CYBER-RESILIENT ARCHITECTURE PATTERNS

HIGH CONFIDENCE SYSTEMS AND SOFTWARE
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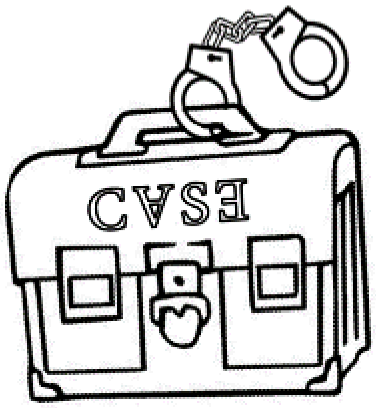
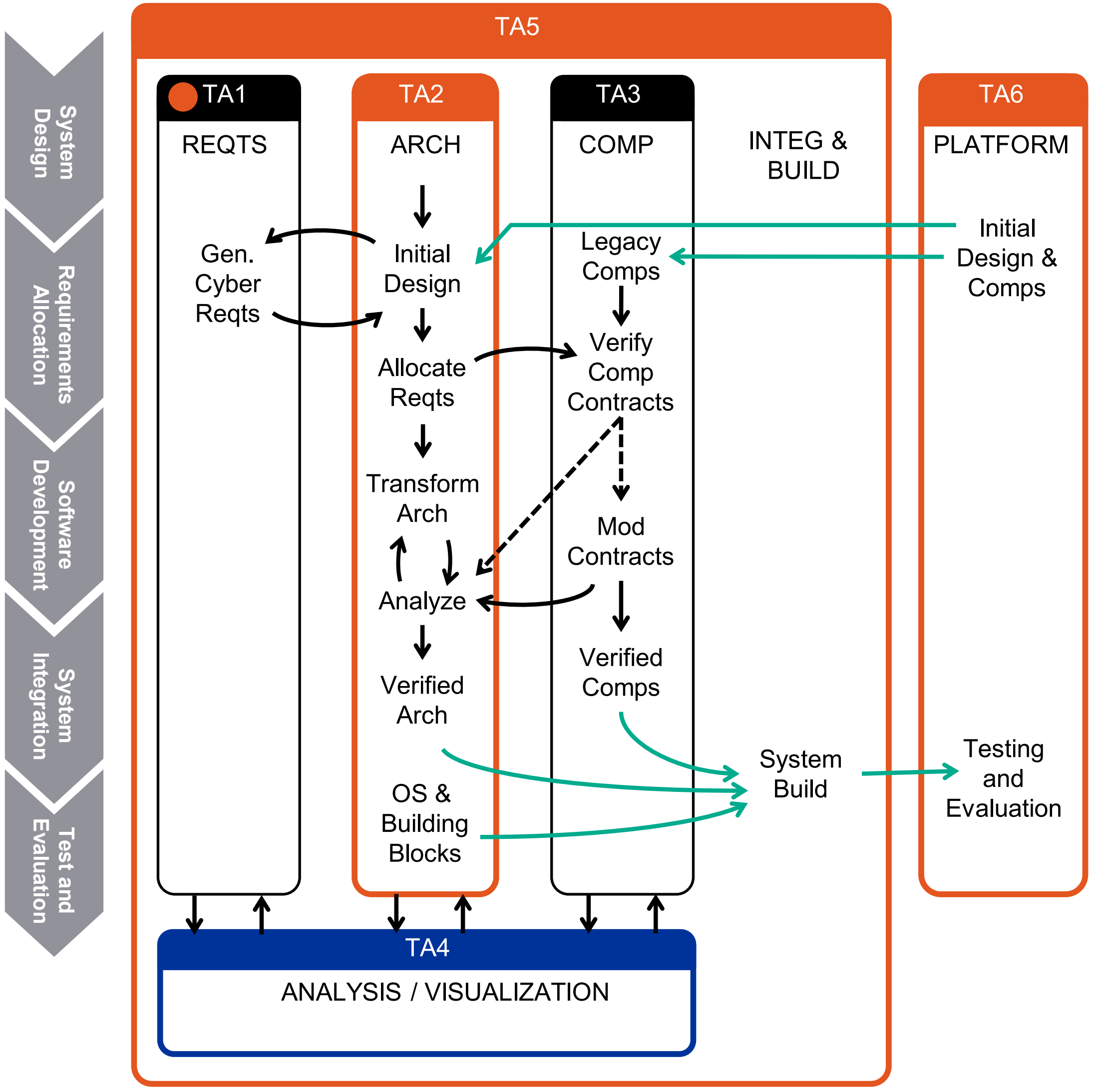
CYBER ASSURED SYSTEMS ENGINEERING (CASE)

- The goal of CASE is to develop the necessary design, analysis and verification tools to allow system engineers to design-in cyber resiliency and manage tradeoffs as they do the other non-functional properties when designing complex embedded computing systems
  - Cyber resiliency means that the system is tolerant to cyberattacks in the same way that safety critical systems are tolerant to random faults – they recover and continue to execute their mission function
  - Cyber security requirements are addressed today by penetration testing late in the development, resulting in expensive rework
  - Cyber requirements are often “shall not” statements about the system, and so are not testable (formal methods required)

CYBER-ASSURED SYSTEMS ENGINEERING

- Innovate
  - Generate cyber-security requirements
  - Cyber-resiliency transformations
  - Verified architectural components (CakeML)
  - New analysis tools
- Cultivate (extend and mature)
  - OSATE/AADL modeling
  - AGREE analysis
  - Resolute assurance cases
- Integrate
  - Tool integration
  - Proof integration
  - System build for seL4
- Demonstrate
  - Phase 1: Simple UAV
  - Phase 2: UxAS + challenge problems
  - Phase 3: CH-47/CAAS + challenge problems

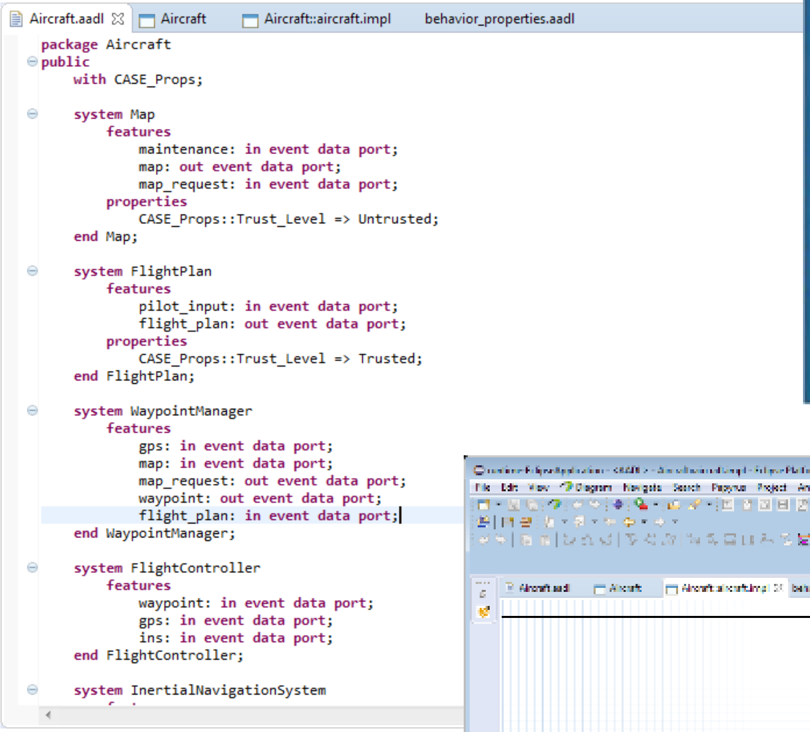


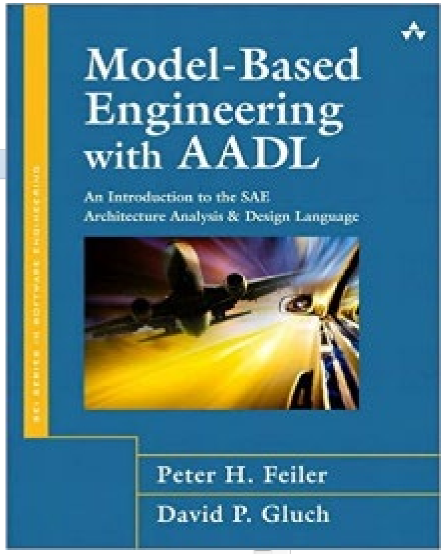


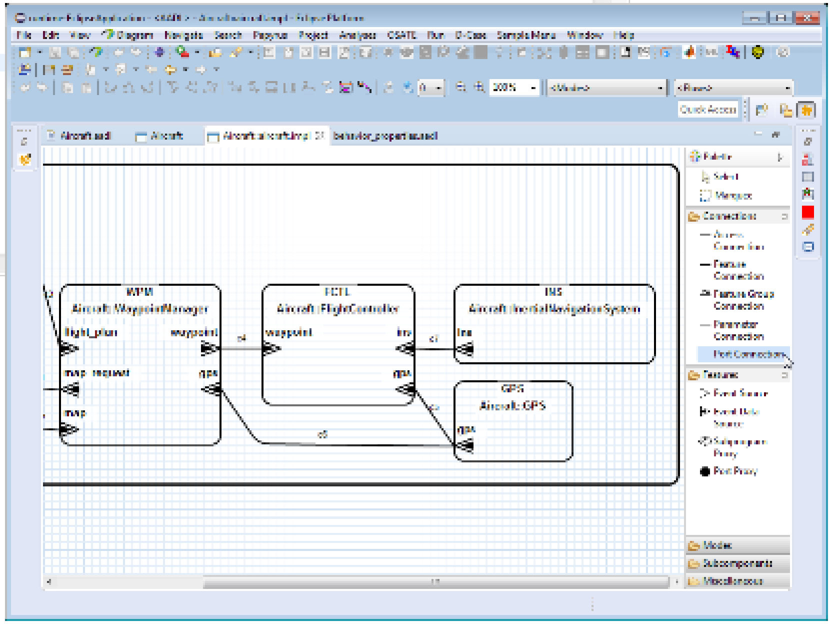
Build revolutionary design resiliency tools for systems engineers that provide cyber assurance for critical DoD systems

ARCHITECTURE ANALYSIS AND DESIGN LANGUAGE (AADL)

- SAE AS5506 standard
- Embedded, real-time, distributed systems
- Physical hardware
  - processors, buses, memory, devices
- Application software
  - software functions, data, threads, processes
- Extendable syntax (annex)
- Open source tools, supported by SEI
  - Open Source AADL Tool Environment (OSATE)







- Sufficiently rigorous semantics to support analysis
- Correct level of abstraction (supports construction)
- Syntax allows addition of new capabilities

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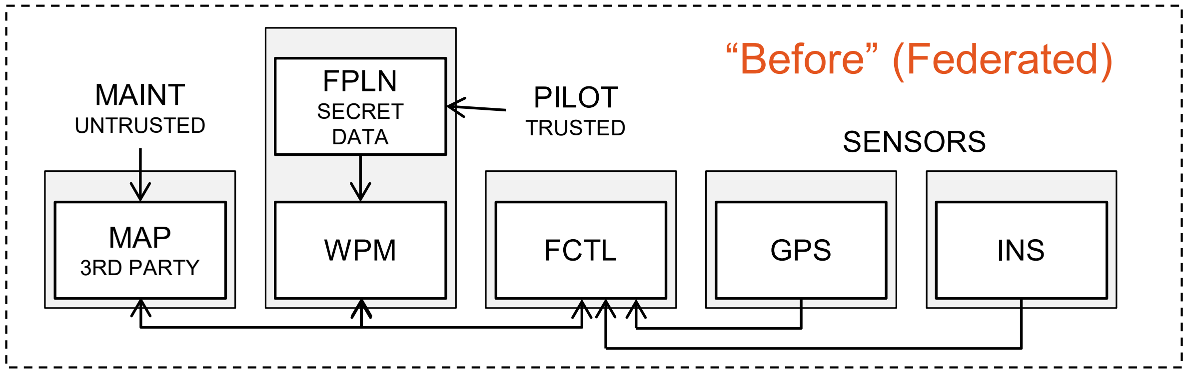
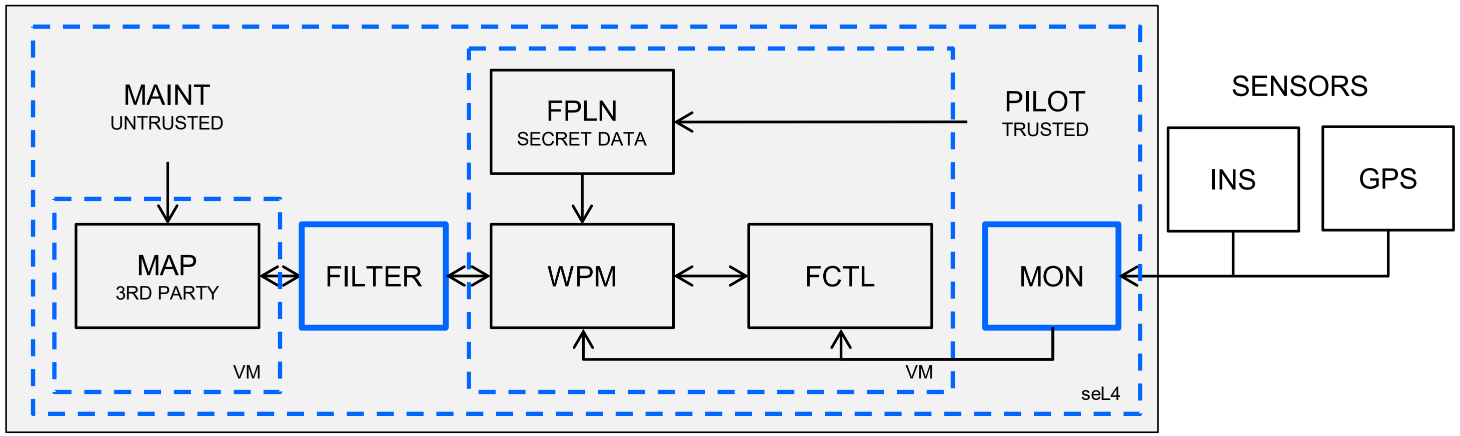
APPROACH

- Start with initial design, new or legacy
  - Federated avionics system
- Generate new cyber requirements
  - Possibly based on modified system architecture
- Tool-assisted transformations of system architecture
  - Satisfy cyber requirements
  - Manage other design trade-offs
  - Insertion/synthesis of high-assurance components may be needed
- Verification of cyber resiliency
- Generate system from architecture model





"After" (Integrated, Cyber-resilient)

1 : CYBER RESILIENCY REQUIREMENTS

- TA1 tools generate cyber requirements based on initial system model (AADL) and (possibly) functional requirements
- TA2 evaluation is still needed to
  - Determine applicability
  - Add additional details
- Assurance case provides a mechanism to receive, implement, and manage cyber requirements and attach them to relevant parts of the design model
- Allows us to specify exactly what evidence is necessary to satisfy each cyber requirement

```
"attack": replay_attack

"mitigation":
Context:MissionComputer.impl

   preventSpoofing(c6)

   preventSpoofing(c : connection) <=
   ** "spoofing of communication on c is prevented" **
   true

**************

"attack": command_injection

"mitigation":
Context: MissionComputer.impl

   well_formed(UARTDriver,WaypointManager,c6)

   permitWellFormedData(s1 : system, s2 : system, c :
      connection) <=
   ** "connection c only permits well-formed data to
      flow from s1 to s2" **
   true
```

Internal connection: N/A

Define "well-formed"?

ARCHITECTURAL ASSURANCE CASE

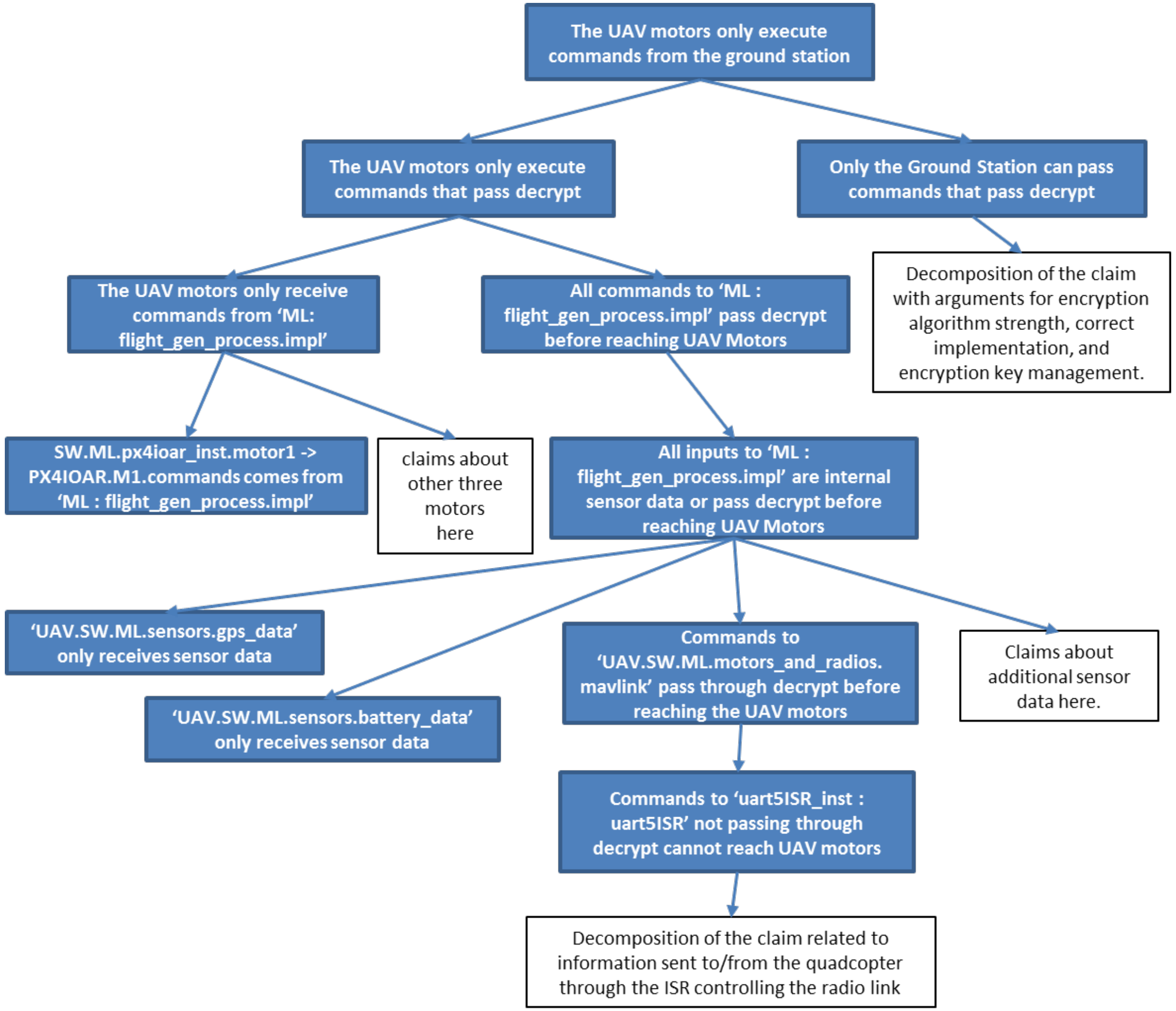
RESOLUTE

An assurance case is:

- Structured argument consisting of a tree of claims (goals), each supported by evidence, or subgoals and arguments
- Mechanism for capturing and combining all the analyses and verification performed on the architecture and its components

Resolute is a logic and tool for embedding assurance cases in AADL models

- Directly linked to architecture
- Includes different types/sources of evidence
- Reviewable by domain experts
- Adds precision to informal reasoning



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2 : CYBER RESILIENT ARCHITECTURE PATTERNS

- Library of general, tool-assisted *architecture model transformations* that mitigate vulnerabilities or address cyber requirements
- Automatic insertion and verification of transform properties as assume-guarantee contracts and assurance case claims
- Examples
    - Filter ✅
    - Attestation ✅
    - Isolation ☑️
    - Monitor/Simplex
    - Distributed Action (e.g., Zeroize)
    - seL4 implementation

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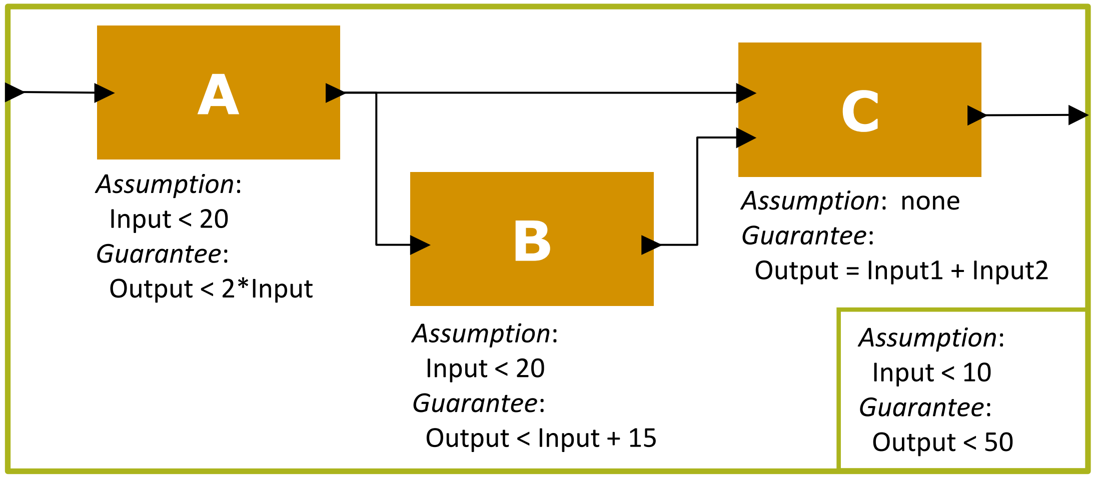
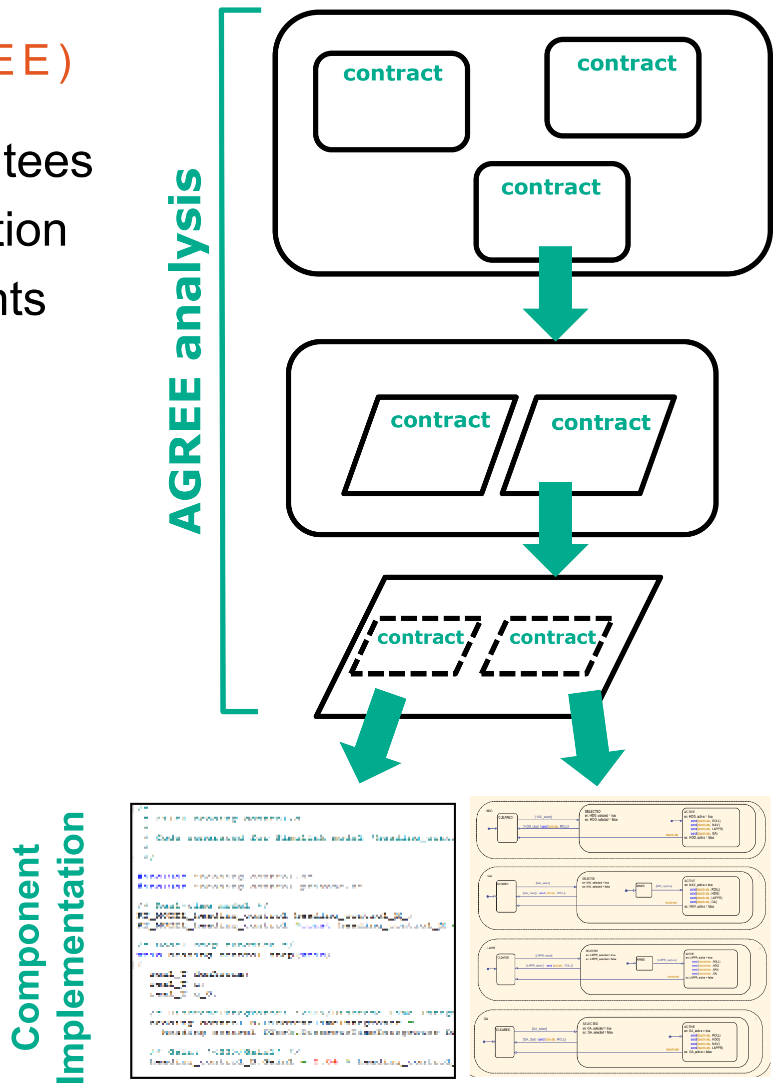
COMPOSITIONAL REASONING

ASSUME GUARANTEE REASONING ENVIRONMENT (AGREE)

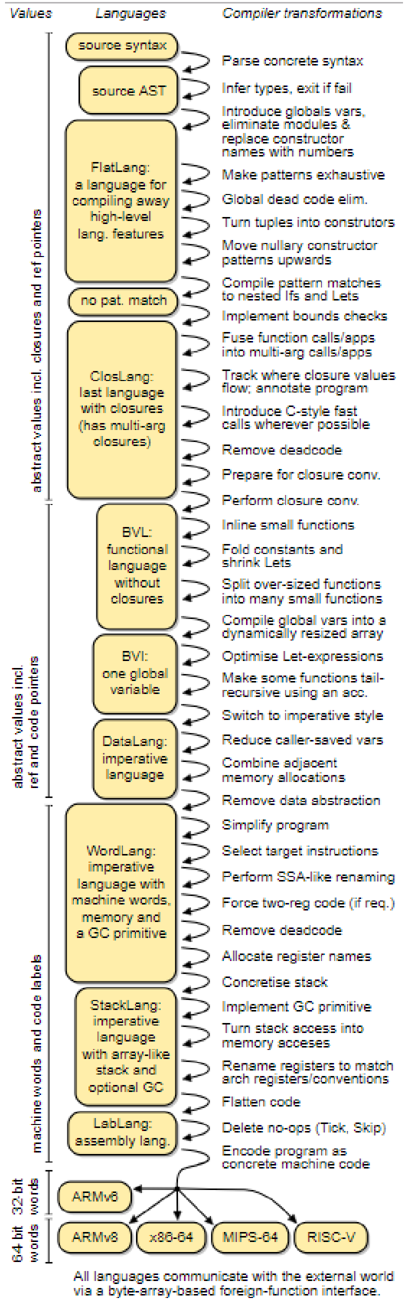
- Each subsystem has a contract consisting of assumptions and guarantees
- The contract of a component abstracts the behavior of its implementation
- Contracts at each layer must be satisfied by contracts of its components
- Leaf component contracts must be satisfied by implementation
- Compositional analysis provides **scalability**





3 : CYBER ASSURED COMPONENTS

- Many architecture transformations require the introduction of new special-purpose components
- These must be high-assurance components
  - Library of pre-verified components, or
  - Synthesized from formal specification (with proof)
- Generate high-assurance components using CakeML
  - AGREE specification -> CakeML specification
  - Provably correct synthesis
  - Additional infrastructure to create component interface
- In addition, we can build systems using the formally verified seL4 kernel and its build system (CAmkES)



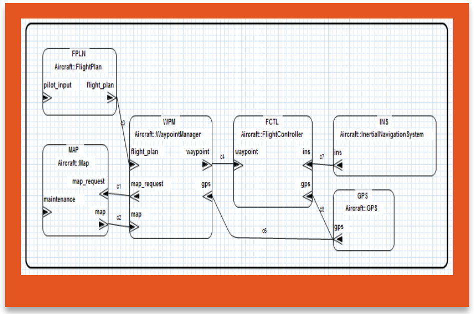
seL4 — Security. Performance. Proof.

CAKEML — A Verified Implementation of ML

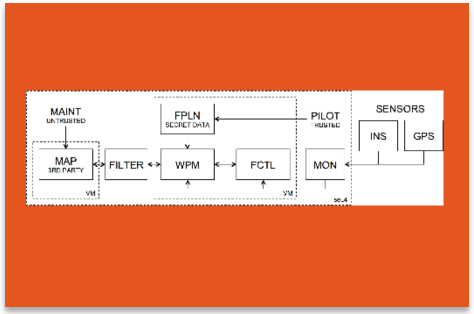
HIGH ASSURANCE IMPLEMENTATION

- Goal: End-to-end verification-based assurance
  - AADL properties -> running system properties

AADL Architecture



CAmkES architecture



seL4-based implementation

Verification of mapping AADL to CAmkES

Verification of mapping CAmkES to seL4

Assurance: separation properties hold for AADL

Assurance: separation properties hold for CAmkES architecture

Assurance: separation properties hold for seL4 implementation

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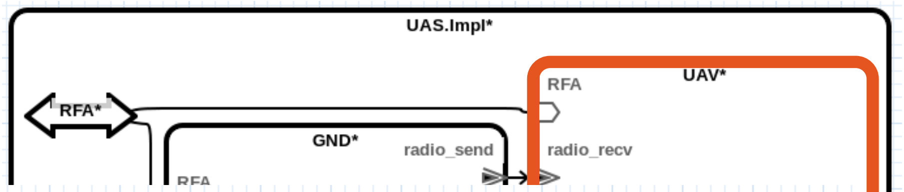
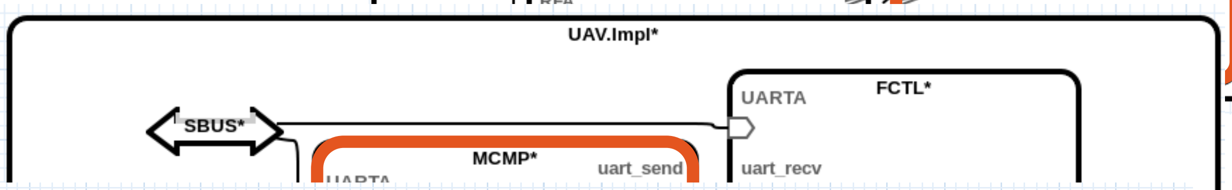
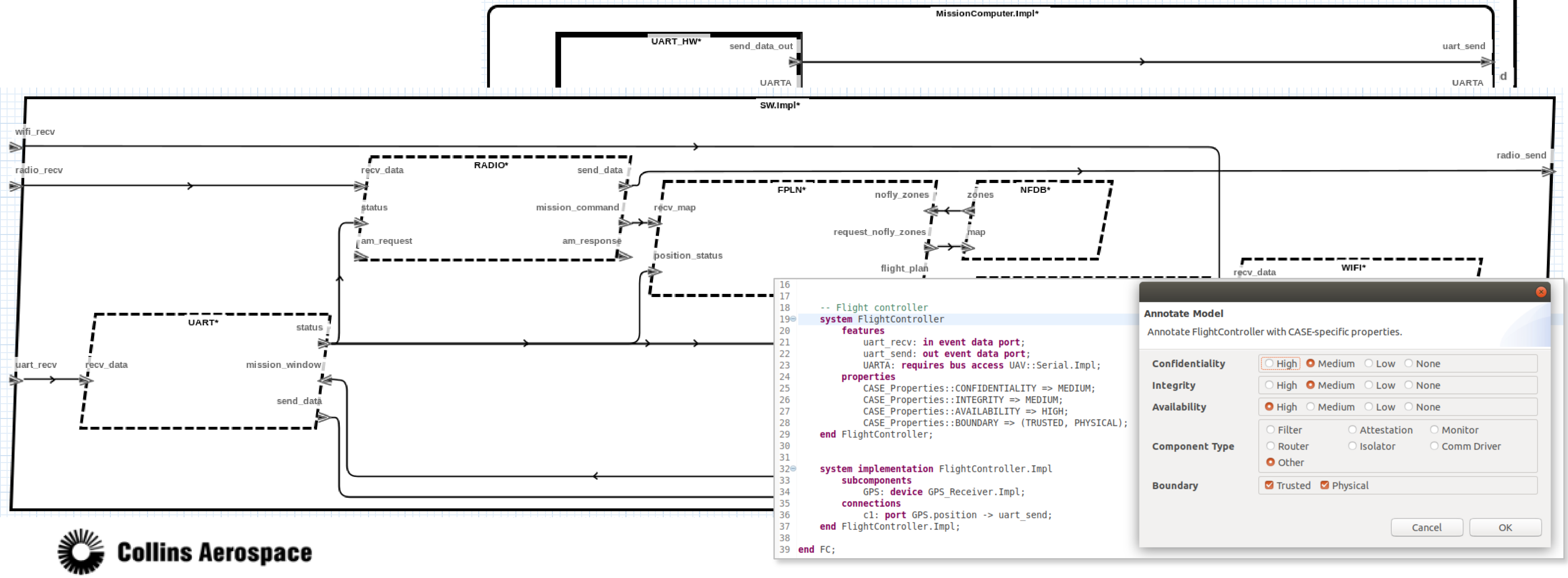
PUTTING IT ALL TOGETHER

- UAV model

https://github.com/loonwerks/CASE/tree/master/CASE_Simple_Example_V3







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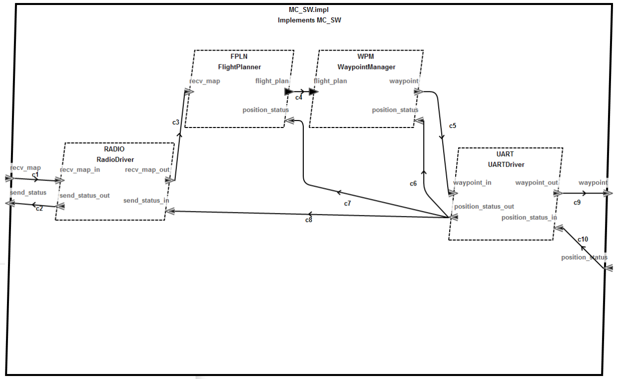
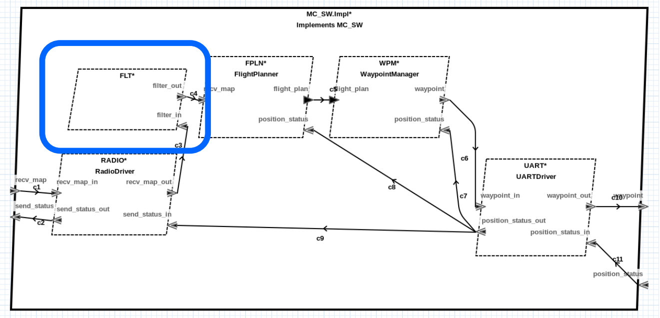
REQUIREMENTS ADDED TO AADL MODEL




```
thread FlightPlanner
    features
        flight_plan: out data port Mission.Impl;
        recv_map: in event data port Command.Impl;
        position_status: in event data port Coordinate.Impl;
    annex agree {**
        assume "The FlightPlanner shall receive a well-formed command from the GroundStation" : FALSE;
        assume "The Flight Planner shall receive an authenticated command from the Ground Station" : recv_map.HMAC = True;
        guarantee "The Flight Planner shall generate a valid mission" : SW.good_mission(flight_plan);
    **};
    annex resolute {**
        prove (well_formed())
    **};
end FlightPlanner;
```

```
package SW_CASE_Claims
  public

    annex resolute {**

        -- This connects to evidence that AGREE was previously run on the current version of the design.
        agree_prop_checked() <=
            ** "AGREE properties passed" **
            analysis("AgreeCheck")

        well_formed() <=
            ** "The FlightPlanner shall receive a well-formed command from the GroundStation" **
            agree_prop_checked()

    **};

end SW_CASE_Claims;
```


TRANSFORMATION: FILTER ADDED TO AADL MODEL




```
thread Filter
    features
        filter_in: in event data port Command.Impl;
        filter_out: out event data port Command.Impl;
    properties
        CASE::COMP_TYPE => FILTER;
        CASE::COMP_IMPL => "CakeML";
        CASE::COMP_SPEC => "(\\i{-90,90}\\i{-180,180}\\i{0,
    annex agree {**
        guarantee "The Flight Planner shall receive a well-
        guarantee "Authenticated command from the Ground Sta
    **};
end Filter;
```

```
package SW_CASE_Claims
  public

    annex resolute {**

        -- This connects to evidence that AGREE was pre
        agree_prop_checked() <=
            ** "AGREE properties passed" **
            analysis("AgreeCheck")

        well_formed(c : component, msg_type : data) <=
            ** "The FlightPlanner shall receive a well-
            agree_prop_checked() and add_filter(c, msg_

    **};

end SW_CASE_Claims;
```

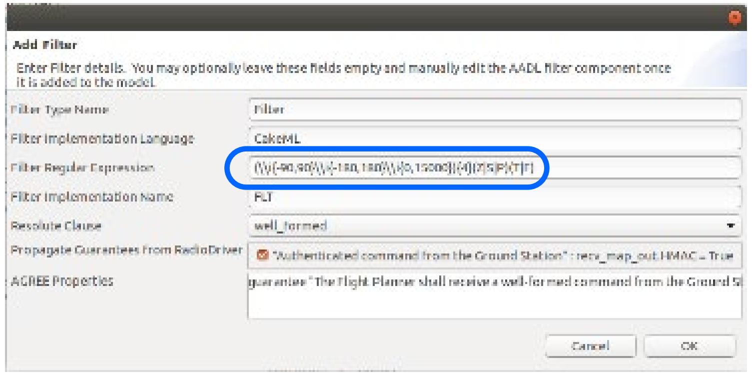
```
package Model_Transformations
public

    with CASE;

    annex Resolute {**

        ----------------------------
        -- MODEL TRANSFORMATIONS --
        ----------------------------

        -- Top-level claim for proper insertion of a filter
        add_filter(c : component, message_type : data) <=
        ** "Filter inserted before " c **
        filter_exists(c) and not_bypassed(c, message_type) and filter_prop_checked()

        -- Top-level claim for proper insertion of a router
        add_router(c : component) <=
        ** "Router inserted after " c **
        true

        -- Top-level claim for proper insertion of a monitor
        add_monitor(c : component) <=
        ** "Monitor inserted on " c **
        true

        -- Top-level claim for proper insertion of an isolator
        add_isolator(c : component) <=
        ** "Isolator added to " c **
        true

        -- Top-level claim for proper insertion of remote attestation
        add_remote_attestation(c : component) <=
        ** "Remote Attestation added at " c **
        true
```

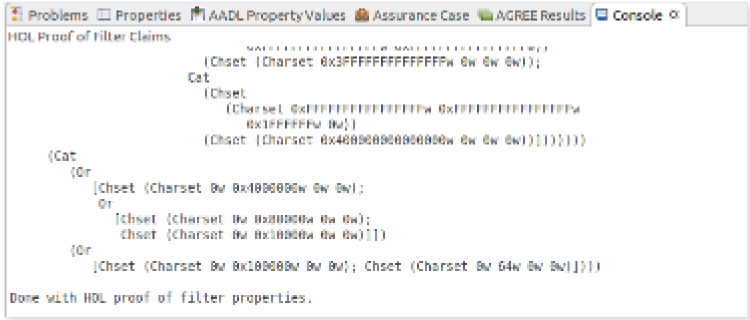
Problems | Properties | AADL Property Values | AGREE Results | Console | Progress | Assurance Case

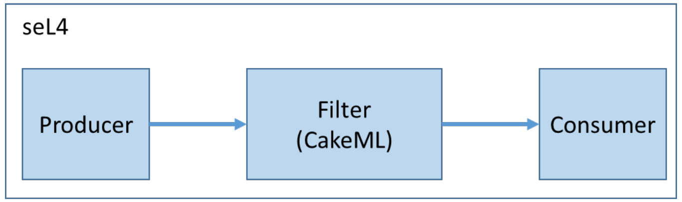
- ✔ well_formed(FPLN : SW::FlightPlanner, "good_gs_command")
  - ✔ FPLN : SW::FlightPlanner only receives well-formed messages
    - ✔ A filter exists on the communication pathway immediately before FPLN : SW::FlightPlanner
    - ✔ Filter cannot be bypassed
    - ✔ Filter property implemented by CakeML
    - ✔ AGREE property passed: [good_gs_command]

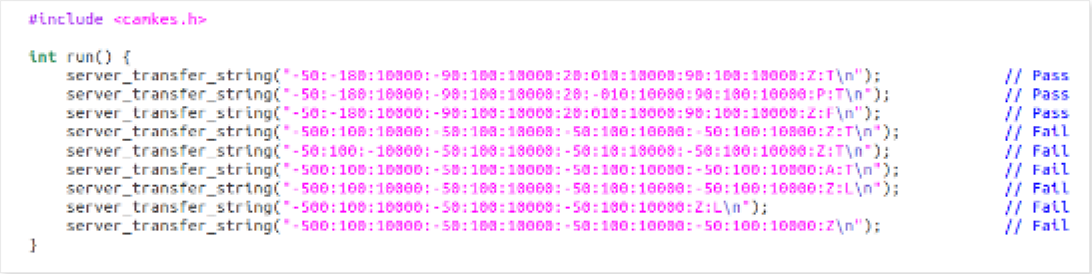
COMPONENT SYNTHESIS

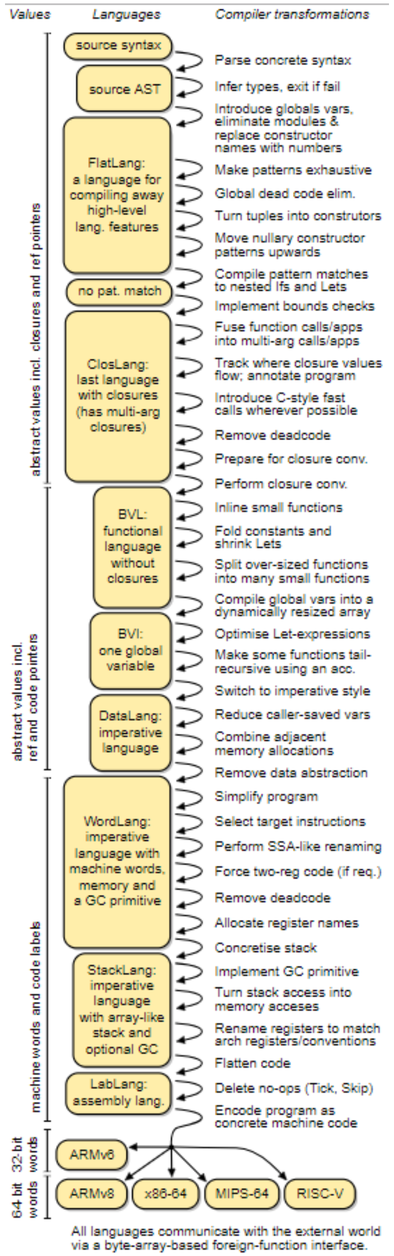
- Verified component built using CakeML
- Generated from regex filter spec
- Proof that regex implements AGREE property
- Generate CAmkES component for insertion into system











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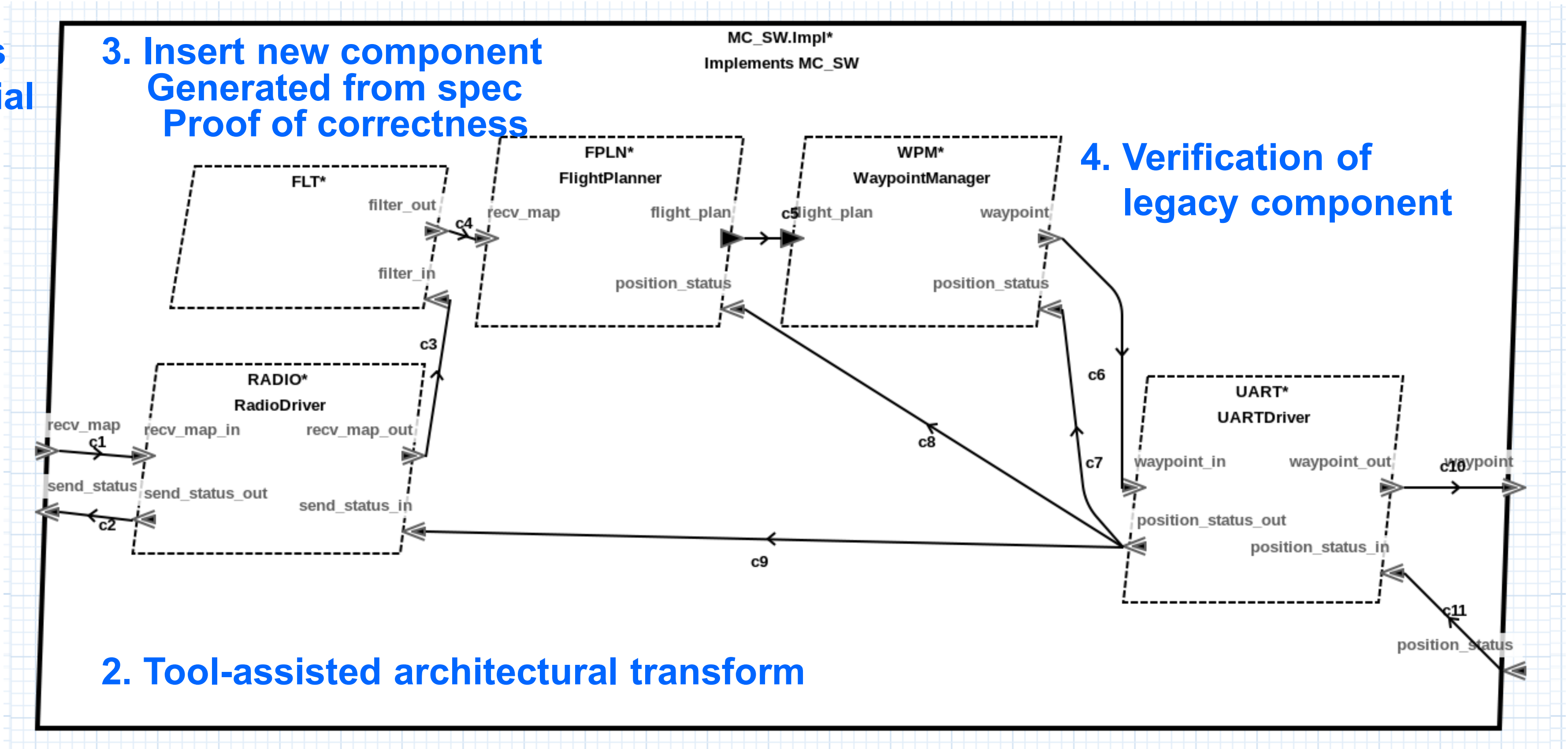
CYBER RESILIENT TRANSFORMED SYSTEM

1. Cyber requirements generated from initial system design

3. Insert new component
   Generated from spec
   Proof of correctness

4. Verification of legacy component

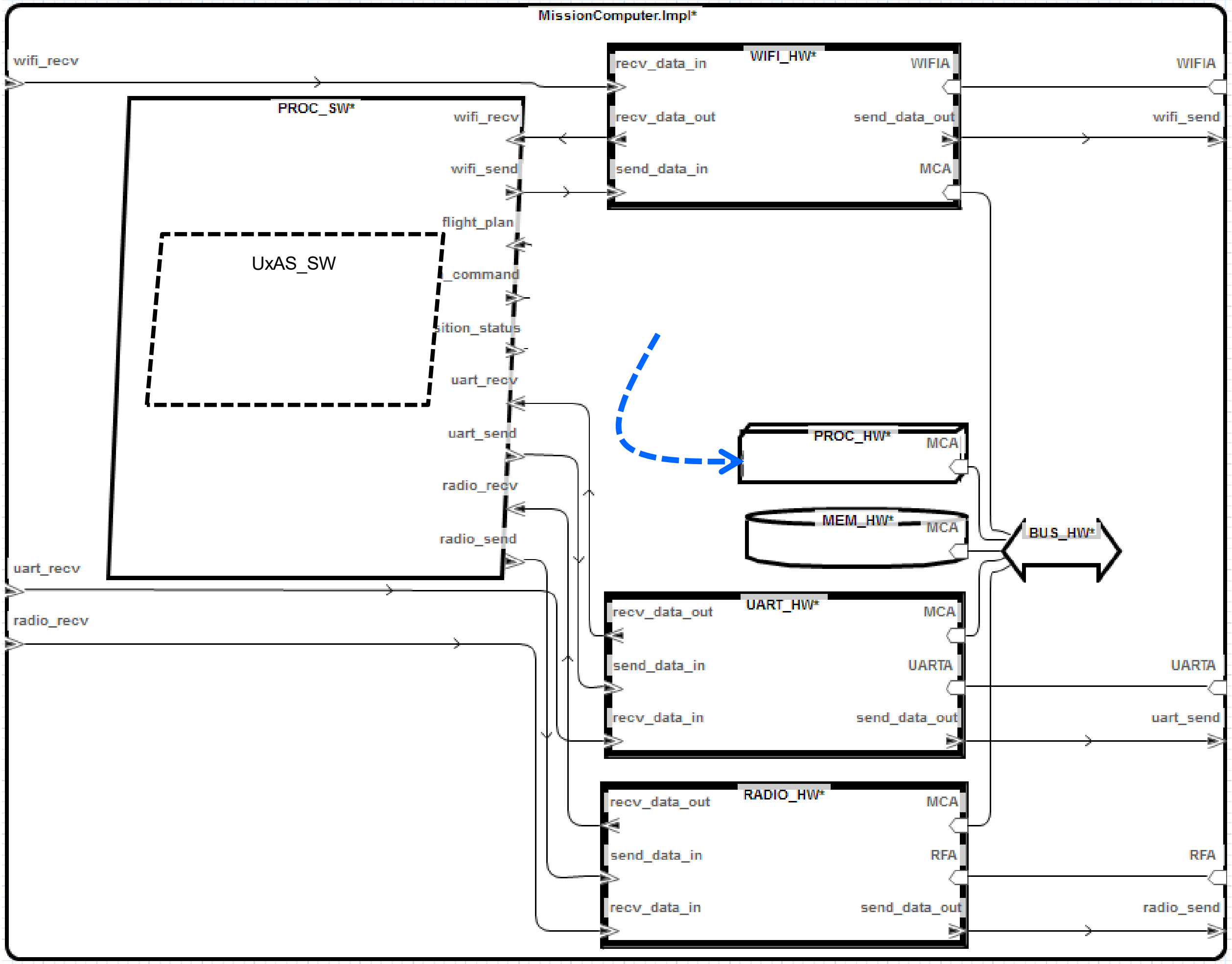


2. Tool-assisted architectural transform

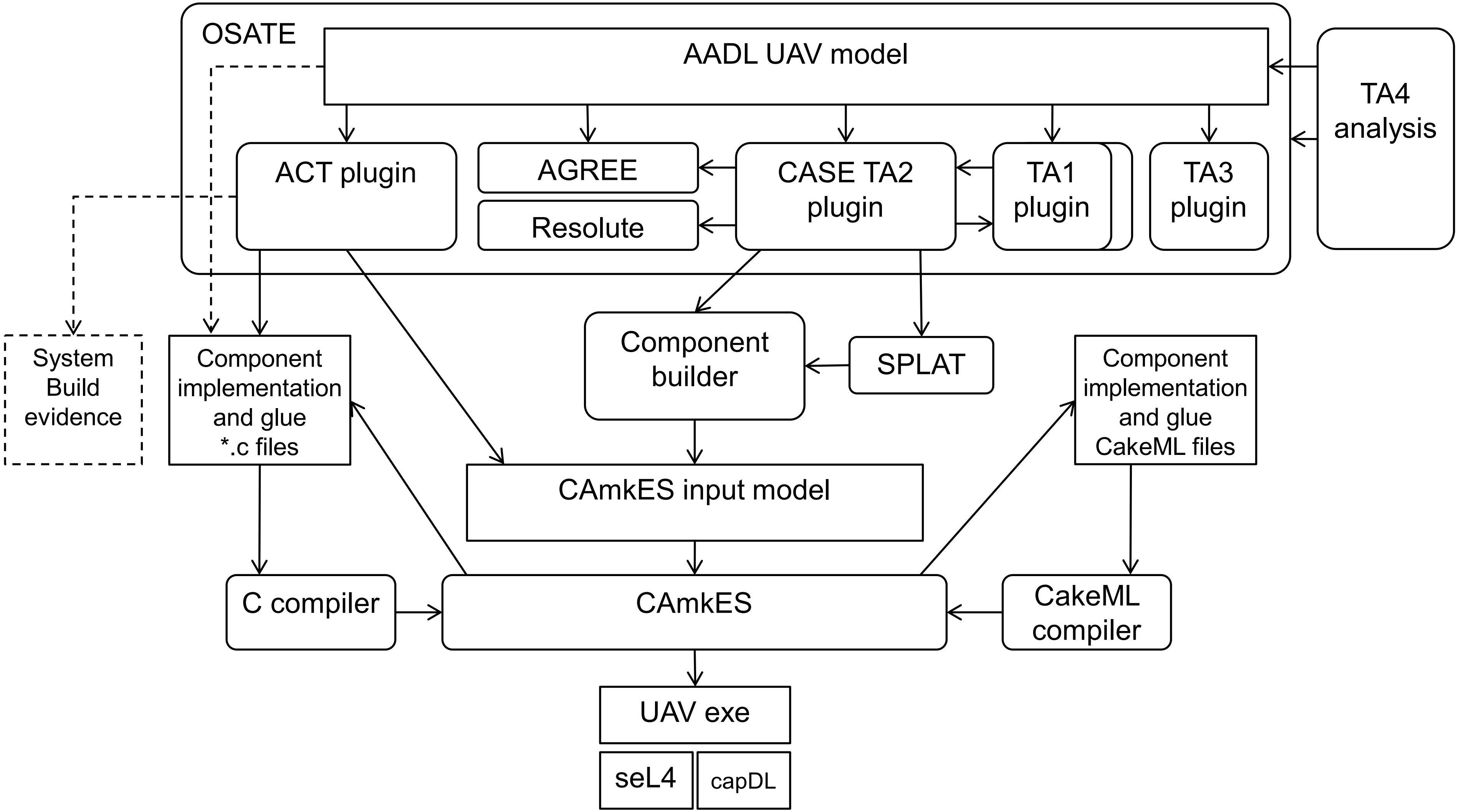
5. Transformed system satisfies cyber requirements
   Assurance case integrates evidence
   Implementation generated from model with proof of equivalence

NEXT : ISOLATION TRANSFORM

- Goal: Automate much of the manual engineering effort from HACMS
- Identify software to be isolated
  - Thread, thread group, or process
- Apply isolation transform
  - Creates virtual processor
  - Converts software to process
  - Converts connections as needed
  - Binds process to virtual processor
- Apply seL4 implementation transform



INTEGRATED TOOL ARCHITECTURE



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CASE TARGETS

- Experimental platform: AFRL UxAS
- Demonstration platform: CH-47 CAAS

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Code, papers, videos available at:

Loonwerks.com