Embedded Control Systems

Lecture: MW 130-3PM 1311 EECS

Labs: 4342 EECS

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Embedded Control Systems

- Background:
  - University of Michigan and Ford Motor Company, 2004
  - Control theorists and computer scientists: why do we have to hire one of each to develop embedded controls?
  - Teach a little computer engineering to control theorists, and a little signal processing and control to computer engineers
  - Also taught at ETH (2008)

Important Points

- No textbook
  - `www.eecs.umich.edu/courses/eecs461`
  - Lecture notes, microprocessor reference material, laboratory exercises, homework problems and lots of other important information will be posted
  - Syllabus lists some useful (but not required) books on embedded systems programming
  - I'll mention during lecture what you should be reading
- Homework will be Matlab, Simulink, Stateflow
  - Problem sets will be posted on the website
  - Typically have one week per problem set. Homework is due at the beginning of class. Late homework will not be accepted. The *Homework Policy is posted on the course website, and included in the syllabus.*

Important Points

- Laboratory exercises
  - 8 laboratory exercises plus a project using the Freescale MPC5553 microprocessor
    - Most labs are "1-day" (1 lab per week)
    - First lab will be two weeks beginning Monday, 12 January – <u>BUT</u> MLK day on 19 January means Monday section has only one scheduled lab
    - Lab instructors will have "open hours" on Friday, 16 January and/or Friday 23 January for Monday students. <u>Check with your lab instructor for times</u>
  - 6 lab stations with 2 students ("self organize")

Important Points

- Special lecture on embedded system programming
  - Important information for lab #1
  - When to do this lecture?
    - Monday? … but lab starts at 3:30
    - Special lecture on Friday?
      - Same time and place, if I can get the room

Important Points

- Laboratory exercises have 3 parts:
  - **Pre-lab:** questions that require you to read the microprocessor reference material and gather the information required to complete the lab exercise
  - **In-lab:** the experiment
  - **Post-lab:** questions that should reinforce what you learned in the lab exercise
  - Read the “lab policy” in the syllabus

Other Useful Information

- Grading:
  - Homework: 25%
  - Laboratory Assignments: 25%
  - Quizzes (tentatively scheduled for February 18th and April 1st): 30%
  - Project: 20%
- Office Hours: 10:00 - Noon, Monday and Wednesday, but feel free to stop by or email me to set up an appointment
- Email alias: `eecs461@eecs.umich.edu`
  - See syllabus for instructions

Outline

- Embedded systems and embedded *control* systems
- Laboratory description
  - Freescale MPC5553 microcontroller
  - Software development environment
  - Haptic interface
- Lecture Topics
- Laboratory Exercises

What is an Embedded System?

- Technology containing a microprocessor as a component
  - cell phone
  - PDA
  - digital camera
- Constraints not found in desktop applications
  - cost
  - power
  - memory
  - interface

$\Rightarrow$ Embedded processor is often the performance and cost limiting component!

What is an Embedded *Control* System?

- Technology containing a microprocessor as a component *used for control:*
  - Automobile
  - Aircraft and UAV
  - Active control of civil structures
  - Manufacturing tools
  - Household appliances
  - Many others …

Characteristics of Embedded Control Systems

- Interface with external environment
  - sensors and actuators
- “Real time” critical
  - performance and safety
  - embedded software must execute in synchrony with physical system
- Distributed control
  - networks of embedded microprocessors

Skills Required for Embedded Controls

- Algorithms (control, signal processing, communications)
- Computer software (real time, multitasking)
- Computer hardware (interfacing, memory constraints)
- Digital electronics
- Sensors and actuators
- Mechanical design

- Multi-disciplinary!

Industry Trends

- Increasing complexity of embedded control systems and software
  - Actuators, sensors, processors, networks
  - Typical small car contains ~70 microprocessors
- Model based embedded control software design
  - Matlab/Simulink/Stateflow
  - Autocode generation
  - Rapid prototyping
  - Hardware in the loop (HIL) testing
- "Separation between *control design* and *controller implementation* is not sustainable in embedded market"*

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* Industry Needs for Embedded Control Education, Tutorial Session 2005 ACC
J. Freudenberg (UM), B. Krogh (CMU), J. Cook (Ford), K. Butts (Toyota), J. Ward (Eaton)

An Embedded Design Team

- May consist of:
  - Applications engineers
    - Model the systems to be controlled, design control algorithms
  - Hardware specialists
    - Low-lever drivers and other hardware specific design
  - Software engineers
    - Write C code from specifications given to them by applications engineers
- Applications engineers, hardware engineers and software engineers have to communicate!

Languages

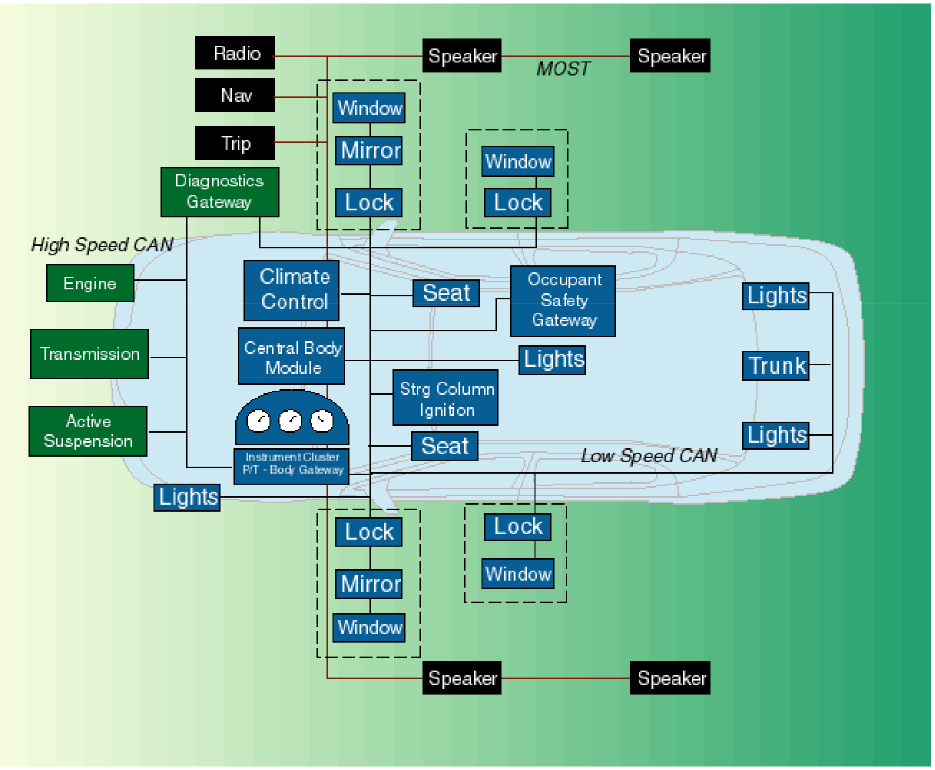
- Some assembly language
  - device drivers, highly optimized code
- Most coding done in C
  - interest in C++ and Java, but too much overhead for highly constrained applications
- Automatic code generation
  - automatically generate C code from a Matlab/Simulink model used to design and test control algorithm
  - currently useful for rapid prototyping on non-production processor
  - also used for high end applications (NASA)

MPC5553/5554 Examples: Automotive Applications

- Powertrain
  - Fuel and ignition control
  - Aftertreatment control for diesels
  - Valve control, turbocharger control, transmission control including CVT
  - Control of hybrid-electric powertrains
- Safety
  - ABS, traction control, electronic stability control, rollover control
- Lots of I/O: sensors & actuators
  - Real time critical: performance & safety
  - Harsh environment (EMI, noise, vibration, temperature)

Automotive Distributed Systems: Mobile Networking

- High-speed CAN
- Low-speed CAN
- Local Interconnect Network (LIN)
- Media Oriented Systems Transport (MOST)
- Bluetooth
- Intelligent Transportation System Data Bus (IDB 1394)
- FlexRay, Time-triggered CAN …



Application of the MPC555 (predecessor of the MPC5553)

- SeaScan transoceanic pilotless aircraft
- ScanEagle Intelligence, surveillance and reconnaissance support; USS Oscar Austin (DDG 79) Guided Missle Destroyer
- The Insitu Group: www.insitu.com

Laboratory Overview

- MPC5553 Microcontroller (Freescale)
  - Originally automotive control, now used in many applications
- Development Environment
  - Debugger (P&E Micro)
  - Codewarrior C compiler (Freescale)
- Haptic Interface
  - Force feedback system for human/computer interaction
- Rapid Prototyping Tools
  - Matlab/Simulink/Stateflow, Real Time Workshop (The Mathworks)
  - RAppID Toolbox (Freescale)
- Real Time Operating System
  - OSEKturbo RTOS (Freescale)

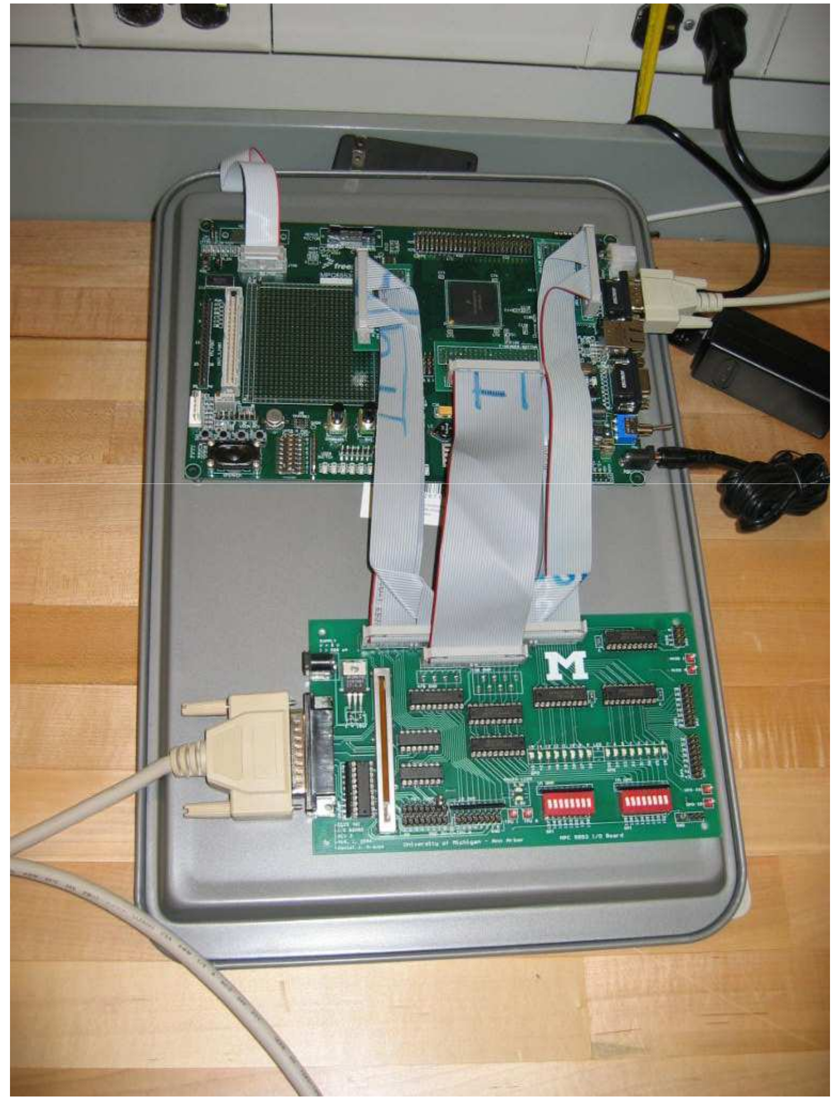
Freescale MPC5553 Microcontroller

- 32 bit PPC core
  - floating point
  - 132 MHz
  - -40 to +125 °C temperature range
- Programmable Time Processing Unit (eTPU)
  - Additional, special purpose processor handles I/O that would otherwise require CPU interrupt service (or separate chip)
  - Quadrature decoding
  - Pulse Width Modulation
- Control Area Networking (CAN) modules
- 2nd member of the MPC55xx family
  - real time control requiring computationally complex algorithms
  - MPC5554 replaces MPC555 for powertrain control
  - MPC5553 has on-chip Ethernet for manufacturing applications

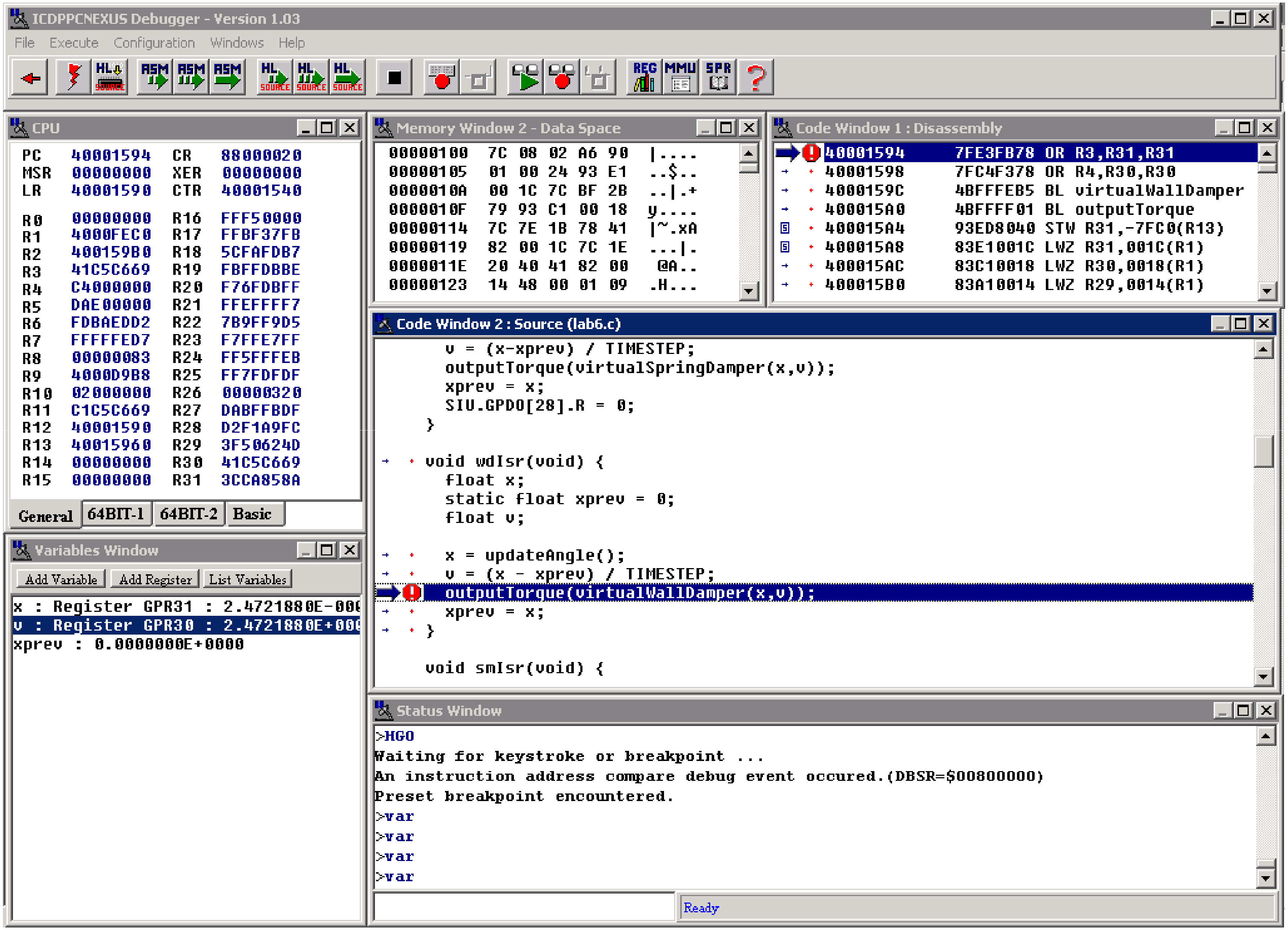
MPC5553 EVB

- Evaluation board (Freescale)
  - -32 bit PPC core
  - -floating point
  - -128 MHz

- Interface board (UofM)
  - – buffering
  - – dipswitches
  - – LEDs
  - – sliding potentiometer



Nexus Compliant Debugger (P&E Micro)



Haptic Interface

- Enables human/computer interaction through sense of touch
  - force feedback joystick
  - virtual reality simulators (flight, driving)
  - training (surgery*, assembly)
  - teleoperation (manufacturing, surgery**)
  - X-by-wire cars
- Human visual sensor: 30 Hz
- Human haptic sensor: 500Hz-1kH

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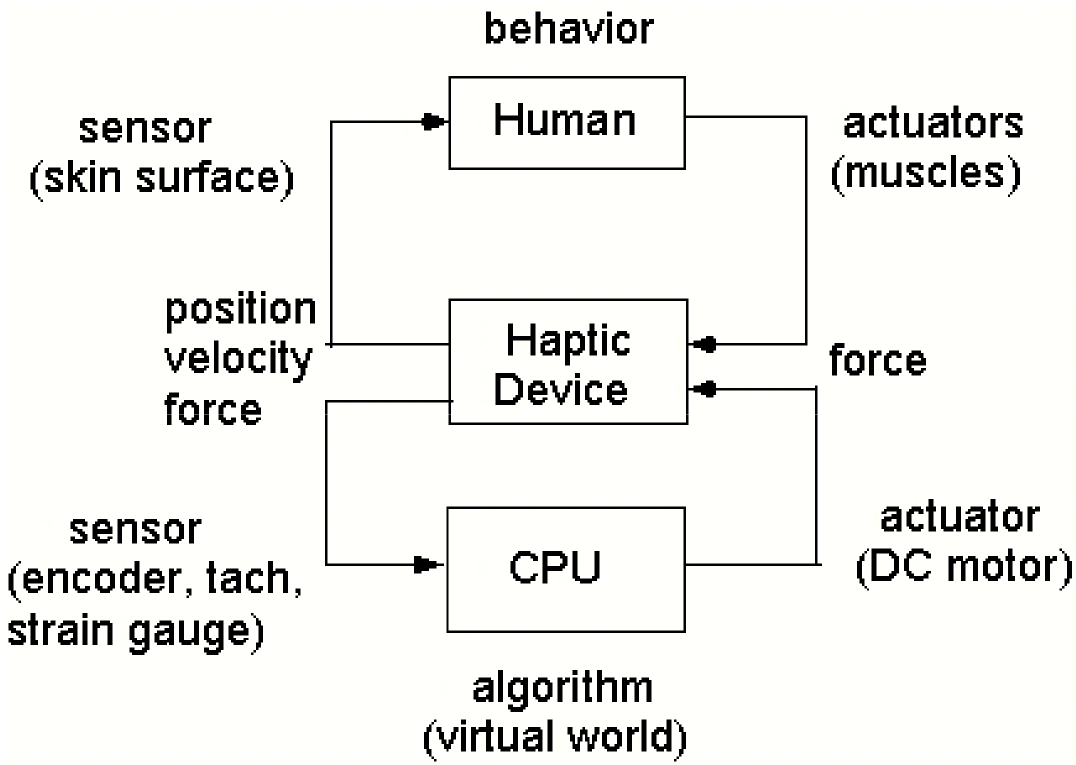
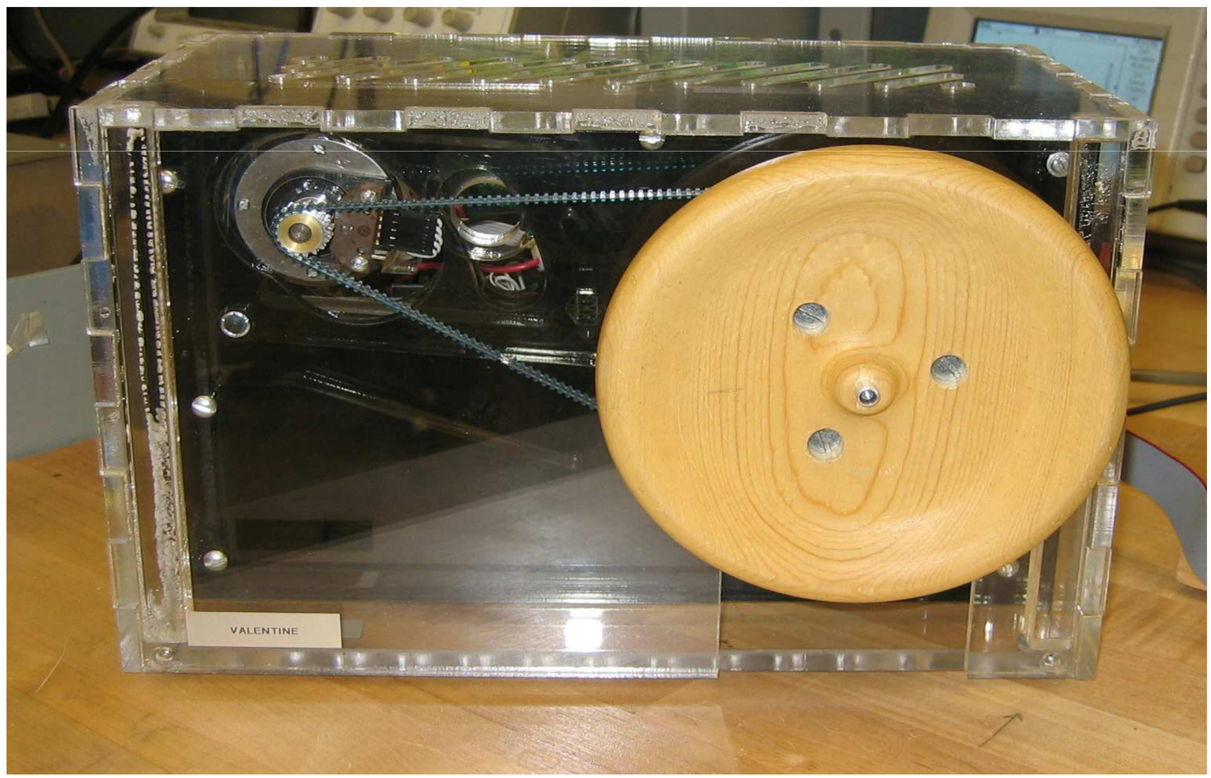
* D. Sordid and S. K. Moore, "The Virtual Surgeon", IEEE Spectrum, July 2000.
** J. Rosen and B. Hannaford, "Doc at a Distance", IEEE Spectrum, October 2006.

Force Feedback

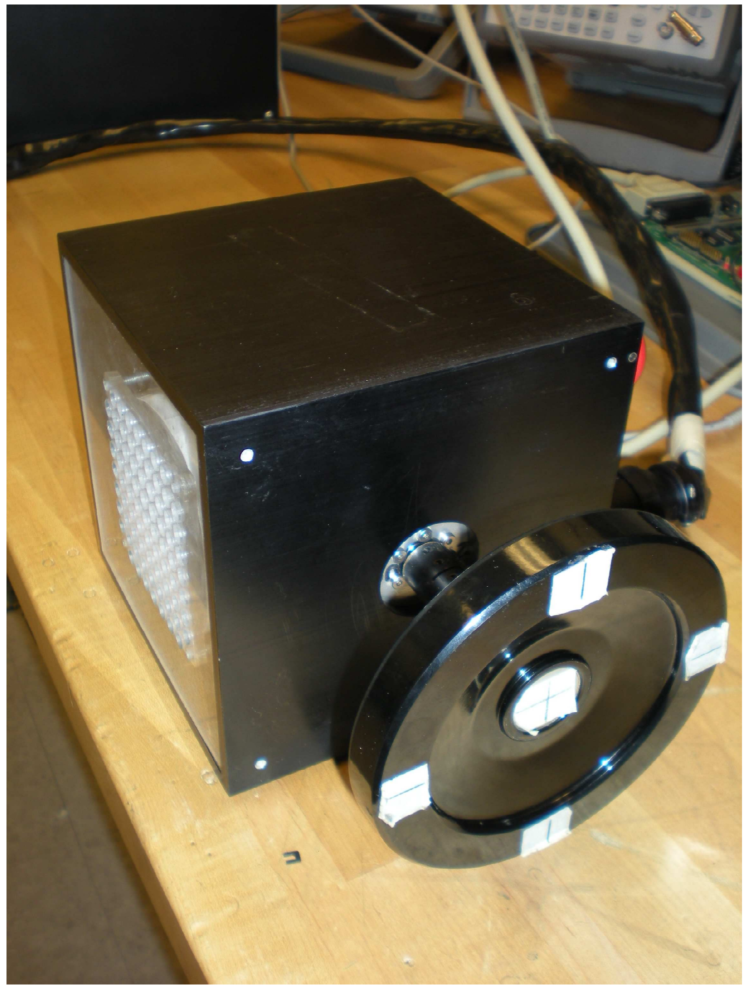


Haptic Wheel

- Prof. Brent Gillespie, Mech Eng Dept, UofM
  - DC motor
  - PWM amplifier w/ current controller
  - optical encoder
  - 128/18 gear ratio

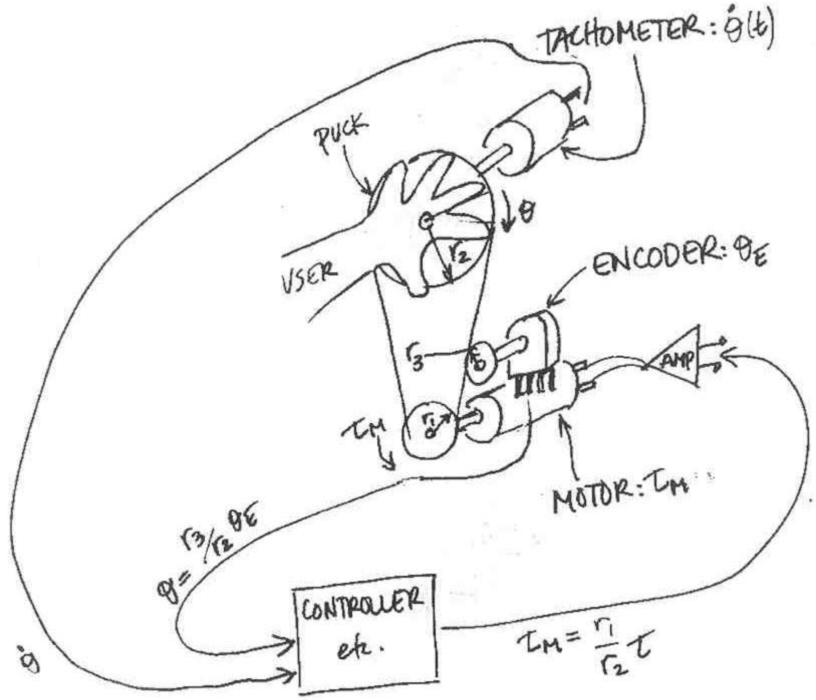


Haptic Wheel
(New and Improved for 2009)

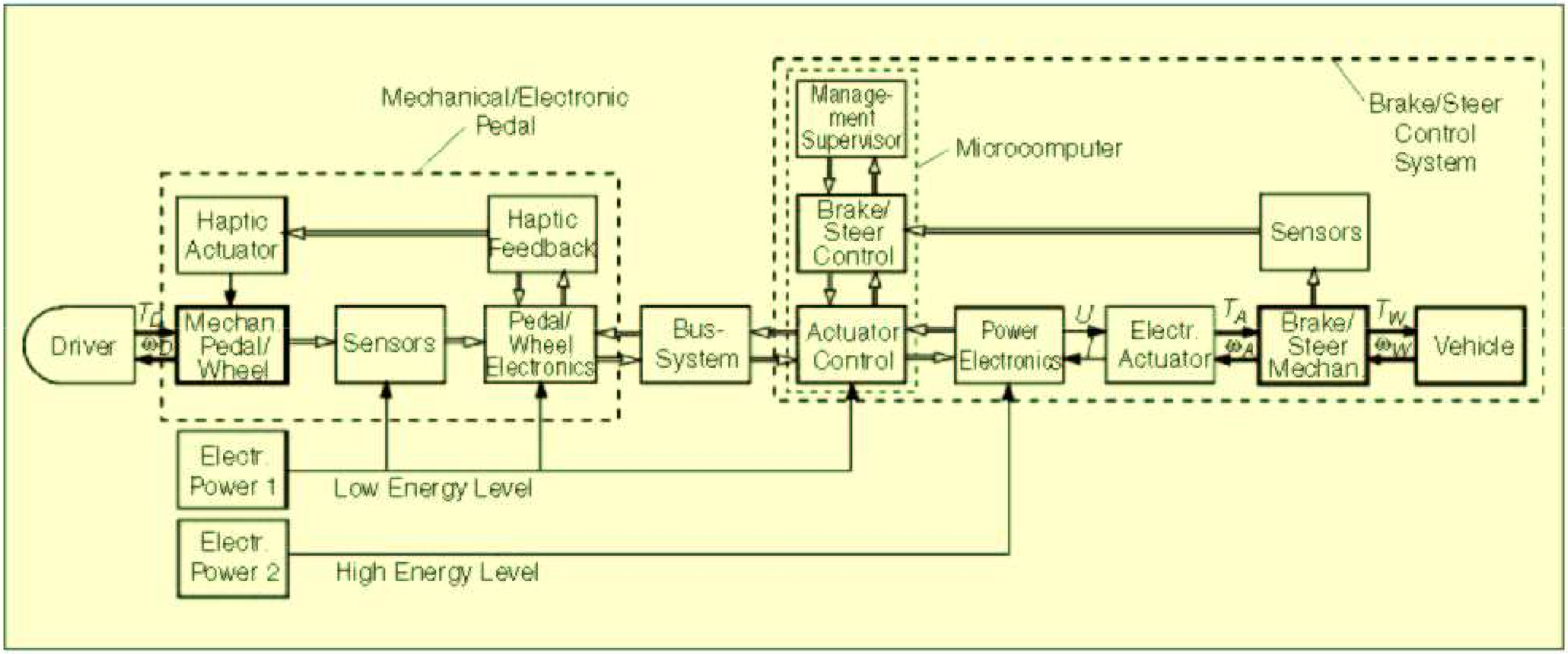


Virtual Environments

- Virtual wall
- Virtual spring-mass



Steer-by-wire Automobiles



R. Iserman, R. Schwarz, S. Stolzl, "Fault Tolerant Steer-by-Wire Systems" IEEE Control Systems Magazine, October 2002.

Lab Station

Lectures (I)

- Quantization
- Sampling
- Linear filtering
- Quadrature decoding
- DC motors
- Pulse Width Modulation (PWM) amplifiers
- Motor control: current (torque) vs. speed
- MPC5553 architecture. Peripherals: eTPUs, eMIOS, eDMA,…
- Haptic interfaces.
  - virtual wall
  - virtual spring/mass/damper
- Simulink/Stateflow modeling of hybrid dynamical systems
- Numerical integration.

Lectures (II)

- Networking:
  - Control Area Network (CAN) protocol.
  - Distributed control
- Interrupt routines: timing and shared data
- Software architecture
  - Round robin
  - Round robin with interrupts
  - Real time operating systems (RTOS)
  - Multitasking
- Shared data: semaphores, priority inheritance, priority ceiling
- Real time computation. Rate monotonic scheduling.
- Rapid prototyping. Autocode generation.
- Model based embedded control software development
- PID control design

Laboratory Exercises

- Each teaches
  - a peripheral on the MPC5553
  - a signals and systems concept
- Each uses concepts (and code!) from the previous labs

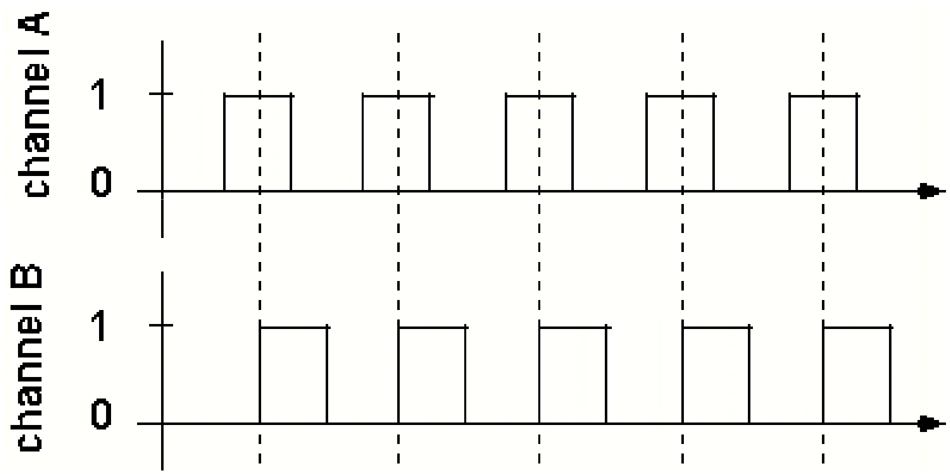
- Lab 1: Familiarization and digital I/O
- Lab 2: Quadrature decoding using the eTPU
- Lab 3: Queued A-D conversion
- Lab 4: Pulse Width Modulation and virtual worlds without time
- Lab 5: Interrupt timing and frequency analysis of PWM signals
- Lab 6: Virtual worlds with time.
- Lab 7: Controller Area Network (CAN)
- Lab 8: Rapid Prototyping

Lab 1: Familiarization and Digital I/O

- Use General Purpose Input/Output (GPIO) on MPC5553
- Read two 4-bit numbers set by dipswitches, add the values and display the results on LEDS

Lab 2: Fast Quadrature Decoding

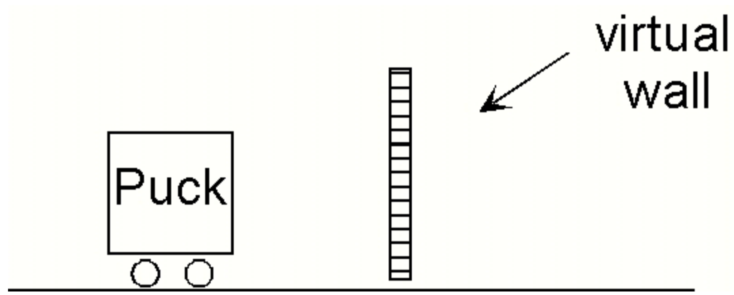
- Position measurement using an optical encoder
- Optical encoder attached to motor generates two 90° out of phase square waves:

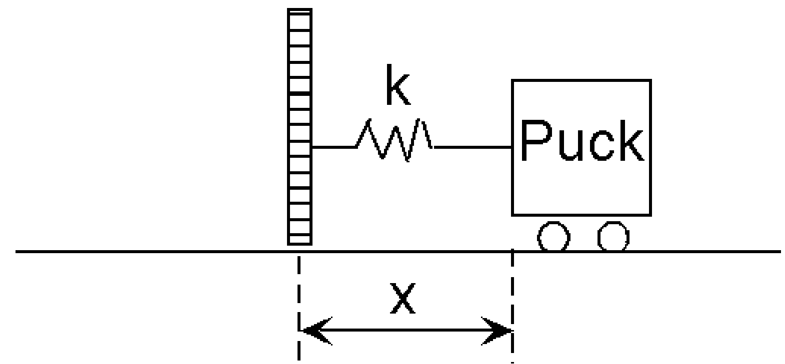


- QD function on MPC5553 eTPU:
  decodes quadrature signal into counter
- CPU must read counter before overflow

<u>Issue</u>: How fast can wheel turn before counter overflows?

Lab 4: Virtual Wall

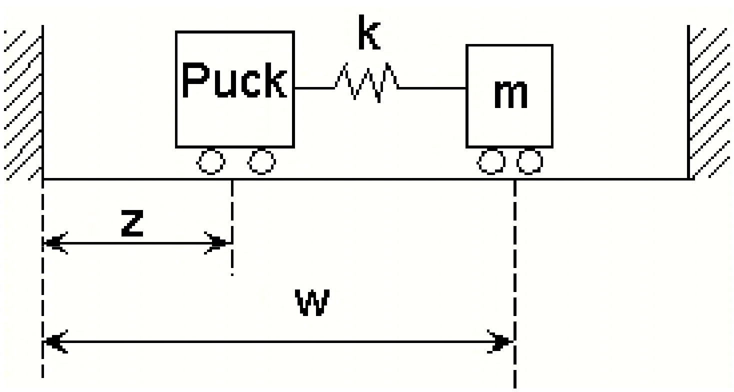




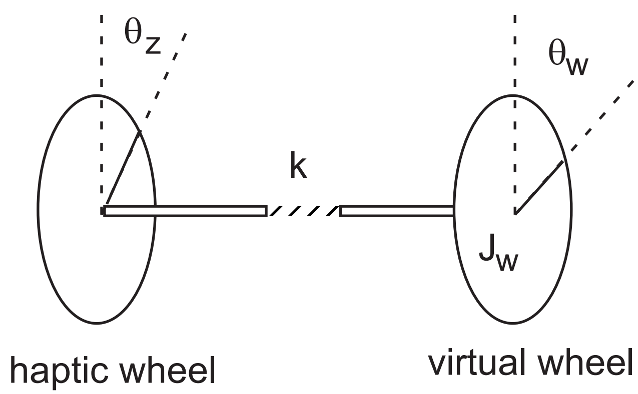
- Software loop
  - read position from encoder
  - compute force $F = 0$ or $F = kx$
  - set PWM duty cycle
- Rotary motion
  - degrees ⇔ encoder count
  - torque ⇔ PWM duty cycle
  - 1 degree into wall ⇔ 400 N-mm torque
- Wall chatter
  - large k required to make stiff wall
  - limit cycle due to
    - * sampling
    - * computation delay
    - * quantization
    - * synchronization

Lab 6: Virtual Spring-Mass System

- Virtual spring-mass system: reaction force $F = k(w-z)$
- Measure z, must obtain w by numerical integration
- Use interrupt timer to generate a time step



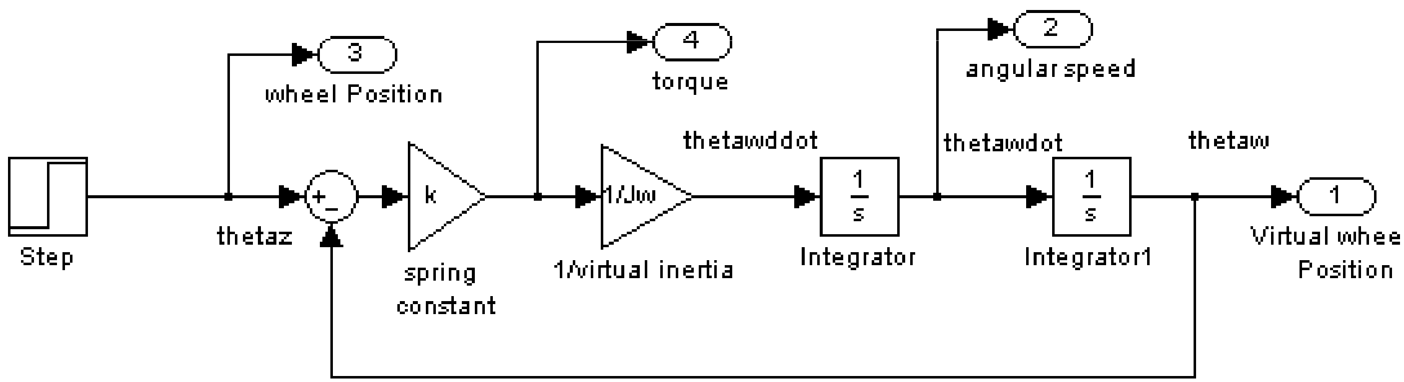
$$\ddot{w} + \frac{k}{m} w = \frac{k}{m} z$$



$$\ddot{\theta}_w + \frac{k}{J_w}\theta_z = \frac{k}{J_w}\theta_z$$

Lab 6: Design Specifications

- Choose k and J_w so that
  - virtual wheel oscillates at 1Hz
  - maximum torque in response to 45 degree step in wheel position is < 800Nmm



- Verify design in Simulink before testing on hardware

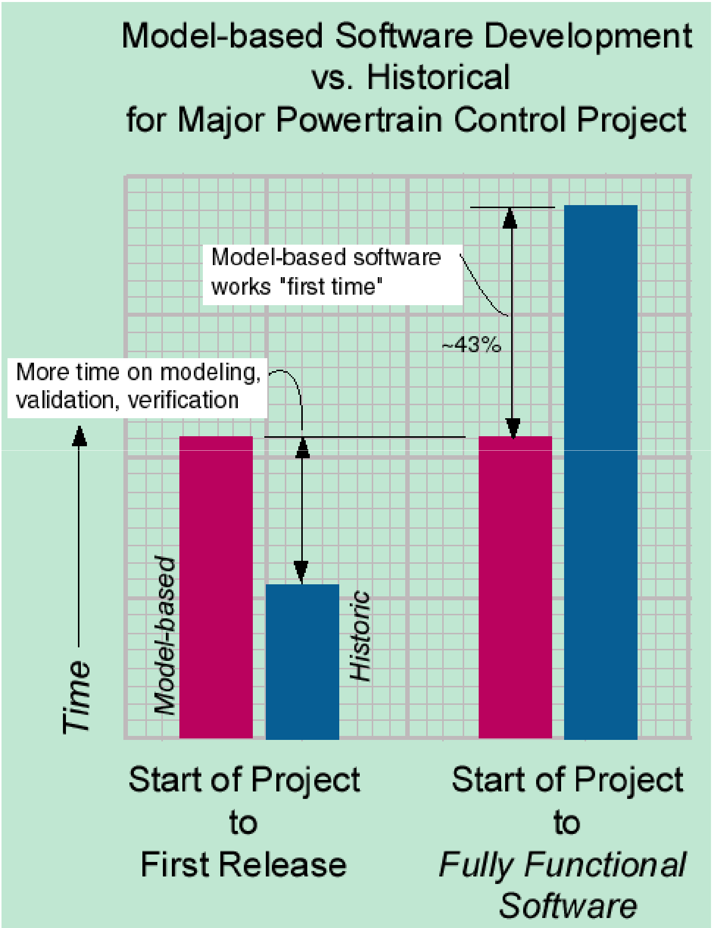
Lab 7: Controller Area Networking (CAN)

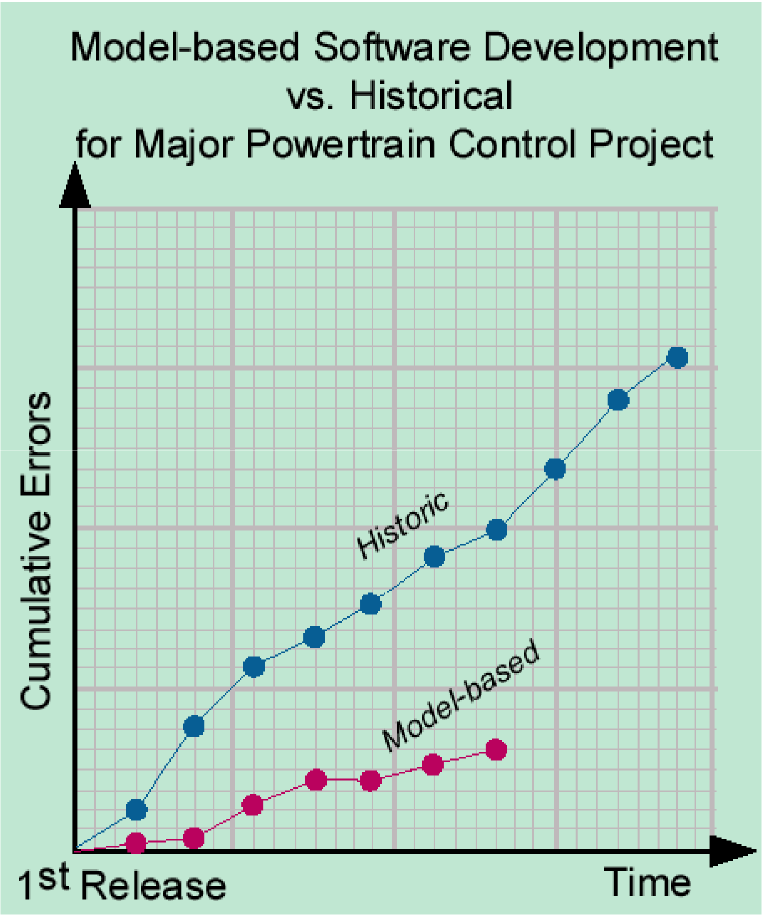
- Networking protocol used in time-critical applications
  - automotive
  - manufacturing
- Messages have unique identifiers: priorities
- Allows computation of worst case response time
- Lab exercises:
  - a wall that is chatter free when wall implemented locally can chatter due to delay when implemented remotely
  - connect each wheel to its virtual neighbors with virtual springs to create a virtual chain of 6 labstations.
  - estimate network utilization.

Rapid Prototyping (I)

- Lab 8 involves automatic code generation from Simulink models:
  - Derive a mathematical model of system to be controlled
  - Develop a Simulink/Stateflow model of the system.
  - Design and test a control algorithm using this model.
  - Use Real Time Workshop (RTW) to generate C-code.
  - Eliminates coding errors.
  - Speeds product development: generated code can be tested in many design cycles
  - Hand coding still required for production

Model Based Embedded Control Software Development



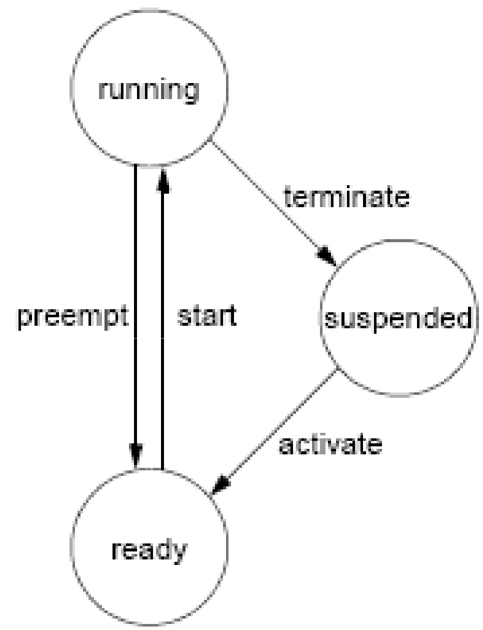


Rapid Prototyping (II)

- Need Simulink blocks:
  - device drivers
  - processor and peripheral initialization
- Issues:
  - efficiency of generated code
  - structure of code
- Multitasking
  - with RTOS, task states
  - without RTOS, nested interrupts

OSEKturbo RTOS (Freescale)

- OSEK/VDX compliant
- Scalable
- Task scheduler
- Priority ceiling protocol
- Eliminates
  - deadlock
  - priority inversion



RAppID Toolbox (Freescale)

- Processor and peripheral initialization blocks
- Device driver blocks
- Enables multitasking with OSEKturbo RTOS or nested interrupts

RAppID MPC5554 Target Setup

System Clock : 128 MHz
Target : MPC5554
Compiler : metrowerks
Target Type : IntRAM
Operating System : simpletarget

RAppID-EC

Lab 8: Two virtual wheels

- Two subsystems:
  – High priority fast subsystem
  – Low priority slow subsystem
- Model the multi-rate system in Simulink
- Demonstrate real-time operating system (RTOS)

Project (at UM): Adaptive Cruise Control

- Distance Control
  - Follows target at timed headway in ACC mode by use of throttle and brakes
- Speed Control
  - Automatically returns to cruise set speed when target clears

Headway Sensor → Path determination algorithm → Adaptive Cruise Control Algorithm

Project: Adaptive Cruise Control

- Driving simulator
- Bicycle model of vehicle
- 6 vehicles interacting over CAN network
- ACC algorithm: 3 states
  - manual (sliding pot)
  - constant speed
  - constant distance
- Takes 3+ weeks, all done with Simulink, Stateflow, and autocode generation