Experimental Platform for Model-Based Design of Embedded Systems

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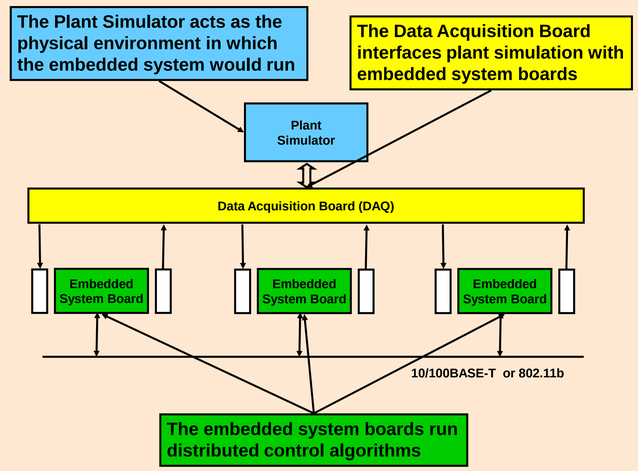
Experimental Platform Architecture



Specifications

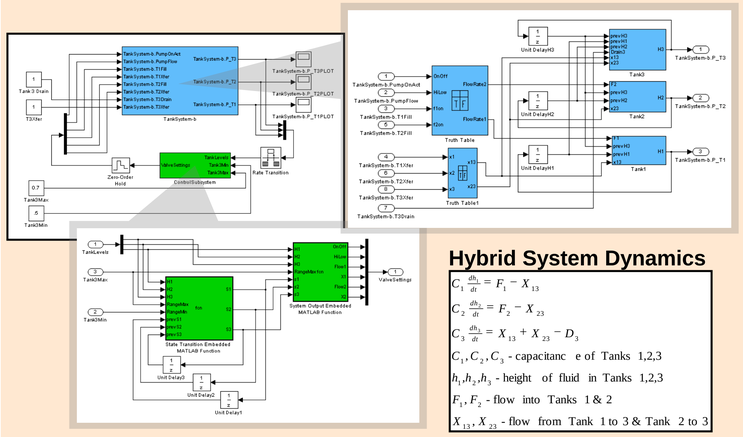
Plant Simulator
- Standard Desktop PC running Mathworks xPC
- DAQ blocks are appended to Plant Models
- xPC Code Generated with Real-Time Workshop

Data Acquisition Board
- Measurement Computing PCI-DDA08/12
- 8 analog output channels (12 bit resolution)
- 48 Digital I/O

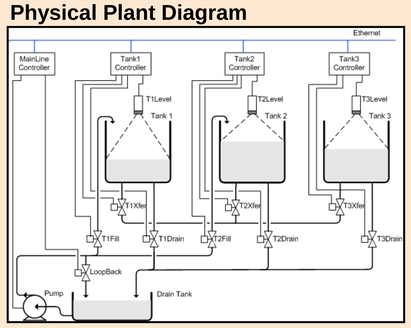
Embedded System Board
- Micro/Sys SBC4495
- Cyrix Intel 486 compatible processor
- 8 Analog Inputs & Outputs (14 bit resolution)
- 24 Digital I/O
- 10/100BASE-T Ethernet, 802.11b
- Supported OS
  - Linux, Windows CE/98, VxWorks, LynxOS, PharLap ETS, MSDOS 5.0

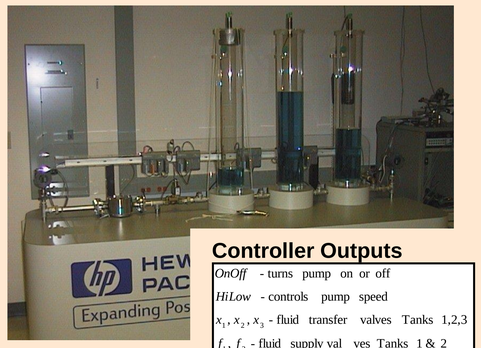
Three Tank System

- System is a test bed for the Modeling and Analysis of Complex Systems (MACS) group at Vanderbilt University
- The three tank system was chosen as an archetypical component controlled by SCADA system
- Three tank systems are common in chemical processing systems
- Tanks 1 & 2 regulate fluid levels in Tank 3 while Tank 3 supplies fluid to some process downstream
- We use this system to demonstrate and test the capabilities of security measures introduced via Model-Based Design



Physical Plant Diagram





Hybrid System Dynamics

$C_1 \frac{dh_1}{dt} = F_1 - X_{13}$

$C_2 \frac{dh_2}{dt} = F_2 - X_{23}$

$C_3 \frac{dh_3}{dt} = X_{13} + X_{23} - D_3$

C_1, C_2, C_3 - capacitanc e of Tanks 1,2,3

h_1, h_2, h_3 - height of fluid in Tanks 1,2,3

F_1, F_2 - flow into Tanks 1 & 2

X_{13}, X_{23} - flow from Tank 1 to 3 & Tank 2 to 3

Controller Outputs

OnOff - turns pump on or off

HiLow - controls pump speed

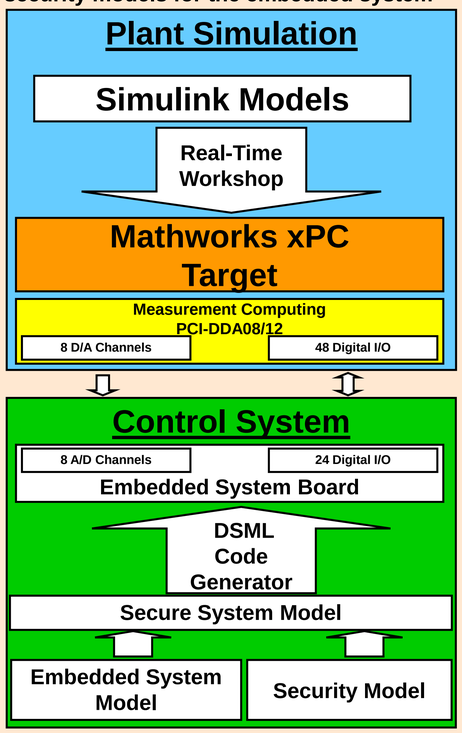
x_1, x_2, x_3 - fluid transfer valves Tanks 1,2,3

f_1, f_2 - fluid supply val ves Tanks 1 & 2

d_3 - Tank 3 drain

Testing Model-Based Security Features

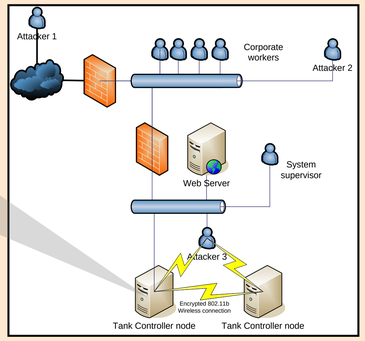
- The experimental platform facilitates "Hardware"-in-the-Loop testing of controllers.
- High fidelity plant simulations behave just as the actual physical environment would.
- Controllers can run on various operating systems with different security designs.
- Code for controllers is generated based on security models for the embedded system



- The experimental platform is configured for specific control problems such as a Three Tank System controlled by a SCADA system.
- We then test a variety of attacks against the system
- This allows us to exercise the code produced from the security models for:
  - Performance overhead
  - Strength of security for specific attacks
  - Comparison between different operating systems

Configuration of Experimental Platform for Three Tank Testing

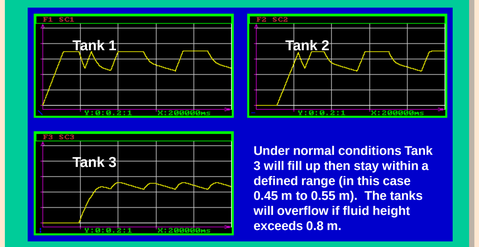
Application Code	Application Code
GRsecurity Extensions	
Gentoo Linux (kernel 2.4.32)	
Device Drivers	
Embedded System Board	



- For the tests conducted on a Three Tank Controller we are running Gentoo Linux (kernel 2.4.32) with GRsecurity extensions.
- GRsecurity adds 3.9% (33 kB) to the kernel footprint
- Performance overhead is 3.5% for non-executable memory protection
- GRsecurity extensions allow fine grained control over system resources
  - I/O registers
  - Memory Protection
  - Inter-process Communication

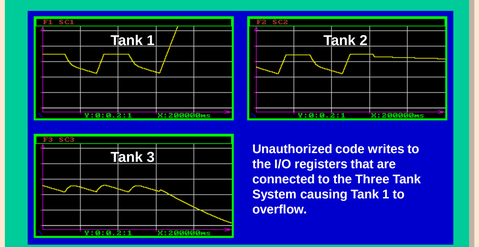
Attacks on Three Tank System

Normal Operation



Under normal conditions Tank 3 will fill up then stay within a defined range (in this case 0.45 m to 0.55 m). The tanks will overflow if fluid height exceeds 0.8 m.

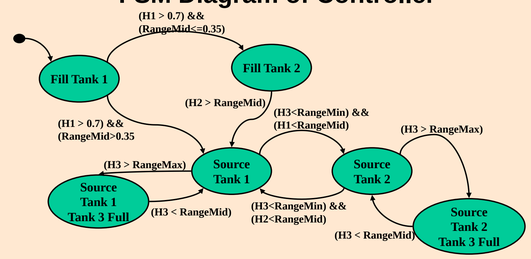
Unauthorized Access to I/O registers



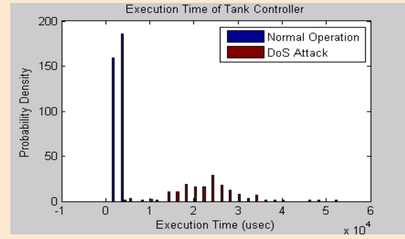
Unauthorized code writes to the I/O registers that are connected to the Three Tank System causing Tank 1 to overflow.

- With I/O register protection only the tank control process has permission to write to I/O channels
- Model-Based approach can map desired security properties to underlying platform services such as POSIX capabilities (e.g. CAP_SYS_RAWIO)

FSM Diagram of Controller



- Denial of Service attack can increase execution time of tank control process
  - Operation under normal conditions
    - Worst case execution time = 12712 µs
    - Mean execution time = 3123 µs
  - Denial of Service attack on network data access component
    - Worst case execution time = 52600 µs
    - Mean execution time = 23200 µs



- DoS attacks cannot be easily prevented without support of platform services such as packet filtering.