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

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Tufts University
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(Slides based on original DARPA HACMS slides)
Pervasive Vulnerability to Cyber Attack

SCADA Systems

Medical Devices

Vehicles

Computer Peripherals

Appliances

Communication Devices
Modern Automobile: Many Remote Attack Vectors

Mechanic

Short-range wireless

Long-range wireless

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

Source: www.custom-build-computers.com
Source: CanOBD2
Source: www.diytrade.com
Source: www.theunlockr.com

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

Source: American Car Company

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

Source: www.bluetooth.com
Source: © Bluetooth SIG, Inc.

Source: WiFi Alliance
Source: © WiFi Alliance

Source: christinayy.blogspot.com
Source: © Bluetooth SIG, Inc.

Source: www.wikihow.org
Source: © WiFi Alliance

Source: www.zedomax.com
Source: © WiFi Alliance

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

Source: www.koscherlab.org
Source: © WiFi Alliance

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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

<table>
<thead>
<tr>
<th>Vulnerability Title</th>
<th>Fix Avail?</th>
<th>Date Added</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linux Kernel Controller Area Network Protocol Local Privilege Escalation Vulnerability</td>
<td>No</td>
<td>8/30/2010</td>
</tr>
<tr>
<td>Red Hat VSIM Module SQL Connection Denial of Service Vulnerability</td>
<td>Yes</td>
<td>8/30/2010</td>
</tr>
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<td>PHP 'base64decode()' Function off-by-one Buffer Overflow Vulnerability</td>
<td>No</td>
<td>8/30/2010</td>
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<td>Internet Explorer 8 &quot;IfModifiedSince&quot; HTML Sanitation Bypass Weakness</td>
<td>No</td>
<td>8/18/2010</td>
</tr>
<tr>
<td>Cisco Unified Wireless Network (UNM) Multiple Security Vulnerabilities</td>
<td>Yes</td>
<td>8/14/2010</td>
</tr>
<tr>
<td>Computer Associates Overview Monitor &quot;Deliver-jp&quot; Remote Code Execution Vulnerability</td>
<td>No</td>
<td>8/14/2010</td>
</tr>
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<td>OpenSSL &quot;SSL_get_cipher_text&quot; Use-After-Free Memory Corruption Vulnerability</td>
<td>No</td>
<td>8/10/2010</td>
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<td>Adobe Acrobat and Reader Java Plugin Remote Code Execution Vulnerability</td>
<td>No</td>
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<td>OpenOffice Impress File Multiple Buffer Overflow Vulnerabilities</td>
<td>No</td>
<td>8/9/2010</td>
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<td>Linux Kernel PA-RISC 'Stack' Stack Buffer Overflow Vulnerability</td>
<td>No</td>
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<td>Microsoft DirectOffice Multiple Denial Of Service Vulnerabilities</td>
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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]

[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

High Assurance: Ensuring Correctness, Safety, Security
## HACMS Program Structure

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### Program Timeline:
- 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 SMACC McCopter Architecture

**Phase 1**

- **Rockwell Collins / UMN**
  - System requirements
  - Monolithic SW
    - No RTOS
    - No security
  - Ardupilot Software
  - HW Abstraction Layer
  - FreeRTOS
  - PX4: ARM Cortex M4

- **NICTA**
  - NICTA RTOS

- **Galois**
  - Embedded DSL (Ivory)
  - Factored autopilot tasks

- **Research Vehicle**
  - Monolithic SW
  - No RTOS
  - No security

**FM Workbench**

- AADL model of HW & SW
- Verification of system requirements
  - AADL translation, generate glue code
- Generate executable
- Response to DoS

**System requirements**

- NICTA RTOS
- Embedded DSL (Ivory)
- Factored autopilot tasks

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The diagram illustrates the evolving architecture of the SMACC McCopter project, detailing the phases and components involved, including software frameworks and security responses.
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

System requirements
- Driver/protocol verification
- Distributed functionality
- Embedded DSL (Ivory)

FM Workbench
- AADL model of Flight + Mission
- Verification of system requirements
- AADL translation
- Generate glue code

Phase 2:
- 18
- 24
- 30
- 34mo.

Rockwell Collins / UMN
- New hardware
- Driver/protocol verification

NICTA
- Embedded DSL (Ivory)

Galois
- Distributed functionality

NICTA
- FM Workbench
- Verification of system requirements
- AADL translation
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New hardware
- PX4: ARM Cortex M4
- Pixhawk
- Odroid: A15

Research Vehicle
- Flight
- CommSec
- Ardupilot
- PX4: ARM Cortex M4
- Flight Computer
- Glue code
- eChronos
- CAN

Mission = CommSec + GCS
- seL4
- Odroid: A15
- Mission Computer
- Glue code
- eChronos
- CAN

Mission
- RED TEAM
- Linux
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?
# HACMS Program Structure

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### 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
Promising, but lots more to do!

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<td>• Proof Engineering</td>
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<td>• Secure composition of high-assurance components</td>
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<td>• Architecture-aware proof support</td>
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<td>• Verified, reusable, exquisite artifacts</td>
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<td>• Verified high-level languages</td>
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<td>• First-class domain-specific languages</td>
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<td>• Program/Proof synthesis</td>
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<tr>
<td>• Improved tactics for theorem provers</td>
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<td>• Attack-resistant control systems</td>
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<td>• Generated safety-envelope monitors</td>
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<td>• Models of “good” and “bad” behaviors</td>
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<td>• Certifying advanced control systems</td>
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Tech Transition Issues