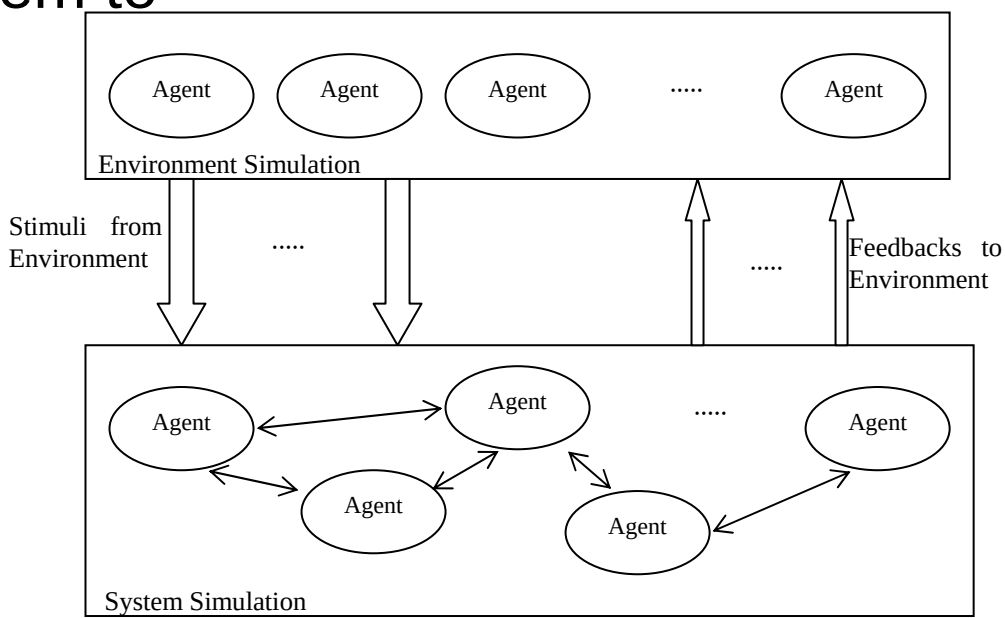


Experiment Results of Static C&C Results

Systems	Type	Experimental/ Industrial	# of Scenarios	# of Conds.	# of Missing C-E Combination	# of Covering Scenarios	Whole/ Partial System
Car Alarm Systems	Centralized application.	Experimental	13	12	547	40	Whole
Banking System	Distributed application		23	2	0	0	Whole
ICS	Distributed real-time application.	Industrial	140	15	396800	29	Whole
RCS	Distributed real-time application.		54	10	1792	4	Partial
LDRS	Distributed real-time application.		10	19	1966080	8	Whole
Communication Processor	Embedded distributed application		31	33	$1.29 * 10^{11}$	27	Partial

Scenario-Based Simulation Architecture

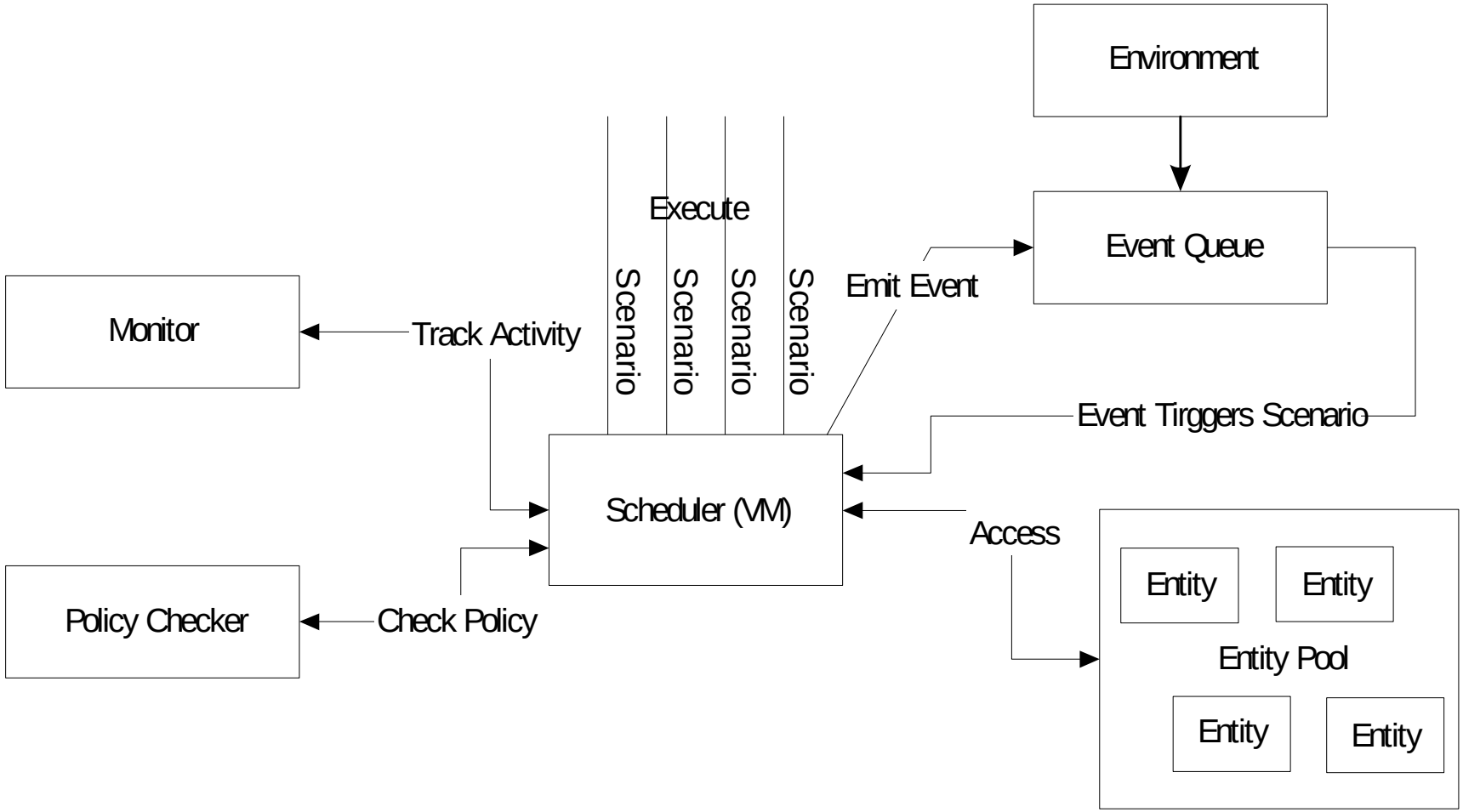
- Scenario-based simulation is divided into two major parts
  - Environment Simulator
    - The behavior of the environment
    - Impact of the system to its environment
  - System Simulator
    - Target system behavior



Rationale for Separating Environment And System Simulation

- It offers the opportunity to observe the behavior of the *system under testing* (SUT) under different loads by varying the environment simulator
- Robustness, reliability and scalability of the system can be determined by generating various inputs to drive the system
  - Generating an incorrect input can evaluate the system's robustness
  - Generating the input according to the operational profile will determine the system's reliability
  - Generating inputs of various sizes to determine the system scalability

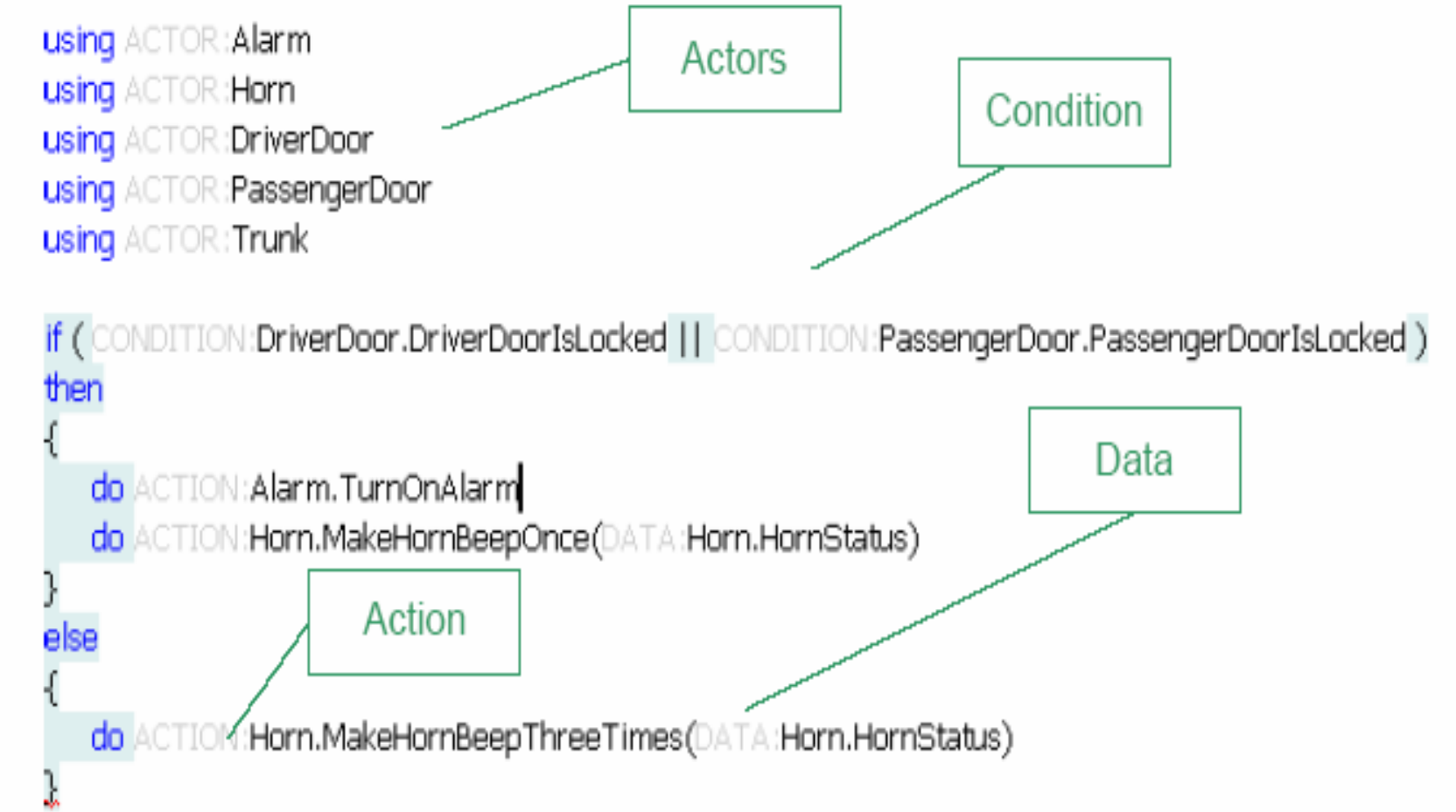
Simulation Engine Architecture



Simulation Code Generation

- The simulation code is generated based on the scenario specification, which includes the ACDATE definition and scenario description
- Each ACDATE model element will be translated to an object with the attributes defined in the specification
- Instrumentation code will be inserted to the objects to interface with the monitor and policy checker
- Each scenario will be translated to a procedure that is basically a sequence of operations on the ACDATE objects or emitting events.
- With these automated simulation code generation, previously Excel-spreadsheet based real-time distributed network-centric C2 systems can be simulated without any additional programming effort saving significant effort.

Simulation Code Generation – Sample Scenario

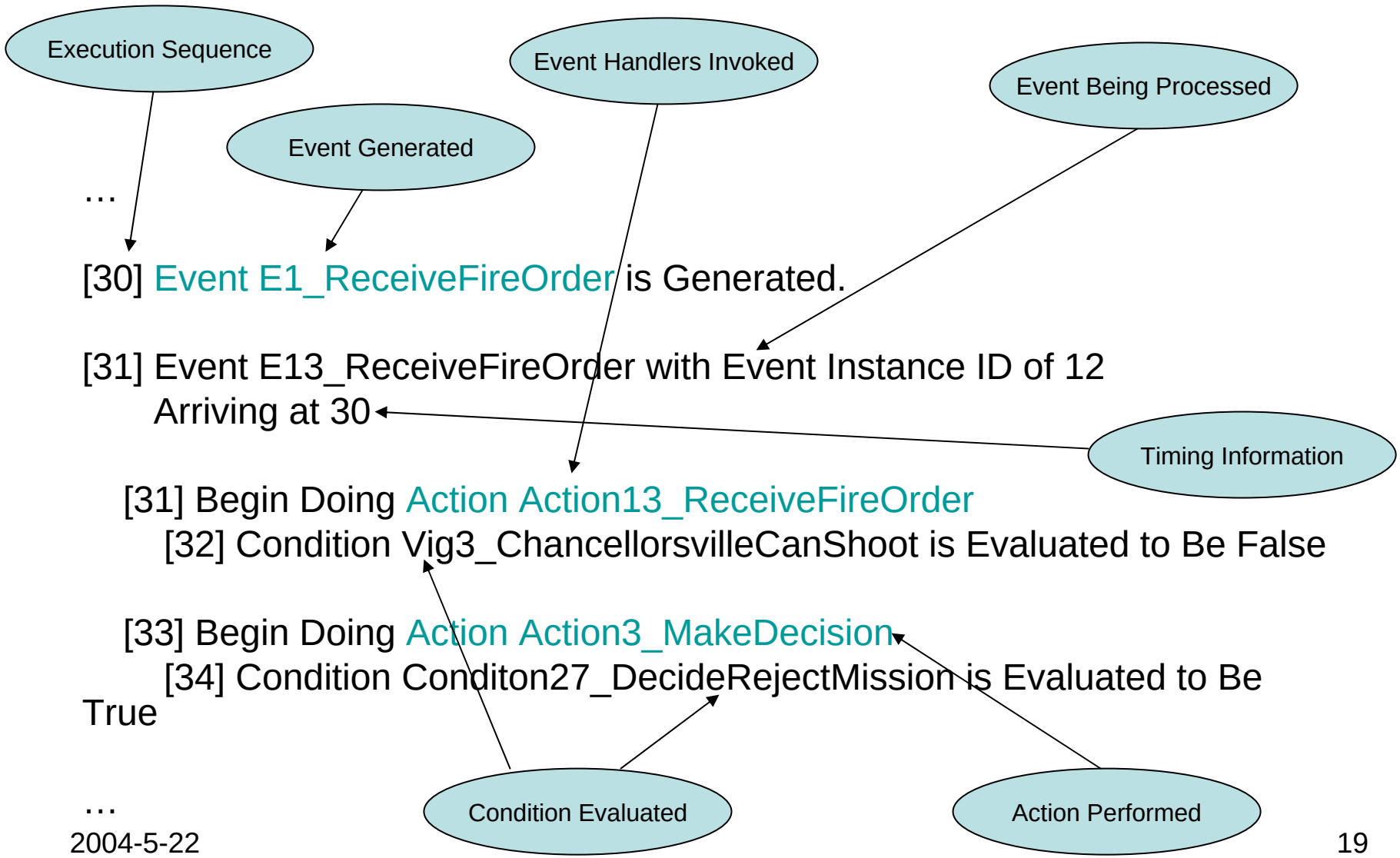


A scenario "*when driver door is locked and passenger door is locked, if remote control is pressed unlock, then the driver door is open*" can be specified using Scenario Specification Language as above

Simulation Code Generation Example – Generated Code

```
scenario_5 = function(co_routine_name, platform)  // a scenario
coroutine.yield();                                // interface to scheduler ...
if (condition_11.Eval() || condition_17.Eval() ) //condition evaluation
then
    action_10:before_do(co_routine_name, platform);  // interface to policy
                                                     //checker embedded here
    action_10_dummy_func(co_routine_name, platform);  // turn on alarm
     action_10:after_do(co_routine_name, platform);
     timer[platform] = timer[platform] + unit;       // advance and record system
                                                     // time ...
     action_17: action_10:before_do(co_routine_name, platform);
     action_17_dummy_func(co_routine_name, platform);   // beep once
     action_17:after_do(co_routine_name, platform);
     timer[platform] = timer[platform] + unit;
else
    action_20: action_10:before_do(co_routine_name, platform);
     action_20_dummy_func(co_routine_name, platform);   // beep three times
     action_20:after_do(co_routine_name, platform);
     timer[platform] = timer[platform] + unit;
end
```

Sample Simulation Result



Dynamic Analyses Performed Based on Simulation

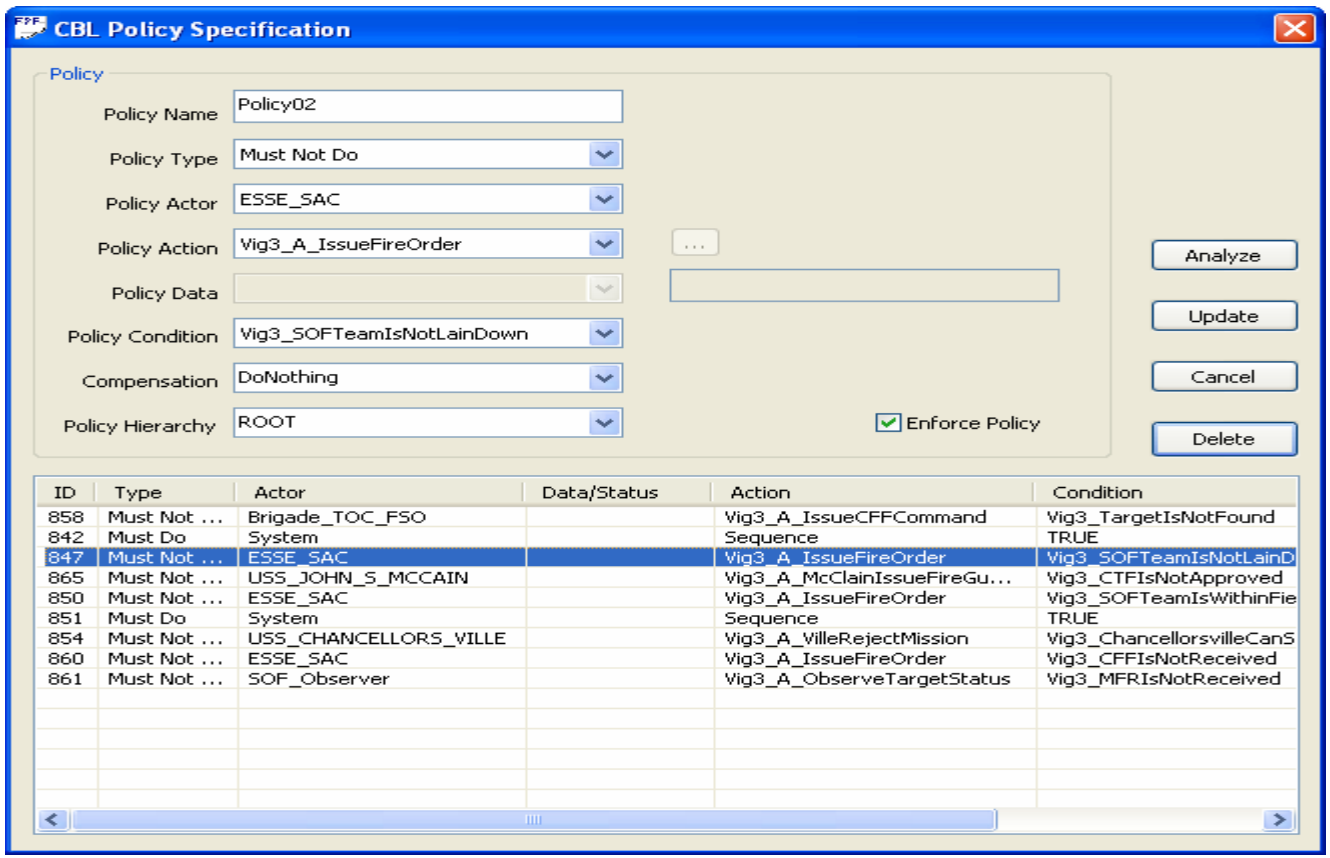
- Once simulation is performed, variety kinds of analyses can be carried out based on simulation, both runtime and off-line:
  - Policy specification and enforcement
  - Dynamic C&C analysis
  - Performance analysis
  - Safety analysis
  - Behavior analysis

Policy Specification and Enforcement

- One can specify kinds of policies in the system ACDATE/Scenario model using our automated scenario tool
- Once policies are specified, simulation can dynamically check and enforce the specified policies at runtime.
- Any policy violation will be reported and recorded in a log file.

Policy Specification

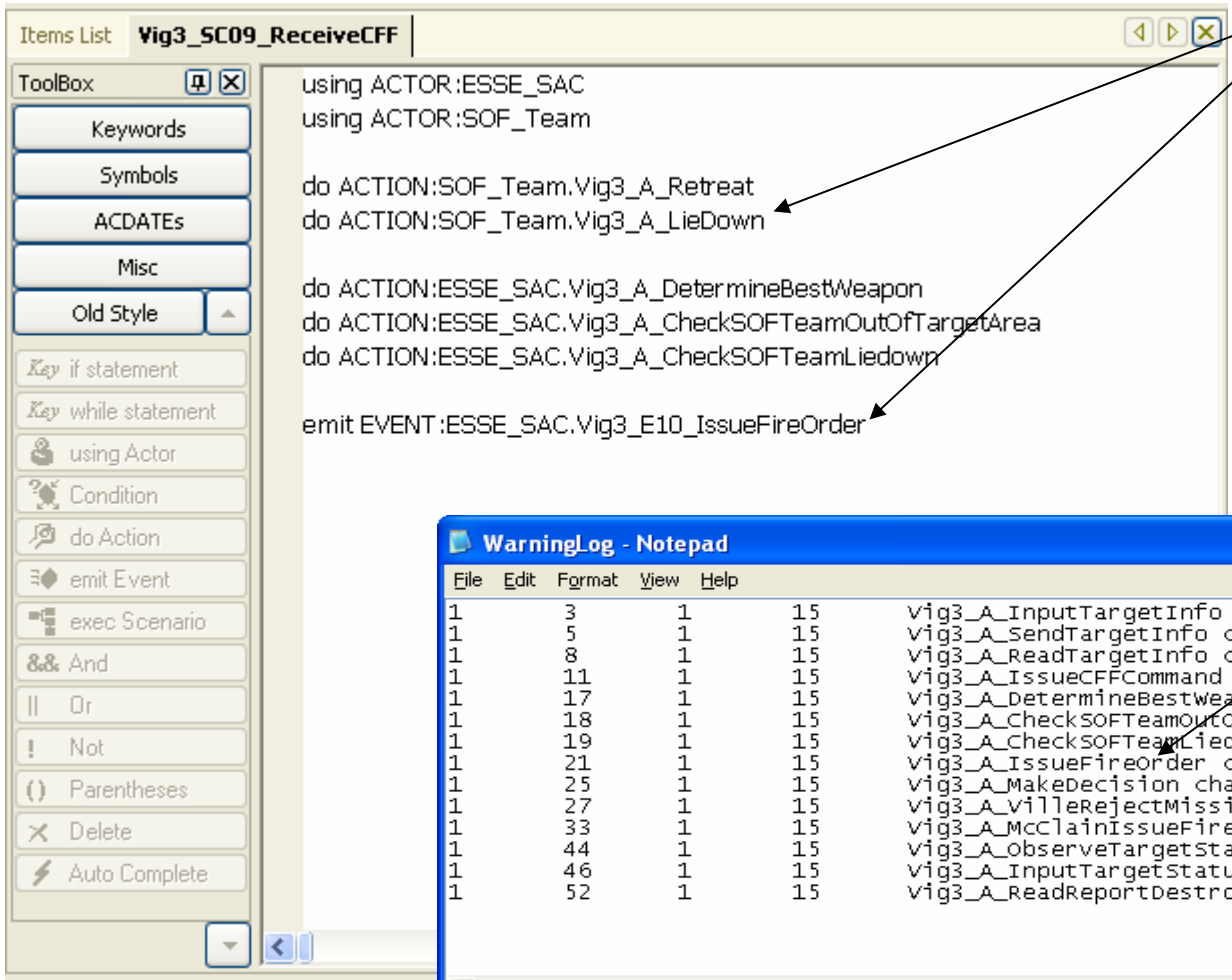
- Policy 2: Supporting Arms Coordinator (SAC) must NOT issue a Fire Order if SOF Team has not laid down
- Specification



Acceptable Scenario

SOF Team lies down before Fire Order is issued

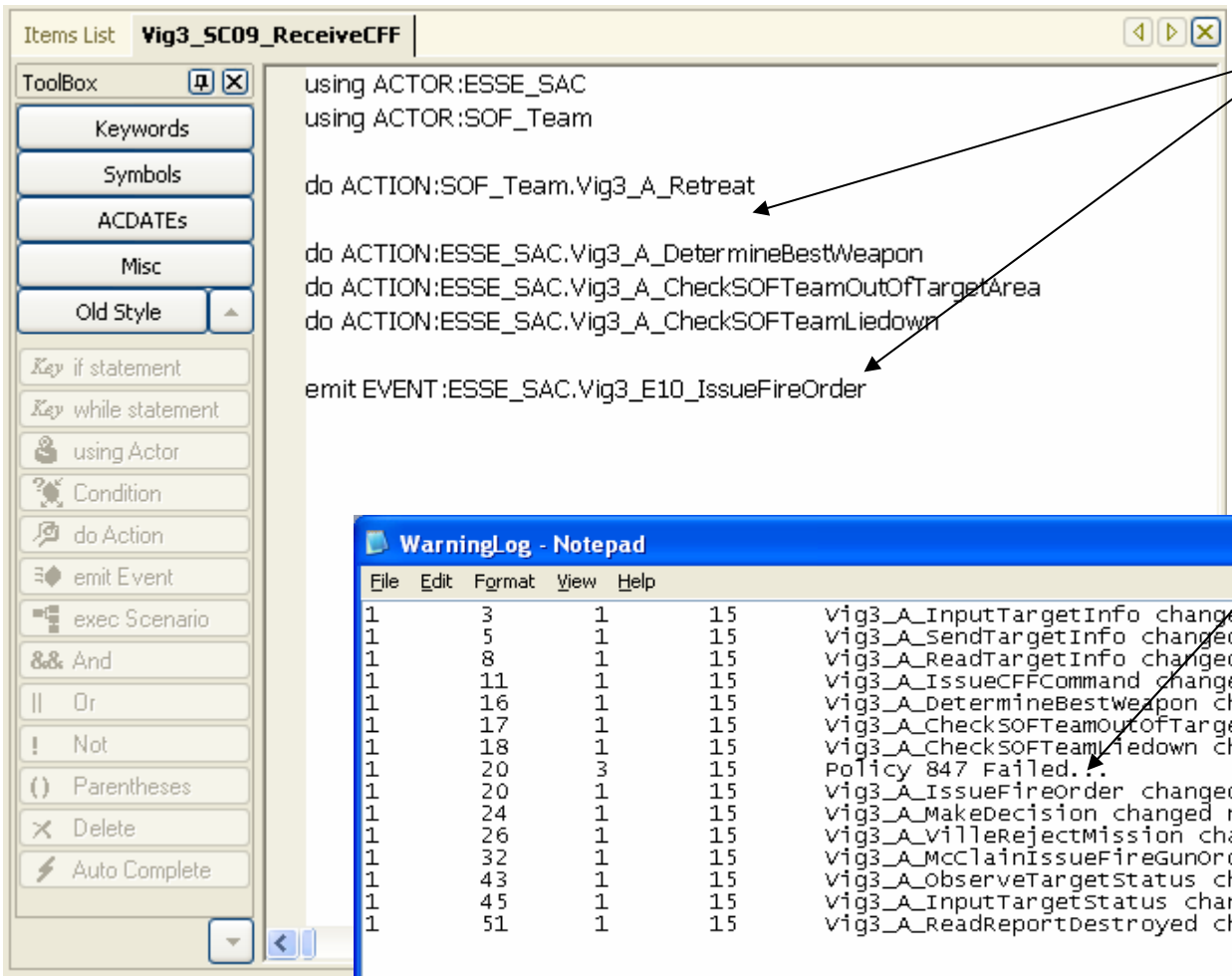
No policy violation detected



Scenario Violating Policy

SOF Team doesn't lie down before Fire Order is issued

Policy violation detected



Dynamic C&C analysis

- Some incompleteness or inconsistency can only be observed during runtime when concurrency comes into play
- In a recent experiment with a real time network-centric C2 system that has around 1000 entities and 120 scenarios, it takes 3 minutes to generate and execute the simulation and it detected around 200 bugs related to incompleteness or inconsistency.

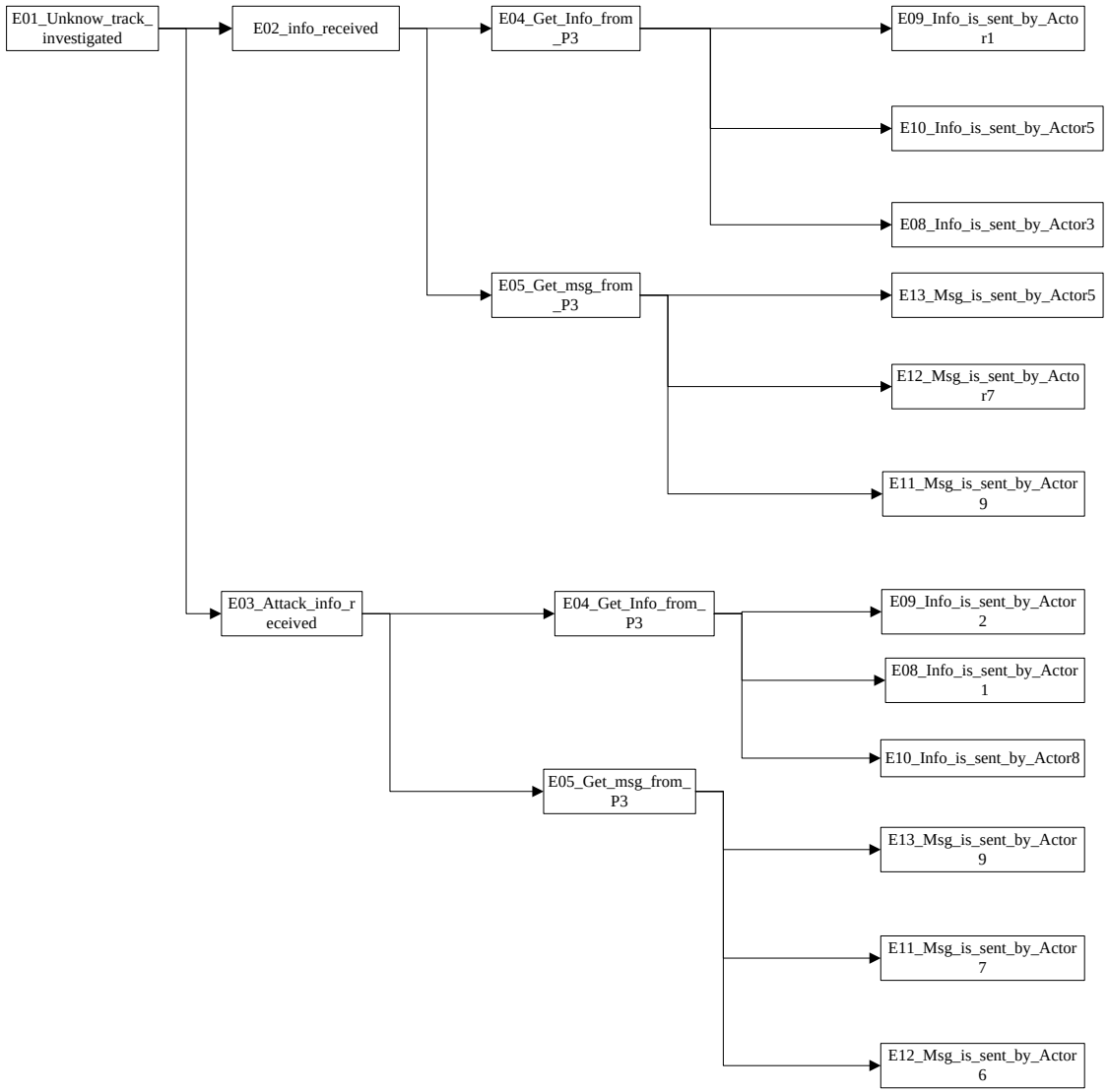
Performance Analysis

- During the simulation, system time will be recorded for each action when it starts or ends, event when it is emitted or handled, and data when the value changes.
- The recorded time information can be used for performance analysis such as the throughput and delay of the system processes.

Safety Analysis

- Event sequence can be useful for safety analysis.
- By using event sequence tree and traditional event tree, one can pinpoint which system components that failed during failure analysis.

Sample Event Sequence Tree



Behavior analysis

- Reachability analysis
- State model generation
- Linear Temporal Logic (LTL) analysis
- Model checking using SPIN
- Sequence diagram generation

State Model Generation

- We can generate the state model from the result of simulation
- Information contained in one entry of the simulation result
  - Time stamp
  - Starting and ending system state
  - Action performed
  - Event that triggers the action

State Model Generation

- From information provided in the result of simulation, we can get the global state transitions and single actor state transitions
- But there is something more for the single actor state transition generation – guard condition, i.e. some state transition can happen when some other actors are in certain conditions. For example, alarm can not be turned on when the driver's door is open.
- State transition for global system:
  - (starting global state) – external event/triggered actions → (ending global state)
- State transition for single actor
  - (starting actor state) – external event[guard condition]/triggered actions → (ending actor state)

Model Checking with SPIN

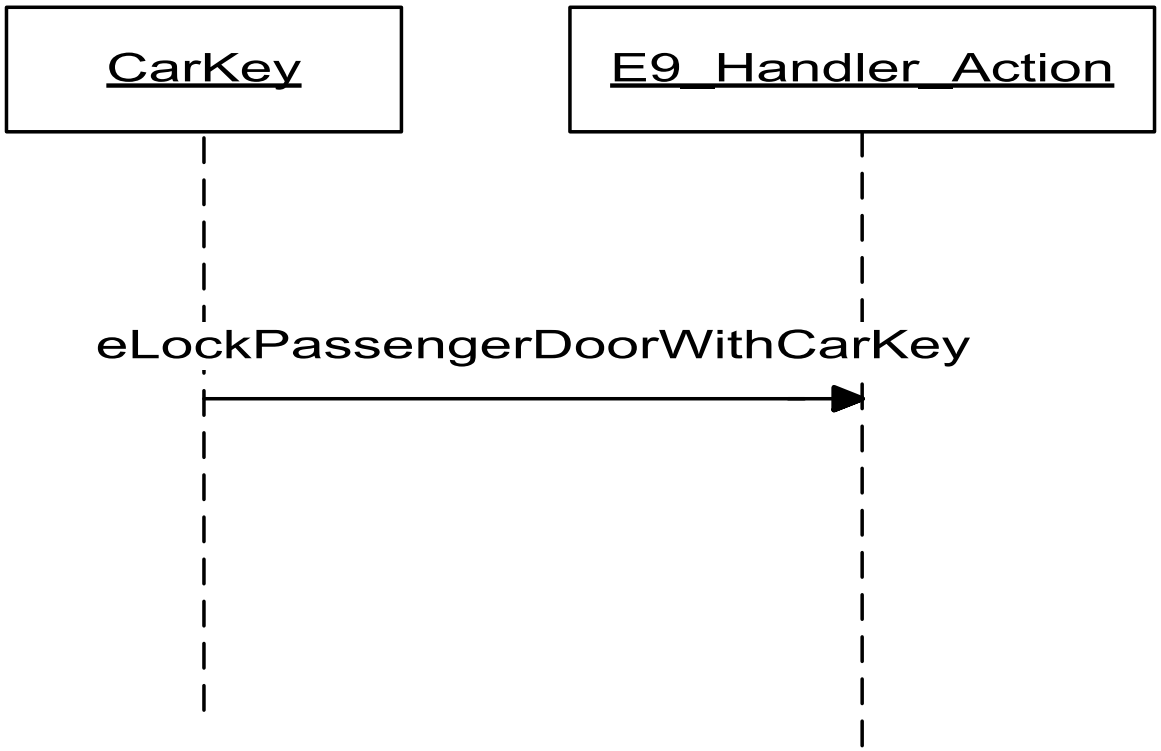
- One can generate the single actor state models automatically from simulation
- One can also generate the single actor state models from requirements or design manually
- Two sets of state models can put into SPIN to perform cross checking

Sample State Model

	A	B	C	D	E	F	G
1	StartState	Event	GuardCondition	Actions	EndState		
2	Door Closed Not Loc	eLock/ArmButtonPressedWRen	Door Closed Not Locked	(Lock driver door) (Lock pa	Door Closed And Locked		
3	Door Closed And Loc	eLockPassengerDoorWKey	No Guard	No Action	Door Closed And Locked		
4	Door Closed And Loc	eLock/ArmButtonPressedWRen	Door Closed And Locked	(Beep Three Times)	Door Closed And Locked		
5	Door Closed And Loc	eLock/ArmButtonPressedWRen	Door Closed And Locked	(Beep Three Times)	Door Closed And Locked		
6	Door Closed And Loc	eLock/ArmButtonPressedWRen	Door Closed And Locked	(Beep Three Times)	Door Closed And Locked		
7	Door Closed And Loc	eLock/ArmButtonPressedWRen	Door Closed And Locked	(Beep Three Times)	Door Closed And Locked		
8	Door Closed And Loc	eLock/ArmButtonPressedWRen	Door Closed And Locked	(Beep Three Times)	Door Closed And Locked		

This is a sample state model for the Driver's Door

Generated Sequence Diagram Sample



Conclusion

- A systematic process to perform variety kinds of static and dynamic analyses based on scenario specification
- Once system scenarios are specified, the simulation code can be automatically generated, and the system can be simulated without any additional programming
- The simulation can be used to perform various dynamic analyses including C&C checking, safety analysis, and performance analysis. The SDSE is being integrated into an automated tool E2E.