Mechatronic System Design at Rensselaer

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Abstract Fast-paced industry technologies originally demanded more of a mechatronic education than the academic arena was easily and comprehensibly able to provide: traditional curricula in mechanical, electrical and computer engineering are mutually exclusive, and within these disciplines the area of control system design is largely split between them, resulting in either a highly specialised or disparately-bridged educational experience. However, emerging technologies increasingly demand conceptualisation, communication, design and fabrication skills in each field simultaneously. As a polytechnic institute, Rensselaer is meeting this challenge by augmenting students' educational experience with the necessary principles of mechatronic design and recruiting industry to provide direct motivation through interactive collaboration on relevant, current-day problem solutions under the mechatronic paradigm. In this paper we present some of the tactics and examples we have successfully used to extend the practical knowledge and skills of our graduates to fluency and proficiency in synergistic, mechatronic design.

1 MECHATRONICS EDUCATION AT RENSSELAER

1.1 Expanding the Curriculum for Mechanical Engineers

What constitutes a winning design? As engineering educators, we strive to address these questions through the courses we teach, since good design skills are paramount to engineering success. From a design point-of-view, *mechatronics* is the synergistic combination of precision mechanical engineering, controls engineering, electronics, and real-time computer programming, all integrated via the design process. From an industrial point-of-view, successful mechanical engineering graduates must possesses all these skills to some degree of sufficiency.

What constitutes a successful design? Starting with design and continuing through manufacture, mechatronic designs optimise the available mix of technologies to produce quality precision consumer products in a timely manner with features the customer wants. If winning designs are to be produced in today' s environment, it is imperative that electronics and computer control be included in the design process at the same time the basic functions and properties are defined. The real benefits of a mechatronic approach to design are shorter development cycles, lower costs, and increased quality, reliability, functionality, and performance.

At Rensselaer Polytechnic Institute we provide our engineering students with a comprehensive methodology for winning design, at both the undergraduate (last or *senior* year) and graduate (first *post-graduate* year) levels, and continue to develop one of the most aggressive mechatronics education curricula in North America. Within the Department of Mechanical Engineering, Aeronautical Engineering and Mechanics, inter-disciplinary design skills and inter-active problem-solving in project teams are stressed. During the last four years, we have introduced three paramount and very popular elective courses to the mechatronics curriculum at R.P.I.; these are *Mechatronics, Mechatronic System Design*, and *Digital Control System Design and Implementation*. These courses integrate well not only with existing strengths in our design curriculum, but also attract significant attendance by pupils in electrical, industrial and operations engineering, business management, and computer science. In these courses we seek to: stimulate interactive learning and problem-solving between students with diverse educational backgrounds; teach students fundamental skills in control system design, electronics, mechanical engineering and computer science, as well as reverse engineering and product design techniques; and solicit pertinent problems from industrial sponsors for mechatronic solution by student teams. The coursework is challenging and rewarding, and heavily laboratory- and project-based, in close collaboration with the R.P.I. Mechatronics Research Laboratory and R.P.I. Active Materials and Smart Structures Laboratory. Other project-oriented courses and research facilities at R.P.I. are inspired by the mechatronics curriculum, as are several local corporations and influential national industry organisations. This is evidenced in part by direct industry interest through consultation requests and the specific hiring of *Mechatronics* graduates from R.P.I., research grants demanding mechatronic component and system design, and interest in on-going mechatronics research at R.P.I. by prospective matriculants from other prestigious universities around the world.

1.2 Our Mechatronics Curriculum in Brief

In *Mechatronics*, a mix of students – predominantly mechanical engineers, with the good remainder electrical engineers, computer scientists, industrial and process engineers, and business management majors – are taught the fundamentals of mechatronic design: reverse engineering techniques; analogue and digital control system design in both the time and frequency domains, and related design issues; analogue and digital electronics; electronics, microprocessor and minicomputer interfacing issues; actuator and sensor use, and control system integration; data analysis tools in MATLAB® and SIMULINK® and control programming using C on both minicomputers and microcontroller boards. This course builds on other required courses at R.P.I. (modelling and analysis of dynamic systems, electronics and instrumentation, basic feedback control, and embedded control applications). Throughout the course mechatronic design principles are stressed and are reinforced through the reverse engineering of successful mechatronic products and systems. This course is heavily laboratory based, and material is presented such that information discussed in lecture is immediately reinforced in the laboratory. A premium is placed on interactive learning through: student-team formation in the lectures and the discussion of design-related issues, hands-on laboratory exercises involving industrial-quality hardware, computer-aided design involving the latest computer control and design software, and the encouragement of critical thinking throughout the course. [1]

In *Mechatronic System Design*, a limited-enrolment course for the more enterprising undergraduates out of *Mechatronics*, sponsors in the engineering industry are sought to provide real problems needing mechatronic solutions; students form teams balanced according to individual skill areas, and generate a project solution, from the conceptual design stage to product delivery, in direct collaboration with their industry sponsor: in short, a complete, real-world mechatronic design experience at the undergraduate level. [2]

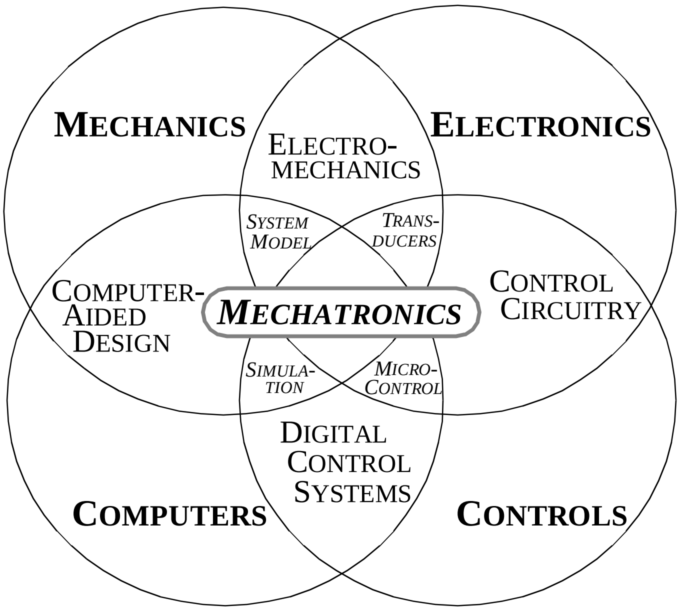
Digital Control System Design and Implementation is a new course specifically targeted toward graduate mechanical engineers with a concentration in control systems, and stresses digital design and hardware implementation issues not covered in typical mechanical engineering curricula; here the material presented in *Mechatronics* is briefly reviewed and then extended to include: emulated and direct digital control system design using z-transform methods, again in both the time and frequency domains; discretisation and quantisation error effects; digital and analogue anti-aliasing filters; continuous and digital gain plot techniques; realistic numerical and temporal computation and control issues (such as time-delay effects, system bandwidth and sampling time selection); active material technologies; time- and frequency-domain system identification techniques; and real-time hardware and software control techniques. All advanced classroom topics are reinforced by demonstration in simulation in MATLAB® and, insofar possible, on actual hardware. Small design teams are formed to address a control problem and/or design of choice, which is presented in detail to the class at the semester's end (a selection of projects from this course are featured in section 3).

1.3 Transforming Disparate Theory into Unified Practice

Many students entering the mechatronics arena with a strict mechanical engineering background find that what most keeps them from being able to turn enterprising design ideas into realisable practise is their unfamiliarity with basic elements of electronics and computing. The mechatronics curriculum at R.P.I. is, in some fundamental sense, intended to alleviate this distress. Mechatronic product design is a current-day reality, and many students interested in design, manufacturing, and production – the means by which final products are created – realise the need to expand their working familiarity with basic electronics and computer applications.

At Rensselaer, computer-aided design and other computing skills are developed at the basic engineering level (comprised of newly matriculated students) using the Rensselaer Computing System, a fairly new campus-wide network made possible in part by donations from International Business Machines. Students learn to use Pro/Engineer® (a professional CAD package), Maple® (a symbolic algebra manipulation environment), MATLAB® (a numerical computation environment), and SIMULINK® (a control systems design and simulation toolbox), and have full access to the Internet via NetScape® (a web browser) and other protocols. Computer programming, however, is typically reserved for computer science majors, unfortunately.

Fundamentals of electronics are taught in an embedded controls laboratory, where circuit-building and -testing is performed interactively with the computer at students' own pace. This course introduces basic component technologies and circuit integration skills, yet inadvertently sacrifices some theoretical attention for the sake of extensive laboratory experience.



Despite the supportive learning environment, students enter *Mechatronics* at quite varied levels of electronics and computing experience: some students come from respective core departments, others arrive with the cunning of good hobbyists or the savvy of on-the-job experience in these non-mechanical fields, yet still a good number of *Mechatronics* students begin the coursework with some tepidity. We therefore introduce/review basic electronics, programming and interfacing theory in order to ensure everyone is on a compatible level; then team partners are assigned in suit with a balance of appropriate skills for each group.
There is certainly a challenge in bridging the inter-disciplinary gaps in students' education, particularly when a mechatronics curriculum is generated from within a traditional engineering discipline, and this situation presents unique challenges to mechatronics educators and students alike. We have found this to be a challenging but nonetheless very successful manner of rounding out the set of design and communication tools available to mechanical engineers, thus transforming them into true mechatronics engineers.

Students within the mechatronics curriculum at R.P.I. are excited by the inter-disciplinary experience, which they feel gives their course-of-study a rejuvenating feel, and a sense of progressiveness. Since the inception of our programme, enrolment demand has increased faster than the resources we are able to supply, *Mechatronics* being one of the most popular senior-year elective courses, despite its challenging reputation (already our laboratory space has trebled over the past four years!).

2 INDUSTRY-MOTIVATED MECHATRONICS

Five dynamical systems are available to students engaged in the study of digital control design. Two of these systems – an electromechanical positioning test bed and an electrohydraulic positioning test bed – are systems used primarily for funded research projects, while the remaining three systems – an inverted pendulum, a magnetic levitator, and a ball-on-beam balancer – are systems built expressly for educational use. Each of the five systems is used regularly in the mechatronics curriculum for the demonstration of class-related topics.

2.1 Electrohydraulic Positioning Test Bed [3]

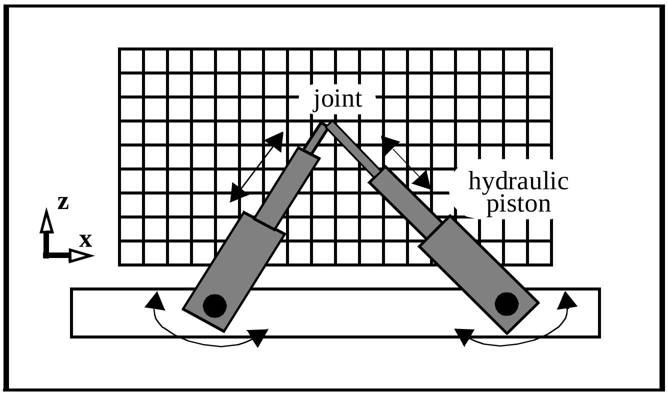


Figure 1: Electrohydraulic Positioning Robot.

An inexpensive mechatronic positioning robot was built in the Mechatronics Research Laboratory at R.P.I. to position heavy parts with critical accuracy, based on specifications commissioned by the Xerox Corporation of an actual industrial manufacturing process. The robot has two linearly-actuating hydraulic arms, spaced apart and connected at their base to the robot's workstation by revolute joints. These arms join at their tips to form a single joint able to move in a planar workspace by extending one or both the arms, and the amount of extension is measured directly by linear incremental optical encoders fed into a microcomputer.

The microcomputer controls two three-position valves to extend or retract each hydraulic arm individually, which together can direct the robot's tip position with an accuracy of better than 0.025mm. On-off and pulse-width modulation control schemes are used, eliminating the need for an expensive hydraulic servovalve. The robot, originally built for proof-of-concept, is now the centrepiece of one of the student workstations in the R.P.I. Mechatronics Education Laboratory.

2.2 Electromechanical Positioning Test Bed [4]

The Active Materials and Smart Structures Laboratory at R.P.I. is in its fourth year of flexible-structure vibration-suppression research. Current research work includes active flexible-beam position- and trajectory-tracking control, and "smart" machine-tool development. The demand for smart, adaptive control of structures is realised by their often complex composite assembly, slight variations in structural dynamics between parts off the same assembly line, random and non-random disturbances during control, and thermal and other (more permanent) loading effects incurred during manipulator use. Recently, the advent of structural sensor/actuator embedding technologies (active materials) has greatly enhanced the rejectability of these adverse effects and thus the controllability of many structures of interest.

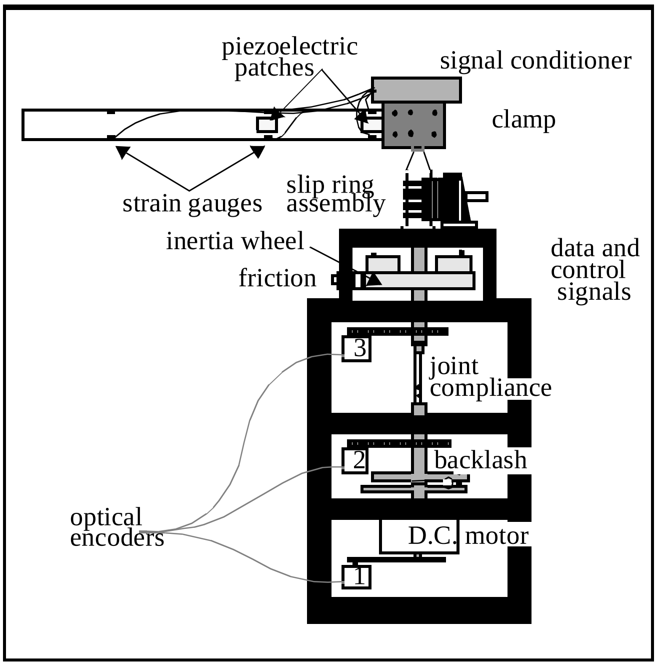


Figure 2: Mechanical Positioning Test Bed with Flexible Beam Attachment.

For controller design and proving purposes a mechanical positioning test bed was specially designed to facilitate investigating the effects of stiction, compliance and backlash in rotating machinery. Specific dynamic structures can be examined by affixing them to the rotating spindle on the test bed, and sensor and actuator signals linked via a 12-channel slip ring to a dedicated computer for data-acquisition and control purposes.

Recently, active beam mode cancellation was successfully achieved using surface-mounted PZTs during a slewing motion induced at the clamped beam end (the hub) by a high-torque DC-motor. In this experiment, a flexible beam is attached to the spindle, and control signals are sent to four co-located piezoelectric transducers while data is obtained from six co-located strain gauges along the beam and three co-located optical encoders along the drive shaft.

This test bed configuration allows investigation of active material use within smart structural mechanisms, in this case piezoelectric transducers with a flexible beam. We are thus able to prove by experiment a good number of control applications heretofore tested only in simulation, and couple related areas of traditional investigation directly. In this particular case, for example, we successfully demonstrate not only the increased controllability of a flexible structure using active materials, but also the extent of instability introduced by unmodeled drive-train effects. The approximation of such a system to the realistic industrial situation of, say, a robot with flexible modes, compliant joints and friction, is naturally much better than one unable to simultaneously mimic these non-linearities. [5]

We therefore also use the test bed as a tool for graduate study outside of research, where the test bed is used to demonstrate and investigate more complex dynamical geometries and smart structure integrations. One such current project is control of a rotary inverted pendulum, a student-designed attachment to the system: in this case the test bed allows full rotation of the pendulum, unlike linear inverted-pendulum experiments, as well as concurrent examination of the realistic disturbance effects of Coulomb friction, backlash and compliance. The device lends itself well to a demonstration variety of classroom examples and its use for educational work is encouraged.

2.3 Other Industrial Projects

Rensselaer continues to foster student-industry interaction using the mechatronics curriculum as a motivational vehicle.

One team designed, tested, and built a self-contained solenoid testing station for a manufacturer. The team was largely self-governing, met regularly with their industry sponsor, and ordered and assembled the necessary equipment on their own. The result was more than a learning experience for the students, who had to design and interface mechanical, electronic and software components from scratch; in fact, the manufacturer was so pleased with the increased efficiency and cost savings created by the students' product that they extended job offers to the team members before the semester was even over.

In Rensselaer's Mechatronics Research Laboratory, a number of industry-sponsored mechatronics projects are evolving, including: acoustic signature cancellation and acoustic enclosure sound insulation using piezoceramics, smart machining systems development, and automated manufacturing process control are among them. All these projects involve the applied integration of electronic, mechanical and computing skills.

Other projects spawned via industry consultation are concerned with the development of completely new smart material sensor systems not even yet in existence, such as active distributed pressure and shape measurement and control sensor/actuator combinations. Such intrinsically co-located input-output transducers are of particular interest because it is these which make a structure “active”. Control algorithm development, and subsequent downloading of the tested design onto microcircuits make it “smart”. These two key elements are at the focus of R.P.I.’s successful drive in meeting the kinds of product specifications sought by industry today.

3 MECHATRONIC CLASS PROJECTS

An equal number of interesting mechatronic projects are the result of in-class participation and team project development. The Mechatronics Education Laboratory hosts a number of independent work stations, among which student teams rotate on a weekly or bi-weekly basis. These include the hydraulics robot described in section 2; pneumatics control; dc motor control; stepper motor control; analogue filtering and digital logic; A/D and D/A converter interfacing, to both minicomputers and microcontrollers. In *Digital Control System Design and Implementation*, students are encouraged to select published control projects for digital implementation; two of these projects are showcased in the following sections for illustrative purposes. Notice in particular the practical issues involved in designing these mechatronic systems: each requires skills in dynamics, electronics, computing and interfacing; mastery of both traditional and modern control techniques in the analogue and digital domains; and theoretical design concurrent with actual implementation, along with the inevitable practical pitfalls and constraints.

3.1 Electromagnetic Levitator

This project is designed to investigate the implementation of a digital control system for a magnetic levitation device. Analogue devices are used more frequently for such applications due to the high bandwidth required to compensate for the inherent instabilities and non-linearities. However, if implemented carefully, a digital system can yield adequate performance. This study is intended to explore the obstacles and difficulties associated with implementing a digital compensator for such a system in which an analogue device is often better suited. Thus, some of the limitations and disadvantages of digital control systems (specifically, quantisation and sampling rate limitations) are clearly identified and studied.

Our control objective is to keep a ferro-magnetic object suspended in midair by controlling the current through an electromagnet. The electromagnetic force must be adjusted to counteract the weight of the object and account for disturbances. This is accomplished by sensing the location of the object and adjusting the current in the electromagnet in order to maintain the object at a predetermined vertical displacement (a regulator control problem).

The starting point for this design is a magnetic levitation project described in [6]; this reference includes an appendix with a general hardware overview, a mathematical model of the associated system dynamics, and a corresponding analogue control system design, for an existing and working novelty device. Based on this description, a similar hardware device was built with a matching analogue control implementation. A digital compensator was then designed and implemented, and its performance compared with the original analogue system.

An analytical model of the system dynamics was developed, the required analogue control system hard-wired, and a corresponding digital control system implement and interfaced via microcontrol. Comparisons between the analogue and digital systems as well as limitations due to quantisation and sample rate are discussed. A more thorough presentation is available [7].

3.1.1 Physical System and Dynamics

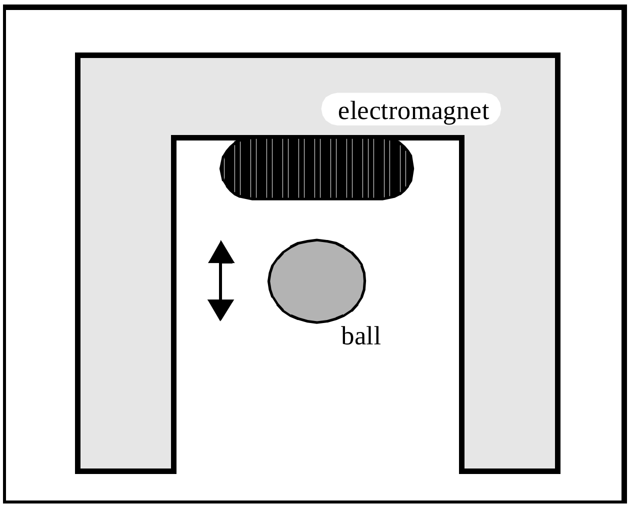


Figure 3: Magnetic Levitator.

The physical system consists of three primary parts; an infrared proximity sensor, an electromagnetic actuator, and the analogue/digital control and interfacing circuitry. The object to be levitated is suspended in mid-air below the electromagnet. The sensor is oriented in a way that allows it to feed back the vertical position of the object. The controller uses this sensor signal to adjust the current in the electromagnet and thus suspend motion of the hanging object. The sensor system consists of an infrared diode (emitter) and a phototransistor (detector). They are placed facing each other across the gap where the object was levitated, in an electric eye configuration: infrared light emitted by the diode is sensed at the base of the phototransistor, the intensity of which induces a roughly proportional current flow through the phototransistor collector-emitter path. When the object completely blocks the visual path of the electric eye, the corresponding current flow is nil, and conversely, with the object completely removed from the path, some predetermined maximum amount of current flows through the sensor circuit. The current flowing through the transistor generates a voltage potential across a resistor downstream which is proportional to the vertical position of the mass in the gap, thus serving as the input voltage to the control system. This sensor differs from that presented in [6].

3.1.2 Actuator System

The actuator consists of a home-made electromagnet and power transistor combination. A long steel screw forms the core of the electromagnet, and around it are wrapped approximately 3500 windings (about 275 metres) of very thin wire in a centimetre-length bundle. With current flow through the electromagnet a magnetic field is generated, attracting the ferromagnetic object to be suspended against gravity. The transistor is set up so that changes in the base voltage of the transistor cause proportional changes in the current flow through the electromagnet, similarly in configuration to the sensor circuit. The electromagnetic field thereby controls the position of the object, simply by adjusting the voltage at the base of this transistor.

3.1.3 Analogue Control System Design (Hardware-Based)

Two different SISO compensators are implemented, one analogue and one digital, which are selectable by a hardware switch (thus facilitating on-line comparison of the two controllers).

The analogue controller consists of a first-order lead compensator (two resistors and a capacitor). The controller gain is adjusted by an inverting operational amplifier with a variable feedback resistance. This variable potentiometer resistance allows the calibration offset (the direct current gain through the electromagnetic coil) to be tuned for the control circuit. The control input is the sensor voltage, and the control output the voltage at the base of the power transistor.

The control system is calibrated by manually hanging or supporting the object to be suspended and twiddling the actuator D.C. gain until it is only just electromagnetically suspended. Once calibrated, the actual behaviour of the operating hardware is found to agree extremely well with the analytically-predicted system behaviour. This is in part because system identification of the feedback loop is used, yielding a fairly precise model of the system dynamics about the operating point. Predicted robustness characteristics are also verified in the hardware: the system is able to levitate any ferromagnetic object that fits beneath the electromagnet! This remarkable robustness to mass variations is one of the key features of analogue control, and is not as easily achievable in its digital counterpart.

3.1.4 Digital Control System Design (Software-Based)

The digital controller consists of the same first-order lead compensator approach, now interfaced to a microcontroller via digital circuitry. Again, the input is the sensor voltage, which is scaled to range between 0 and 5V, the limits of the 12-bit A/D converter on our microcontroller board. A difference equation is computed by the microcontroller and its output sent through an 8-bit port to a D/A converter. The signal is subsequently scaled and offset, and then fed into the same operational amplifier and potentiometer used to drive the power transistor for the analogue controller.

Before the digital compensator was designed, we found it necessary to determine some additional key parameters in order to best understand limitations introduced by digital control design. Primarily to keep the system portable and self-contained (independent of a minicomputer system), it is natural to implement the digital compensator on a microcontroller. This introduces limitations in word size and sample rate which had to be addressed in the control system design, but allowed the system to better serve its intended function as an educational instruction tool. Sample rate selection and quantisation issues also become prominent design factors in translation from the analogue to digital domain.

The digital control algorithm basically implements a difference equation based on the z-transform. The minimum achievable sample period of the microcontroller is found to be 3.5 milliseconds, and a program flowchart used to map out the C code eventually downloaded onto the controller board. Both emulated and direct digital designs are implemented on the levitation device, for robustness comparisons.

Design by emulation refers to the technique in which a classically-designed continuous compensator is transformed directly into an equivalent digital compensator [8]. The Tustin method (also known as the bilinear transformation) with frequency warping is the most commonly used transformation associated with this approach, because it best preserves frequency response characteristics at the critical system frequencies (those associated with the inherent system time constants). It is also used often because it is much simpler to simply emulate analogue controller designs rather than re-design them in the digital domain. This is particularly true of real-world analogue systems which are “upgraded” to digital controllability. However, unless system dynamics are sufficiently slow, pushing the performance boundaries will also push the system closer to instability. For this reason we consider it insufficient to learn emulation techniques alone, and rather stress the use of emulation as a general, conservative indication of the system performance envelope. Direct digital design is taught for those cases where emulation does not satisfy both performance and robustness specifications simultaneously.

In order for the digital compensator to behave similarly to the continuous magnetic levitation compensator, it is found that a sampling rate of about 20 times the closed-loop bandwidth is desired. In our set-up this translates to a sampling period of less than or equal to 0.78 milliseconds, whereas the minimum possible sampling rate on the Blue Earth microcontroller we used is 3.5 milliseconds, introducing a real-world constraint into the theoretical design problem. Since the desired sample rate is about 4.5 times larger than the achievable sample rate, we discover that indeed the digital controller resulting from the emulation design cannot, in this particular case, meet the necessary performance for digital magnetic levitation control, and, more seriously, may in fact result in fully unstable control. It is still informative, however, to complete the emulation design in order to gather guidance and insight into a realisable direct discrete design approach. Implementation of the emulated control system with the analogue-equivalent gains in fact did show the system to become unstable. A direct digital design is thus necessary, and is implemented, in order to obtain a stable control design meeting the desired system specifications.

3.1.5 A Comparison of the Analogue and Digital Controls

It is informative to briefly summarize the comparisons between the digital and analog control systems. First, the bandwidth of the analogue system was 400 $^{rad}/_{s}$ and for the digital system was 307 $^{rad}/_{s}$. The result is a more robust system in the analogue domain, presumably due to the higher bandwidth. The digital system could not achieve higher bandwidth due to limitations on the physically achievable sampling frequency of the microcontroller.

Both systems are found to have reasonably good disturbance rejection qualities. In fact, the direct digital system has sufficient disturbance rejection to handle quantisation effects in the sensing mechanism. The total disturbance rejection for the digital control system is approximately -20 dB at low frequencies – not as good as the analog system, but nonetheless adequate for system performance.

Note that it is often the case that while pure emulated designs may work under minicomputer control, which in some sense assumes a digital machine fast enough to carry out the required control computations through some input-output hardware architecture, microcontrollers, due to their relative compactness, will typically exhibit much greater performance constraints. Because microcontrol is implied in embedded systems design, this is a key point we teach our students, and is also the motivation behind our complementing their classical controls background with a foundation in direct digital control system design and implementation, as the title of the class suggests. In the words of Franklin, Powell and Workman: “Carrying out the initial design using continuous methods is a good idea independent of whether it will be used in a subsequent emulation step or merely as a guide for a direct discrete design.” [8]. In our case, the emulated design approach offers valuable insight into the placement of the compensator pole and zero, which subsequently can be applied during the direct digital design of the compensator to yield a final control design to successfully balance the small mass.

The analogue system is ultimately more robust than the digital system, but a digital system is found to nevertheless work under the relatively constrictive sampling frequency limitations of the microcontroller. In order to minimise quantisation effects, it is deemed useful to design the digital compensator with a unity D.C. gain so as to utilise the full available output range of the 8-bit D/A converter.

There are two main techniques which could still be pursued for future work, that may increase the robustness of the digital system with respect to quantisation effects. Firstly, a dither signal could be summed with the controller voltage to combat limit cycling between two neighbouring quantisation levels at the D/A converter output, one technique known to increase the stability margins of a digital control system. Secondly, low-pass filtering of the control signal output can, and in fact typically should, be used to smooth the controller output (eliminating potential aliasing effects on the system response); the bandwidth of such a filter must be high enough so as to minimise resultant phase lag in the control at low output frequencies.

3.2 Ball-on-Beam Balancer

In the preceding study, digital design methods are used mainly to compare analogue and digital design methods for illustrative purposes. In many more realistic situations, on the other hand, digital control becomes the only feasible control method for controlling certain system behaviours. Digital control has two intrinsic and quite advantageous properties, that analogue systems typically do not: modular, software-controllable reconfigurability; and multi-taskability, the ability to interleave independent functional objectives. The following showcase is an example where robust system stability can only be achieved under digital control, in spite of the various inherent limitations thereof discussed in the previous example.

A ball-on-beam balancer is described with regard to further issues in digital control system design and implementation. An analytical model is again formulated, based on linearisation of the physical system about its operational equilibrium. The pertinent parameters of the system are experimentally determined to represent a more truthful mathematical model of the actual system. Classical control methods are first used to develop an analogue controller for balancing the position of a ball in the centre of a see-saw-like beam, which is then implemented in hardware.

Sensor noise from the ball position sensor is recognized as a performance limitation. A digital controller is thus developed and implemented with the idea that the increased flexibility of software control allows these sensor disturbances to be rejected. The digital control system requires greater development effort, but indeed proves to be much more effective at regulating the ball position over a wider range of motion than is possible using analogue control. A more thorough design treatment is given in [9].

3.2.1 Physical System and Dynamics

In a mechatronic system design, not only the mechanical system, but also the sensors, actuators, and electronics, must be modelled and analysed for design optimisation. Six major components comprise the ball-on-beam system: a beam with a ball constrained to roll along (and ideally remain on) its length, a ball-position sensor, a beam-angle sensor, a D.C. motor, and associated control electronics.

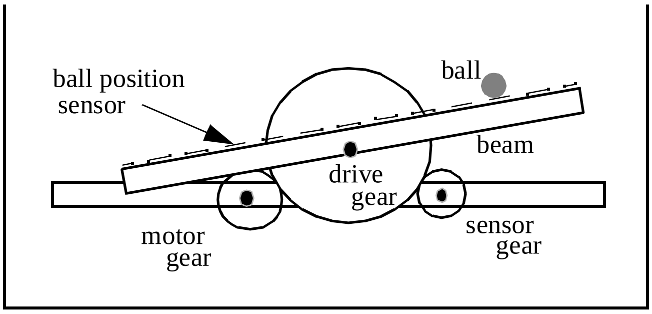


Figure 4: Ball-on-Beam Balancer.

The beam angle is measured by a rotary potentiometer through the “sensor gear” as shown above. Because of this gear reduction, the beam angle sensor resolution is increased by a factor of four. The beam is wooden, centrally hinged and grooved to ensure unrestricted movement of the ball along the full length of the beam. Along either side of the groove is a NiChrome (a nickel-chromium alloy) wire, which together interact with the ball as a ball-position sensor: a voltage is placed across one of the nichrome wires, and the ball acts as a bridge to the other wire, which registers a potential loss at one end proportional to the linear displacement of the ball, in effect acting like a linear potentiometer. This is possible because the NiChrome has a high resistance per unit length. A diagramme elucidating the sensor circuit is shown on the following page.

The control actuator is a D.C. motor connected to a bearing-supported beam shaft via a gearing mechanism (to increase the effective torque of the motor). The motor is driven by a power (operational) amplifier.

3.2.2 Analogue Control System Design (Hardware-Based)

Once the system model is developed and all the parameters are determined, a controller is designed using classical control methods. This controller is cast as a regulator problem with unspecific performance specifications other than a rise time below five seconds (the length of time required for the ball to naturally roll from the equilibrium position off the end of the beam), with good disturbance-rejection characteristics. The design and analysis of the controller is performed using MATLAB®. A root locus approach is used for this purpose.

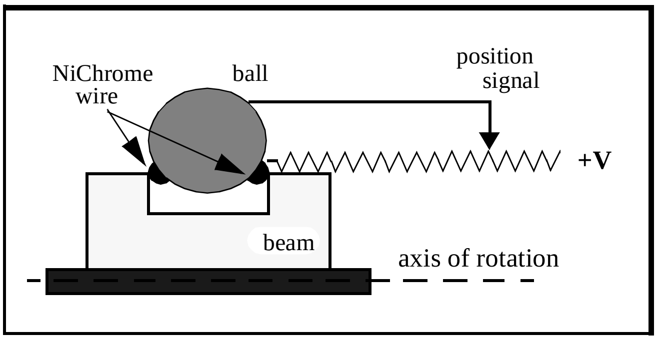


Figure 5: Ball Position Sensor.

The implementation portion of the design consists of three components: a filter stage, lead compensator, and gain circuit. Filters are used to reduce high frequency noise from the power supply and the NiChrome wire ball position sensor (because the rolling ball was used as the contact between the wires, the signal was very noisy due to inconsistency in the electrical bridge). The sampling rate is initially chosen to be about 80 Hz, 240 times the closed loop system bandwidth. Given this rather lenient margin, the first digital compensator is designed via emulation, using MATLAB®. The controller is subsequently implemented both in hardware and software formats.

In practise it is found that when the ball nears either end of the rotating beam and is about to spill off, noise in the NiChrome position sensor cause the controller to over-adjust in such a way that the ball is often launched into the air (!). To reject such noise discontinuities in the signal, a straightforward filtering scheme is implemented in the software version: in the event that the sensor voltage changes suddenly (greater than 10% between consecutive samples), the previous command voltage is issued and the most recently sensed voltage discarded. Note that this implementation is possible only under digital control, which provides a natural environment for control scheduling, of which this particular control solution is a perfect example.

Nonetheless, signal noise remains a constant problem simply because of the rolling motion of the ball, and quantisation noise in the torque amplifier input. Noise levels have a great influence on how well an A/D converter performs, and can cause instability when input quantisation levels oscillate. In this case, a persistent 300mV at about 250-Hz noise is detectable in the input signal and the A/D converter will not function properly until it is removed from the signal. This is easily accomplished using an analogue low-pass (anti-aliasing) filter with dynamics sufficiently low to remove the unwanted noise, yet also sufficiently high to capture the range of system and control dynamics.

Another important issue in digital control scheme implementation is control law calculation delay and round-off effects. Whereas floating-point calculation imposes a huge burden on a microcontroller without intrinsic floating-point computational capabilities (such as a minicomputer with a math co-processor), integer math, while faster, must be carefully managed to ensure sufficient control resolution is maintained (in essence, round-off error can act like an internal quantisation error). Tests show that the microcontroller employed in this project can sample at a maximum of 57 KHz in a tight, dedicated loop, at 2 KHz using integer control law computation, or at about 88 Hz with floating point calculation of the control command signal. Since the ball-on-beam system has a relatively low closed-loop bandwidth (about 0.3 Hz), floating-point calculation remains a feasible strategy for maintaining computational resolution in this application. A control system needing a higher sampling rate would be better formulated as a combination of integer calculations.

In summary, great flexibility can be achieved in a digital control system because of the rapid changes in control formulation allowable by software implementation. The system design presented shows digital control to be superior to corresponding analogue control in terms of performance, but inferior when measures of development time, simplicity and cost are factored in, as might be expected.

3.3 Conclusions

The challenge of developing a system model corresponding to a real plant, linearising that model appropriately, and implementing the resultant design in hardware are not part of the traditional graduate automatic controls curriculum, yet these elements are often the most challenging and instructive components of a control systems case study. *Mechatronics, Mechatronic System Design and Digital Control System Design and Implementation* emphasise the importance of a thorough mechatronic design methodology. It is evident during this process that the design, construction and testing of a complete control system or mechatronic product from start-to-finish allows analytical modelling information to contribute constructively to control development without hindering specific optimisation based on direct digital control techniques, and that a comprehensive understanding of both physical and electronic dynamical interaction greatly facilitates hardware implementation of working controls for real systems.

4 TOWARDS THE FUTURE

This summer, Professors Stephen Derby and Kevin Craig are overseeing construction of the Center for Advanced Technology in Automation, Robotics and Manufacturing at R.P.I. (CAT), a two-million-dollar project jointly sponsored with the State of New York. This endeavour will link the existing Advanced Manufacturing Laboratory, where students have access to special flexible manufacturing facilities for rapid prototype manufacture, to a new Mechatronics Resource Laboratory, designed to promote: rapid response to new product and process design; specially-designed software linking CAD software, C code and robotic instrumentation control for modular manufacturing problem solution; a broad student talent pool for implementing said solutions; and a cutting-edge facility for high-tech. industrial training programmes.

The uniqueness of this latest development is evidenced by the creation of an industrial environment which takes the laboratory mechatronics experience one further step: here students will interact in a truly interdisciplinary environment in teams, using actual high-tech. industrial manufacturing equipment to solve real-world problems brought by industry. This greatly extends the array of tools available to student design teams previously working in educational laboratory workstations alone and closes the gap between the department's well-established design and newly-developing mechatronics curricula. Although R.P.I. is not a trade school by profession, we have a very strong reputation within industry because of our practical bent. The new CAT Center at Rensselaer will provide us with the tools not only to bring students a very practical industrial design and manufacturing experience in a truly multi-disciplinary environment, but rather formulate completely new and innovative manufacturing strategies, via rapid-response, flexible design and automation using high-technology industrial workcells with integrated software and prototyping machine and robotic assembly tools directly on the manufacturing floor.

5 CONCLUSIONS

Mechatronic design principles are well-suited to students with a mechanical engineering background. These students have a working knowledge and “feel” for dynamical system behaviour, and a classical (analogue, time-domain) controls foundation which gives them some insight into controlling such behaviour. Theoretically, mechatronics represents a fairly equal distribution of skills across the spectrum of design (creative conception and computer-aided design skills), engineering (mechanics, electronics and computers) and production (materials science, manufacturing, assembly and marketing), but in reality, the mechatronics engineer may only possess these skills to a degree sufficient to promote coordination and understanding throughout each of a project's production phases. Since mechanical engineers have some mastery of the mechanical aspects due any given project, their required knowledge of electrical engineering, computer science and other aspects to the project need not be as sophisticated. A fundamental working knowledge of interfacing electronics and computer application skills, for example, is sufficient for either direct implementation of the necessary control algorithms or close collaboration towards the same with an expert in the field; familiarity with the physical abilities and constraints of particular actuators and sensors, along with a knowledge of the electrical equivalents of mechanical components, similarly opens up the field of mechatronics to mechanical engineers, although in most cases these ideas are equally instructive to disciples in other fields. One of the interesting ramifications of the mechatronic paradigm as a whole is the realisation that mechatronics demands, and therefore encourages, participation from a number of engineering fields currently strong in existence but relatively dissociated; in mechatronics we teach students how to draw from experience in all these different areas and pull them into a concerted, elegant, efficient and enriched design experience. These basic tenets are espoused by the mechatronics curriculum at Rensselaer Polytechnic, and form our foundation for teaching mechatronic design to mechanical engineers, as well as electrical and industrial operations engineers, computer scientists, business and production managers, and others.

In order to actualise students' mechatronic education we augment classroom study with a challenging and thorough hands-on laboratory experience. This element takes the form of fundamental exercises in electronics, computing and "real-world" analysis, and student-governed project-building. We find this approach truly indispensable, if that is even strong enough a characterisation, because most mechatronics students encounter new problems in the lab which they have never had a chance to grapple with before. The laboratory accelerates their apprehension of the key lecture concepts, interests and motivates their learning experience, and exposes them to real-life problems encountered only during the actual physical realisation of theoretical design concepts, whether in the form of a computer programme, electronic circuit or assembly process. Similarly, industry-motivated and -selected design projects give students the exact sort of experience their job market is looking for, thereby obviously benefiting the reputation and working relationship of the mechatronics curriculum and school on the whole. We stress that industry originally motivated the need for a mechatronics curriculum, and thus we meet this challenge head-on by constantly seeking their close and continued collaboration.

Advanced students, particularly Master's and Doctoral candidates, are, supposedly, in school because they are not working in industry, and therefore we try to expand the working knowledge they already bring into our programme. At the same time, those advanced students matriculating without the benefit of a programme of study in design as comprehensive as that offered to the undergraduates at R.P.I., may nonetheless require a terser version of fundaments like *Mechatronics*. The advanced mechatronics curriculum thus includes some review of basic control design issues in greater detail, and follows up with a comprehensive look at more intricate design-related issues. For example, digital control is emphasised here for obvious and immense practical reasons, whereas in the undergraduate Mechatronics time does not fully permit this. Students are encouraged to formulate independent projects related to current published work or funded work in progress in our mechatronics laboratory facilities. The extent to which a thorough grappling with, and consequent mastery of, practical mechatronic control design issues often not fully appreciated or understood during lecture alone is unparalleled in this method of approach.

This concludes the outline of a number of particular educational formulations and techniques we employ at Rensselaer Polytechnic Institute, which we are able to generalise to an approach for proper mechatronics education as a whole. Some of our conclusions are specific to the problem that, as of yet, only select universities offer mechatronic engineering as a self-contained curricular programme; ours, for example, rests mainly within our Department of Mechanical Engineering, Aeronautical Engineering and Mechanics. However, we believe our basic philosophies and approach to the need for educating engineers in mechatronic design techniques can be extended as key principles. We attempt to outline these, namely the need for a foundation in mechanics, electronics, computing and control design theory and practise, and also provide examples of successful integration of these themes within our own mechatronics curriculum. We find that the most effective elements of successful mechatronic design include, roughly: sensor and actuator use; control theory, particularly in the digital domain; intense laboratory use and association with on-going sponsored research programmes; multi-disciplinary design fundamentals (electronics, computer programming and applications use); and most importantly, strong collaboration with industry, either through direct industry contact or industry-sponsored research grants. Rensselaer continues to forge new industry collaborations, motivate academic initiatives, and otherwise spearhead innovation in mechatronics education.

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APPENDIX

The following is a brief (but growing!) list of mechatronics and related courses currently offered within the Department of Mechanical Engineering, Aeronautical Engineering and Mechanics at Rensselaer Polytechnic Institute [10] (please inquire for further information, or look up our Internet homepage):

Mechatronics (undergraduate).
First introduced Autumn of 1991 by Dr Kevin C. Craig.
Two or three teaching assistants; enrolment upwards of 90.
Eight weekly laboratories in groups of two per work station.

Creativity Workshop (open to community).
First introduced during Winter Interim of 1993 by Dr Burt L. Swersey and Dr Larry Kagan, in cooperation with the R.P.I. Visual Arts Department. No assistants; enrolment of about 25. An intensive four-weekend workshop exploring creativity in design and paradigm shifting through artistic expression.

Mechatronic System Design (graduate and undergraduate).
First introduced Spring of 1993 by Dr Kevin C. Craig.
Two teaching assistants; enrolment limited to 25.
Self-managed project schedule with weekly presentations.

Machine Diagnostics (graduate).
First introduced Autumn of 1994 by Dr C. James Li.
Two teaching assistants; enrolment of about 25.
Lecture and term project on digital signal processing diagnostics and control design of machine tools.

Digital Control Design and Implementation (graduate).
First introduced Spring of 1995 by Dr Kevin C. Craig.
No teaching assistants; enrolment of about 20.
Lecture concurrent with a serious, detailed term project.

(Management in) Creative Engineering Design (graduate).
First introduced Spring of 1995 by Dr Burt L. Swersey, in cooperation with the School of Management.
Features guest entrepreneurs; enrolment popular but limited.
Creative weekly assignments, concurrent with product design from conception to presentation, and possible patenting.

Design with Active Materials (graduate).
For introduction in Autumn of 1995 by Dr Kevin C. Craig.
Selected topics in novel sensor and actuator design and application, with project using state-of-the-art lab equipment.