Int. J. Engng Ed. Vol. 11, Nos 4 and 5, pp. 336–342, 1995
Printed in Great Britain.

0949-149X/91 $3.00+0.00

A New Laboratory Course in Controlled Electromechanical Dynamics: Unifying Engineering Techniques in Analysis and Synthesis

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This paper describes a new NSF-ILI-funded laboratory course which unifies several fields for junior/senior level electrical engineers. The course objectives are to: teach the design cycle to students through a sequence of laboratory assignments; unify many of the engineering techniques taught in previous courses; and introduce the students to modern computer, sensing and control equipment. Novel elements of the course include: requiring the students to acquire facility with the C programming language quickly;introducing bond-graph modelling techniques at the junior/senior level; and requiring the students to design and evaluate real-time control programs executing within a multiprocessor system. The resulting course differs considerably from traditional courses in 'motors'. Rather than analyze the predicted and measured response of motors to open-loop transients, the students utilize their analytic knowledge of motors to design control software which induces desirable responses. Through laboratory experiments, the students gain an understanding of how their analytic skills can be applied to the design process. A description of the course organization, laboratory facilities and assignments is given.

AUTHOR QUESTIONNAIRE

1. The paper describes new training tools or laboratory concepts/instrumentation/experiments in:
   Electromechanic dynamics and controls.
2. The paper describes new equipment useful in the following courses
   Power electronics; 'motors' (electromechanical dynamics); introduction to control theory.
3. Level of students involved in the use of the equipment
   Juniors and seniors.
4. What aspects of your contribution are new?
   Integrates multiple disciplines (system modelling, characterization, instrumentation, real-time control) and incorporates both analysis and synthesis in software design for achieving target dynamics.
5. How is the material presented to be incorporated in engineering teaching?
   Similar courses could be offered which are more 'horizontal' in nature, incorporating elements from multiple specializations in a design synthesis activity.
6. Which texts or other documentation accompany the presented materials?
   Course notes still under development. Anticipate public release in 1996. Also, the NSF-ILI grant no. EID-8951327 final report contains text of the lab assignments, and additional equipment detail.
7. Have the concepts presented been tested in the classroom? What conclusions have been drawn from the experience?
   The course is currently being offered in its fourth year. Conclusions are offered in the text of the paper.
8. Other comments on benefits of your presented work for engineering education
   Course notes, equipment details and lab assignments should be useful in establishing similar courses at other institutions.

INTRODUCTION

ENGINEERING education faces extensive challenges. At the bachelor's level, we find that the course requirements which we consider essential can hardly be satisfied within four years. At the same time, we at Case have observed our students inadequately integrating the material learned in separate courses. The problem becomes particularly apparent at the senior level, when the students perform design-based senior projects. While the senior project is a design education in itself, we recognize that the students must begin to integrate their engineering knowledge earlier. This paper describes a new course offering in 'controlled electromechanical dynamics', the development of which was supported by an NSF Instrumentation and Laboratory Improvement (ILI) grant. The course has been designed to help unify engineering concepts, reinforce education of the design process, and do so using modern engineering equipment. The course is normally taken by juniors in the spring semester, and carries four semester-hour credits. The course and laboratory were designed over the summer and the fall semester, 1990, and the new course was first offered spring semester, 1991.

A former version of the present course, colloquially known as 'motors', covered the traditional aspects of the electromechanical energy conversion, with the usual emphasis on synchronous rotating machinery. The course was redesigned to address three educational issues: (i) to update the laboratory to incorporate modern developments, including power electronics, computer I/O, and applications of microprocessors in control; (ii) to teach the design cycle of analysis, synthesis and evaluation through laboratory experiments in characterization and control of electromechanical devices; and (iii) to unify many of the engineering techniques taught in prior, separate courses, including magnetic fields, circuit analysis, dynamics, ordinary differential equations, design of real-time software, and elementary control theory.

The new course is focused on the laboratory. Lectures, reading and occasional problem sets are organized to introduce, clarify and amplify the laboratory assignments. This paper describes the laboratory facilities, the specific sequence of laboratory experiments, and the novel combination of elements used in the lectures.

ORGANIZATION OF THE COURSE

The course consists of eight laboratory assignments, two extended homework assignments, and 27 75-min lectures over one semester. Course topics covered, in order, are:

- Maxwell's equations and magnetic circuits
- An introduction to Unix and C
- Theory and operation of the laboratory equipment
- Properties of magnetic materials
- An introduction to electric machines
- Electromechanical energy conversion
- Modelling dynamic systems
- An introduction to feedback control of dynamic systems
- DC machines
- Rotating fields
- Stepper motors and brushless motors
- Electronic commutation
- Induction motors
- Flux vector control
- Bond-graph modelling

Homework assignments are given to enforce an analytic understanding of magnetic circuits and of magnetic energy and co-energy. Laboratory assignments are performed by laboratory groups, each consisting of three team members. Laboratory assignments, in order, are:

1. Introduction to Unix and C
2. Introduction to the multiprocessor and physical I/O
3. DC motor characterization
4. Motor dynamics and control
5. Analysis and control of variable reluctance motors
6. Control of AC servo motors
7. Flux vector control of induction motors
8. Feedback linearization of a magnetic bearing

Text selection for this course was particularly difficult. In traditional 'motors' texts, substantial detail of transient operation under open-loop control (particularly open-loop voltage excitation) is covered. In the present course, however, the theme was quite different. Rather than analyze electromechanical devices to predict their transient response, analysis is used to design software which induces desirable responses. This variation reflects the dramatic recent changes in the cost and power of computing and of power semiconductors, making feedback control practical for even inexpensive motor applications. More important than the introduction of such new technology, though, is the opportunity for the students to invoke their analytic skills for synthesis, in this case for synthesizing controls.

Lacking a single text, readings were assigned from three texts. *Electromechanical Motion Devices*, by Krause and Wasynczuk [1], was utilized for magnetic circuits, magnetic forces and co-energy, description of induction motors and variable-reluctance motors, and the use of state-space in developing dynamic equations. Dynamic modelling was reinforced in by lectures and readings in bond graphs from *Introduction to Physical System Dynamics* by Rosenberg and Karnopp [2]. For learning C, readings were assigned from a recommended text, *C: The Complete Reference* by Schildt [3].

An appropriate text for this course would include: electromechanics, dynamic modelling, elementary controls, computer interfacing, and instrumentation. The lack of such a survey text suggests the extent to which our courses tend to become specialized and lack integration. To successfully develop this course, it was necessary to create a detailed set of notes covering the topics surveyed. These notes are made available on-line, and they can be accessed by the students from the laboratory's computers as well as over the campus fiber-optic network.

TECHNICAL MOTIVATION OF THE LABORATORY ASSIGNMENTS

Laboratory assignments in this course emphasize unifying engineering principles. With regard to electromechanical devices, a theme of this course is that the magnetic structure of a device determines its capability. The complex, myriad labelling distinction among electromagnets, solenoids, DC and AC servomotors, synchronous motors, stepper motors and induction motors are shown to be arbitrary. Using techniques such as feedback linearization, electronic commutation and flux-vector control, a variety of electromagnetic devices can satisfy a given performance specification. A varied collection of representative devices is chosen, and the students analyze these devices to predict their dynamic properties. These devices are then characterized experimentally, resulting in state-space models of the electromechanical dynamics. In the final step, the students use these models to design controls that obtain a desired response from each device. In particular, non-linear devices (a variable-reluctance stepper motor, a three-phase induction motor, and a magnetic bearing) are characterized to obtain their torque production as a function of state variables. Corresponding inverse mathematical relations are then programmed by the students to control current as a function of sensed state to achieve a servoed torque (or force) response. This inner, linearizing commutation control executes on a dedicated processor within a multiprocessing system. Subsequently, the students construct simple linear control algorithms and profiled path generation programs, which execute in parallel on separate processors within the multiprocessor. Real-time data acquisition is performed by reading and logging state variables, which are kept updated in global memory. The data acquisition process executes on its own processor board, thus permitting variations to the analysis programs without disrupting the commutation, feedback control, or path generation processes.

At first glance, it may seem that the use of multiprocessors for this course is unnecessarily complex. In fact, the use of multiprocessors helps to reduce code development time and student frustration. By developing programs to run concurrently on separate processor boards, it is simpler to divide assignments into multiple tasks to be performed by individual laboratory group members. Integration of each group's efforts is relatively simple, since the separate programs need only to share a single, common memory definition header. This structure permits avoidance of variable definition conflicts or critical timing mismatches. Further, relatively involved assignments are naturally broken down into subproblems (separate processes), and processes from earlier labs can be reused or modified to be invoked in subsequent assignments. Through this process, the students gain an appreciation for the value of multiprocessing and become comfortable with the concept.

In addition to the motivation of unifying electromechanical devices, a second theme of the laboratories is modelling and control of system dynamics. Motors offer particularly illustrative examples of coupled-system dynamics. The relationship between voltage and torque constants is measured in the labs, and shown to be equivalent in consistent units; this equivalence is explained in terms of energy transfer among generic multiport devices. System dynamics are described in terms of bond graphs, which are translated into systems of linear differential equations expressed in state-space form. Position and velocity feedback are described in terms of state space, and it is shown how these terms appear as equivalent mechanical springs and dampers. These feedback terms are programmed by the students, and their effects are tested and shown to conform to the analysis.

Having obtained a firm grasp of the coupled dynamics and the equivalence of linear controls to physical elements, the students utilize their analysis to synthesize controls. Assignments include obtaining maximum velocity and acceleration from variable reluctance and AC synchronous motors and achieving servo-positioning control of three-phase induction motors. While such operation of these types of motors is not yet commonplace, it is useful and practical given an adequate understanding of the basic principles of electromagnetic devices and controls. More importantly, the students practice invoking their understanding of these devices to achieve a target performance—often in spite of the manufacturer's narrowly defined intended role for a given motor.

LABORATORY FACILITIES AND ASSIGNMENTS

The laboratory assignments are designed to lead the students incrementally, albeit swiftly, through the material. The initial two assignments introduce the students to the computer system and the instrumentation, which they subsequently use on characterization and control of increasingly complex electromechanical devices.

The first two laboratory assignments give the students three weeks to gain a familiarity with the computer environment. The laboratory uses modern engineering workstations (Sun Microsystems SPARCstations) and VME-based multiprocessors. In the first labs, the students acquire facility with Unix (logging in, using on-line manual pages, editing, compiling, file systems) as well as gaining an introduction to C (program syntax, user I/O, variable declarations, math library, header files). Specific exercises and editing of raw programs available on-line provide a gentle first start with C. As this course does not require use of sophisticated data structures or string handling, much of the detail of C can be bypassed. Instead, hardware I/O and issues in time-critical execution are emphasized.

Each computer control and data-acquisition station consists of: a Sun Microsystems SPARCstation SLC; a SCSI to IEEE-488 converter, which permits the workstation to communicate through its SCSI port; an IEEE-488 to MVE converter, which permits the VME-bus-based single-board computers to communicate with the host Sun workstation; and a 12-slot VME-backplane computer rack with a variety of VME-compatible plug-in modules. Modules included in the VME stations are: four MC68020-based single-board computers; a four-channel 12-bit digital-to-analog converter (DAC) card; a 16-channel 12-bit analog-to-digital converter (ADC) card; a quadrature counter incremental encoder board; a 14-bit, two-channel resolver-to-digital converter board; and the VME-to-IEEE488 converter.

The multiprocessor system was developed earlier as part of the author's research program in mechatronics. Details of this system can be found in [5] (though there are some custom variations for this teaching lab). The VME-encoder and resolver board designs also derived from the author's research [4]. Real-time data display software which executes on the Sun hosts, called 'SunScope', also descended from the mechatronics laboratory.

Host workstations are networked to a common fileserver. Thus, class assignments and examples are accessible from any of the nodes, as is each student's home directory. Useful software available on the system includes a WYSIWYG-style word-processor (for composing laboratory reports), a windows-based text editor (for editing C code), electronic mail services, and data analysis programs (MatLab and Xmath).

The students gain initial familiarity with the multiprocessor, with real-time programming and with physical I/O by writing the C code for a simple waveform generator. Waveforms are specified by interrogating a user, and the generated output is displayed on an oscilloscope.

Having gained facility with the computer system, the class then performs a series of experiments on DC servo motors, including measuring voltage and torque constants, Coulomb and viscous friction, velocity saturation (due to amplifier voltage limits), and motor inertia, and reconciles this data with observed electromechanical time constants. Time-constant analyses are made possible by recording transient behavior using multiple motors and external load resistors.

In these assignments, the students use magnetic resolvers, optical encoders, tachometers, reactionless torque meters, and pulse-width-modulated (PWM) transconductance-mode power amplifiers. Each station includes a four-channel rack of PWM amplifiers, rated at 1.5 kW continuous per channel. The amplifiers operate in transconductance mode, resulting in a controlled current in response to a voltage-level command from the computer DACs. Given control of current levels in the windings of each device, it is easier for the students to analyze response and synthesize software controllers.

After characterizing the DC servomotors, the students attempt their first feedback controls. Simple position and velocity feedback is invoked. Graphical 'slider pots' are provided to the students to permit varying control parameter values while the controller is running. Transients are recorded to document and analyze the effect of mechanical loads on the controlled system. Subsequent analysis in terms of state-space reconciles the measurements with theory.

At this point, the students have a stronger grasp of dynamic modelling and control, and of the computer system, programming, and the instrumentation. In the next lab, a highly non-linear, though conceptually simpler electromagnetic device is introduced: the variable-reluctance stepper motor. In fact, this type of motor is virtually obsolete, though it is highly instructive. This type of motor exhibits a very non-linear torque versus current and angle relationship. Since this characterization is tedious, the students are given the measurement data. Their task is to utilize the characterization data to achieve widely different types of behavior. Initially, the students program the motor to operate as a stepper (as originally intended by the manufacturer). Next, the motor is driven as an AC-synchronous device. Finally, the students invert the characterization data to produce a software program which effectively turns this device into a controlled torque source. By controlling the motor to mimic a controlled torque source, higher-level control is identical to that of the DC servomotor. Thus, the class sees the same device perform in three radically different modes through the use of sensory feedback. This laboratory assignment illustrates the artificial categorization of electromechanical devices. It also teaches how proper software design can yield widely different behaviors from a given electromechanical device.

Having mastered the various modes of the stepper motor, the students do the same with a high-performance, three-phase AC servo motor. This device is driven to mimic a stepper motor, a synchronous motor, and finally a servo motor. In this lab, the students again experience how knowledge of a device's electromechanical equations can be used to synthesis software which leads to a wide variety of motion-control behaviors.

In addition to performing electronic AC commutation, this laboratory assignment introduces trajectory profiling for high-performance tracking. The non-linear effects of amplifier current and voltage saturation are illustrated in step-input position-control transients, motivating the use of continuous trajectory generation. The students utilize their knowledge of dynamics and the motor and amplifier parameters to derive a near-optimal trajectory profile generator, which executes on a separate processor board.

The penultimate laboratory assignment is to perform similar controls on a three-phase induction motor. This type of motor has the most non-linear and complex dynamics of those studied, yet it is also by far the most prevalent. Based on class lectures, the students develop a mathematical model for the motor, then test the model and measure the model parameters in the lab. Given the motor model, a linearizing 'flux-vector control' algorithm is synthesized, thus converting the induction motor into an equivalent servomotor. Having accomplished this design, the students apply the position control and trajectory-generation processes developed in earlier labs. Thus, it is illustrated how modelling, analysis and control, through the application of sensors and computers, can convert low-performance devices into high-performance devices.

In the final laboratory assignment, the students perform characterization and control of an electromagnetic suspension device. The experimental apparatus consists of a pair of opposed electromagnets, attracting a soft magnetic core in opposite directions. The core is mounted on a linear slide, permitting only a single, translational degree of freedom. Position of the slide is detected by a linear variable differential transformer (LVDT). For static characterization, a strain gauge measures the force on the magnetic core (versus current and position). Such measurements should be consistent with the students' analytic predictions.

Subsequent to characterization, the students utilize their non-linear model of the magnetic bearing, to design linearizing software which produces a controlled force, independent of core displacement. Using this force-control software as an inner control loop, an outer control loop is constructed which controls the position of the core to achieve the equivalent of a magnetic bearing device.

OBSERVATIONS ON THE COURSE

Some risks were taken in attempting to cover as much material as was done. However, it was, in the end, possible to span the described range without overtrivializing the material. Naturally, no one topic could be covered in the depth associated with speciality courses (e.g. programming techniques, computer interfacing devices and techniques, modern control theory, specific variations of commercial motor designs, dynamic system modelling). Rather, the 'horizontal' nature of the course sacrificed some specific depth in motors for enhanced integration of analysis and synthesis.

One risk taken was the presumption that juniors could learn enough about C and Unix within a few weeks to perform all of the required laboratory work. In fact, I found that the students were highly adept at absorbing the computer material. Further, in three successive years of teaching this course, the students demonstrated increasing computer competence and preparedness. Nonetheless, it was fruitful to provide a library of useful, debugged C-functions to help reduce the students' software development time. A second risk was that of teaching state-space methods within only two weeks without presuming a prior course in control theory. In this, it was necessary to restrict consideration to elementary control system design. The value to utilizing the state-space notation was that it helped to unify system modelling and control with electromechanical energy conversion. Finally, attempting to introduce bond graphs in only two weeks was a risk. However, in the context of an electromechanical dynamics course, the elements of multiple energy domains, transformers, gyrators, capacitors, inductors and dissipators are all considered, of necessity. Thus, introducing bond graphs required relatively little additional overhead, and the concepts were successfully introduced rapidly (as evidenced by problem set results).

CONCLUSION

A laboratory course in 'controlled electromechanical dynamics' was designed and tested on junior-level electrical engineering students. Novel components included: teaching elementary C and Unix within two weeks; teaching and using introductory bond-graph techniques within two weeks; and introducing elementary state-space based control theory. While each of these topics can easily consume a detailed course in its own right, each is included as a component element of the present course. While the core of this course is electromechanical devices, the intent is to integrate various engineering techniques. Within the illustrative contexts of electromechanics, the course emphasizes integration of analysis, characterization and synthesis in the design process. In the present case, simple commutation, motion control and trajectory generation algorithms are designed. A consequence of the laboratory assignments is that the students learn to appreciate how all electromagnetic devices are related. The process, though, requires analysis, measurement and concept generation common to a broad range of engineering practices.

Acknowledgements—Development of this laboratory course would not have been possible without the support of a grant from the National Science Foundation Instrumentation and Laboratory Improvement program, grant no. EID-8951327, and the generous support of the Case Alumnae Association. Additional support was provided through equipment donations and/or price reductions from local corporate benefactors, including Reliance Electric, Allen-Bradley, and Cleveland Machine Controls. Integrated Systems, Inc. donated a license to their Xmath software used in this course. Support from these institutions and companies is gratefully acknowledged.

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APPENDIX

Laboratory equipment integrated in the laboratory to support the described experiments is detailed here. A view of one of the laboratory benches is displayed in Fig. 1. This figure shows a pair of opposed DC servomotors (on the bench above the workstation), coupled through a reactionless torque meter. The Sun SPARCstation SLC (center) hosts the VME-based multiprocessor (to right of workstation), which includes a variety of digital and analog I/O. The multiprocessor drives the PWM power amps (not shown), and reads encoder, resolver, and/or LVDT signals. Three such benches are in operation.

The motors used in this course consist of the following:

- Baldor DC brushed servo motors (with integral resolver and tachometer)
- Superior Electric three-phase variable-reluctance stepper motors (with isolated phase windings)
- Reliance Electric three-phase induction motors (with phase windings altered for isolation of three independent windings)
- Pacific Scientific three-phase AC servo motors (with phase windings altered for isolation of three independent windings)
- Magnetic bearings (custom designed)

Motors are coupled to angular sensors, controlled loads and torque meters via Thomas Flexible Disk Couplings, which tolerate shaft misalignment while offering high torsional stiffness in the direction of shaft rotation.

All devices were driven by a general-purpose power amplifier. The power amplifier associated with each test bench consisted of four independent PWM modules, each rated at 1.5 kW continuous power (CSR model NC710 amps in a four-axis rack).

Computer components associated with each multiprocessor include:

- Motorola 12-slot VME card cage
- Motorola MVME 133-A, MC68020-based single-board computers (four per station)
- Analog Devices RTI-500/RTI-602 VME-bus analog I/O boards

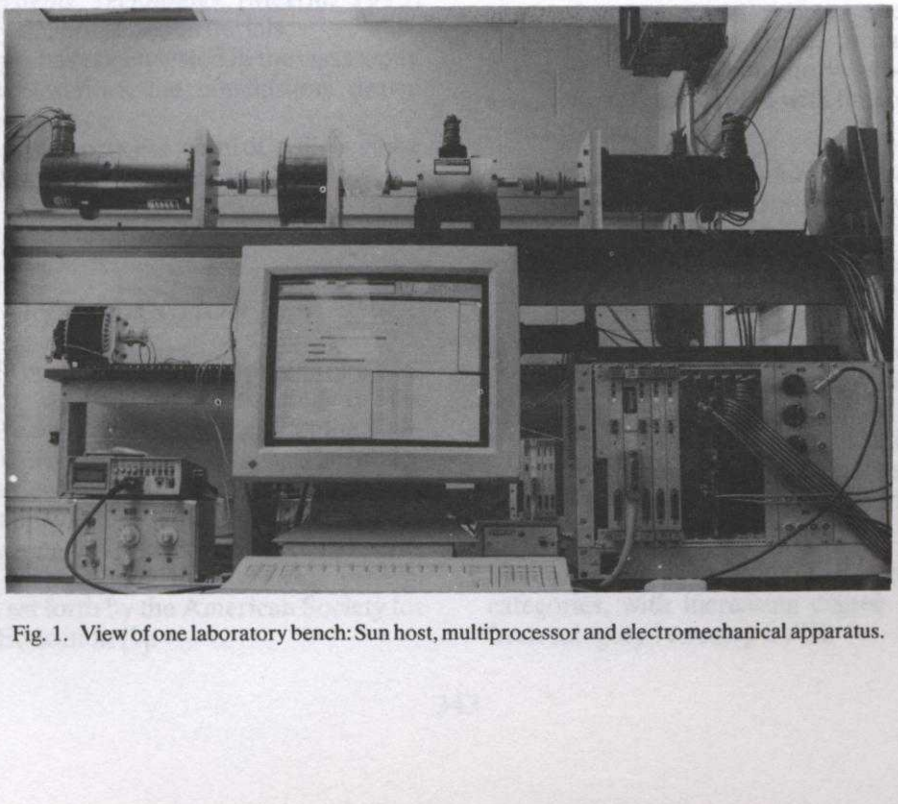

Fig. 1. View of one laboratory bench: Sun host, multiprocessor and electromechanical apparatus.

- CAISR VME Quadrature Encoder Interface
- CAISR VME Resolver Interface
- IOtech SCSI488/S3 SCSI to IEEE488 converter
- National Instruments GPIB-1014-EH IEEE488-to-VME converter
- Sun SPARCstation SLC workstation

Sensors used include:

- Harowe resolvers (integrated in DC and AC servos)
- Dynapar incremental optical encoders
- Omega LCL-020 strain-gauge instrumented load beams
- Himmelstein MCRT 24-02T reactionless torque meters and amps
- Daytronic LVDT/signal conditioner

Software utilized in this course includes:

- Integrated Systems, Inc, Xmath
- Island Graphics, Inc, IslandWrite and IslandPaint
- The Math Works, Inc., MatLab
- Custom mouse-driven control panels and oscilloscope emulation

These components offer a valuable exposure to the most common varieties of actuators and sensors, while supporting the experiments that illustrate modern electromechanical control techniques.