Using Formal Methods to Enable More Secure Vehicles: DARPA's HACMS Program

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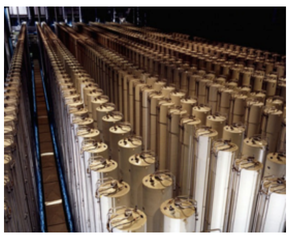
(Slides based on original DARPA HACMS slides)

Pervasive Vulnerability to Cyber Attack

SCADA Systems



Medical Devices

Computer Peripherals

Communication Devices

Vehicles

Appliances

Modern Automobile: Many Remote Attack Vectors

Mechanic

Source: CanOBD2

Source: www.custom-build-computers.com

Short-range wireless

© Bluetooth SIG, Inc.

Source: www.diytrade.com

Long-range wireless

© WiFi Alliance

Source: www.theunlockr.com

Source: American Car Company

Source: christinayy.blogspot.com

Source: Koscher, K., et al.
"Experimental Security Analysis of a Modern Automobile"

Source: www.wikipedia.org

Source: www.zedomax.com

Entertainment

Securing Cyber-Physical Systems: State of the Art

Control Systems

- Air gaps & obscurity

> Forget the myth of the air gap – the control system that is completely isolated is history.
> *-- Stefan Woronka, 2011*
> *Siemens Director of Industrial Security Services*

- Trying to adopt cyber approaches, but technology is not a good fit:
  - Resource constraints, real-time deadlines
  - Extreme cost pressures
  - Patches may have to go through lengthy verification & validation processes
  - Patches could require recalls

We need a *fundamentally different* approach

Cyber Systems

- Anti-virus scanning, intrusion detection systems, patching infrastructure
- This approach *cannot* solve the problem.
  - Not convergent with the threat
  - Focused on known vulnerabilities; can miss zero-day exploits
  - Can introduce new vulnerabilities and privilege escalation opportunities

October 2010 Vulnerability Watchlist

Vulnerability Title	Fix Avail?	Date Added
Linux Kernel Controller Area Network Protocol Local Privilege Escalation Vulnerability	No	8/25/2010
Red Hat VDSM Module SSL Connection Denial of Service Vulnerability	Yes	8/24/2010
PHP 'ibase_gen_id()' Function off-by-one Buffer Overflow Vulnerability	No	8/20/2010
Internet Explorer 8 'toStaticHTML()' HTML Sanitization Bypass Weakness	No	8/18/2010
Microsoft Windows Kerberos 'Pass The Ticket' Replay Security Bypass Vulnerability	No	8/17/2010
Cisco Unified Wireless Network (UWN) Multiple Security Vulnerabilities	Yes	8/16/2010
Computer Associates Oneview Monitor 'doSave.jsp' Remote Code Execution Vulnerability	No	8/16/2010
OpenSSL 'ssl3_get_key_exchange()' Use-After-Free Memory Corruption Vulnerability	No	8/12/2010
Adobe Acrobat and Reader Font Parsing Remote Code Execution Vulnerability	No	8/10/2010
OpenOffice Impress File Multiple Buffer Overflow Vulnerabilities	[illegible]	[illegible]
Linux Kernel PA-RISC 'led.c' Stack Buffer Overflow Vulnerability	[illegible]	[illegible]
VxWorks Debugging Service Security-Bypass Vulnerability	[illegible]	[illegible]
VxWorks Multiple Security Vulnerabilities	[illegible]	[illegible]
Microsoft Internet Explorer Frame Border Property Buffer Overflow Vulnerability	No	7/29/2010
Symantec Antivirus Corporate Ed. Alert Management Service Remote Privilege Escalation Vulnerability	No	7/28/2010
Microsoft Outlook Web Access for Exchange Server 2003 Cross Site Request Forgery Vulnerability	No	7/26/2010
Microsoft DirectX DirectPlay Multiple Denial Of Service Vulnerabilities	No	7/22/2010

1/3 of the vulnerabilities are in security software!

SAT Solvers and Infrastructure Development: Critical Enablers for High Assurance Systems

Interactive Theorem Provers

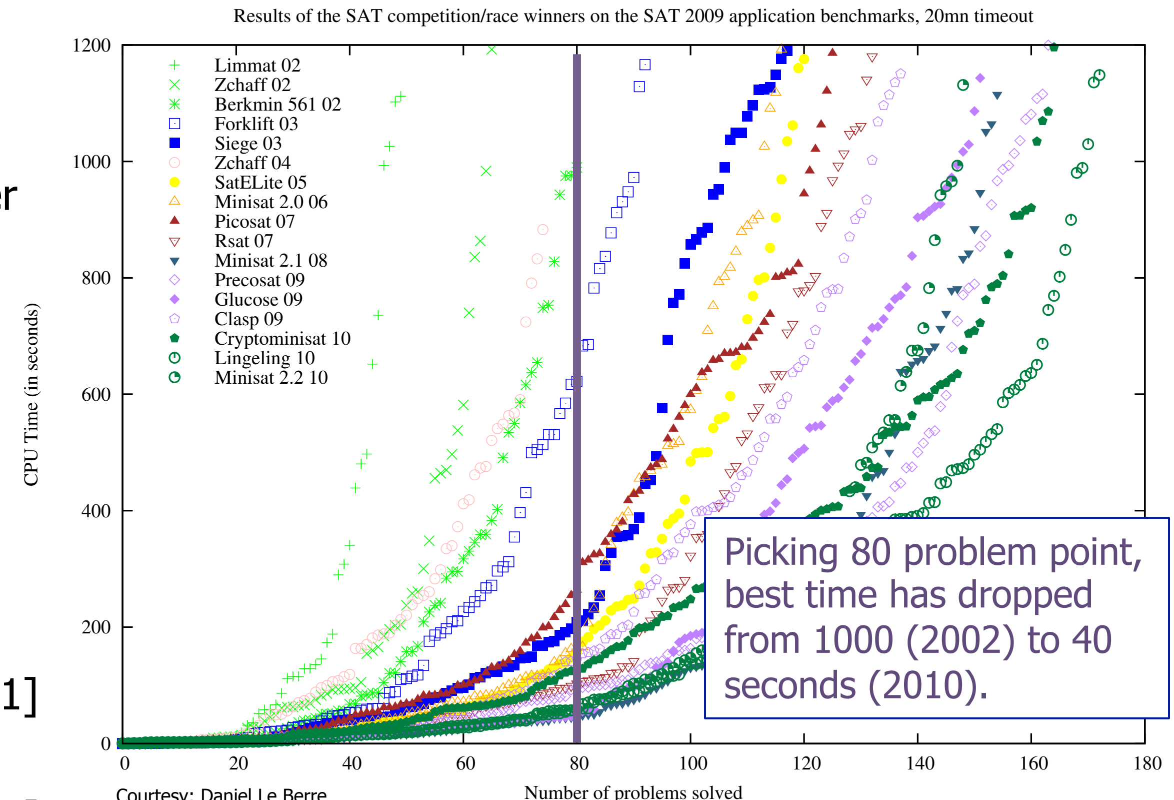
- seL4 microkernel [9000 LoC:C, SOSP 09]
- compCert verifying C compiler [6K LoC:ML, POPL 06]

Automatic Theorem Provers

- Verve OS Nucleus [1.5K LoC:x86, PLDI 10]
- Baby Hypervisor [1K LoC:C, VSTTE 10]

Model Checkers

- Microsoft device drivers [30K LoC:C, PLDI 01, CACM 11]
- ADGS-2100 Window Manager [16K Simulink blocks, CACM 10]

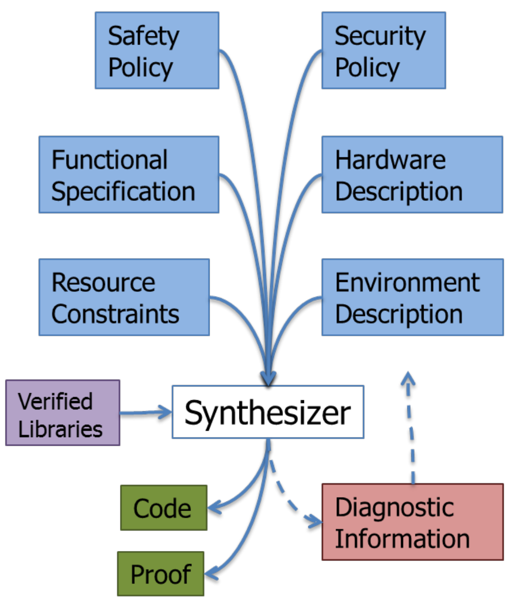


Courtesy: Daniel Le Berre

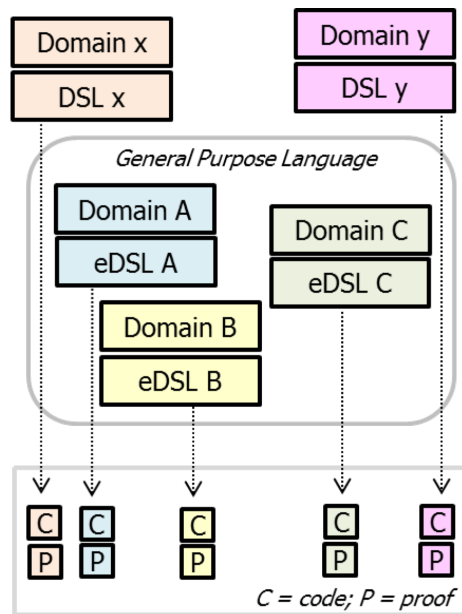
> [A] significant part of the effort in existing projects was spent on the further development of verification tools, on formal models for low-level programming languages and paradigms, and on general proof libraries. The sharing of substantial parts of the verification tools between Verisoft and L4.verified demonstrates that there is a significant degree of re-usability... Future efforts will be able to build on these tools and reach far-ranging verification goals faster, better, and cheaper.
>
> Gerwin Klein, *Formal OS Verification—An Overview*.

HACMS:
Clean-Slate Methods for High-Assurance Software

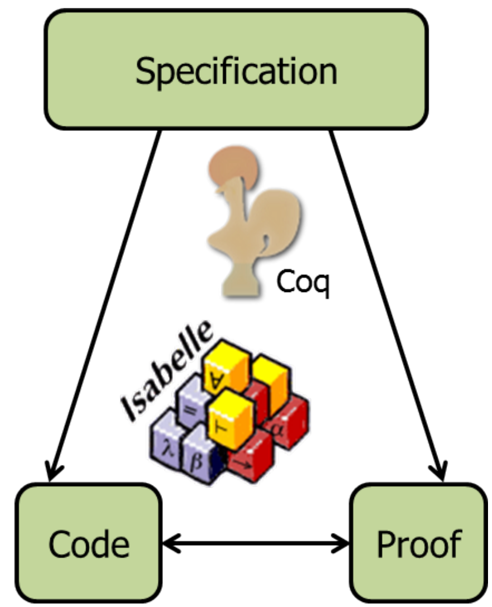
Code Synthesis



Domain Specific Languages (DSLs)



Interactive Theorem Prover as PL



High Assurance: Ensuring Correctness, Safety, Security

HACMS Program Structure

1. Vehicle Experts	2. Operating Systems	3. Control Systems	4. Research Integration	5. Red Team
Boeing Pilot-able Unmanned Little Bird Helicopter	**NICTA** Synthesize file systems, device drivers, glue code; Verified sel4 kernel; Verified RTOS	**Galois** Embedded DSLs; Synthesize and verify control system code	**RC*/U. Minn** Compositional verification; Integrated workbench	**DRAPER*/AIS/ U. Oxford** Traditional penetration testing; novel formal methods approach
HRL*/GM American-Built Automobile	**SRI*/UIUC** EF-SMT solvers; Synthesize monitors and wrappers	**SRI*** Synthetic sensors; Synthesis for controllers of hybrid systems	**SRI*** Lazy Composition; Evidential Tool Bus & Kernel of Truth; Vehicle Integration	
 © Boeing	**Princeton*/Yale/ MIT** Build & verify in Coq OS for vehicle control; Verifying compiler for concurrent code; Program logics	**CMU*/Drexel/ SpiralGen/UIUC** Map high-level spec into low-level C code; Extend Spiral for hybrid systems		
 Source: American Car Company	**Kestrel*** Synthesize protocols: refinement of high-level spec to low-level implementations	**UPenn*/UCLA** Synthesize attack-resilient control systems		

Program Timeline:
- BAA Release: Feb 23, 2012
- Kick-Off: Aug 8-10, 2012
- End of Phase 1: Jan 2014
- End of Phase 2: July 2015
- End of Phase 3: Jan 2017

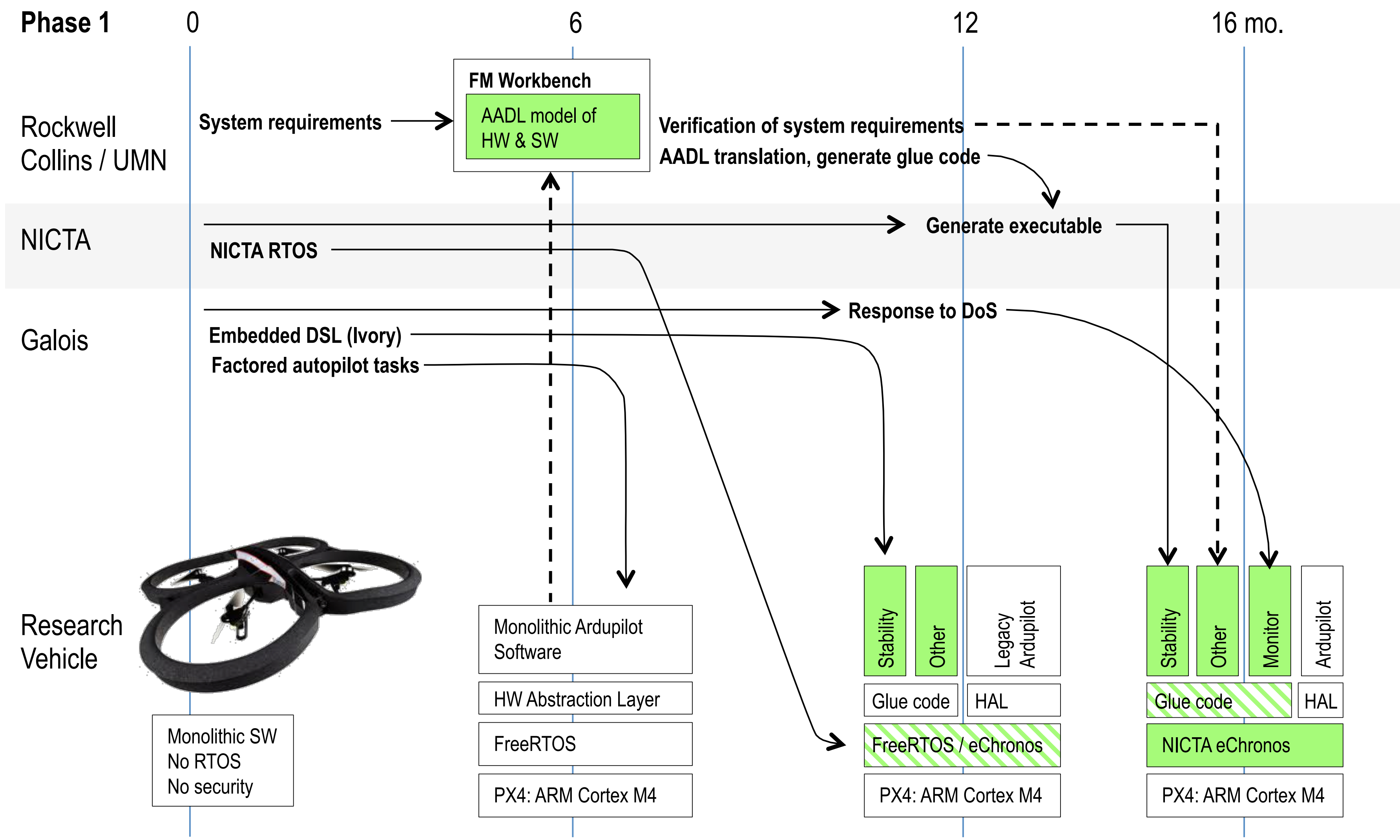
Performers:
- 8 Primes (*)
- 22 Organizations Total

Quadcopter: Initial Security Assessment

Attacker could crash legitimate ground control station & hijack quadcopter in flight.

(Systems were designed to ensure connectivity, not security)

The Evolving SMACCMCopter Architecture



The SMACCMCopter: 18-Month Assessment

- The SMACCMCopter flies:
  - Stability control, altitude hold, directional hold, and DOS detection and response.
  - GPS waypoint navigation 80% implemented.
- Air Team proved system-wide security properties:
  - The system is memory safe.
  - The system ignores malformed messages.
  - The system ignores non-authenticated messages.
  - All “good” messages received by SMACCMCopter radio will reach the motor controller.
- Red Team: *Found no security flaws in six weeks with full access to source code.*
- Penetration Testing Expert:
  The SMACCMCopter is probably “the most secure UAV on the planet.”

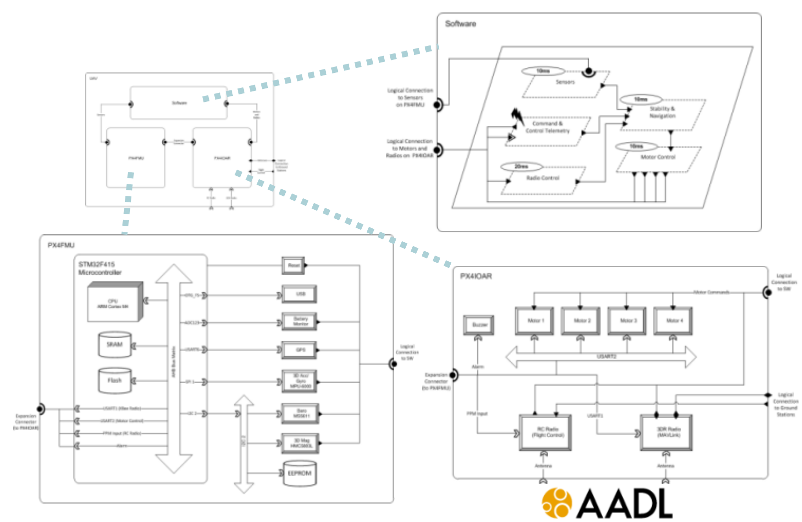
Open source: autopilot and tools available from http://smaccmpilot.org

Rockwell Collins (UMinn) – Technical Area 4

- Task Summary
  - Develop formal architecture model for SMACCMCopter and Boeing's Unmanned Little Bird (ULB)
  - Develop compositional verification tool (AGREE) and architecture-based assurance case tool (Resolute)
  - Develop code synthesis tools to generate build code
- Performance Summary
  - Generated software for Research Vehicle (~75KLOC), 60% high assurance.
  - Created AADL models of HW & SW architecture for SMACCMCopter (~3.6K LOC) and ULB
  - Extended AGREE tool for compositional reasoning and proved 10 properties about vehicle safety
  - Developed Resolute tool for capturing & evaluating assurance case arguments linked to AADL model
  - Developed assurance cases for 6 security requirements for information flow and memory safety
  - Developed synthesis tool to generate configuration data & glue code for OS/platform HW

References

- Your What is My How,
  IEEE Software (March 2013)
- Resolute: An Assurance Case Language for
  Architecture Models, HILT (October 2014).



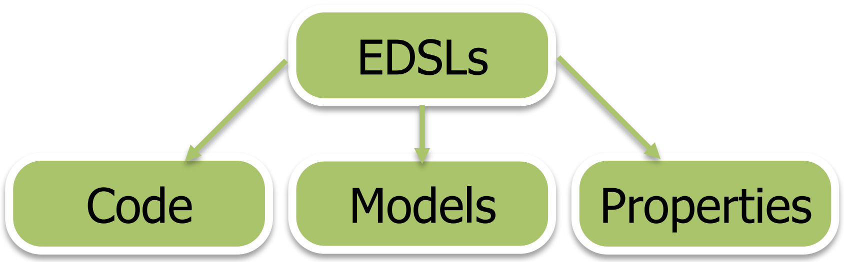
Galois – Technical Area 3

- Task Summary
  - Synthesize flight-control code, models, and properties from one specification
  - Generate safe low level-code in a scalable way by creating embedded domain-specific languages (Ivory and Tower) and using the host language (Haskell) as an expressive macro language.
- Performance Summary

  - Created Ivory, an open-source EDSL for synthesizing safe low-level code.
    - No buffer overflows, no null pointer dereference, no memory leaks, safe system calls.
  - Created Tower, an open-source EDSL for describing tasks and the connections between them.
    - Hides dangerous low-level scheduling primitives, tracks channel type information, generates AADL code to support analysis and glue-code generation
  - Designed & built SMACCMCopter, the first high-assurance UAV autopilot, in <2 engineer-years
    - ~10KLOC Ivory & Tower yields ~50KLOC C++
    - EDSL compilers automatically generate >2500 properties, 6KLOC of architecture models
    - Hardware Abstraction Layer (HAL) from SMACCMPilot in current use by hobbyist UAV community with over 40K members
    - Flew demo at Pentagon (altitude hold, position hold, stability, DOS detection)
  - Designed & built secure communication system:
    - Open-source, low-bandwidth secure communication protocol for small UAVs
    - Transitioned to Boeing and hobbyist community

Reference:

Building Embedded Systems with Embedded DSLs (Experience Report), ICFP (Sept 2014)

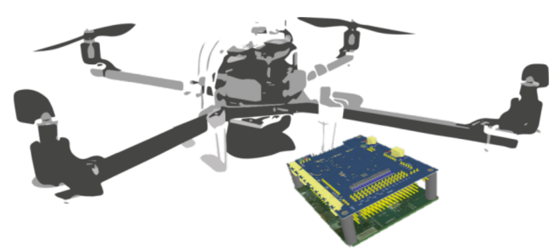


NICTA – Technical Area 2

- Task Summary
  - Formally verify OS kernels: seL4 microkernel (*now open-source!*) and eChronos RTOS
  - Synthesize OS components and automated proofs from DSLs (file systems and device drivers)
  - Provide verified CAmkES component platform for rapid system construction
- Performance Summary
  - seL4: First formally-verified OS microkernel
    - Ported to run on SMACCMCopter and ULB
    - Formal specification and implementation of new HW-virtualization features
    - Previously verified: correctness of kernel binary
    - Security properties: integrity and confidentiality
    - Code: 8830LoC C; Proof: 400KLoC Isabelle
  - eChronos: high-assurance RTOS product line
    - 6 RTOS variants generated (76 possible)
    - Code: 2.4KLoC, Variant Specification: 650LoC Isabelle
    - Automatic proof of safe execution.
Proof of high-level properties, e.g. scheduler fairness, correct signaling: 5 KLoC
  - Formally Verified OS Components
    - Generated high-assurance FLASH file system from 2 domain specific languages (3KLoC), 10KLoC language correctness proofs. File system design performs on par with mainstream file systems.
    - High-performance CAN and SPI drivers implemented as CAmkES components (5.6KLoC)
    - Security analysis of air-ground link protocol
  - CAmkES: High-Assurance Component Platform
    - Formal semantics for CAmkES component platform ADL (1.2KLoC)
    - Generated glue-code in Isabelle/HOL (generated glue code spec, 5.3KLoC generator)
    - Generated correctness proofs (1.2KLoC) & proof of safe execution

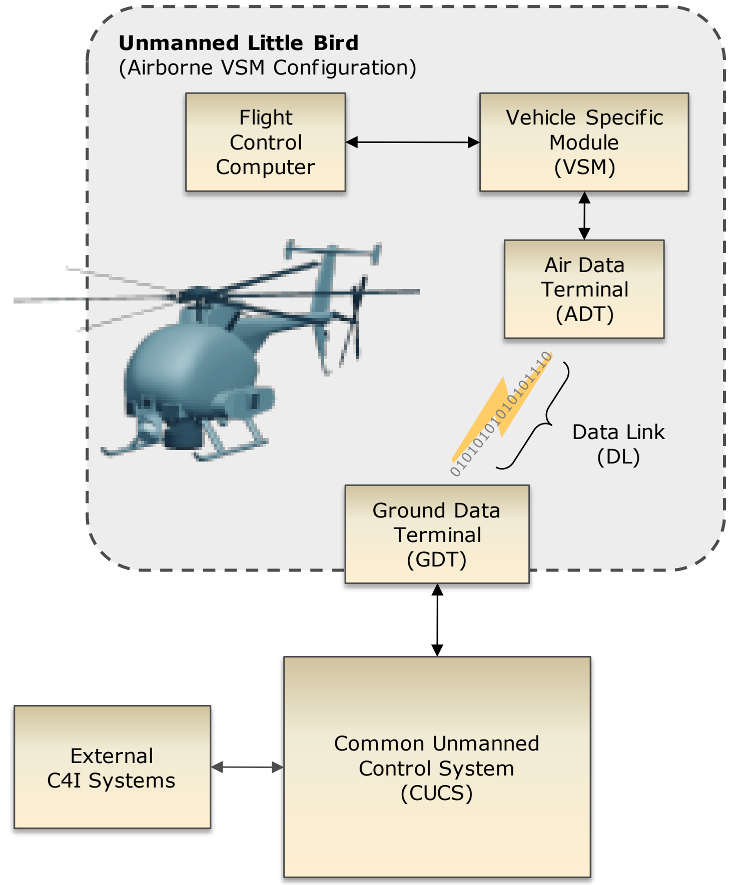
Reference:

Comprehensive Formal Verification of an OS Microkernel, TOCS (Feb 2014)



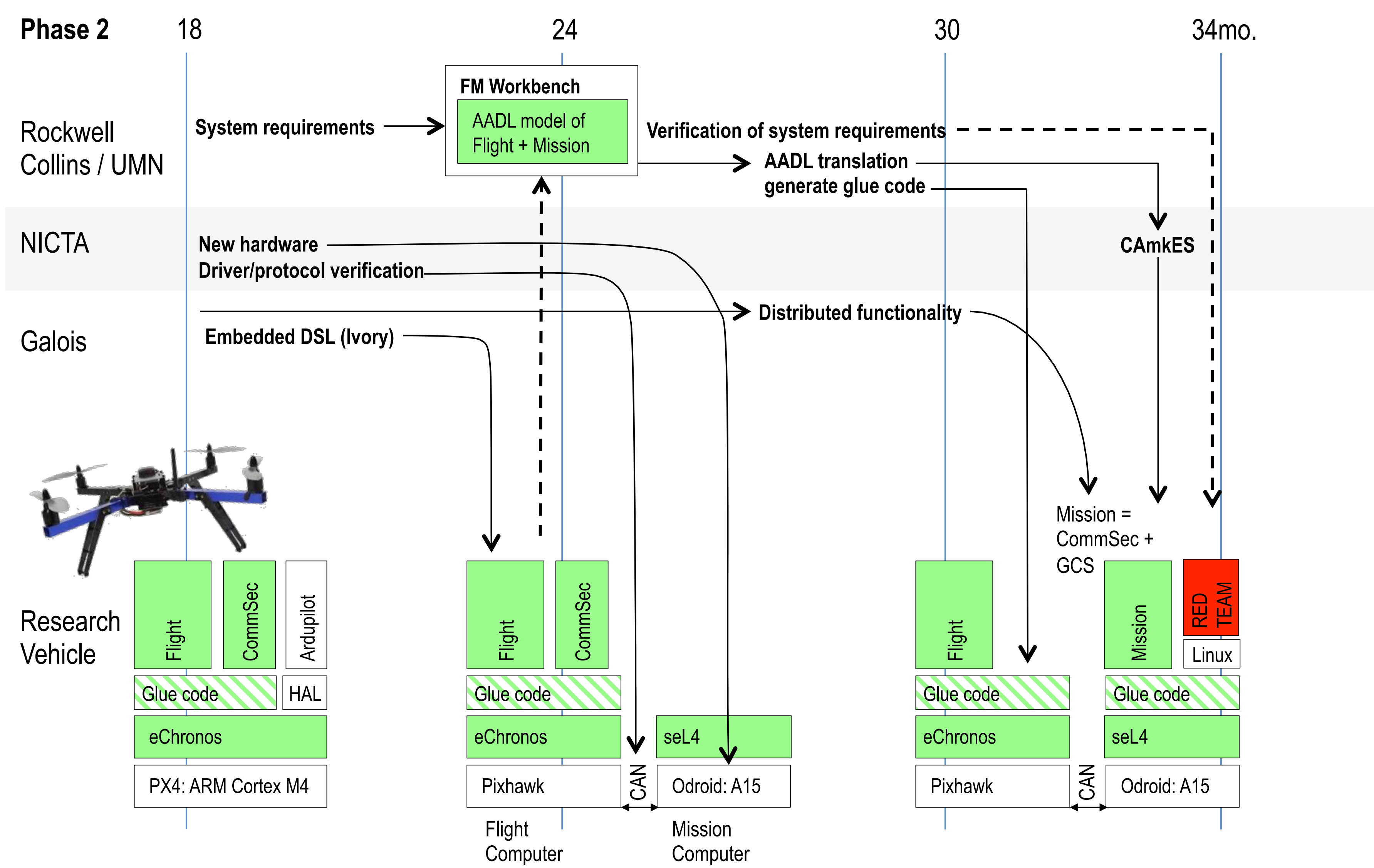
Boeing – Technical Area 1

- Task Summary
  - Integrate HACMS technologies into ULB
    - Substitute eChronos on the Flight Control Computer and seL4 on the Vehicle Specific Module (VSM)
    - Use HACMS-generated secure components to replace elements of the existing ULB software
  - Use the HACMS workbench to verify security properties of the resulting system
  - Support flight demo at the end of Phase 3.
- Performance Summary
  - Ported VSM to run on seL4
    - New hardware supports seL4 memory protection
    - Incorporates Air Team authentication protocol
  - Phase 2 VSM architecture designed to support application of all 3 Air Team technologies
    - Completed initial AADL model of Phase 2 architecture for use in HACMS Workbench



The air team is on-track for a live flight demo on the Unmanned Little Bird at the end of the Phase 3

Air Team: SMACCMCopter



Tech Transition

Barriers to adoption of HACMS-like technology:

- Lack of trained workforce (estimated <1000 formal methods experts in US)
- Lack of commercial support for formal-methods tools (COTS rules!)
- Difficulties interfacing with legacy tools (thousands) and code bases (millions)
- Uncertainty about maintainability of high-assurance artifacts
  - The B-52 has been flying since 1955
- Qualification of tool chain (eg, DO-178C, DO-326)
- Need for traceability
- Resource constraints (hardware, SWAP)
- Multicore (gulp!): chips may be multicore whether desired or not
- What is the business case? Quantification is important.

Questions?

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Promising, but lots more to do!

Building High-Assurance Systems
- Proof Engineering
- Secure composition of high-assurance components
- Architecture-aware proof support
- Verified, reusable, exquisite artifacts

Formal Tools
- Verified high-level languages
- First-class domain-specific languages
- Program/Proof synthesis
- Improved tactics for theorem provers
- Model checker/theorem prover integration

Control Systems
- Attack-resistant control systems
- Generated safety-envelope monitors
- Models of "good" and "bad" behaviors
- Certifying advanced control systems

Resources
- Reasoning about time
- Reasoning about memory usage
- Verified protocols for distributed systems

Specifications
- Specification analysis
- Specs for environmental assumptions
- Specs for attacks

Tech Transition Issues