Magnetic Levitation System

Dr. Kevin Craig
Professor of Mechanical Engineering
Rensselaer Polytechnic Institute

Introduction to Mechatronics

Motivation for the Study of Mechatronics
Mechatronics is the synergistic integration of physical systems, electronics, controls, and computers through the design process, from the very start of the design process, thus enabling complex decision making. Integration is the key element in mechatronic design as complexity has been transferred from the mechanical domain to the electronic and computer software domains. Mechatronics is an evolutionary design development that demands horizontal integration among the various engineering disciplines as well as vertical integration between design and manufacturing. Mechatronics is the best practice for synthesis by engineers driven by the needs of industry and human beings.
Multidisciplinary Systems Engineering

Modern Mechatronic System

Other Components
Communications

Operator Interface
Human Factors

Computation
Software, Electronics

Actuation
Power Modulation
Energy Conversion

Instrumentation
Energy Conversion
Signal Processing

Physical System
Mechanical, Fluid,
Thermal, Chemical,
Electrical, Mixed

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Real-Time Software

- **Real-Time Software is at the heart of mechatronic systems.**
- Real-time software differs from conventional software in that its results must not only be numerically and logically correct, they must also be delivered at the correct time.
- Real-time software must embody the concept of duration, which is not part of conventional software.
- Real-time software used in most physical system control is also safety-critical. Software malfunction can result in serious injury and/or significant property damage.
- Asynchronous operations, which while uncommon in conventional software, are the heart and soul of real-time software.
The WHY of Mechatronics

• Companies must:
  – have the ability to increase the competitiveness of their products through the use of technology
  – be able to respond rapidly and effectively to changes in the market place

• Mechatronic strategies:
  – support and enable the development of new products and markets
  – enhance existing products
  – respond to the introduction of new product lines by a competitor
• The adoption by a company of a mechatronic approach to product development and manufacturing provides the company with a strategic and commercial advantage:
  – through the development of new and novel products
  – through the enhancement of existing products
  – by gaining access to new markets
  – or by some combination of these factors
The HOW of Mechatronics

- The achievement of a successful mechatronics design environment essentially depends on the ability of the design team to innovate, communicate, collaborate, and integrate.
- Indeed, a major role of the mechatronics engineer is often that of acting to bridge the communications gaps that can exist between more specialized colleagues in order to ensure that the objectives of collaboration and integration are achieved.
- This is important during the design phases of product development and particularly so in relation to requirements definition where errors in interpretation of customer requirements can result in significant cost penalties.
Challenge of Mechatronic System Design

- Master the future increase of system complexity
  - Innovative Excellence
    - Yielding new products with distinctive functionality, better quality and/or a cost advantage
  - Operational Excellence
    - Effective and highly efficient processes for product design, manufacturing, and calibration
Is Mechatronics New?

- Mechatronics is simply the application of the latest, cost-effective technology in the areas of computers, electronics, controls, and physical systems to the design process to create more functional and adaptable products. It is just Good Design Practice! Many Forward-Thinking Designers and Engineers have been doing this for years!
- Mechatronics is a significant design trend – an evolutionary development – a mixture of technologies and techniques that together help in designing better products. Mechatronics demands horizontal integration among the various disciplines as well as vertical integration between design and manufacturing.
Compelling Questions

Multidisciplinary engineering systems have as integral parts electronics, computers, and controls. Performance, reliability, low cost, robustness, and sustainability are absolutely essential.

How can Engineering Educators best transform students to become engineers poised to solve mankind’s problems of the 21st century?

How can a company transform itself to successfully design multidisciplinary engineering systems?
Educational Challenge

- Control Design and Implementation is still the domain of the specialist.
- Controls and Electronics are still viewed as afterthought add-ons.
- Very few practicing engineers perform any kind of physical and mathematical modeling.
- Mathematics is a subject that is not viewed as enhancing one’s engineering skills but as an obstacle to avoid.
- Very few engineers have the balance between analysis and hardware essential for success in Mechatronics.
Balance: The Key to Success

Theory
- Modeling & Analysis

Practice
- Experimental Validation & Hardware Implementation

Multidisciplinary Systems Engineering

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Physical & Mathematical Modeling

Less Real, Less Complex, More Easily Solved

Truth Model | Design Model

More Real, More Complex, Less Easily Solved

Hierarchy Of Models
Always Ask: Why Am I Modeling?
MECHATRONICS EXPO
THE HOTTEST TRENDS IN ENGINEERING TODAY

Attendees will...
- Walk away with an understanding of how Mechatronics, properly implemented, can improve every aspect of design engineering.
- Meet skilled Design Engineers from diverse backgrounds who are looking to expand their understanding of Mechatronics.
- Learn Best Practices in applying Mechatronics design within your organization.
- Hear from experts in different disciplines who will share the value of tighter integration.

Date: October 9, 2007
Time: Registration and breakfast at 7:30 a.m.
- A separate address starts the day at 8:30 a.m.
- Breakout sessions begin at 9:30 a.m.
- Concluding with a cocktail reception at 5:30 p.m. open to all.
Place: Burlington Marriott, One Mall Road, Route 128 & 3A, Burlington, Massachusetts 01803.
Who: Engineers — EE / ME / CE

Register Today at www.designnews.com/mechexpo

Keynote Presentation
Kevin Craig, Ph.D.,
Professor of Mechanical Engineering, Rensselaer Polytechnic Institute.
Professor Craig explains the essential elements of mechatronics and tells why this design approach is essential for engineering success in countless products.

Expo: Ballroom foyer for trade show booths, accessible to attendees at all times. A perfect opportunity for you to get “face to face” with technology experts.

One Day Seminar Series
- Essential Mechatronics Tools for Efficient Design
  This session takes an in-depth look at new simulation-based approaches to designing machines. Engineers will learn how to link control and 3D CAD tools to simulate machine operation, size motors and tune control algorithms.
- Linking Systems Engineering to the Product Life Cycle
  Learn how to integrate systems engineering with the entire product development cycle, including mechatronics design, ergonomics, software, testing, manufacturing, cost controls, maintenance issues and much more.
- Small and Practical Mechatronics Systems
  While engineers may think of mechatronics in terms of elaborate factory automation systems, the same design concepts apply to countless products, from household appliances to medical devices. A major key to many of these designs: powerful but compact embedded control.
- Mechatronics Design in Industrial Automation
  Hear examples of how mechatronic design is helping factory automation OEMs improve their machines and get them to market faster.
- Expo Wrap-up Panel Discussion: “Real-world Mechatronics Solutions”
  A panel discussion featuring representatives from National Instruments, Siemens, UCS and Microchip, together with engineers from New England companies that have implemented successful mechatronics design.

This exclusive event is sponsored by:
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Fiat Mechatronics Workshop
Torino, Italy
Summer 2006

Mechatronics Workshop
Bergamo, Italy
March 2007
(Tetra Pak, Salvagnini, Electrolux, Fiat, ABB)
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Dade Behring Mechatronics Workshop
Newark, Delaware, August 2007
RPI Mechatronics Graduates

- 35 M.S. Graduates (3 in progress)
- 19 Ph.D. Graduates (1 in progress)

Visit to Samsung, Seoul, South Korea, March 2006

Fred Stolfi
Professor
Columbia U.
Ph.D. 1998

Jeongmin Lee
Samsung
Mechatronics
Research Engineer
Ph.D. 2001
Relentless & Restless

Eight of engineering’s best discuss what comes next and the courage needed to pull it off, p72

MECHATRONICS IN DESIGN

Modeling: Essential Key to Mechatronics Design

A six engineers what a model is and you may get six different answers. In mechatronics, the word model carries a specific meaning, and modeling is perhaps the single most important activity in mechatronic system design.

There are two models of an actual physical system: a physical model and a mathematical model, and the distinction between them is most important. The physical model resembles an actual physical system in its salient features, but this model is also more ideal, and is thereby more amenable to analytical studies. It is a slice of reality, and in modeling dynamic systems, we use engineering judgment and simplifying assumptions to develop a physical model.

In design, an engineer rarely starts with a blank sheet of paper. Designers are usually the result of the improvement of an existing system, the innovative combinations of existing systems, or the application of new technology or new knowledge to an existing system. In all this, understanding what exists is paramount, and modeling is essential to that understanding. Also, once a concept has been developed in the conceptual phase of design, you can evaluate it through modeling — not by building and testing sensors, actuators and controls.

H. J. Cordfang of the University of Twente in the Netherlands gives a great example of the use of modeling in his concept for a pick-and-place device for mounting chips on a printed circuit board (Figure 1). To evaluate this concept, we initially neglect the motor dynamics, the compliances of the bistable belts and spindles, the friction in the system and any hysteresis and parasitic effects. A low-order dynamical model (Figure 2) takes into account only the rigid-body mode and the lowest mode of vibration, in this case from the frame. With just a few parameters, this model completely describes the performance-limiting factors and provides reliable estimates of the dominant dynamic behavior and the attainable closed-loop bandwidth.

The aim of conceptual design is to obtain a feasible design for the part generator, control system and electromechanical plant with appropriate sensor locations in an integrated way.

Besides providing real understanding of the behavior of physical systems on which to base improved performance and added functionality, modeling enables an engineer to evaluate integrated design concepts early in the design process without having to build and test each one. All engineers need to embrace physical and mathematical modeling.
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Get Your Passport to 21st Century Design

How can today's engineers be successful when faced with the tough job of integrating electronics, computers and control systems in design? To add to the challenge, they must not only work with components that offer high performance, reliability, low cost and robustness. The answer is to learn to master the essentials of mechatronics, which is fast becoming a 21st century approach to engineering design for an increasingly wide range of products.

As in the case of mechatronics, it is the synergistic integration of physical systems, electronics, controls and computers throughout the entire design process. Integration is the key, since complexity has been transferred from the mechanical domain to the electronic and computer software domain. Mechatronics also demands horizontal integration among the various engineering disciplines, as well as vertical integration between design and manufacturing processes.

The diagram below shows a modern mechatronics system and its four key elements: mechanical system, actuation, instrumentation and computation. As Professor Dave Aukander and Masayuki Ino of UC Berkeley point out, these components are energetically isolated, with computation playing the central role. Engineers can exploit this real-time computation to create systems that are quite different from any that came before. Real-time computation, unlike conventional computation, must deliver correct results at the correct time. It also embodies the concept of a digital, interchangeable product and often must include safety-critical factors.

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Leashing the Potential of the IC Engine

Despite talk of its demise, the outlook for the venerable internal combustion engine remains sunny. The future lies in making its proven technology with new mechatronics-related concepts.

To meet demanding challenges in emission control and engine efficiency, while still maintaining high engine performance, today’s automobiles have already become a comprehensive mechatronic system. More than 80 percent of all automotive innovation stems from electronics. Highly reliable and fault-tolerant electronic control systems — X-by-wire systems — do not depend on conventional mechanical or hydraulics mechanisms. Such dynamically configurable electronic mechatronic elements are triggering system-wide integration, making vehicles lighter, cheaper, safer, more fuel-efficient and less harmful to the environment.

In fact, mechatronic features have become the products differentiator for a consumer’s desired mutter functions in their cars. Now, the challenge in automotive mechatronic system design is the dramatic jump in complexity (doubling every two to three years), almost comparable to the complexity increase in microelectronics. This added complexity needs to be managed and controlled. That calls for continued innovation to create products with distinctive functionality, better quality, and a cost advantage. At the same time, we need highly efficient processes for product design, manufacturing and calibration.

In the case of the internal combustion engine, many opportunities for innovation remain. Using an analogy to the human body, imagine you inhaled and exhale the same volume of air with every breath and that there was no such thing as deep or shallow breathing. Somewhere between tightening down and ascending several flight of stairs, your lungs would reach a point where they would be working at optimum capacity. That is the nature of the internal combustion cycle operating with fixed valves that open and close the intake and exhaust valves by the same amount and in the same position in the cycle every time, regardless of engine speed, load, or external conditions.

However, with increased component modeling capability, we now have a better understanding of the IC engine and how to improve it. Engine spark and fuel metering have already exceeded their bounds of purely mechanical control, engine calibration will be next. Engine designers love degrees of freedom, and adding on-demand and variable controls to almost any system can improve fuel economy and lower parasitic losses. But the average engine has only two variables: electronic fuel injection and electronic spark timing. Think about the trade-offs on a car to achieve engine performance, high speeds versus idle. An engine designer doesn’t have a free wheel of innovation. The component design is the solution.

A camless engine with an electronic camshaft valve-train actuator adds six degrees of freedom to engine control: three intake valve and three exhaust valve, corresponding to a valve operating, closing and lift. Efficient throttling would be eliminated, and cylinder and valve deactivations would lead to better fuel economy.

Thanks to mechatronics design, the camless engine is nearing full-scale implementation. The issues still to be addressed in the actuator design include: cost, reliability, packaging, power consumption, noise and operation. Noise may be the main problem, resulting from high-contrast velocities at the moving parts. At 3000 rpm, each electromagnetic valve moves a distance of about 8 inches, 100 times a second. In moving with current camshafts, engine builders would replace a single reliable component with a complex system with many more components. The essential monitoring technologies will be controls, featuring more computing power and speed, along with better and more durable sensors. Modeling will improve sensing through real-time, model-based observers.

Already, we’ve seen the continuously variable transmission, once just a theoretical vision, become a reality. Through a mechatronics approach, camless engines will follow the same path.
Changing the Culture for Mechatronics

“Who Says Elephants Can’t Dance?” former IBM CEO Lou Gerstner recalls, when it came to turning Big Blue around, “culture wasn’t just one aspect of the game — it was the game.”

The same can be said of many engineering-driven companies as they shift into a mechatronics’ approach to design. This is more often entails a change in corporate culture. Take Proctor & Gamble, for instance. The consumer goods giant makes a raft of products families all over the world depend on. But underlying its success are engineering innovations that help the firm beat the competition in a very tough market. In short, the machines making P&G products are modern marvels of engineering design — mechatronic system design.

I recently talked to Eric Berg, technical section head for Mechatronics and Intelligent Systems in Cincinnati, where many of the company’s machines are designed, built and tested. What follows are his observations on mechatronics and its impact on P&G.

Transparent Engineering

P&G’s purpose is to provide branded products of superior quality and value that improve the lives of consumers. We want consumers to identify with our products and brands, not our engineering. So, the engineering that goes into delivering our products must be transparent. However, internally within P&G, engineers are often kept at arm’s length and we are under constant pressure to improve quality, reduce cost and accelerate speed to market.

Big Time Savings

Mechatronics got P&G leadership’s attention when a handful of engineers, using mechatronics’ models, stopped one major program headed in the wrong direction and got a few other programs back on track, saving millions of dollars and years of development effort. A common element in early mechatronics’ models was the holistic approach to modeling the system dynamics, a relatively modest investment in time, but with a considerable result.

Going to School on it

P&G has invested a formal mechatronics’ training program. Engineers are taught in the analysis and synthesis (modeling) of systems, as well as the skills needed to convert models into commercial hardware and software. On the front end, engineers learn that the dynamics of most production systems can be described by a handful of ideal elements that have analogues behavior, regardless of whether the system is electrical, mechanical, thermal, gas or liquid flow. The four common analogues elements are: capacitance, resistance, inertia and dead-time. Engineers soon discover that most of the systems they care about are governed by the first-order lag transfer function. As a result, they quickly realize the benefits of re-application from one project to the next.

Practical Approach

“The key to improving becoming proficient at mechatronics’ analysis is to connect their industry experience with their academic skills. They also need to implement their designs using commercial components.”

Leveraging the Effort

“The fact that some dynamic processes we work with are governed by the first-order lag transfer function makes broad re-application throughout P&G’s manufacturing enterprise straightforward. For technicians on the factory floor, the underlying theory is not as important as they understand the process characteristics. Over the years, we’ve found a number of applications that are governed by higher-order, multiple-input, multiple-output, coupled, linear and non-linear models. However, these applications are the exception and we can handle these problems with a handful of engineers who have advanced mechatronics’ skills.”

The bottom line from Berg’s experience is mechatronics has helped P&G make significant gains in engineering productivity. What’s more, the company has achieved these results by teaching engineers how to make the most of their academic skills.

How ‘Observers’ Enhance Closed-loop Control

Take a look at mechatronics’ applications in diverse industries, such as automotive engine systems, hard-disk drives and Web transport systems, and you’ll find a growing emphasis on “sensor-less control” and the use of “observers” in control systems design.

These terms may be unfamiliar to you, but they are becoming increasingly relevant for design engineers as they decide on control systems for mechatronics’ projects. To understand why, let’s look at a typical mechatronic system.

From a cost and reliability perspective, engineers should use the fewest number of physical sensors possible and you want the physical sensors that you do use to perform optimally, despite noise and inherent response limitations. Also, certain mechanical variables necessary for control may not be measurable due to operational or environmental conditions. To help address these issues, we need to tap the physical and mathematical modeling that is essential in mechatronic system design. And we need to consider this concept of an observer.

The principle of an observer works like this: By combining a measured feedback signal with knowledge of the physical plant and physical sensor, the behavior of the plant can be known with greater accuracy and precision than by using the feedback signal alone. An observer is a mathematical structure that combines actual sensor output and plant excitation signals with models of the plant and sensor. It compares the actual sensor output with the observed sensor output and it drives that error signal with a high-gain PID type compensator, the observer controller.

If you do a block diagram on this page, you’ll see there are five elements of an observer: two inputs — the actual sensor output (V) and the measured controlled output (plant excitation) — and the observer compensation. One application of the observer, as shown in this diagram, is to use it in closed-loop control. In this example, the observer is used to control the plant state (CO), to control the control loop, as shown in the diagram. The observer output (Y) is no longer used to close the loop. What we really need here is to drive the observer to control the plant state. CO. As a result, you can remove most of the phase lag and attenuation of the sensor, in the frequency range of interest for the control loop.

In many such applications, observers can augment or replace existing physical sensors, which makes observers an exciting alternative to adding new sensors or upgrading existing ones. But keep in mind the four major components of observer design: modeling the sensor, modeling the plant, selecting the observer compensator and training the compensator. The main sources of sensor model inaccuracy, disturbances, and noise. You need to understand these factors well and effectively apply the observer as part of a control system design. But the potential benefits of observers, in terms of cost reduction, reliability and performance, can be enormous.

For further guidance on this important tool in mechatronics design, consult this valuable book, “Observers in Control Systems,” by George Ellis (Academic Press, 2010).

Interested in attending a Mechatronics Expo?

To learn more, e-mail mechatronics@reedbusiness.com

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Unleashing the Internal Combustion Engine Through Mechatronics
• **The Automobile – A Comprehensive Mechatronic System**
  
  – Today, mechatronic features have become the product differentiator in these traditionally mechanical systems.

  – This is further accelerated by:
    
    • Higher performance-price ratio in electronics
    • Market demand for innovative products with smart features
    • Drive to reduce cost of manufacturing of existing products through redesign incorporating mechatronics elements

  – The use of electronics in automobiles is increasing at a staggering rate.
Examples of new applications of mechatronic systems in the automotive world include:

- semi-autonomous to fully-autonomous automobiles
- safety enhancements
- emission reduction
- intelligent cruise control
- brake-by-wire systems eliminating the hydraulics

Mechatronic systems will contribute to meet the challenges in emission control and engine efficiency.

Clearly, an automobile with up to 60 microcontrollers and 100 electric motors, about 200 pounds of wiring, a multitude of sensors, and thousands of lines of software code can hardly be classified as a strictly mechanical system.
By-Wire Systems
Replace Mechanical Systems
In Automobiles
• **Expanding Automotive Electronic Systems**
  
  – Cost of electronics in luxury vehicles can amount to 23% of the total manufacturing cost.
  
  – More than 80% of all automotive innovation now stems from electronics.
  
  – High-end vehicles today may have more than 4 kilometers of wiring compared to 45 meters in vehicles manufactured in 1955.
  
  – In 1969, Apollo 11 employed a little more than 150 Kbytes of onboard memory to go to the moon and back. 30 years later, a family car might use 500 Kbytes to keep the CD player from skipping tracks.
  
  – The resulting demands on power and design have led to innovations in electronic networks for cars.
Researchers have focused on developing electronic systems that **safely and efficiently** replace entire mechanical and hydraulic applications.

Highly reliable and fault-tolerant electronic control systems, X-by-wire systems, do not depend on conventional mechanical or hydraulic mechanisms. They make vehicles lighter, cheaper, safer, and more fuel-efficient.

Increasing power demands have prompted the development of 42-V automotive systems.

X-by-wire systems feature dynamic interaction among system elements.

Replacing rigid mechanical components with dynamically-configurable electronic elements triggers a **system-wide level of integration**.
Dynamic Driving Control Systems
• **Challenges of Automotive Mechatronic System Design**
  
  – For typical mechatronic systems, there has been a dramatic increase of complexity during the past few years (doubling every 2-3 years) almost comparable to complexity increase in microelectronics.
  
  – System complexity can be measured by different parameters, e.g., number of components and their level of interaction, code size of software.

**Challenge**
Mastering the future increase of mechatronic system complexity
The Camless Dream Meets Reality

Current

Future

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Auto Fundamentals 2005

Valeo

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May 2005 – Industry experts say “Don’t expect to see the internal-combustion engine evaporate as a viable power source anytime soon.” There are still many more improvements remaining.

As computer-modeling capability improves, there is a better understanding of the IC engine and how to improve it, e.g., variable valve timing, combustion development, and fuel-injection systems.

There will be significant improvements in fuel economy, emissions, and performance.
• Technologies related to the engine itself – not so much technologies within the engine itself – have dramatically accelerated.

• Controls, with computing power and speed, and sensors, capable and durable, are enabling technologies!

• Goal of manufacturers: build engines with high levels of fuel economy, power, and torque, along with low emissions levels – and to do so at very high volumes – better than ever in terms of reliability and durability.

• Advanced technologies will focus on “variable everything.” Adding on-demand and variable controls to almost any system can improve fuel economy and lower parasitic losses.
• The last two decades have seen the ever-increasing usage of **electronics and microcontrollers** in response to the need to meet regulations and customer demands for high fuel economy, low emissions, best possible engine performance, and ride comfort.

• This has also lead to the development of **new engine control methods with new sensors and new actuators**.

• Devices have gone from purely mechanical to electro-mechanical with electronic control, e.g., carburetors and injection systems.

• New actuators have been added, e.g., exhaust gas recirculation (EGR), camshaft positioning, and variable geometry turbochargers (VTG).
Today’s combustion engines are completely microcomputer controlled with:

- many actuators (e.g., electrical, electro-mechanical, electro-hydraulic, electro-pneumatic influencing spark timing, fuel-injector pulse widths, EGR valves)
- many measured output variables (e.g., pressures, temperatures, engine rotational speed, air mass flow, camshaft position, exhaust gas oxygen-concentration)
- taking into account different operating phases (e.g., start-up, warming-up, idling, normal operation, overrun, shut down.)

The microprocessor-based control has grown up to a rather complicated control unit with 50-120 look-up tables, relating about 15 measured inputs and about 30 manipulated variables as outputs.
• Because many output variables (e.g., torque and emission concentrations) are mostly not available as measurements (too costly or short life time), a majority of control functions is feedforward.

• Increasing computational capabilities using floating point processors will allow advanced estimation techniques for non-measurable qualities like engine torque or exhaust gas properties and precise feedforward and feedback control over large ranges and with small tolerances.

• New electronically controlled actuators and new sensors entail additional control functions for new engine technologies (e.g., VTG turbo chargers, dynamic manifold pressure, variable valve timing (VVT) of inlet valves, combustion-pressure-based engine control).
• Overview of Engine Control Structures of State-of-the-Art Spark Ignition Engines

Simplified Control Structure of a SI Engine

• The engine control system must be designed for 5-10 main manipulated variables and 5-8 main output variables, leading to a complex nonlinear MIMO system.
Modern IC engines increasingly involve more actuating elements. SI engines have the classical inputs like amount of injection, ignition angle, injection angle, but also additionally controlled air/fuel ratio, EGR, and VVT.

Location of Sensors and Actuators of a SI Engine
(all are state-of-the-art in current engine control units except cylinder pressure sensors)
• In the May 2003 ASME Mechanical Engineering magazine, an excellent analogy was presented in the article Controlled Breathing
  – Climb a mountain! Thinner air at elevation makes you work harder to get the same amount of oxygen into your blood as at sea level.
  – Engines gasp for air just like mountain climbers do.
  – If during your climb, you strap a pressurized oxygen mask to your face, you would be revived. You need oxygen to perform.
  – Turbochargers boost engine performance in the same way that bottled oxygen helps mountaineers climb high.
Imagine that with every breath you inhale and exhale the same volume. There is no such thing as deep or shallow breathing. Somewhere between standing up and ascending the steepest sections of the climb, your lungs reach a point where they are working at optimum capacity.

That is the nature of the internal combustion cycle operating with fixed cams which open and close the intake and exhaust valves by the same amount and at the same point in the cycle every time, regardless of engine speed, load, or external conditions.
• Engine spark and fuel metering have already escaped their bonds of purely mechanical control; engine respiration will be the last of the combustion triumvirate to fall.

• A fuel-injected engine feeds on a mixture of gasoline and air. By monitoring the amount of air coming through the intake manifold, the fuel control dispenses an allotment of gasoline for efficient burning in the cylinders. In stepping on the gas pedal, a driver in actuality increases oxygen flowing to the engine by opening a throttle plate that sits in the path of incoming air. When the driver lets off the gas, this plate closes, throttling the engine.

• Although proven as an effective method of controlling engine speed, throttling wastes energy. A constricted intake forces the pistons to pull against a partial vacuum, creating pumping losses.
• BMW in 2000 eliminated the throttle plate and began using the valves themselves to control engine speed. An eccentric shaft that acts upon intermediate rocker arms adjusts the stroke lengths of the valves. A motor moves the eccentric shaft in response to driving conditions.

• Providing engine designers with even greater flexibility to move valves any way they want will improve engine performance. **Engine designers love degrees of freedom** and the average car today has only two: electronic fuel injection and electronic spark timing.

• Yesterday’s engine control systems took an empirical approach to telling engine actuators where they should be for any particular set of conditions. The engine was considered to be a black box!
• Next-generation controls are based on models! With these models, control engineers can characterize the flow through an engine, for example.

• Think about the tradeoffs a cam has to make on engine performance, high speeds vs. idle. With camless valve trains, one doesn’t have to live with compromise.

• Consider a camless engine with an electromechanical valve-train actuator. Camless valve trains add six degrees of freedom to engine control: three per intake valve and three per exhaust valve, corresponding to a valve’s opening, closing, and lift.

• This eliminates the need for inefficient throttling and could deliver higher torque. Also, a camless engine could deactivate unneeded cylinders for better efficiency. It could dispense with having to recirculate exhaust gases through EGR systems.
• But a camless engine could be noisy and susceptible to wear, as we will see.
• At 3000 rpm, each electromechanical valve moves a distance about 8 mm, 100 times a second. Sensors and controls will tell the story!
• In moving away from camshafts, engine builders would replace a single reliable component with a complex system comprising many more components of dubious integrity. Reliability of the camless engine will have to be built in through a combination of sensors, estimators, and diagnostic routines.
• Continuously variable transmissions, CVTs, started as theoretical visions also; now they are commercial entities. Camless engines may follow the same path.
Valeo replaces camshaft with smart valve actuation (SVA)

When the upper electromagnet is activated, the vane is held upward. The valve is in the closed position.

When the upper electromagnet's magnetic field is disrupted, the vane is pulled downward by springs. Actuation of the lower electromagnet maintains the valve in the open position.

CHARACTERISTICS
- 20% reduction of fuel consumption
- 20% reduction of pollutant emissions
- 20% increase in low-end engine torque

Optimization of air-fuel mixture and motion
Each engine valve operates independently from the others and independently from the piston position.
• These devices are presently being developed for implementation of advanced combustion strategies in internal combustion engines.

• Issues with the deployment of EMVs in internal combustion engines include:
  – Noise produced when the energized plunger strikes the core
  – Control of the seating velocity
  – Improved energy consumption
  – Trajectory shaping with a minimum number of measurements
  – High actuation speeds

• It is necessary to have tighter control tolerances and more in-depth models of the latest generation EMA.
• The overall system also must be **cost effective**. This means that the system may have to optimize performance with fewer available sensors.

• These demands, coupled with the strongly nonlinear dynamics of the EMA, make the use of classical sensor-based control strategies a less attractive option.

• The EMV is one of the promising solutions to the challenge of reduction in fuel consumption and vehicle emissions and improved engine performance. The idea of individual cylinder control and camless engines has reinvigorated interest in the concept of variable valve timing (VVT) or fully flexible valve actuation (FFVA) systems, i.e., direct control of both valve timing and valve lift.
• The plunger-striking problem, which may contribute to reduced structural integrity, as well as noise, can be addressed by reducing the plunger seating velocity (plunger speed before it impacts the core or housing of each electromagnet).

• Plunger seating velocity reduction can be obtained partly by mechanical design and entirely by electronic control.

• Modeling is essential and the model of the EMV actuator is nonlinear with secondary nonlinearities like saturation, hysteresis, bounce, and mutual induction. These nonlinearities are important in modeling the electromagnetic force to a reasonable degree of accuracy since the force exhibits these characteristics.
• The control of the EMV actuator entails modulating some measured mechanical variable like velocity or position.
  – Certain mechanical variables may not be measured accurately due to operational or environmental conditions.
  – From a cost perspective, it is also advantageous to use the least number of sensors possible.
  – There is a need to use other signals, usually an electrical variable, from which information on certain mechanical variables could be inferred. This is called sensorless estimation.
Magnetic Levitation System

Electromagnet
Infrared LED
Phototransistor
Levitated Ball

Electromagnetic Valve Actuator
For a Camless Automotive Engine
Magnetic Levitation System

- Electromagnet
- Infrared LED
- Levitated Ball
- Phototransistor

A Genuine Mechatronic System
Engineering System Investigation Process

The cornerstone of modern engineering practice!

Engineering System Investigation Process

Physics System

1. System Measurement
2. Measurement Analysis
3. Comparison: Predicted vs. Measured
   - Is the Comparison Adequate? [YES/NO]
5. Design Changes

Parameter Identification

- Physical Model
- Mathematical Model
- Mathematical Analysis
Magnetic Levitation System

A Genuine Mechatronic System

**Electromagnet**

**Infrared LED**

**Phototransistor**

\[ V_{\text{sensor}} = 5.44 \text{ V} \]

**Levitated Ball**

\[ m = 0.008 \text{ kg} \]

\[ r = 0.0062 \text{ m} = 0.24 \text{ in} \]

**Equilibrium Conditions**

\[ x_0 = 0.003 \text{ m} \]

\[ i_0 = 0.222 \text{ A} \]
**Electromagnet Actuator**

- Current flowing through the coil windings of the electromagnet generates a magnetic field.
- The ferromagnetic core of the electromagnet provides a low-reluctance path in which the magnetic field is concentrated.
- The magnetic field induces an attractive force on the ferromagnetic ball.

**Electromagnetic Force**

Proportional to the square of the current and inversely proportional to the square of the gap distance.

\[
f(x, i) = C \left( \frac{i^2}{x^2} \right)
\]
The electromagnet uses a ¼ - inch steel bolt as the core with approximately 3000 turns of 26-gauge magnet wire wound around it.

The resistance of the electromagnet at room temperature is approximately 32 Ω.
Elementary Electromagnet

- The system consists of:
  - stationary core with a winding of N turns
  - block of magnetic material is free to slide relative to the stationary member

\[ x = x(t) \]
\[ v = ri + \frac{d\lambda}{dt} \]  

voltage equation that describes the electric system

\[ \lambda = N\phi \]

\[ \phi = \phi_L + \phi_m \]

\( \phi_L = \text{leakage flux} \)

\( \phi_m = \text{magnetizing flux} \)

\[ \phi_L = \frac{Ni}{R_L} \]

\[ \phi_m = \frac{Ni}{R_m} \]

flux linkages  

(the magnetizing flux is common to both stationary and rotating members)

If the magnetic system is considered to be linear (saturation neglected), then, as in the case of stationary coupled circuits, we can express the fluxes in terms of reluctances.
Electrical-Magnetic Analogy

\[ V = \mathbf{i} R \]
\[ \mathcal{I} = \Phi \mathcal{R} \]

\[ V \iff \mathcal{I} \quad \mathbf{i} \iff \Phi \quad R \iff \mathcal{R} \]

\[ \mathcal{I} = N \mathbf{i} \quad \text{magnetomotive force (At)} \]
\[ \mathcal{R} = \frac{\ell_c}{\mu A} \quad \text{reluctance (At/Wb)} \]
\[ \frac{1}{\mathcal{R}} = \text{permeance} \]

Analogy between the Electric Circuit (a) and the Magnetic Circuit (b)
\[ \lambda = \left( \frac{N^2}{\mathcal{R}_\ell} + \frac{N^2}{\mathcal{R}_m} \right)i \quad \text{flux linkages} \]

\[ L_\ell = \text{leakage inductance} \]

\[ L_m = \text{magnetizing inductance} \]

\[ \mathcal{R}_m = \mathcal{R}_i + 2\mathcal{R}_g \quad \text{reluctance of the magnetizing path} \]

\[ \mathcal{R}_i \left\{ \begin{array}{l}
\mathcal{R}_i \quad \text{total reluctance of the magnetic material} \\
\text{of the stationary and movable members} \\
\mathcal{R}_g \quad \text{reluctance of one of the air gaps} \\
\end{array} \right. \]

\[ \mathcal{R}_i = \frac{\ell_i}{\mu_r \mu_0 A_i} \]

\[ \mathcal{R}_g = \frac{x}{\mu_0 A_g} \]

Assume that the cross-sectional areas of the stationary and movable members are equal and of the same material.
This may be somewhat of an oversimplification, but it is sufficient for our purposes.

\[
\mathcal{R}_m = \mathcal{R}_i + 2\mathcal{R}_g
= \frac{1}{\mu_0 A_i} \left( \frac{\ell_i}{\mu_{ri}} + 2x \right)
\]

Assume that the leakage inductance is constant.

The magnetizing inductance is clearly a function of displacement.

\[x = x(t) \text{ and } \mathcal{L}_m = \mathcal{L}_m(x)\]

When dealing with linear magnetic circuits wherein mechanical motion is not present, as in the case of a transformer, the change of flux linkages with respect to time was simply \(L\frac{di}{dt}\). This is not the case here.
\[ \lambda(i, x) = L(x)i = \left[L_e + L_m(x)\right]i \]

\[ \frac{d\lambda(i, x)}{dt} = \frac{\partial \lambda}{\partial i} \frac{di}{dt} + \frac{\partial \lambda}{\partial x} \frac{dx}{dt} \]

The inductance is a function of \( x(t) \).

\[ v = ri + \left[L_e + L_m(x)\right] \frac{di}{dt} + i \frac{dL_m(x)}{dx} \frac{dx}{dt} \]

The voltage equation is a nonlinear differential equation.

\[ L_m(x) = \frac{N^2}{\frac{1}{\mu_0A_i} \left(\frac{l_i}{\mu_{ri}} + 2x\right)} \]

Let’s look at the magnetizing inductance again.

\[ L_m(x) = \frac{k}{k_0 + x} \]

\[ k = \frac{N^2\mu_0A_i}{2} \]

\[ k_0 = \frac{l_i}{2\mu_{ri}} \]

\[ L_m(0) = \frac{k}{k_0} = \frac{N^2\mu_0\mu_{ri}A_i}{l_i} \]

\[ L_m(x) \approx \frac{k}{x} \quad \text{for} \; x > 0 \]
Detailed diagram of electromagnet for further analysis

Electromagnet

Magnetic Levitation System
$L_m(x) \approx \frac{k}{x}$ for $x > 0$  

Use this approximation

$L(x) \approx L_\ell + L_m(x) = L_\ell + \frac{k}{x}$ for $x > 0$

$\lambda(i, x) = L(x)i = [L_\ell + L_m(x)]i$

The system is magnetically linear:  

$W_f(i, x) = \frac{1}{2}L(x)i^2$

$f_e(i, x) = \frac{\partial W_c(i, x)}{\partial x} \quad \rightarrow \quad f_e(i, x) = \frac{1}{2}i^2 \frac{\partial L(x)}{\partial x}$

$= -\frac{ki^2}{2x^2}$
• The force $f_e$ is always negative; it pulls the moving member to the stationary member. In other words, an electromagnetic force is set up so as to minimize the reluctance (maximize the inductance) of the magnetic system.

• Equations of Motion:

$$v = ri + \ell \frac{di}{dt} + e_f$$

$$f = M \frac{d^2x}{dt^2} + D \frac{dx}{dt} + K(x - x_0) - f_e$$

Steady-State Operation (if $v$ and $f$ are constant)

$$v = ri$$

$$f = K(x - x_0) - f_e$$
Steady-State Operation of an Electromagnet

\[ f = K(x - x_0) - f_e \]

\[ -f_e = f - K(x - x_0) \]

\[ -\left( -\frac{ki^2}{2x^2} \right) = f - K(x - x_0) \]

**Parameters:**
- \( r = 10 \, \Omega \)
- \( K = 2667 \, \text{N/m} \)
- \( x_0 = 3 \, \text{mm} \)
- \( k = 6.283E-5 \, \text{H} \cdot \text{m} \)
- \( v = 5 \, \text{V} \)
- \( i = 0.5 \, \text{A} \)

Stable Operation: points 1 and 2

Unstable Operation: points 1' and 2'

(f = 4 N)

(f = 0)
Magnetic Levitation System Derivation

\[
\phi = \phi_l + \phi_m \quad \text{Neglect } \phi_l \quad \phi_m = \frac{Ni}{R_m}
\]

\[
\lambda = N\phi = N\phi_m = \frac{N^2i}{R_m} = L_m i
\]

\[
R_m = R_{\text{core}} + R_{\text{gap}} + R_{\text{object}} + R_{\text{return path}}
\]

Define: \( R = R_{\text{core}} + R_{\text{object}} + R_{\text{return path}} = \text{constant} \)

\[
R_{\text{gap}} = \frac{x_{\text{gap}}}{\mu_0 A_{\text{gap}}} \quad L_m = \frac{N^2}{R_m} = \frac{N^2}{R + \frac{x_{\text{gap}}}{\mu_0 A_{\text{gap}}}} = \frac{\mu_0 A_{\text{gap}} N^2}{\mu_0 A_{\text{gap}} R + x_{\text{gap}}}
\]

\[
W_{\text{field}} = \frac{1}{2} L(x) i^2 = \frac{1}{2} \frac{\mu_0 A_{\text{gap}} N^2}{\mu_0 A_{\text{gap}} R + x_{\text{gap}}} i^2
\]

\[
f_c = \frac{1}{2} i^2 \frac{dL(x)}{dx} = -\frac{1}{2} \frac{\mu_0 A_{\text{gap}} N^2}{\mu_0 A_{\text{gap}} R + x_{\text{gap}}} \left( \frac{1}{R + x_{\text{gap}}} \right)^2 = -K_1 \left( \frac{i}{K_2 + x_{\text{gap}}} \right)^2
\]
Ball-Position Sensor

LED Blocked: $V_{\text{sensor}} = 0 \text{ V}$
LED Unblocked: $V_{\text{sensor}} = 10 \text{ V}$
Equilibrium Position: $V_{\text{sensor}} \approx 5.40 \text{ V}$

$K_{\text{sensor}} \approx 4 \text{ V/mm}$ Range $\pm 1\text{mm}$

Magnetic Levitation System
• Ball-Position Sensor
  - The sensor consists of an infrared diode (emitter) and a phototransistor (detector) which are placed facing each other across the gap where the ball is levitated.
  - Infrared light is emitted from the diode and sensed at the base of the phototransistor which then allows a proportional amount of current to flow from the transistor collector to the transistor emitter.
  - When the path between the emitter and detector is completely blocked, no current flows.
  - When no object is placed between the emitter and detector, a maximum amount of current flows.
  - The current flowing through the transistor is converted to a voltage potential across a resistor.
- The voltage across the resistor, $V_{\text{sensor}}$, is sent through a unity-gain, follower op-amp to buffer the signal and avoid any circuit loading effects.
- $V_{\text{sensor}}$ is proportional to the vertical position of the ball with respect to its operating point; this is compared to the voltage corresponding to the desired ball position.
- The emitter potentiometer allows for changes in the current flowing through the infrared LED which affects the light intensity, beam width, and sensor gain.
- The transistor potentiometer adjusts the phototransistor current-to-voltage conversion sensitivity and allows adjustment of the sensor’s voltage range; a 0 - 10 volt range allows for maximum sensor sensitivity without saturation of the downstream buffer op-amp.
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Block Diagram

Linear Feedback Control System to Levitate Steel Ball about an Equilibrium Position Corresponding to Equilibrium Gap $x_0$ and Equilibrium Current $i_0$

From Equilibrium:
As $i \uparrow$, $x \downarrow$, & $V_{\text{sensor}} \downarrow$
As $i \downarrow$, $x \uparrow$, & $V_{\text{sensor}} \uparrow$

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Voltage-to-Current Converter

\[ i_M = \left( \frac{R_2}{R_1 + R_2} \right) \left( \frac{1}{R_S} \right) e_{in} \]

Assume Ideal Op-Amp Behavior

\[ e^+ = e^- \]

OPA544
High-Voltage, High Current Op Amp

R_1 = 49KΩ, R_2 = 1KΩ, R_S = 0.1Ω
Non-Ideal Op-Amp Behavior

\[ e_o = \frac{A}{\tau s + 1} \left( e^+ - e^- \right) \]

\[ e_{out} - e_1 = (L_M s + R_M) i \]

\[ e_1 = R_S i \]

\[ e_{out} - e_1 = (L_M s + R_M) \frac{e_1}{R_S} \]

\[ e_{out} = \left( \frac{L_M s + R_M + R_S}{R_S} \right) e_1 \]
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Control System Design

Equation of Motion:

\[ m \ddot{x} = mg - C \left( \frac{i^2}{x^2} \right) \]

At Equilibrium:

\[ mg = C \left( \frac{i^2}{X^2} \right) \]

Linearization:

\[
\begin{align*}
C \left( \frac{i^2}{x^2} \right) & \approx C \left( \frac{i^2}{X^2} \right) - C \left( \frac{2i}{X^3} \right) \dot{x} + C \left( \frac{2i}{X^2} \right) \dot{i} \\
C \left( \frac{i^2}{x^2} \right) & = mg - C \left( \frac{i^2}{X^2} \right) + C \left( \frac{2i}{X^3} \right) \dot{x} - C \left( \frac{2i}{X^2} \right) \dot{i} \\
m \ddot{x} & = C \left( \frac{2i^2}{X^3} \right) \dot{x} - C \left( \frac{2i}{X^2} \right) \dot{i}
\end{align*}
\]
Use of Experimental Testing in Multivariable Linearization

\[ f_m = f(i, y) \]

\[ f_m \approx f(i_0, y_0) + \left( \frac{\partial f}{\partial y} \right)_{i_0, y_0} (y - y_0) + \left( \frac{\partial f}{\partial i} \right)_{i_0, y_0} (i - i_0) \]
\[ V_{\text{desired}} + \Sigma \rightarrow G_c(s) \rightarrow \Sigma \rightarrow V_{\text{bias}} + \rightarrow \text{Controller} \rightarrow \Sigma \rightarrow \text{Current Amplifier} \rightarrow i \rightarrow G(s) \rightarrow \text{Magnet + Ball} \]

\[ V_{\text{actual}} \rightarrow \text{Sensor} \rightarrow K_{\text{sensor}} = 4 \text{ V/mm} \]

\[
m = 0.008 \\
g = 9.81 \\
x = 0.003 \\
\bar{i} = 0.222
\]

\[
m \dddot{x} = C \left( \frac{2 \bar{i}^2}{x^3} \right) \dddot{x} - C \left( \frac{2 \bar{i}}{x^2} \right) \dddot{i}
\]

\[
\ddot{x} = 6540 \dddot{x} - 88 \dddot{i}
\]

\[
mg = C \left( \frac{\bar{i}^2}{x^2} \right) \rightarrow C = 1.4332 \times 10^{-5}
\]

\[
\frac{\dot{x}}{\dot{i}} = \frac{-88}{(s^2 - 6540)}
\]
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Open-Loop Transfer Function

\[ \frac{88}{s^2 - 6540} \times (0.2)(4000) = \frac{70400}{s^2 - 6540} \]

Lead Controller

\[ K \left[ \frac{s + z}{s + p} \right] = 1.5 \left[ \frac{s + 100}{s + 500} \right] \]

PD Controller

\[ \frac{K_p + K_D s}{\tau s + 1} \]

\[ K_p = 0.3 \]

\[ K_D = 0.003 \]

Root Locus Plot

Open-Loop Bode Plot
LabVIEW Control Front Panel

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LabVIEW Control Block Diagram