Systems Dynamics and Control, Proposed Course Overview and Education Oriented Approach for Mechatronics Engineering Curricula

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ABSTRACT: Mechatronics engineer is expected to design engineering systems with synergy and integration toward constrains like higher performance, speed, precision, efficiency, lower costs and functionality. To meet such integrated abilities and knowledge requirements, it is desired that Mechatronics engineering curricula, to include a proper integrated courses' description, with specific topics, lab sessions, student projects and methods of integrated abilities and knowledge delivery. This paper proposes, a proper for Mechatronics education, Systems Dynamics and Control course detailed description, topics with specific learning objectives, prerequisites, administration, simple but effective teaching approach supported by simple and easy to memorize education oriented steps and tables, that integrate course outcomes, to solve control problems, all intended to support educators in teaching process, help students in concepts understanding, maximum knowledge and skills transfer / gaining in solving controller/algorithm selection and design problems as a stage of Mechatronics system design stages, to equip students with the key abilities and knowledge, required for further courses in Mechatronics curricula.

Keywords: Mechatronics Education, Teaching Approach, Course Description, Dynamics Control Design, Modeling

I. INTRODUCTION

The continuous progress in information technology and the synergetic implementation of different engineering aspects caused the engineering problems to be harder, scientific problems are normally multidisciplinary and to solve them we require a multidisciplinary engineering systems procedures, such systems are used to be called Mechatronic systems. In the same time engineers affront hard challenges and in competitive market they must provide high attendance by presenting their selves as innovative, integrative, conceptual, and multidisciplinary. Engineers must be capable of treating in depth different engineering disciplines with a balance between theory and practice, therefore, they must have breadth in business and human values, an engineer with such qualifications is called Mechatronics engineer. Mechatronics engineer is hoped to design engineering systems with synergy and integration toward constrains like higher performance, speed, precision, efficiency, lower costs and higher functionality.

Role of Control Subsystem in Mechatronics System and Its Design; Mechatronics can be defined as a multidisciplinary concept, where mechanical engineering, electric engineering, electronic systems, information technology are integrated, moreover intelligent control system, and computer hardware and software are involved to manage complexity, uncertainty, and communication through the design and manufacture of products and processes from the very start of the design process, thus enabling complex decision making. Modern products are used to be called Mechatronics products, when the comprehensive systems are fully integrated. Today for improving development processes in industry two top drivers are considered: shorter product-development schedules and increased customer demand for better performing products, The Mechatronic system design process is a modern interdisciplinary design procedure, it is the concurrent selection, evaluation, synergetic integration, and optimization of the whole system and all its sub-systems and components as a whole and concurrently, where all the design procedures should work in parallel and collaborative manner throughout the design and development process to produce an overall optimal design [1, 3].

Integration refers to combining disparate data or systems so they work as one system. The
Integration within a Mechatronics system can be performed in two kinds, 
a) through the integration of components (hardware integration) and 
b) through the integration by information processing (software 
integration) based on advanced control function. The integration of components results from designing the 
Mechatronics system as an overall system, and embedding the sensor, actuators, and microcomputers into 
the mechanical process, the microcomputers can be integrated with actuators, the process, or sensor or be 
aranged at several places. Integrated sensors and microcomputers lead to smart sensors, and integrated 
actuators and microcomputers developed into smart actuators. For large systems bus connections will replace 
the many cable. Hence, there are several possibilities to build up an integrated overall system by proper 
integration of the hardware. Synergy refers to the creation of a whole final products that is better than the 
simple sum of its parts, the principle of synergy in Mechatronics means, an integrated and concurrent design 
should result in a better product than one obtained through an uncoupled or sequential design, synergy can be 
generated by the right combination of parameters, [1, 14]

Mechatronics systems are supposed to be designed with synergy and integration toward constrains like 
higher performance, speed, precision, efficiency, lower costs and functionality and operate with exceptional 
high levels of accuracy and speed despite adverse effects of system nonlinearities, uncertainties and disturbances, 
Therefore, one of important decisions in Mechatronics system design process are, two directly related to each 
other subsystems, the control unit (physical-unit) and control algorithm subsystems selection, design and 
synergistic integration. During the concurrent design of Mechatronic systems, it is important that changes in the 
mechanical structure and other subsystems be evaluated simultaneously; a badly designed mechanical system 
will never be able to give a good performance by adding a sophisticated control system, therefore, Mechatronic 
systems design requires that a mechanical system, dynamics and its control system structure be designed as an 
integrated system (this desired that (sub-) models be reusable), modelled and simulated to obtain unified model 
of both, that will simplify the analysis and prediction of whole system effects, performance, and generally to 
achieve a better performance, a more flexible system, or just reduce the cost of the system. Possible physical-
control subsystem and algorithm options are shown in Figure 1. As shown, three components can be identified at 
this level; the control system, control algorithm and the electronic unit subsystems. The control unit is the 
central and most important part (brain) of Mechatronic system, it commands, controls and optimizes the process, 
by reading the input signals representing the state of the system and environment, compares them to the desired 
states, and according to control algorithm, outputs signals to the actuators to control and optimise the physical 
system and meeting specifications. Control subsystem must ensure excellent steady-state and dynamic 
performance [1, 7].

[Diagram: Mechatronics system design approach]

**Figure 1a.** Components at control stage: Control system, algorithm and electronic unit subsystems.
II. "CONTROL SYSTEMS DESIGN AND ANALYSIS" COURSE

This is a basic course, consisting of two parts; system dynamics and their control process. It focuses on gaining adequate abilities and knowledge in mathematical modelling of dynamic systems and corresponding selection and design of control system to meet and maintain desired performance. The course is taught in all mechanical, electric and Mechatronics engineering curricula and tracks; including: General mechanical engineering, Mechatronics engineering, Industrial engineering, Control engineering, Automation engineering, also can be found taught in other departments such as science/math. Departments. Depending on institution, department, minor's specific requirements and educators, it may have different description and titles, also is taught from different points of view and applying different approaches. Titles such as: Controlled differential equations, System dynamics and control, Dynamic systems and control, Control system design and analysis, Feedback control system, Control and engineering, introduction to control systems, and others [11].

A unified course description, with specific learning objectives/outcomes, correct prerequisites, other courses to which, this course is a prerequisite, also, simple but effective teaching approach supported with tables, that can help in achieving learning objectives, is highly required. This paper proposes, a proper for Mechatronics education, course detailed description, topics with specific learning objectives, correct prerequisites, administration, simple but effective teaching approach supported by simple and easy to memorize education oriented steps and tables, that integrate course outcomes, to solve control problems, all intended to support educators in teaching process, help students in concepts understanding, maximum knowledge and skills transfer/gaining in solving controller/algorith selection and design problems as a stage of Mechatronics system design stages, and prepare them for other further courses applied in Mechatronics curricula including; Mechatronics fundamentals, Process control, Mechatronics systems design, Embedded systems design, Robotics, PLC, CNC and others [4, 13].

2.1. Proposed Course Description, Audience, and Course Learning Objectives

2.1.1. Course Learning Objectives

Course learning objectives (CLOs) are the key abilities and knowledge that to be assessed in a course. One of main aims of Mechatronics curricula is to equip the students with multidisciplinary capabilities to design Mechatronics systems, the course is required, and is a basic course in the control of dynamical systems, intended to provide students with abilities and knowledge in control system/algorith, selection and design. It is prerequisite for a group of further subjects/courses, mentioned above, in Mechanical/Mechatronics engineering program. By analysing what abilities and knowledge are desired for the student to have before attending each of these courses, it can be clarified what CLOs are desired. In particular, after taking this course, students should be able to:

a) Understand fundamentals associated with control theory; analysis, design, performance, response, types and role of: control, control loops, control loop components, control units, control algorithms there mathematical models, their effects upon process performance and selection criteria (summarized in Table 6).

b) Apply fundamentals associated with representation of physical systems and related concepts; Represent a plant (process) mathematically, using block diagrams, transfer function, flow graphs, state equation (Build control-oriented models of dynamic systems; electrical, mechanical, hydraulic and pneumatic).

c) Develop engineering and physical insights into analysis and evaluation (interpretation) of a plant's performance (or how systems respond to an input?), in terms of key characteristics of developed mathematical model (summarized in Tables 3, 4, 5). To analyze whether a given control system is stable or not?, what needs to be done to make it stable (analyze)?, how this can (should) be done (synthesis)? And how his solution will affect the system performance (evaluation)?, Also to anticipate system's stability and response, based on poles (zeros) nature, location, damping ratio (summarized in Table 3).

d) Understand the conceptual selection and design of a control unit/algorith, in time/frequency/state space domains, and apply principles and tools of feedback and control to select and design a control system/algorith to design a control system to meet and maintain desired performance specification, despite adverse effects of system nonlinearities, uncertainties and
disturbances. (e) Apply fundamentals associated with the use of control systems analysis and design software (e.g. MATLAB, Labview) with facility to aid in the analysis, design and simulation of control systems. All these are described according to ABET in next section. For the next courses, to which course is a prerequisite, the following “control course” based abilities and knowledge given by (a to e) are desired: Mechatronics fundamentals (a, b, c), Mechatronics systems design: (a, b, c, d, e), Process control (a, b, c, d, e), Embedded systems design (a, b), Robotics (a, b, c, d), PLC (a, b, c), CNC (a, b, c). [2, 6].

2.1.2. Course Prerequisites
The course is intended to be taken by students with a diverse mathematics background, [2, 8]. To gain the key abilities and knowledge, associated with mentioned CLOs, and based on institution, Department and minor requirements, the following courses could be general prerequisites: Differential equations, Laplace transformations, Linear Algebra, Mechanical Vibrations, engineering dynamics. For Mechatronics engineering students, the required prerequisites are: Differential equations, Mechanical Vibrations, Basic electrical circuits.

2.1.3. Course Outcomes (ABET*)
(a): Ability to apply the knowledge of mathematics, science, and engineering, (have the knowledge and the ability to apply intermediate and advanced mathematics; differential calculus, Laplace transformations, and linear algebra). (b): Ability to design and conduct experiments, as well as to analyze and interpret data, (able to identify the measurable parameters, able to identify different methods for measuring the phenomenon. able to identify the relationship between the phenomenon and the measured parameters. able to demonstrate general lab safety. able to follow experimental procedures for the experiment while maintaining all safety precautions. able to collect and record data using appropriate units of measurements and identify the dependent and independent variables in the experiments, ability to analyze the data to generate the required parameters. ability to discuss the raw and derived data/graphs and assess the validity of the results. ability to relate how experimental result can be used to improve a process). (c): An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability, (able to identify the customer and the needs, able to identify and list the design objectives, able to identify the design constraints. able to define the design strategy and methodology, to identify the types of information needed for a complete understanding of all aspects of the project. able to define functional requirements for design. able to transform functional requirements into candidate solution concepts/ mathematical modelling, able to evaluate candidate solutions to arrive at feasible. able to develop final design specifications). (d): An ability to function on multidisciplinary teams. (e): An ability to identify (understand), formulate, and solve engineering problems (f): An understanding of professional and ethical responsibility (use-apply of handbooks, codes, and standards) in obtaining, reporting, analyzing data or in design). (g): An ability to communicate effectively, (able to: demonstrate knowledge and understanding of the subject. Able to: organize presentation in well structured logical sequence making it easy for audience to follow the content with clear understanding. Able to: stay within time limits). (h): The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context.(i): Recognition of the need for, and the ability to engage in life-long learning (able to identify and take advantage of learning opportunities available on internet and elsewhere such as seminars, conferences, workshops, and tutorials. Able to independently acquire additional knowledge and data needed for solving the problem). (k): An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice, (able to solve problems using current software used in the discipline, such as Matlab) [9].

2.1.4. Recommended Textbooks and Other Course Materials/References

2.1.5. Proposed Description
"Introduction to control theory and related concepts (Control, control systems, control algorithm, types of control, classification of control loops, components/role of control system, response, performance,...). Mathematical foundation: Review of related mathematical theories; (Differential equations, Complex-variable
theory and Laplace & z-transforms). System representation; mathematical modelling represent physical systems (electrical, mechanical, hydraulic and pneumatic) using the following forms; differential equations, Block diagrams (and corresponding algebra), transfer function (poles, zeros, pole zero map), state space equation, and signal flow graphs (Mason’s gain formula). Analysis and evaluation of system (plant) performance (transient and steady state response measures of I and II order system, dominant poles of higher order systems). Selection and design of control system/compensators in time domain, to meet and maintain desired overall system performance. Analysis and design in frequency domain. Analysis and design in state space domain. Control systems analysis and design software (e.g. MATLAB, Labview) with facility to aid in the analysis, design and simulation of control systems, (MATLAB built-in function for analysis and plotting systems’ response, Introduce control system toolbox sisotool and rtool and corresponding design and analysis) [9].

2.1.6. Proposed Simple and Easy to Memorized and Follow Control System Design Teaching Approach,

To support educators in knowledge delivery, and help students in achieving CLOs abilities and knowledge and solve control problems, the course topics and CLOs/outcomes are organized and integrated in simple and easy to memorized and follow steps, to select and design a control system to meet and maintain a desired performance. These steps are shown in Figure 2. Depending on institution, Department and minor, educator's back ground, these steps are given in different forms/details, shown in Figures 2a, b, c.

To evaluate concepts and gain required associated integrated abilities and knowledge desired for further courses, the description and the teaching approach, are supported with tables (1c: 7) and graphs, that are recommended to provide students with, and ask to bring on every lecture, where: In Table 1, the proposed course description and topics is explained in details, in particular, main topics mapped with their specific subtitles, objectives, number of lectures and weeks. In Table 2: Some basic rules of block diagram algebra. In Table 3a,b first and second order systems modelling, response measures and general forms of transfer function. In Table 3c the nature of second order system poles (roots) and the effect of changing damping and undamped natural frequency on systems response. In Table 4: the steady state error dependence on input signal and system type. In table 5 Control systems/algorithms transfer function, actions, selection criteria and root locus sketching rules. Table 6 analysis and design in Frequency domain [12]. Table 7 analysis and design- the modern State space (variable) approach. [10].

2.1.7. Recommend Course Administration

The course is taught in 14/15 weeks, with two (I and II) midterm exams, 3 Lab session (to convey concepts when possible, along with simulations and interactive MATLAB sessions), Course Project, Homework sets, and a final exam.

2.1.8. Class Schedule

4 Credits hours, (4: 2, 1, 1): 100-minutes lecture per week, 100-minutes tutorial per week, and 150-minutes laboratory hours every three weeks:

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Hours Per Week</th>
<th>Sessions Per Week</th>
<th>Weeks Per Semester</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lecture</td>
<td>2</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>Tutorial</td>
<td>2</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>Labs</td>
<td>3/every three weeks</td>
<td>1/every three weeks</td>
<td>3</td>
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2.1.9. Recommended Grading System

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<table>
<thead>
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<tbody>
<tr>
<td>Class performance (Atten., particip., assignments)</td>
<td>10%</td>
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<tr>
<td>Labs (3)</td>
<td>15%</td>
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<tr>
<td>Quizzes/ Tests (3-5)</td>
<td>10%</td>
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<tr>
<td>First Exam I</td>
<td>10%</td>
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<tr>
<td>Second exam II</td>
<td>10%</td>
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<tr>
<td>Project; Written/Oral; (Report + Presentation)</td>
<td>15%</td>
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<tr>
<td>Final</td>
<td>30%</td>
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<tr>
<td>Total</td>
<td>100%</td>
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</table>

2.1.10. Pre-course

A special pre-course recommended to be offered in the week before the course begins. This pre-course gives a concise introduction to four main topics: linear algebra, ordinary differential equations, complex theory and dynamical systems.
III. TEACHING PLAN AND TOPICS EXPLAINED

Table 1c. Teaching plan and explained topics of the course.

<table>
<thead>
<tr>
<th>Topics to be covered</th>
<th>Page</th>
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</thead>
<tbody>
<tr>
<td>1) Introduction to control theory and related concepts. (T1:1, 1, 2); First Week, 1 Lecture, 2 Hours.</td>
<td>1</td>
</tr>
<tr>
<td>a) Course overview: first day materials; describe course structure, objectives, administration..</td>
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<tr>
<td>b) Definition of main control concepts and terminologies; Control, control system, Controller, control algorithm, control system components; Sensor, Actuator, Plant, Process. Input, output, disturbance, test input signals, response and plots (transient &amp; steady state), performance, steady state error, performance evaluation, Control low, Design, Analysis, Control history.</td>
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<tr>
<td>c) Advantages of control systems and application examples.</td>
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<tr>
<td>d) Definition and classification/types of each of: Control (automatic and manual), Processes (SISO, MIMO), Control systems (Discrete (ON/Off), Multistep, Continuous (P, PI, PD, PID, Lead, Lag,...)), control loops (A single variable control loop (Feedback, Feedforward), Multivariable Control loop (Feedback plus Feedforward, cascade control, ratio control)).</td>
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<tr>
<td>e) Introduce (proposed) steps for control system selection and design Figure 2a, b, c.</td>
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<tr>
<td>f) Introduce role of control systems analysis and design software (e.g. MATLAB, Labview) to aid in the analysis, design and simulation of control systems.</td>
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<tr>
<td>2) Mathematical foundation: Review of related mathematical theories; differential equations, Complex-variable theory and Laplace transform. (T2:1, 1, 2); First week, 1 lecture, 2 hours.</td>
<td>2</td>
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<tr>
<td>a) Ordinary differential equations (First and Second order HODE, solving/ plotting solution, relating differential equation terminologies with control system terminologies (e.g. solution/response, particular integrate/ transient response, forced function/steady state response, characteristic equation ...).</td>
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<tr>
<td>b) Complex variables (complex plane, complex conjugate, phase, magnitude, Complex Arithmetic.</td>
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<tr>
<td>c) Laplace transform and elements of the Laplace transform (Laplace table)</td>
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<tr>
<td>3) System representation-modeling: represent physical systems (electrical, mechanical, hydraulic and pneumatic) using differential equations, Block diagrams, transfer function, state space equation, and signal flow graphs.</td>
<td>3</td>
</tr>
<tr>
<td>(T3:2-4, 5, 10); II by IV Week, 5 Lectures, 10 Hours.</td>
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<tr>
<td>a) Introducing I &amp; II order systems, why in control engineering, we most interested in study of such systems?.</td>
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<tr>
<td>b) Modeling basics and definition of concepts. Forms of mathematical models (differential equations, state space equations, transfer function, block diagrams...). Developing mathematical model in the form of differential equations for mechanical systems (translational, rotational, and combination, mechanical elements; Spring, Mass, Damper), Electric systems (circuits &amp; elements; resistor, capacitor, inductor RC, RLC circuits), electromechanical (DC motor), hydraulic and pneumatic systems, including: First order systems (car spring-damper suspension system, car cruise control, tank level control, pressure control, RC circuit), and Second order systems (Two tank system, Spring-mass-damper...), higher order system (e.g. DC motor, Two-degrees-of freedom system), analogies.</td>
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<tr>
<td>c) Linearization of nonlinear systems.</td>
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<tr>
<td>d) Representing system using state equations. Concepts, definition and equations development.</td>
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<tr>
<td>e) Representing system using Block diagram and Block diagram algebra; block diagrams reduction techniques (Table 2), Representing system using signal flow graphs, Mason's gain formula.</td>
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<tr>
<td>f) Representing system using transfer function: forward, open loop, closed loop, overall transfer function, Poles, Zeros, Pole-Zero map. Most of proposed is recommended to be taught in parallel, e.g. derive mathematical model of a given system in the form of differential equation, (and/or write state equations), apply Laplace transform, develop transfer function, find Poles, Zeros, and plot pole-zero map.</td>
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<tr>
<td>4) Analysis and evaluation of (basic) system (plant) performance: Stability and (transient and steady state) response analysis of first and second order systems, dominant poles of high order systems. (T4:4-7, 6, 12); IV by VII Week, 6 Lectures, 12 Hours.</td>
<td>4</td>
</tr>
<tr>
<td>a) Introducing design steps depicted in Figure 2</td>
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<tr>
<td>b) Introduce the three predominant objectives of systems' performance analysis and design with corresponding concepts and definitions. a) Stability analysis: Ensure stability and the degree or extent of system stability, b) Transient performance analysis; calculate transient performance specification (measures); c) Steady-state performance analysis; Calculating cascaded state error, test input signals.</td>
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<tr>
<td>c) Stability analysis (absolute and relative) in time and state space domains. Routh-Hurwitz stability criterion: relative stability analysis: parameters change, to determine system parameters (and ranges) to yield stability, critical stability and instability, design using Routh-Hurwitz stability criterion.</td>
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<tr>
<td>d) Test input signals, definition and application.; pulse, impulse, step, ramp, parabolic, sinusoidal.</td>
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<tr>
<td>e) Response analysis of I order system; concepts, definition and classification (transient response and steady state response). Response specifications/Measures, Introducing Table 3a, and for the next below topics:</td>
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<tr>
<td>f) Response analysis of I order systems (Introducing Table 3a): Time constant is the only parameter needed to evaluate I order system performance. General form of I order systems without zeros, in terms of differential equation, transfer function, and both in terms of time constant. Forms of I order system response (natural growth/decay). I order system response measures (T, Tc, DC gain, etc. The effect of changing (increasing/decreasing) time constant (pole location on complex plane) upon system response curve (speeds-up/slow response...). Application examples of I order systems (Car spring-damper suspension system, Car cruise control, level control, pressure control, RC circuit...).</td>
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<tr>
<td>g) Response analysis of II order system (Introducing Table 3b, c): The two parameters needed to evaluate II order system performance (damping ratio and undamped natural frequency). General form of II order systems without zeros, in terms of differential equation, transfer function, and in terms of these two parameters. (Table 3b, c) The four forms of stable II order system responses (Undamped, underdamped, critically damped, overdamped). The relations between damping ratio (ζ), Poles (roots) nature, location and response form, properties and time solution for performance/error prediction. II order system response measures in term of damping ratio and undamped natural frequency (Tc, Tζ, ST, Tr, Ts, Mζ%OS...). The effect of changing (increasing/decreasing) time constant or damping ratio and/or undamped natural frequency upon system response curve (speed up/slow response, increased natural frequency from plant's parameters, and from poles location on complex plane (phase and magnitude of complex pole). Damping ratio line and overshoot,</td>
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magnitude of complex pole-circle and undamped natural frequency. Application examples of II order systems (Spring-mass-damper, two tank system, RLC circuit...).

h) Response analysis of higher than second order systems: Dominant poles and systems approximation, finding dominant pole(s), DC motor as application example (speed and position control), dominant poles in terms of damping ratio and undamped natural frequency.

i) Writing/Finding transfers function and/or plant parameters from response curve or from transfer function. Convert between differential equation/transfer function / state-space models. Finding time response from the state-space representation.

j) The effects of nonlinearities on the system time response. I and II order systems with zeros.

k) Response analysis; Steady state error (introducing Table 4): measure of system accuracy, relation between input signal R(s), system type and steady-state error for performance/error prediction. Steady-state error in terms of open loop and closed loop transfer functions. Static error constants. Finding the steady-state error for a unity and non unity feedback system. Finding the steady-state error for systems represented in state-space.

l) Selective design: (e.g. achieving desired response without adding control system), to select (I or II order) system's parameters to result in desired response specification, done by reverse solving system's parameters in terms of desired response specification.

m) Analysis and evaluation of system performance using analysis and design software (e.g. MATLAB, Labview) to aid in the analysis, design and simulation of control systems (MATLAB built-in functions for analysis and plotting of systems' response subjected to an input signal. Introducing control system toolbox sixtool and rtool).


(T4-LI, 1, 3): VII Week, 1 Session, 3 Hours.

Review: (T1-7, 5, 1); VIII Week, 0.5 Lecture, 1 Hour.

First exam: (1 hour); Covering all previous (up) topics (T1-5, 7, 0.5, 1); VIII Week, 0.5 Lecture, 1 Hour.

5) Selection and design of control system in time domain, to meet and maintain desired overall system performance.

(T5-7-10, 5, 10): VIII by X Week, 5 Lectures, 10 Hours.

a) Introducing Table 5: Review; Definition and classification/types of control systems; (Discrete (ON/Off), Multistep, Continuous (P-, PI, PD, PID, Lead, lag,...)), control loops (A single variable control loop (Feedback, Feedforward), Multivariable Control loop (Feedback plus Feedforward, cascade control, ratio control)), with emphasize on Continuous feedback (closed loop) control systems.

b) Types (modes), mathematical model, and transfer function of control systems/compensators; P-, PI, PD, PID, Lead, lag and leadlag. Controllers' gain definition. Effect of each controller mode on system's response (transient and steady state). Equivalency of each controller mode in terms of pole/zero addition to plant's transfer function. Controller selection Criteria. Implementing controllers using passive components (amplifier-resistor-capacitor) and concept of gains.

c) Introductory review to control system selection and design: (Calculating damping ratio and undamped natural frequency from poles location on complex plane (phase and magnitude of complex pole. Damping ratio line and overshoot, magnitude of complex pole-circle and undamped natural frequency) and corresponding response measures). The design region in the complex plane where a pair of second-order poles must be located to satisfy specification.

d) Controller design in time domain: Selective design: Review (achieving desired response without adding control system). Comparison for design: comparing a given form of systems closed-loop transfer function (e.g. with P-controller) with the corresponding "standard" form of I or II -order systems, and by comparison to calculate the controller's gain(s).

e) Control system design via root locus; definition, power of root locus (provide solutions for stability and response analysis and design for systems of order higher than second order, analysis and design for stability; ranges for stability, instability and break into oscillation). Sketching rules. Control systems/compensators (P-, PI, PD, PID, Lead, lag and leadlag) design via root locus; applying controller pole/zero addition, angle criterion, magnitude criterion, design verification.

f) MATLAB built-in function for control system design and analysis e.g. f(s), rlocus. Applying control system toolbox (sixtool and rtool) to select and design a control system (P-, PI, PD, PID, Lead, lag and leadlag) to achieve desired performance.

Project assignment: (Report + oral presentation): Given and explained in: week No. X. So as students can apply, gained abilities and knowledge in solving control system/algorith selection and design as a stage of Mechatronics system design, the course, as many other, Mechatronics courses, is project-based and include a project on the selection and design of control system/algorith to control a given Mechatronic device based on/to meet given objectives and design specifications. Recommended: Given a dynamic system e.g. DC motor based motion control application (robot arm, mobile robot, suntracker, Automated conveyor system, electric car) with defined parameters, and desired performance specification (or student can select desired actual system response specifications). Each student is to apply all selection, design and analysis steps to design a control system to meet desired performance, and using MATLAB), and verify design.

Second exam: (T1-4-10, 1, 0.5): X week, 0.5 lecture, 1 hours.

Covering selection and design of control system in time domain, to meet and maintain a desired performance.

Lab (2): (T4L2LI, 1, 3): XI Week, 1 Session, 3 Hours

Identify closed-loop systems components and their role. System representation. Data collecting, response plotting and interpreting: Analysis of open and closed loop response and/or observing effects of plant's parameters (and/or T, ωc, ωn) change on resulting step/ramp/parabolic response of I and II order systems, and/or observing effects of PID-modes and parameters-gains change on system response. Selection and design of control system to meet desired performance: e.g. DC motor based motion control (speed/position); Robot arm, Ball and beam system.

6) Controller design in frequency domain: 

(T6-11-12, 4, S): XI by XII week, 4 lectures, 8 hours.

a) Introducing Table 6.

b) Definition of main concepts; History, Frequency transfer function, advantages and applications of the frequency response techniques.

c) The three graphical representations tools of the frequency response representation (Bode diagrams, Nyquist diagrams, and Nichols charts).


e) Controller selection and design in frequency domain: Design Lead/Lag compensators to achieve closed loop bandwidth and
7) Introduction to analysis and design in state-space: (T7:13, 2, 4); XIV week, 2 lectures, 4 hours.
   a) Introducing Table 7,
   b) The general state-space representation,
   c) Stability analysis in state space,
   d) Steady-state error for systems in state space,
   e) Controller design in state space (pole placement)

Lab (3): frequency response
(T4-L3.14, 1, 3); XIV Week, 1 session, 3 Hours.

Course Project defense: (Report + Oral) (T1-7:14, 1, 2); XIV Week, 1 Lecture, 2 Hours.

Course Review of: objectives / gained abilities and knowledge, Selection and design examples, relation to other subjects. (T1-7:14, 1, 2); XIV week, 1 lecture, 2 hours.

TOTAL: 7 Topics, 15 weeks, 28 lectures, 2 lectures for Midterms + quizzes, 60 hours, 3 Lab sessions 9 hours.

**Pre-Study Process (The problem statement):**

- Establish control problem objectives to achieve
- Identify plant's parameters (M, B, K, R, L, C, ...) and variables to be controlled (Input, Output): X, Y, Z
- Identify physical configurations (Depending on the plant/process): sensors, actuators, controller
- Identify physical space (Model type: Linear, Non-Linear, Time variant, Time invariant)

**System Representation**

- Physical model
- Schematic model
- Mathematical model
- Block diagram model
- Differential equation model
- Transfer function model
- State space model
- Signal Flow Graph

**Development (draw) functional block diagram model:**

- Develop mathematical (differential equations) model: using physical law (Newton’s, Kirchhoff’s, …) to represent (model) each component of the system. The model can be expressed in each block diagram model.

**Development mathematical transfer function model:**

- Develop mathematical state space model: applied for systems that can’t be represented using linear differential equations (by transfer function model). Also used to model systems for simulation on computer

**Analysis and evaluation of basic system performance**

- Stability analysis: absolute, relative, steady-state error
- Solve mathematical model and plot the solution response (of differential equation or transfer function, or state space model), subject the system to test input signal
- Transient response analysis: T, T_t, M, GPD, etc
- Steady-state performance analysis: accuracy

**Select and design of control system (Algorithm)**

- Control system design:
  - Select and design for closed loop control system, different design methods exist
  - Verification and optimization

**Simulation process:**

- Prototyping, testing, evaluation, and optimization
- To take into account the unmodeled errors and enhance precision, performance and gather early user feedback

**Manufacturing and Commercialization**

- Support, Service and Market feedback analysis

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**Figure 2a.** Course proposed design steps, for selection and design of control systems.
Figure 2b. Proposed design steps, for selection and design of control systems.
Pre-Study Process (The problem statement)

- Establish control problem objectives to achieve
- Identify variables to be controlled (Input, Output): \( X, \upsilon, \theta, \omega, P, T, V, I \)

Identify desired performance specifications requirements to meet and maintain

- In Frequency domain/peak response: \( M_r, \omega_r, BW, G_m, P_m \)
- In time domain (transient and steady state): \( T, T_e, T_r, MP, OS\%, E_{SS} \)

System Representation

- Physical model
  - Block diagram model
  - Signal flow graph model
  - Mathematical model
  - Differential equation model
  - State space model
  - Transfer function model
  - TF frequency model

Analysis and evaluation

- Stability analysis
  - Transient response analysis
  - Steady state response analysis

Select and design and control system (Algorithm)

- \( P, P_f, PD, PID, Lead, Lag, Lead/Lag \)
- Select Controller’s gains
  - \( M_r, \omega_r, BW, \omega_b, CR \)

Testing & Verification of Control system selection & design, meeting requirements? (Mathematically or using computer simulation e.g. MATLAB)

- Ensuring Stability
- Ensure achieving desired transient response
- Ensure achieving desired steady state response

Refine controller parameters.

- Robustness
- Disturbance rejection
- Low sensitivity

Prototyping, testing, evaluation and optimization

To take into account the unmodeled errors and enhance precision, performance and gather early user feedback.

Refine controller parameters.

Implement

Figure 2c. Flowchart; proposed design steps, for selection and design of control systems.
Table 2. Some basic rules of block diagram algebra [3].

<table>
<thead>
<tr>
<th>Original Block Diagrams</th>
<th>Equivalent Block Diagrams</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Diagram 1]</td>
<td>![Diagram 2]</td>
</tr>
<tr>
<td>![Diagram 3]</td>
<td>![Diagram 4]</td>
</tr>
<tr>
<td>![Diagram 5]</td>
<td>![Diagram 6]</td>
</tr>
</tbody>
</table>

Table 3a. 1st order systems modelling, response analysis, Performance measures, control loop, and general forms of transfer function $G(s)$.
Table 3b. II order systems modelling, response analysis, Performance measures and general forms of transfer function $G(s)$.

Table 3c. The nature of second order system poles (roots) and the effect of changing damping and undamped natural frequency on systems response.
Table 4. The steady state error dependence on input signal and system type.

The steady state error $E_{ss}$ in terms of open loop transfer function $G(s)$ or closed loop transfer function $T(s)$ can be expressed as:

$$E_{ss} = \lim_{s \to 0} s \cdot G(s)$$

### System Types

- **Type 0 System**
  - Examples: $G(s) = \frac{K}{s}$
  - Step Response: $e(t) = K$ (Constant)
  - Ramp Response: $e(t) = \frac{K}{2} t$
  - Parabolic Response: $e(t) = \frac{K}{3} t^2$

- **Type 1 System**
  - Examples: $G(s) = \frac{K}{s+1}$
  - Step Response: $e(t) = K (1 - e^{-t})$
  - Ramp Response: $e(t) = \frac{K}{2} (1 - e^{-t}) t$
  - Parabolic Response: $e(t) = \frac{K}{2} (1 - e^{-t}) t^2$

### System Types

- **Type 2 System**
  - Examples: $G(s) = \frac{K}{s^2 + 2s + 1}$
  - Step Response: $e(t) = K (1 - e^{-t} \cos \omega t)$
  - Ramp Response: $e(t) = \frac{K}{2} (1 - e^{-t} \cos \omega t) t$
  - Parabolic Response: $e(t) = \frac{K}{6} (1 - e^{-t} \cos \omega t) t^2$

**Ex. (input $R(t)$) & System type:**

- Static error constants
  - Type 0: $e_0 = \frac{K}{2}$
  - Type 1: $e_0 = \frac{K}{2}$
  - Type 2: $e_0 = 0$

**Test input reference signals, $R(t)$**

- Ramp: $R(t) = at$
- Parabolic: $R(t) = \frac{at^2}{2}$
- Trapezoidal: $R(t) = \begin{cases} 0, & t < 0 \\ at, & 0 \leq t < T \\ b, & T \leq t \end{cases}$

Table 5a. Control systems/algorithms transfer function, actions, selection criteria.

**Controller's mathematical Model and transfer functions (Control algorithms):**

<table>
<thead>
<tr>
<th>Type</th>
<th>Controller</th>
<th>Matematical Model</th>
<th>Transfer Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 0</td>
<td>PI</td>
<td>$e(t) = K (1 - e^{-t})$</td>
<td>$T(s) = \frac{K}{s}$</td>
</tr>
<tr>
<td>Type 1</td>
<td>PD</td>
<td>$e(t) = K (1 - e^{-t} \cos \omega t)$</td>
<td>$T(s) = \frac{K}{s^2 + 2s + 1}$</td>
</tr>
<tr>
<td>Type 2</td>
<td>PID</td>
<td>$e(t) = K (1 - e^{-t} \cos \omega t) t$</td>
<td>$T(s) = \frac{K}{s^2 + 2s + 1}$</td>
</tr>
</tbody>
</table>

**Compensator's transfer functions:**

- Lead compensator: $K = \frac{K_p}{s + \omega_0}$
- Lag compensator: $K = \frac{K_p}{\omega_0}$
- Band-stop filter: $K = \frac{K_p}{s^2 + \omega_0^2}$

**PID models in feedback loop & implementing controllers using Passive components:**

1. Find the characteristic equation for desired response specification.
2. Plot the root locus plot for desired response specification.
3. Identify the gains $K_p$, $K_i$, and $K_d$ from the root locus plot.
4. Implement the PID controller by selecting the appropriate gains for the desired response.
5. Check the stability of the system by plotting the root locus plot and verifying that all roots lie within the unit circle.

**Effect of Pole-Zero addition on overall response:**

- Pole addition will improve thesettling time and decrease the overshoot.
- Zero addition will improve the rise time and decrease the steady-state error.

**Root locus plots for different types of systems:**

- Type 0: Single real pole.
- Type 1: Single real pole and zero.
- Type 2: Complex poles and zeros.

**Note:** The root locus plots and transfer functions are essential for analyzing the system behavior and design control systems to achieve desired performance criteria.
Table 5b. Control algorithm design via root locus.

Table 6a. Analysis and design in Frequency domain.

Introduction to Analysis and Design in Frequency domain.

Bode plots: Two separate graphs of open loop transfer function.
- a) Plot of open loop magnitude, log |G(jω)| vs. log ω
- b) The phase part of open loop phase, Θ(jω) vs. log ω

Bode’s amplitude equations: For the frequency response of the open loop system given a gain less than unity (0< |G(jω)|< 1), the phase is 0°.

Bode’s phase equations: The phase can be calculated as the log ω of phase G(jω).

The frequency transfer function of the closed-loop system can be obtained from the frequency-domain plots of G(jω) by setting a) T(jω) = G(jω) / (1 + G(jω))

Graphical representations and analysis tools: Plots of the frequency response are: Bode plots, Nyquist diagram and Nichols chart. All methods display the same information, but the difference lies in the way it is presented.

Nyquist plot: The open loop transfer function of the system is plotted on the complex plane. The phase margin is calculated as the angle between the line from the origin to the point on the Nyquist plot.

Phase margin: The phase margin is the angle between the line from the origin to the point on the Nyquist plot.

Nyquist criterion: The Nyquist criterion is used to determine the stability of the system.

Gain crossover: The gain crossover is the point where the gain of the system is unity.

Phase margin: The phase margin is the angle between the line from the origin to the point on the Nyquist plot.

Nyquist criterion: The Nyquist criterion is used to determine the stability of the system.

Gain crossover: The gain crossover is the point where the gain of the system is unity.
Table 6b. Analysis and design in Frequency domain.

Table 7a. The modern State space (variable) approach.
IV. CONCLUSIONS

In this paper, are proposed and discussed, a proper for Mechatronics education, Control systems design and analysis course detailed description, topics with specific learning objectives, prerequisites, administration, simple but effective teaching approach supported by simple and easy to memorize education oriented steps and tables, that integrate course outcomes, to solve control problems, all intended to support educators in teaching process, help students in concepts understanding, maximum knowledge and skills transfer/gaining in solving controller/algorithm selection and design problems as a stage of Mechatronics system design stages, and prepare them for other further courses applied in Mechatronics curricula including; Mechatronics fundamentals, Mechatronics systems design, Process control, Embedded systems design, Robotics, PLC, CNC and others.

REFERENCES