EECS 373
Design of Microprocessor-Based Systems

Robert Dick
University of Michigan

Lecture 14: Crash Course in Mechatronics

7 March 2017

Outline

- Context and review
- Student talks
- Power and energy
- Power integrity
- Solenoids
- Motors
  - DC
  - Stepper
  - Servo
  - Linear
- H bridges
- Shaft encoders

Context and review

- Done with normal material for course.
- Will still cover material to help with projects.
- Lectures will become less frequent.
  - All of us will be in lab more frequently.
  - Next Tuesday, no lecture.
  - Mon-Wed: Travel for research project.
- Material comprehension
  - Midterm: 48.5% min, 74.5% median, 92.5% max.
- Project progress
  - Tremendous improvement in proposals!
  - Really looking forward to seeing them working.
  - Lots of fun times in the lab.

C scalar data types

- Why? Essential basic knowledge for using C.
  - Assumed students knew this coming in.
- char: Smallest addressable unit capable of storing basic character set.
- short: At least 16 bits. Usually a half-word.
- int: At least 16 bits. Usually a word.
- long: At least 32 bits.
- long long: At least 64 bits.
- int**N**_t: Exactly **N** bits.
- Unsigned types are analagous.
- Why use non int**N**_t types, like int?
  - To say, “I want the fastest thing on this machine that has at least 16 bits.”
- If you don't need particular width or consistent width across platforms, old-style better.
- Otherwise, new-style better.

Outline

- ~~Context and review~~
- Student talks
- Power and energy
- Power integrity
- Solenoids
- Motors
  - DC
  - Stepper
  - Servo
  - Linear
- H bridges
- Shaft encoders

Student talks

- Titles and ordering due 10 March.
  - Put in on-line spreadsheet.
- 5 minutes max.
- PDF format.
- Slides due night before talk.
- Will merge on my laptop.

Outline

- ~~Context and review~~
- ~~Student talks~~
- Power and energy
- Power integrity
- Solenoids
- Motors
  - DC
  - Stepper
  - Servo
  - Linear
- H bridges
- Shaft encoders

Definitions

- Why? Power, temperature, energy, performance, and reliability important and deeply connected.
- Understand
  - why system failing and
  - why it consumes power.
- Temperature: Average kinetic energy of particle.
- Heat: Transfer of this energy.
  - Heat flows from regions of higher temperature to regions of lower temperature.
- Particles move.
- What happens to a moving particle in a lattice?
- Power: Rate of energy transfer (watts).

Why do wires get hot?

- Scattering of electrons due to destructive interference with waves in the lattice.
- What are these waves?
- What happens to the energy of these electrons?
- What happens when wires start very, very cool?
- What is electrical resistance?
- What is thermal resistance?
- Why do metals often have low thermal resistances?

Why do transistors get hot?

- Scattering of electrons due to destructive interference with waves in the lattice.
- Where do these waves come from?
- Where do the electrons come from?
  - Intrinsic carriers.
  - Dopants.
- What happens as the semiconductor heats up?
  - Carrier concentration increases.
  - Carrier mobility decreases.
  - Threshold voltage decreases.

Power consumption trends

- Initial optimization at transistor level.
- Further research-driven gains at this level difficult.
- Research moved to higher levels, e.g., RTL.
- Trade area for performance and performance for power.
- Clock frequency gains linear.
- Voltage scaling V_{DD}^2 – very important.

Power consumption

- $P = P_{SWITCH} + P_{SHORT} + P_{LEAK}$
- $P_{SWITCH} = C \cdot V_{DD}^{2} \cdot f \cdot A$
- $P_{SHORT} = b/12 \cdot (V_{DD} - 2 \cdot VT)^3 \cdot f \cdot A \cdot t$
- $P_{LEAK} = V_{DD} \cdot (I_{SUB} + I_{GATE} + I_{JUNCTION} + I_{GIDL})$
- C : total switched capacitance
- V_{DD} : high voltage
- f : switching frequency
- A : switching activity
- b : MOS transistor gain
- V_T : threshold voltage
- t : rise/fall time of inputs
- † PSHORT usually ≤ 10% of PSWITCH
- Smaller as $V_{DD} \rightarrow V_T$

DVFS

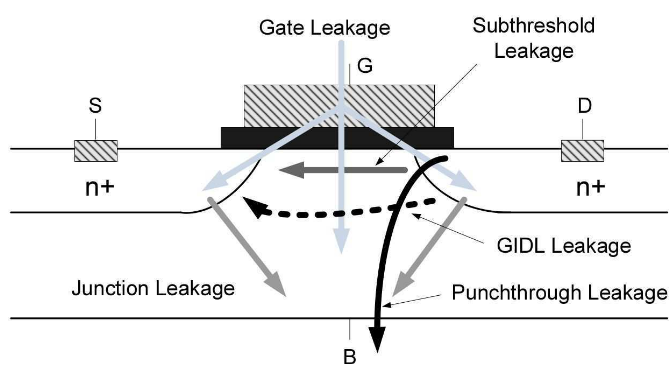
- Power drops superlinearly in V.
- Performance drops linearly in V.
- Double transistor count.
- Drop V.
- Drop f.
- Net result.
  - Reduced power.
  - Reduced energy, even though t increases.
- Fails when Vdd → Vth.

Typical control policies

- If utilization < ~80%, drop V, f.
- If utilization > ~80%, increase V, f.
- Latency: >100ms in some cases.
- Based on flawed assumption for interactive systems.

- If device has been used within X minutes, keep on.
- Otherwise, put in lower power management state.

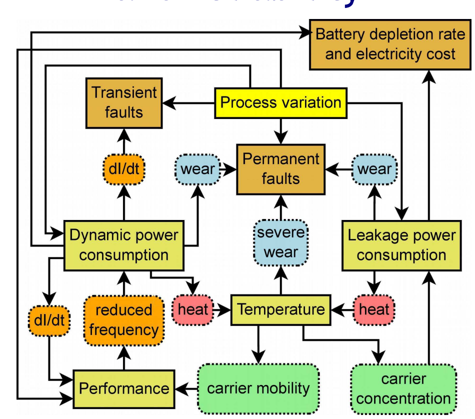
Leakage paths



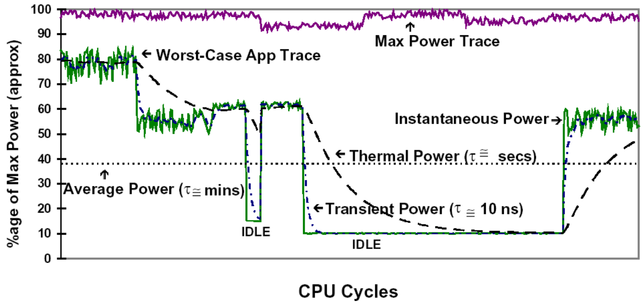
Subthreshold leakage

- $I_{subthreshold} = A_S\, W/L\, v_T^2\, (1 - \exp(-V_{DS}/v_T)) \cdot \exp((V_{GS} - V_{th}) / n\, v_T)$
- where A_s is a technology-dependent constant,
- V_{th} is the threshold voltage,
- L and W are the device effective channel length and width,
- V_{GS} is the gate-to-source voltage,
- n is the subthreshold swing coefficient for the transistor,
- V_{DS} is the drain-to-source voltage, and
- v_T is the thermal voltage.

Power, temperature, performance, and reliability



Power time series



- **Max Power:** Artificial code generating max CPU activity
- **Worst-case App Trace:** *Practical* applications worst-case
- **Thermal Power:** Running average of worst-case app power
- over a time period corresponding to thermal time constant
- **Average Power:** Long-term average of typical apps (minutes)
- **Transient Power:** Variability in power consumption for supply net

Energy

- Power integrated over time.
- Average power multiplied by time.
- J or mAh.

State-based power modeling

- For each component.
  - For each state.
    - Sum time spent in state × average power for state.
- Time-dependent state transitions are central.
- Big eaters
  - Displays.
    - Fluorescent tubes.
    - OLEDs.
  - Wireless interfaces.
    - Cellular.
    - WiFi.
    - Bluetooth.
  - CPU.

Outline

- ~~Context and review~~
- ~~Student talks~~
- ~~Power and energy~~
- Power integrity
- Solenoids
- Motors
  - DC
  - Stepper
  - Servo
  - Linear
- H bridges
- Shaft encoders

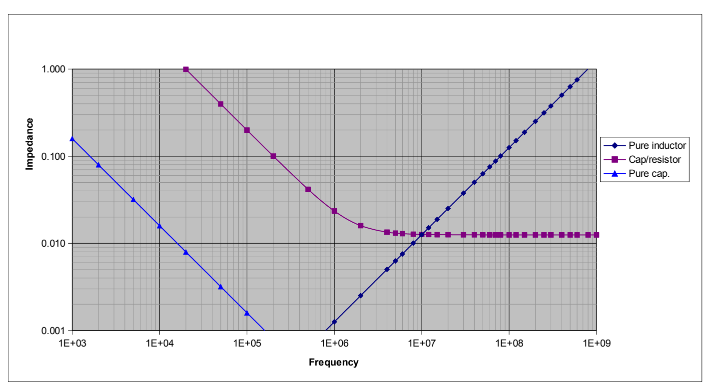
Power integrity

- Why? Get it wrong and board resets itself or worse for no apparent reason.

EECS 215/Physics 240 "review"

A look at impedance

(with capacitors, inductors and resistors vs. frequency)



Notice the log scales!

Power integrity related faults

- Even short "power droops" cause failure.
- Stable power = power Integrity.
- Does C fix?
  - No: parasitics.

Non-ideal devices

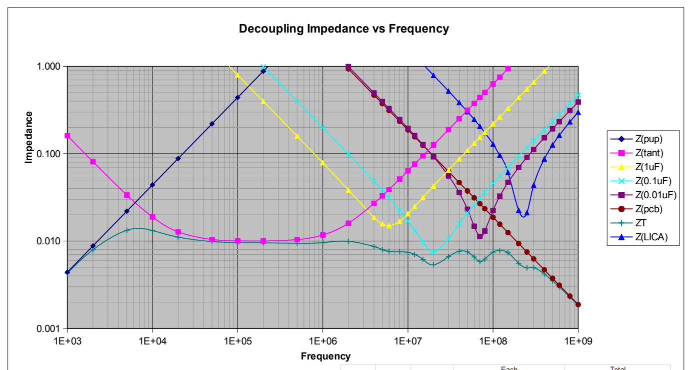
		Each			Total		
Device	Quantity	Cap	ESR	ESL	Ceff	ESR	ESL
DC/DC Converter	1		1.00E-04	7.00E-07		1.00E-04	7.00E-07
Tantalum Capacitors	3	3.30E-04	3.00E-02	3.00E-09	9.90E-04	1.00E-02	1.00E-09
0603 Ceramic Caps.	2	1.00E-06	3.00E-02	7.00E-10	2.00E-06	1.50E-02	3.50E-10
0603 Ceramic Caps.	8	1.00E-07	6.00E-02	6.00E-10	8.00E-07	7.50E-03	7.50E-11
0603 Ceramic Caps.	8	1.00E-08	9.00E-02	5.00E-10	8.00E-08	1.13E-02	6.25E-11
0603 Ceramic Caps.	10	1.00E-09	1.50E-01	5.00E-10	1.00E-08	1.50E-02	5.00E-11
PC Board	1	8.50E-08			8.50E-08		

- ESR is Effective Series Resistance
- ESL is Effective Series Inductance
- Ceff is the effective capacitance.
  - How does quantity effect these values?
- Obviously impendence will be varying by frequency.

Other things can add to ESR/ESL

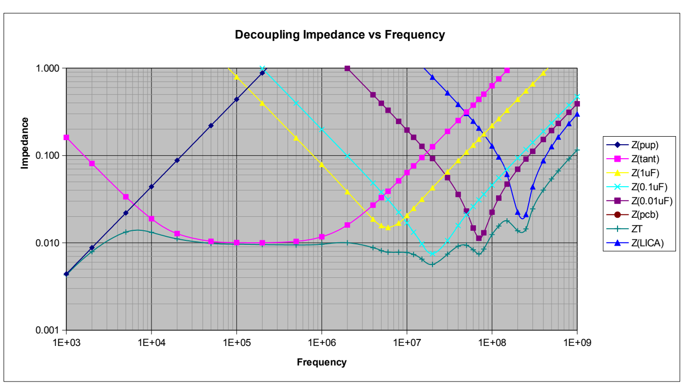
- Bad solder jobs make ESR/ESL worse.
- Bad solder jobs make everything worse.
- Packaging has an impact
  - SMT eliminate wire parasitics.
- Pads can have an impact

Given the previous table



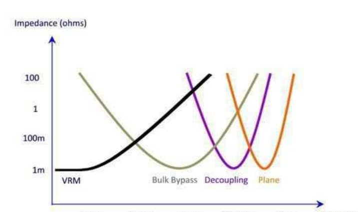
		Each			Total		
Device	Quantity	Cap	ESR	ESL	Ceff	ESR	ESL
DC/DC Converter	1		1.00E-04	7.00E-07		1.00E-04	7.00E-07
Tantalum Capacitors	3	3.30E-04	3.00E-02	3.00E-09	9.90E-04	1.00E-02	1.00E-09
0603 Ceramic Caps.	2	1.00E-06	3.00E-02	7.00E-10	2.00E-06	1.50E-02	3.50E-10
0603 Ceramic Caps.	8	1.00E-07	6.00E-02	6.00E-10	8.00E-07	7.50E-03	7.50E-11
0603 Ceramic Caps.	8	1.00E-08	9.00E-02	5.00E-10	8.00E-08	1.13E-02	6.25E-11
0603 Ceramic Caps.	10	1.00E-09	1.50E-01	5.00E-10	1.00E-08	1.50E-02	5.00E-11
PC Board	1	8.50E-08			8.50E-08		

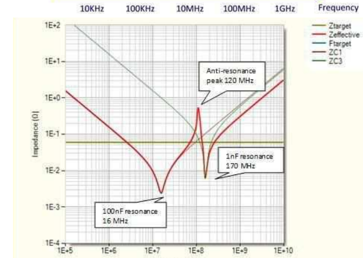
Removing the PCB



Staged capacitors

- VRM
  - Voltage regulator module
- bulk bypass (tantalum) and decoupling capacitors (ceramic).
  - These capacitors supply instantaneous current (at different frequencies) to the drivers until the VRM can respond.
- However sets of different capacitors cause problems!





Power integrity summary

- Use range of C values.
- Model frequency response
  - Consider parasitics.
- SPICE works.

Other sources of information

- http://alternatezone.com/electronics/files/PCBDesignTutorialRevA.pdf
  - **Very** nice tutorial/overview
  - Seems to have strong viewpoint
- http://www.goldengategraphics.com/pcgloss.htm
  - Some definitions taken verbatim.

Outline

- ~~Context and review~~
- ~~Student talks~~
- ~~Power and energy~~
- ~~Power integrity~~
- Solenoids
- Motors
  - DC
  - Stepper
  - Servo
  - Linear
- H bridges
- Shaft encoders

Solenoids

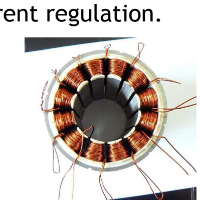
- Why?
  - Release kibble.
  - Ring bells.
  - Kick ball.
  - Open binary valve.
- Electromagnet-based actuator.
- Typically linear.
- Typically binary.
- Typically very fast.
- Poor controllability.
- Heat dissipation is major concern.
  - Only when on.
- Major E and EM noise source!

Outline

- ~~Context and review~~
- ~~Student talks~~
- ~~Power and energy~~
- ~~Power integrity~~
- ~~Solenoids~~
- Motors
  - DC
  - Stepper
  - Servo
  - Linear
- H bridges
- Shaft encoders

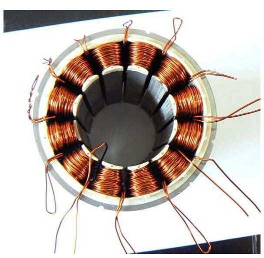
DC motors

- General purpose: turn things.
- Must switch magnetic field polarity during turn.
  - Brushed: carbon common, wears out.
  - Brushless: solid-state DC → AC converter first.
- Back-EMF
  - Motors are also generators.
    - When turning, opposes applied voltage.
  - Speed-dependent: bigger when moving.
  - Noise source.
  - Permits current regulation.



Drone/disc motors

- Big advanced recently for UAVs/drones.
  - Wide instead of long. Better heat dissipation.
  - High-efficiency.
  - High-torque.
  - Require special drivers.
  - Require sensors.



Outline

- ~~Context and review~~
- ~~Student talks~~
- ~~Power and energy~~
- ~~Power integrity~~
- ~~Solenoids~~
- Motors
  - ~~DC~~
  - Stepper
  - Servo
  - Linear
- H bridges
- Shaft encoders

Stepper motors

- Position at precise orientation.
- Toothed magnets.
  - Moves in small increments.
- High torque when stationary.
- Torque drops a lot at high speed.
- Works w.o. sensors / back EMF based control.
  - Don't use open-loop anywhere near limits.
- Reliable.
- Lock-in requires continued power.
- Use for precise orientation control.

Outline

- ~~Context and review~~
- ~~Student talks~~
- ~~Power and energy~~
- ~~Power integrity~~
- ~~Solenoids~~
- Motors
  - ~~DC~~
  - ~~Stepper~~
  - Servo
  - Linear
- H bridges
- Shaft encoders

Servo motors

- Position at very precise (continuous) orientation.
- Requires sensors for closed-loop control system.
- Zero power once at rest.
- Expensive.

Outline

- ~~Context and review~~
- ~~Student talks~~
- ~~Power and energy~~
- ~~Power integrity~~
- ~~Solenoids~~
- Motors
  - ~~DC~~
  - ~~Stepper~~
  - ~~Servo~~
  - Linear
- H bridges
- Shaft encoders

Linear motors/actuators

- Why: Launching objects.
- Moving objects along long paths.
- Unwind stator → linear array of electromagnets.

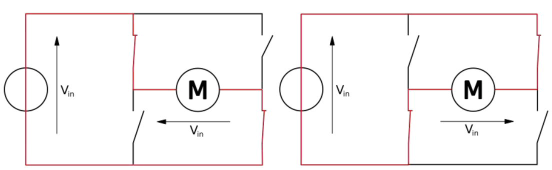
- Could use for linear actuator.
  - Leadscrews and rotary more common.

Outline

- ~~Context and review~~
- ~~Student talks~~
- ~~Power and energy~~
- ~~Power integrity~~
- ~~Solenoids~~
- ~~Motors~~
  - ~~DC~~
  - ~~Stepper~~
  - ~~Servo~~
  - ~~Linear~~
- H bridges
- Shaft encoders

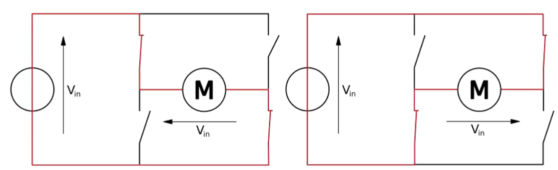
H bridges

- Why? Control direction of current through device.
- How? BJTs or FETs on "H" legs.



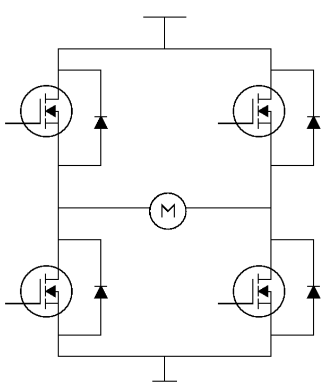
H bridge diodes

- What can go wrong?
  - Switch suddenly.
  - Stored energy in coil produces very reverse voltage until discharged.
  - Of FETs are off (they are), can be destroyed.



H bridge diodes

- Use diode in || with each switch.
- May be free w. MOSFETs.
- Where does current go when FET off?

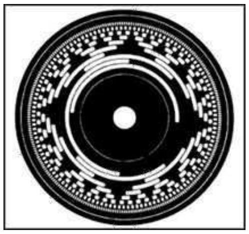


Outline

- ~~Context and review~~
- ~~Student talks~~
- ~~Power and energy~~
- ~~Power integrity~~
- ~~Solenoids~~
- ~~Motors~~
  - ~~DC~~
  - ~~Stepper~~
  - ~~Servo~~
  - ~~Linear~~
- ~~H bridges~~
- Shaft encoders

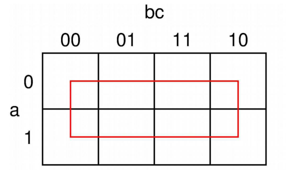
Shaft encoders

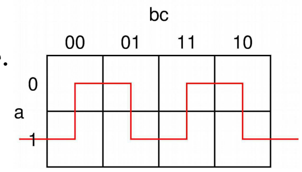
- Why? Know relative or absolute orientation.
- Linear arrangement of binary numbers.
- Can reuse numbers.
  - Lose absolute position.
- Adjacency essential.
  - Race conditions.
-



Shaft encoders

- How to design?
  - K-Map cycle.
  - 000 → 001 → 011 → 010 → 110 → 111 → 101 → 100 →
- 0 → 1 → 0 → 1 fine, too.
- How to read?
  - LED+photodetector.
  - Reflective or transmissive.





Summary: you don't know motors

- You do know enough to get started.
- Have some understanding of uses.
- Strengths and weaknesses.