INTRODUCTION TO FEEDBACK CONTROL

1.1: What is feedback control?

- Control-system engineers often face this question (or, "What is it that you do, anyway?") when trying to explain their professional field.
- Loosely speaking, control is the process of getting "something" to do what you want it to do (or "not do," as the case may be).
  - The "something" can be almost anything. Some obvious examples: aircraft, spacecraft, cars, machines, robots, radars, telescopes, etc.
  - Some less obvious examples: energy systems, the economy, biological systems, the human body...
- Control is a very common concept.

  e.g., Human-machine interaction: Driving a car.

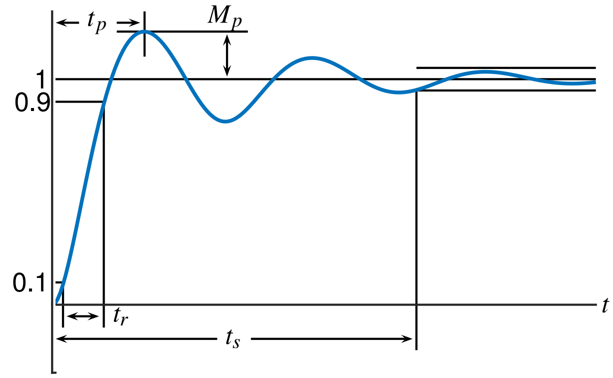
  ➤ Manual control.

  e.g., Independent machine: Room temperature control. Furnace in winter, air conditioner in summer. Both controlled (turned "on"/"off") by thermostat. (We'll look at this example more in Topic 1.2.)

  ➤ Automatic control (our focus in this course).

DEFINITION: Control is the process of causing a system variable to conform to some desired value, called a reference value. (*e.g.*, variable = temperature for a climate-control system)

- Usually defined in terms of system step response (cf. notes Chap. 3).
- Critical values for control-system design: "rise time" t_r, "settling time" t_s, and "peak overshoot" M_p.



DEFINITION: Feedback is the process of measuring the controlled variable (*e.g.*, temperature) and using that information to influence the value of the controlled variable.

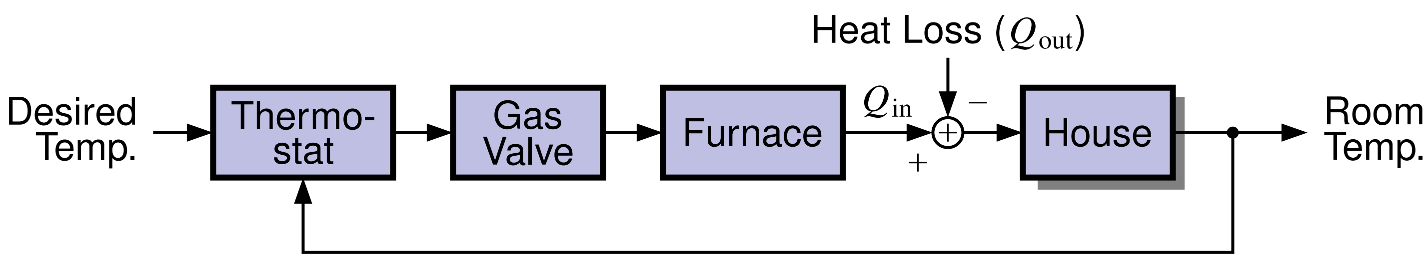
- Feedback is not necessary for control. But, it is necessary to cater for system uncertainty, which is the principal role of feedback.
- Control theory is truly a multi-disciplinary study that cuts across boundaries of many disciplines.
  - Math is the cornerstone of control theory.
  - Electrical engineering is also an important building block, though mostly from the aspect of signals and systems, and less from circuits.
  - Mechanical engineering is likewise an important fundamental, chiefly from the standpoint of dynamic system behavior.
  - Other important foundational elements come from: physics (conservation of energy), thermodynamics (entropy), and other scientific first principles.
- Control engineers bring value across a very wide array of industries:
  - Automotive, aerospace, electronic, medical, financial. . . (see next page for a synopsis).

	Some applications of feedback control
Categories	Specific applications
Ecological	Wildlife and forest growth management (reference = population); control of plant chemical wastes via monitoring lakes and rivers; air pollution abatement (reference = chemical concentrations); water control and distribution; flood control via dams and reservoirs (reference = water flow rate).
Medical	Medical instrumentation for monitoring and control (reference = dosage); artificial limbs (prosthesis; reference = limb position).
Home appliances	Home heating, refrigeration, and air conditioning via thermostatic control; electronic sensing and control in clothes dryers; humidity controllers; temperature control of ovens (references = desired temperature, humidity).
Power/energy	Power system control and planning; feedback instrumentation in oil recovery; optimal control of windmill blade and solar panel surfaces; optimal power distribution via power factor control; power electronics for dc-dc conversion, battery chargers, motor controls (references = power level, optimization criteria).
Transportation	Control of roadway vehicle traffic flows using sensors; automatic speed control devices on automobiles; propulsion control in rail transit systems; building elevators and escalators (references = vehicle flow rate, speed, position and speed together).
Manufacturing	Sensor-equipped robots for cutting, drilling die casting, forging, welding, packaging, and assembling; chemical process control; tension control windup processes in textile mills; conveyor speed control with optical pyrometer sensing in hot steel rolling mills (references = position–speed profiles).
Aerospace and military	Missile guidance and control; automatic piloting; spacecraft control; tracking systems; nuclear submarine navigation and control; fire-control systems (references = position and attitude).

(adapted from: J.R. Rowland, "Linear Control Systems: Modeling, Analysis, and Design," John Wiley & Sons, (New York: 1986), p. 6.)

1.2: An illustrative example of a feedback control system

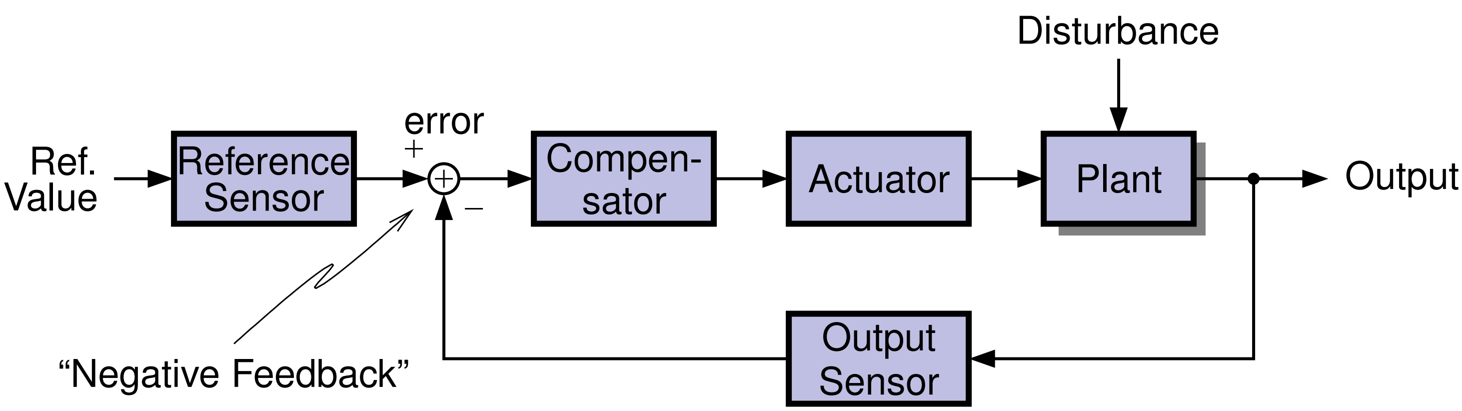
- We proceed by looking at an example that allows us to define some important terminology.
- Consider the system designed to maintain the temperature of your house/apartment.
- We can draw a block diagram, which identifies the major components of the system, and omits unnecessary details. It also highlights the information/energy flows:



- Central component = process or plant, one of whose variables we want to control. *e.g.*, Plant = __________; Variable = __________.
- Disturbance = some system input that we do not control. *e.g.*, Disturbance = __________.
- Actuator = device that influences controlled variable. *e.g.*, Actuator = __________.
- Reference sensor measures desired system output.
- Output sensor measures actual system output.
- Compensator or controller = device that computes the control effort to apply the the actuator, based on sensor readings. *e.g.*, __________ combines the last three functions.

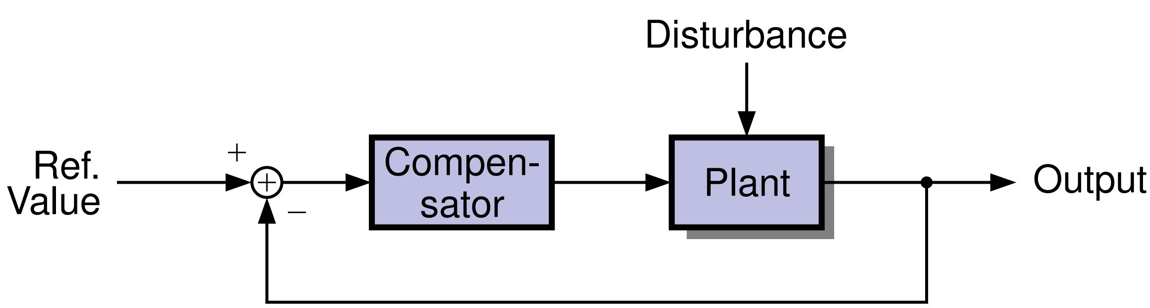
A more abstract block diagram

- The detail in the prior block diagram is helpful to identify the physical components of the particular system of interest.
- However, we can abstract the ideas from the prior diagram to arrive at a more general block diagram that is applicable to most scenarios of interest:



An even more abstract block diagram

- Finally, by assuming the presence of (perfect) sensors and actuators (absorbed into the plant), we can make an even more abstract block diagram.



- This is the picture of a feedback control system that you should have in mind for the remainder of this course.

The control problem/solution methodology

- Now that we have identified the main components of a feedback control system, we consider the problem that a control system is designed to solve, and the methodology for solution.
- The objectives of any control-system design include:
  - "Reject" disturbance (plant response to disturbance input minimized).
  - Acceptable steady state errors (response after a "long" time).
  - Acceptable transient response (short-term dynamics).
  - Minimize sensitivity to plant parameter changes ("robustness").
- Solutions are reached via the methodology:

  1. Choosing output sensors.

  2. Choosing actuators.

  ***3.** Developing plant, actuator, sensor equations (models).

  ***4.** Designing compensator based on the models and design criteria.

  ***5.** Evaluating design analytically, with simulation and prototype.

  ***6.** Iteration!! (In part because actual system will be different from model.)
- Steps 1 and 2 are sometimes out of our purview. Our focus in this course is on steps 3–6.
- In the next section, we will look at a lengthy example of these six steps.

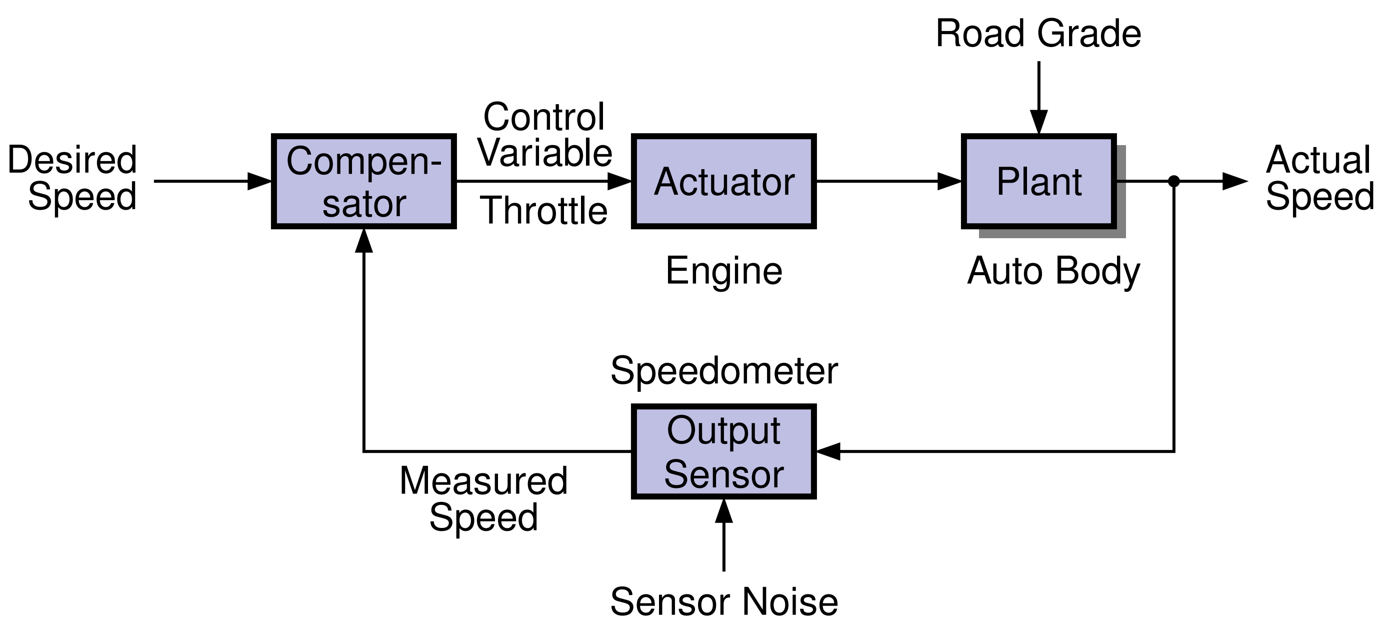
1.3: A first analysis: Auto cruise control

- As an example, suppose that we wish to design a cruise-control system for an automobile.
- Generically, we wish to control the car's speed (and possibly acceleration profile).
- Following our design methodology, steps 1–2 are:

1. Output sensor = speedometer.

2. Actuator = throttle and engine.

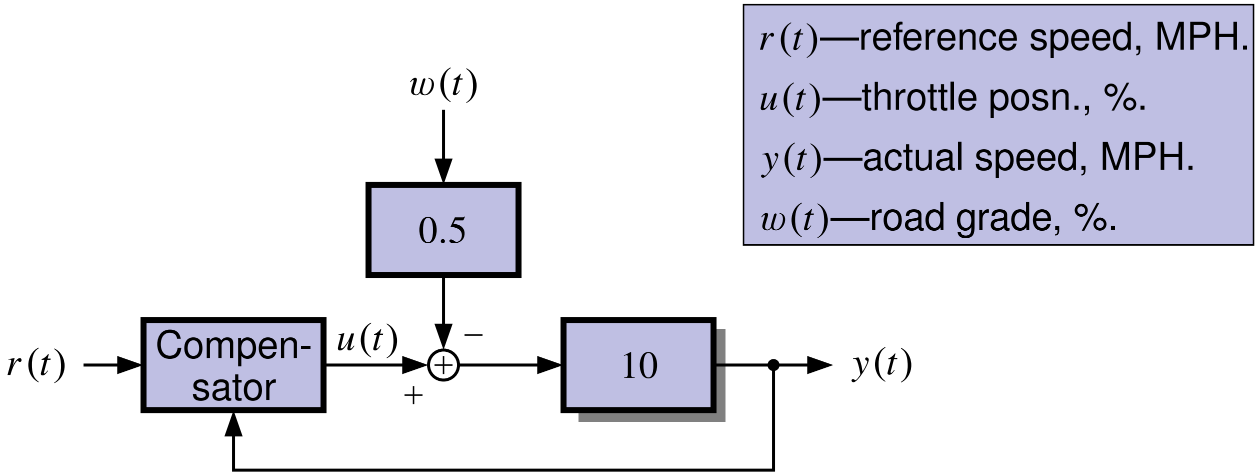
- Block diagram:



3. Model of system:

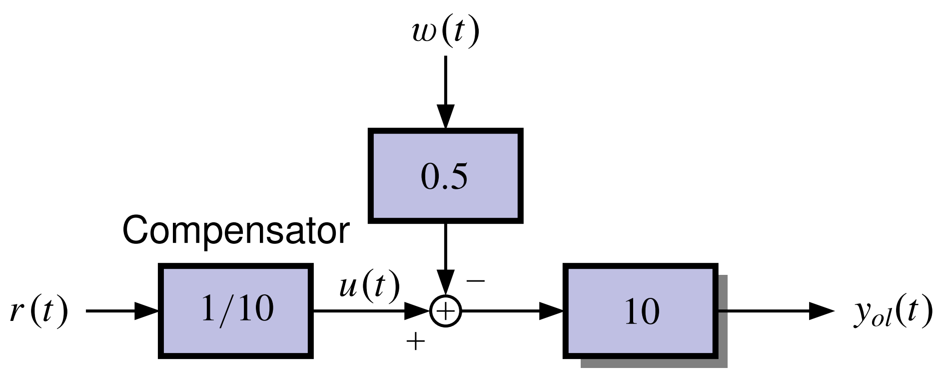
1. Operate system ≈ 55 MPH. Assume linear response near 55 MPH.
2. Measure: 1 % change in throttle ➠ 10 MPH change in speed.
3. Measure: 1 % change in grade ➠ 5 MPH change in speed.
4. Measure: Speedometer accurate to a fraction of 1 MPH, so is assumed exact.

5. Functional block diagram:



4. Design compensator/controller

- First attempt = "open loop" controller.



$$\begin{aligned} y_{ol}(t) &= 10\,(u(t) - 0.5w(t)) \\ &= 10\left(\frac{r(t)}{10} - 0.5w(t)\right) \\ &= r(t) - 5w(t). \end{aligned}$$

5. Evaluate design: Percent error is computed as $100\left(\dfrac{r(t) - y_{ol}(t)}{r(t)}\right)$

- $r(t) = 55, \quad w(t) = 0 \Rightarrow y_{ol}(t) = 55.$ No error... Good.
- $r(t) = 55, \quad w(t) = 1 \Rightarrow y_{ol}(t) = 50.$ $\approx 10\,\%$ error... Not good.

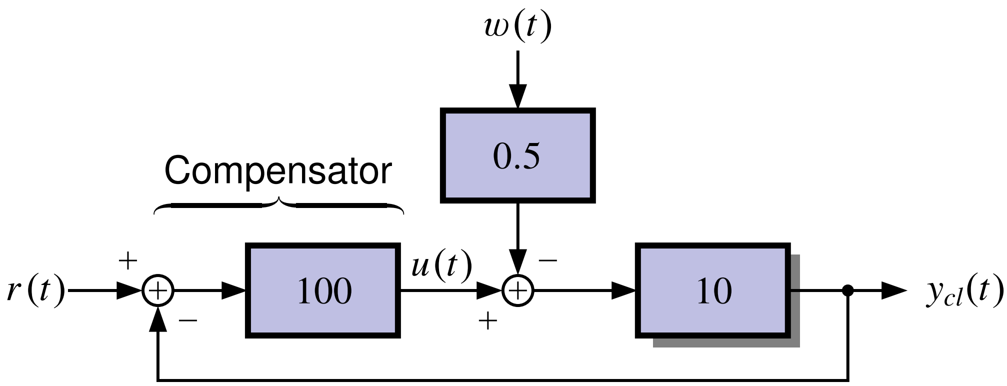
- $r(t) = 55, \quad w(t) = 2 \Rightarrow y_{ol}(t) = 45.$ $\approx 20\,\%$ error. . . Not good.
- Suppose you load the trunk with all your ECE4510/ECE5510 notes and the car becomes more sluggish.
  e.g., the gain "10" becomes "9"
- $r(t) = 55, \quad w(t) = 0 \Rightarrow y_{ol}(t) = 49.5.$ $\approx 10\,\%$ error. . . Not good.
- $r(t) = 55, \quad w(t) = 1 \Rightarrow y_{ol}(t) = \ldots$

6. Iterate design. Go to step #4.

Auto cruise-control example (attempt #2)

- Our first attempt at the cruise-control design didn't go too well.
- So, we try again, with a different approach.

4. Second attempt = Feedback controller



- Multiply your output error by 100; feedback gain = 100

$$y_{cl}(t) = 10u(t) - 5w(t)$$

$$u(t) = 100(r(t) - y_{cl}(t))$$

$$\text{so, } y_{cl}(t) = 1000r(t) - 1000y_{cl}(t) - 5w(t)$$

$$1001y_{cl}(t) = 1000r(t) - 5w(t)$$

$$y_{cl}(t) = 0.999r(t) - 0.005w(t)$$

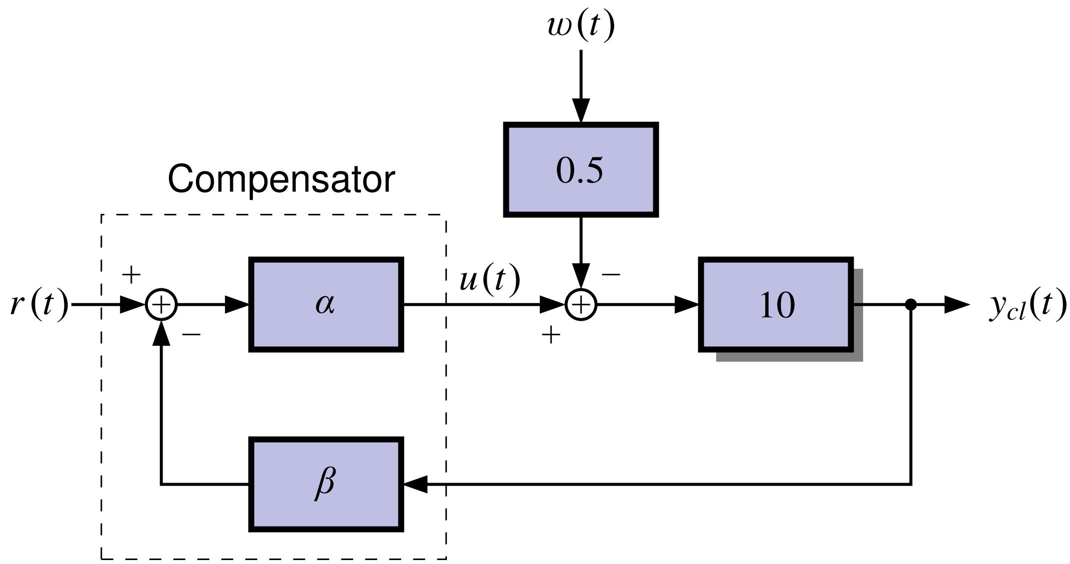
5. Evaluate design.

- $r(t) = 55, \quad w(t) = 0 \Rightarrow y_{cl}(t) = 54.945$
- $r(t) = 55, \quad w(t) = 1 \Rightarrow y_{cl}(t) = 54.94$
- $r(t) = 55, \quad w(t) = 2 \Rightarrow y_{cl}(t) = 54.935$
- $r(t) = 55, \quad w(t) = 10 \Rightarrow y_{cl}(t) = 54.895 \quad \ldots$ $\approx$ 0.2 % error!
    - ➤ Feedback system rejects disturbances.
    - ➤ Feedback system has steady state error.
- $r(t) = 55$, $w(t) = 0$, plant="9", not "10" $\Rightarrow y_{cl}(t) = 54.939$
    - ➤ Feedback system less sensitive to system parameter values.

NOTE! High feedback gain = good performance here. *Not always true! e.g.*, Public address amplifier.

Auto cruise-control example (attempt #3)

4. Third attempt. Try to get rid of steady state error.



$$y_{cl}(t) = 10\left[\alpha\left(r(t) - \beta y_{cl}(t)\right)\right] - 5w(t)$$

$$
\begin{aligned}
&= 10\alpha r(t) - 10\alpha\beta y_{cl}(t) - 5w(t) \\
y_{cl}(t) &= \frac{10\alpha r(t) - 5w(t)}{1 + 10\alpha\beta} \\
&= \underbrace{\left(\frac{10\alpha}{1 + 10\alpha\beta}\right)}_{\text{set to 1: } \beta = 1 - \frac{1}{10\alpha}} r(t) - \left(\frac{5}{1 + 10\alpha\beta}\right) w(t) \\
&= r(t) - \frac{5}{10\alpha} w(t).
\end{aligned}
$$

- Best results yet! (Try for yourself with $\alpha = 100$.)

1.4: Examples of senior-design/MSEE controls topics

- As we conclude this chapter of notes, we consider how you might benefit from learning about control systems in your educational journey.
- The thermostat example seems pretty "low tech," but recently the Nest Learning Thermostat has made quite a splash in the tech industry.
- Control-system design is an integral component to a lot of innovation, and is very often a basic element of senior-design projects and MSEE thesis topics.
- A few prior senior-design projects in the controls area include:
  - N. Shaffer, J. Alvarez, J. Valenzuela, R. Hindley, "Autonomous Robot Delivery System."
  - B. Lessard, K. Stetzel, "Novel Solar Tracking Charge Device."
  - S. Bretzke, G. Deemer, "Deetzke Coffee-Bean Roaster."
  - R. Gallegos, T. McCorkle, L. Morgan, "Mag-pulsion Track Vehicle."
  - M. Anderson, S. Hopp, C. Cotey, "Automated Personal Use Bartender (A.P.U.B.)."
  - T. Bouma, E. Silva, "Automatic Temperature Regulated Vehicle Power Window Controller."
  - A. Levasseur, P. Cotey, C. Runyan, "P.O.T.T. (Phone Operated Toy Truck)."
- Several past MSEE thesis/project topics in the controls area include:
  - R. Jobman, "Implementation of a Quad-Rotor Control System."
  - H. Shane, "Model Predictive Control of the Magnetic Levitation Device."
  - J.A. Stewart, "Linear Optimal Control of a Two-Stage Hydraulic Valve Actuator."
  - R. Murray, "Pole Placement and LQR Methods to Control a Focus Actuator of An Optical Disk Drive."
  - J.D. Musick, "Target-Tracking a Non-Linear Target Path Using Kalman Predictive Algorithm."
  - M. Seil, "Adaptive Neural Network Control of Cylinder Position Utilizing Digitally Latching Pneumatic Poppet Valves."
  - I. Rueda, "Regeneration Control via Traction Estimation in E.V."
  - H. Böttrich, "Adaptive Inverse Control of Nonlinear Systems Using Recurrent Neural Networks."

Our research area: xEV applications of control systems

- At UCCS, our research is focused on applications of control systems to hybrid- and electric-vehicle battery management.
  - The battery is the heaviest and most expensive component in the electric drivetrain.
  - Battery packs are presently over-designed/underutilized in an effort to extend life.
  - Understanding the physical mechanisms that degrade life, and controlling battery packs to avoid conditions that accelerate these mechanisms will extend life.
- In the past, we have had projects in topics including:
  - Collecting data from laboratory tests to understand ideal-cell and degradation dynamics.
  - Modeling hysteresis effects in battery cell voltage.
  - Making reduced-order models of full-order physics models of cells.
  - Using model-predictive controls for fast-charge.
- Presently, we have projects in topics including:
  - Optimal balancing of cells in a large battery pack.
  - Building a hardware battery pack simulator.
  - Building a hardware battery management system.
  - Internal state estimation of battery cells.
  - Reduced-order degradation models of battery cells.
  - System identification of battery cell model parameters.
  - Physics-based power limits to optimize life.

Control systems in the ECE Department at UCCS

- The following graphic shows what control-systems courses are offered by ECE at UCCS:

- We also have a Graduate Certificate Program in Electric Drivetrain Technology, and an MSEE option in Battery Controls.
  - cf. `http://mocha-java.uccs.edu/IDEATE/`