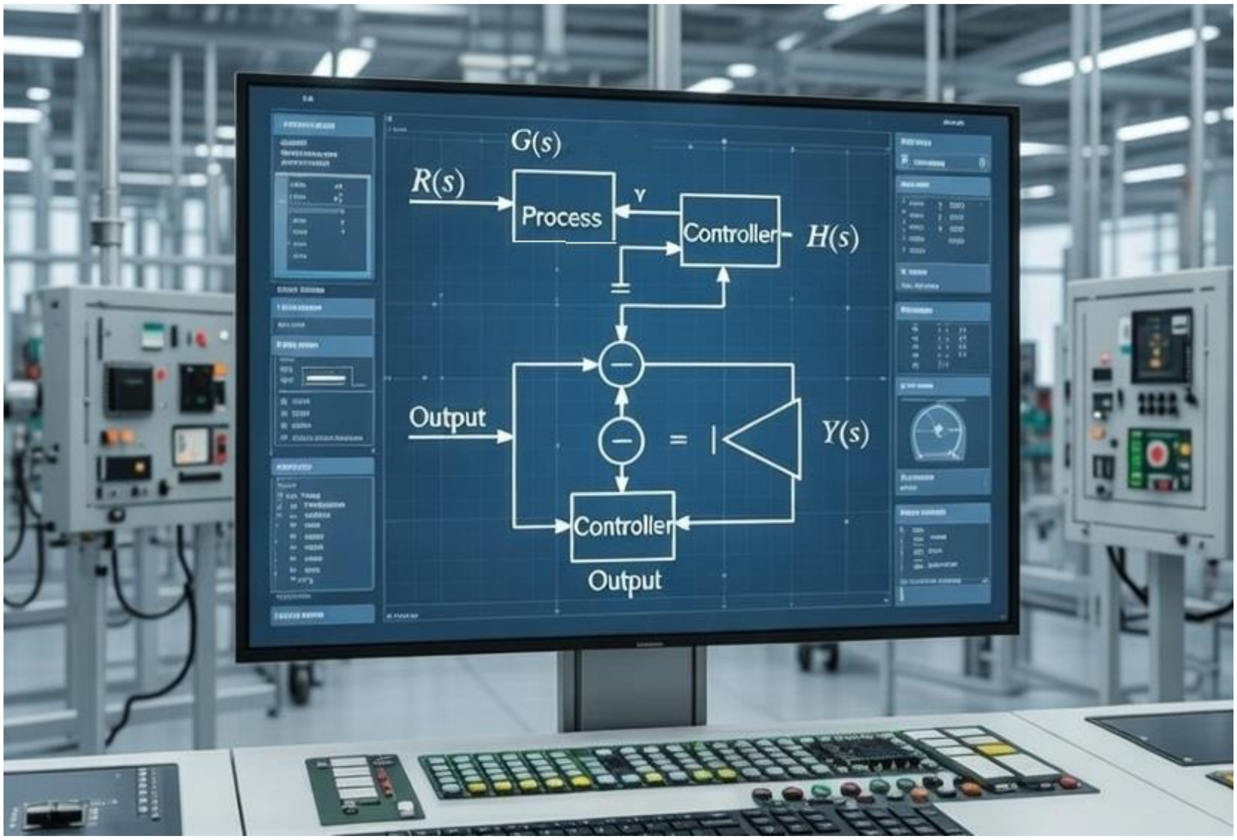
Lab Manual:
Introduction to Controls Theory
for EE & ECE courses

Using the EMONA Controls Explorer board for ADS MAX



SAMPLE MANUAL

EMONA
tims
WIRELESS SIGNALS LAB EQUIPMENT

Contents

Introduction

This Controls Explorer Lab Manual covers an introductory selection of controls theory principles through to a complete PID control loop design for various plant. Each experiment is written to support the theoretical concepts introduced in the class work of a first course in Control Theory for EE and ECE undergraduate students..

In order to make the student's learning experience more memorable, the student is able to view a variety of signals on the ADS MAX oscilloscope.

Each lab experiment presents an interesting, hands-on learning experience for the student. In each experiment the student is challenged to build, measure and consider: there are no “instant” or “cookbook-style” experiments. The EMONA Controls Explorer Board is actually a true engineering modeling system where students see that the block diagrams so common in their textbooks represent real functioning systems.

Learning Objectives

After completing the labs in this manual, you should have the ability to complete the following actions.

1. Describe how step responses etc of a system can inform us about how system operates.

2. Describe how the theory behind a system is implemented in a tangible way in real world applications

Prerequisites

Experiments in this volume have been prepared for students with only a basic knowledge of mathematics and a limited background in physics and electricity.

Students with a higher level of competence in mathematics will also gain a deeper understanding of controls theory by using this system. Due to the engineering “modeling” nature of the board, they will be able to investigate more complex issues, carry out additional measurements and then contrast their findings to their theoretical understanding and mathematical analysis.

This lab manual was designed for students who have completed the following courses and have a working knowledge of the following hardware, software, and tools.

Completed Courses

1. Basic mathematics
2. Introductory Controls lectures
3. Basic simulation skills

Hardware, Software, and Tool Knowledge

1. Basic test instruments eg Oscilloscope, Function Generator, Spectrum Analyzer
2. Software knowledge of simulation eg MATLAB, Simulink required

Organization of the Lab Manual

Each experiment in this Lab Manual provides a basic introduction to the topic under investigation, followed by a series of carefully graded hands-on activities. At the conclusion of each sub section the student is asked to answer questions to confirm their understanding of the work before proceeding.

It should be noted that the included modules on the board can implement many more experiments than are documented in this Lab Manual and further experiments may be released in later manuals or can be written by faculty as required.

Finally, since the EMONA Controls Explorer board is a true modeling system, the instructor has the freedom to modify existing experiments or even create completely new experiments to convey new and course-specific concepts to students.

Documented capabilities of the Emona CONTEx Controls board

Experiment 1: First and Second order systems

-To characterize the first order system.
-To analyze the characteristics of first-order system with typical input signals.
-You will be able to relate the responses of first and second order systems with usage of transfer functions.

Experiment 2: State-space approach

-To introduce a method of mathematical modeling known as state-space representation for linear time invariant (LTI) systems.
-To represent the systems mentioned in Experiment 1 as state-space models.
-How to convert a state-space representation to a transfer function (general formula derivation).

Experiment 3: Stability & Routh-Horwitz criterion

-To introduce a mathematical method known as Routh Hurwitz Criterion to check the stability of an LTI closed-loop system in transfer function form.
-To discuss the effect of poles and zeros on system response and graphically depict using pole-zero maps.

-To differentiate the cases of marginally stable and stable for a 4th order cascaded RLC network.

Experiment 4: Frequency & Phase response

-Understand the meaning of frequency and phase response of a system.
-Measure and plot the actual frequency and phase response of a few systems

Experiment 5: Designing for PID control of plant

-To examine the benefits of feedback in a control loop.
-Consider mathematical computation of controller values.

-To understand the 3 parts of a PID controller

-To introduce a manual tuning methodology.
-To develop intuitive understanding for the effects of feedback

Experiment 6: Gamifying PID design for optimum performance

-Understand the need for a response which meets undefined needs
-Contrasting the balance between response time, overshoot and settling time in a random environment
-Gamify the design process by introducing a human element into the loop

Background: Teaching methodology behind the “block diagram approach”

The Emona Controls Explorer board (CONTEx-511) draws on a well-established experimental methodology that brings to life the “universal language” of system design, the BLOCK DIAGRAM. Originally utilized in the 1970’s by Tim Hooper, a senior lecturer in telecommunications at The University of New South Wales, Australia, and further developed by Emona Instruments, this modeling approach is used by thousands of students around the world.

Block Diagrams

Block diagrams are used to explain the principle of the operation of electronic systems without worrying about how the circuit works. Each block represents a part of the circuit that performs a separate task and is named according to what it does. Examples of common blocks in controls equipment include the source, difference junctions, plant, PID controller, gain stages and so on.

The board is a collection of blocks (called modules) that are patched together to implement multiple controls experiments exploring the fundamental theory underlying control theory.

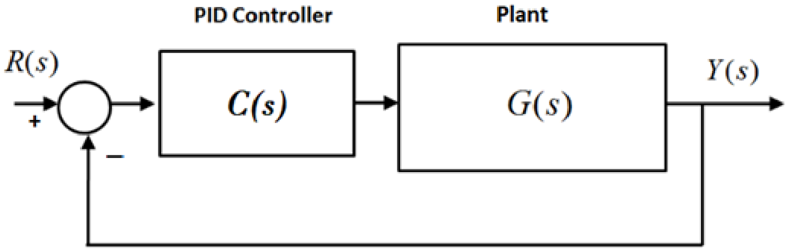


Figure 1: Example block diagram

This collection of blocks is used in conjunction with the ADS MAX providing the instrumentation.

This approach to implementing controls experiments through realizing BLOCK DIAGRAMS has the following benefits in the educational environment:

- Students gain practical experience with true mathematical modeling hardware, designed specifically for implementing controls theory.

- Students actually build each experiment stage-by-stage, in an engineering manner, by following the BLOCK DIAGRAM.
- Students are free to try “what-if” scenarios to validate their understanding of the theory being investigated, by viewing real, real-time electrical signals.
- The board is designed to allow students to make mistakes, hence students will learn from their hands-on experiences as they investigate their findings.

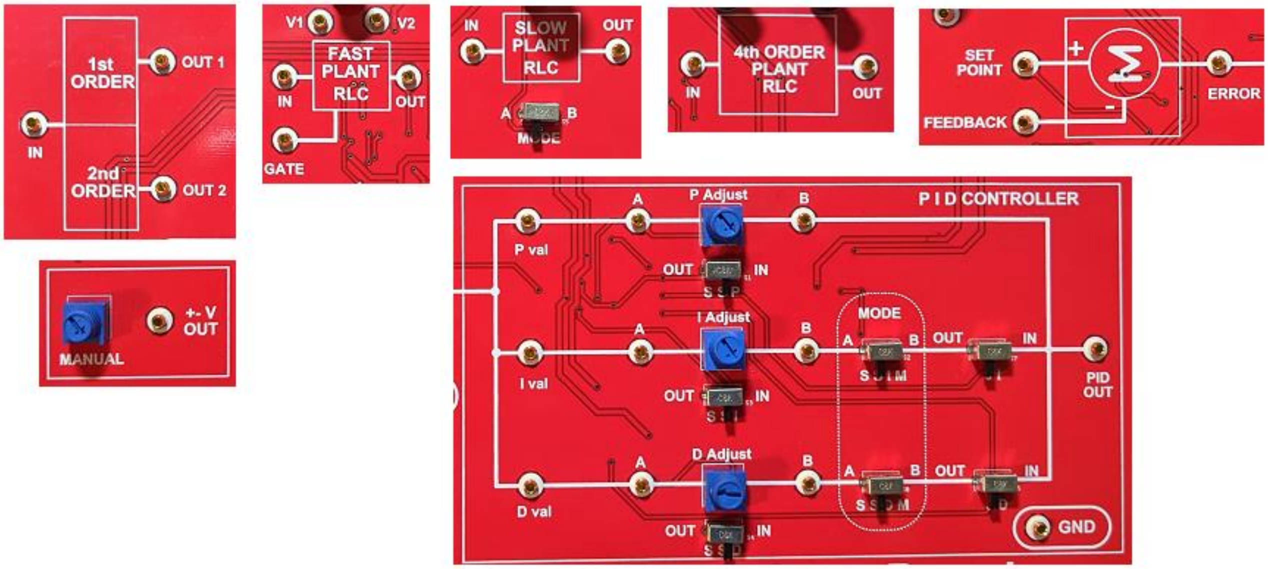


Figure 2: Example individual circuit blocks

One-to-One Relationship

The figure above illustrates the one-to-one relationship between each block of the BLOCK DIAGRAM and the independent functional circuit blocks of the board.

The functional blocks of the board are used and re-used in experiments, just as blocks of the block diagram reappear in many different implementations, and just as LabVIEW or Simulink blocks are interconnected to form program flows.

Guidelines for Using the Lab Manual

This manual covers a introductory selection of controls concepts, from fundamental topics familiar to all students, such as step response, through to the underlying principles used in the PID control loops. In each experiment, the core technology is revealed to the student, at its most fundamental level. The first chapters also provide a introduction to the ADS MAX platform.

Chapters can be covered in any order, however, it is imperative that all students complete the first chapter before proceeding to the subsequent chapters.

- Introduction to the MONA Controls Explorer board

Tips for Success

An important factor which makes the learning experience more valuable for the student is that the student is allowed to make wiring mistakes. Inputs and outputs can be connected in any combination, without causing damage. As the student builds the experiment, they need to make constant observations, adjustments and corrections. If signals are not as expected then the student needs to make a decision as to whether the correction required is an adjustment or an incorrectly placed patching wire.

Follow these tips to be more successful and avoid common pitfalls in this lab manual.

- ✓ Build and test each stage as you go. Be systematic.
- ✓ Confirm your expectations with measurements. Be precise.
- ✓ Confirm that measurements make sense as you go through each stage. Think about what you are doing and don’t rush ahead hoping that it will all work first time. Be realistic.

Introduction to the EMONA Controls Explorer board

Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. For this experiment you will familiarize yourself with the various circuit modules available on the Controls Explorer board and how they are used.
2. Students will understand the specifications of each module, and their various limitations.

Required Tools and Technology

Platform: ADS MAX

Instruments used in this lab:

- Oscilloscope-Time
- Oscilloscope-FFT
- Function Generator

Hardware: Emona Controls Explorer Board

Components used in this lab:

- Six BNC to 2mm banana-plug leads
- Assorted 2mm banana-plug patch leads

Software: DIGILENT WAVEFORMS
EMONA Controls Explorer ADSMAX.zip

Expected Deliverables

In this lab, you will collect the following deliverables:

- ✓ Observations

Your instructor may expect you complete a lab report. Refer to your instructor for specific requirements or templates.

It should only take you 20 minutes to browse through this Lab.

Section 1: Introduction

1.1 Methodology

The experiments possible with the EMONA Controls Explorer board bring together worlds of mathematical theory and practical implementation. We are able to explore, in a hands-on manner, the representation of physical processes by mathematical models and test and measure the benefits and limitations of such models. We explore the complementarity of the time and frequency domains and practice thinking and theorizing in both. Through measurements, calculations and observations we can consolidate our understanding of these domains.

The Controls Explorer board customizes the instrumentation available on the ADS MAX to create experiment-specific instruments which can be used to create many different circuit structures.

As well, the ability to programmatically control, measure and automate our measurements using WAVEFORMS software from DIGILENT bring us closer to real-world practices of system control and monitoring.
Although the principles of being studied date back several centuries their application in real world devices is continually being explored and implemented. The instrumentation used has changed substantially however the rigorous nature of the mathematical process remains the same and is a skill which is best learned in a hands-on manner.

By implementing the many mathematical model and theorems in real hands-on circuit based experiments, the student reinforces and actualizes their understanding of these principles to create a solid foundation for future learning.

An important skill for the engineer and scientist is the ability to take rigorous and precise measurements, often repetitively, in order to study the phenomena at hand. The EMONA Controls Explorer Board (CONTEx-511) provides an abundance of opportunities to learn and practice experimental methodology in a variety of related topics which are common ground for engineering students of several disciplines.

Powering up the ADS MAX + EMONA CONTEx Board

1. Ensure that the ADS MAX Application Board power button at the top left corner of the unit is OFF (not illuminated).

2. Carefully plug the Emona CONTEx into the ADS MAX ensuring that it is fully engaged both front and back.

3. Ensure that you have connected the ADS MAX to the PC using the USB cable and that the PC is turned on.

4. Turn on the Application Board *Power* button by pressing it once and confirm that it is illuminated. The LEDs on the CONTEx should also be illuminated. If they are not, then switch the unit off immediately and check for connection or insertion errors.

5. Open the WAVEFORMS software on your PC.
   Open the supplied workspace file for this experiment.
   The instrument panel will open into a convenient configuration relating to this experiment. You can modify and save the workspace configuration to suit yourself

6. RUN each of the tabbed instruments when needed and when switching between tabs. Refer to the WAVEFORMS User documentation for details about each instrument.

1.2 Board overview

The Controls Explorer board is a collection of independent circuit blocks which each implement a single simple function. No one block is a complete experiment, however several blocks together can implement a wide variety of different experiments. The block inputs and outputs are patched together with 2 mm patching leads according to the block diagram as documented in this Lab Manual or from the many texts available on this topic.

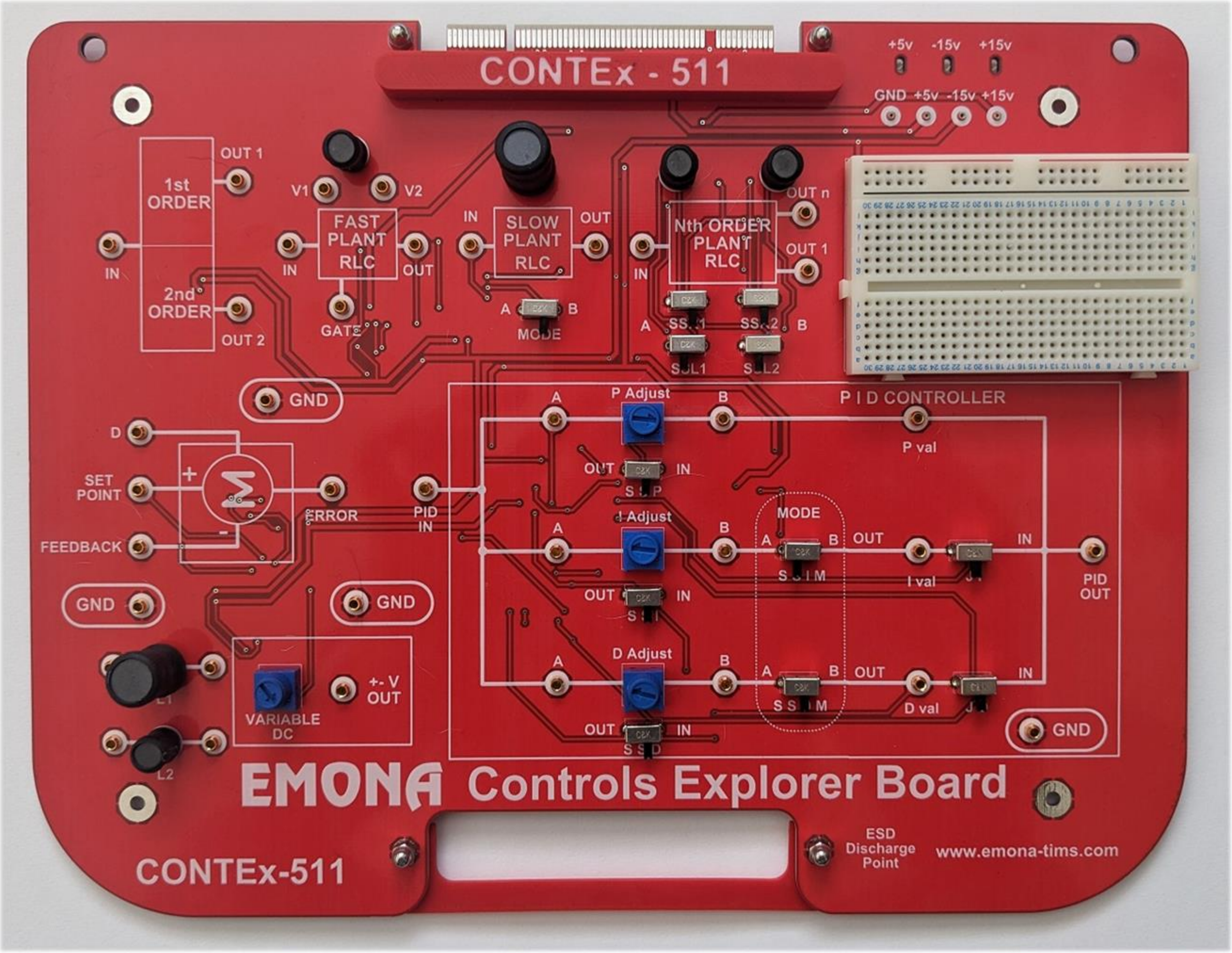


Figure 4: EMONA Controls board topside layout

This chapter discusses the functionality of each module briefly and further details such as specifications are contained in the EMONA Controls Explorer User Manual.

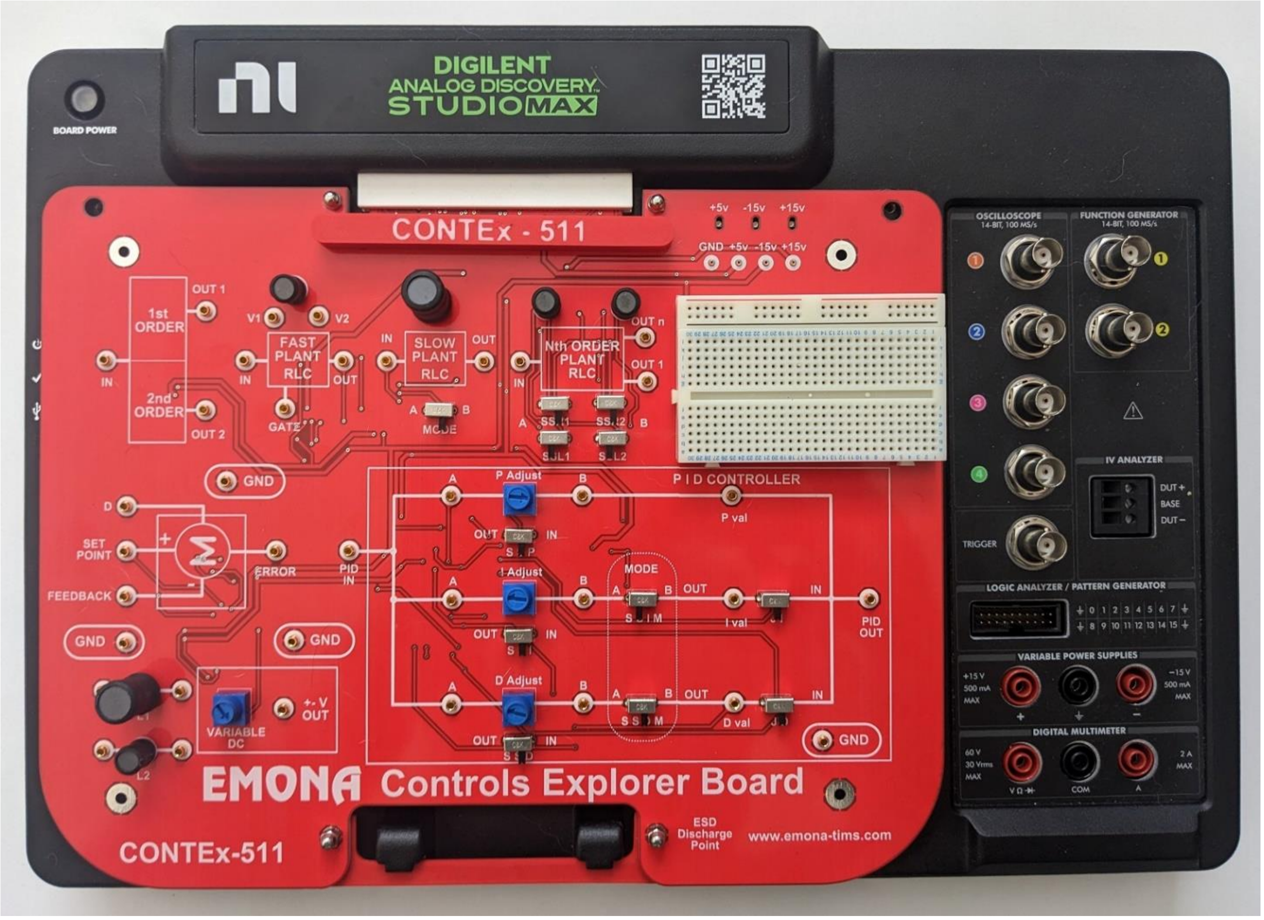


Figure 5: ADS MAX and EMONA Controls Explorer board bundle

2.1 CONTROLS board circuit modules

2.2 1st and 2nd Order Plant

Two consequtive1st order RC LPF blocks are provided.

The blocks share one input and have two outputs after the 1st order and then the 2nd order filter block.

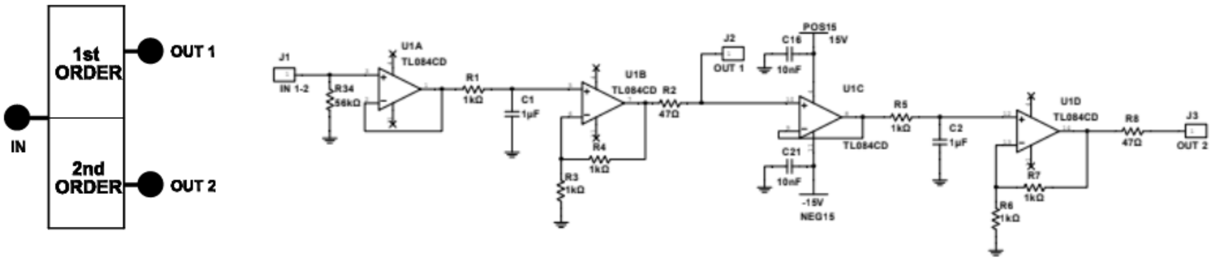


Figure 6: !st and 2nd order Plant block and circuit

The gain and parameters are fixed for both blocks.

BASIC SPECIFICATIONS

1st order RC filter block

Input –IN

Gain = 1

Output: OUT 1

Bandwidth approx 20 kHz

2nd order RC filter block

Input – from the 1st order block

Gain = 1

Output: OUT 2

Bandwidth approx 20 kHz

0-1 Which components in this circuit contribute to the filter response ?

2.3 FAST Plant

A 2nd order RLC filter block with underdamped characteristics and a “fast” response time.

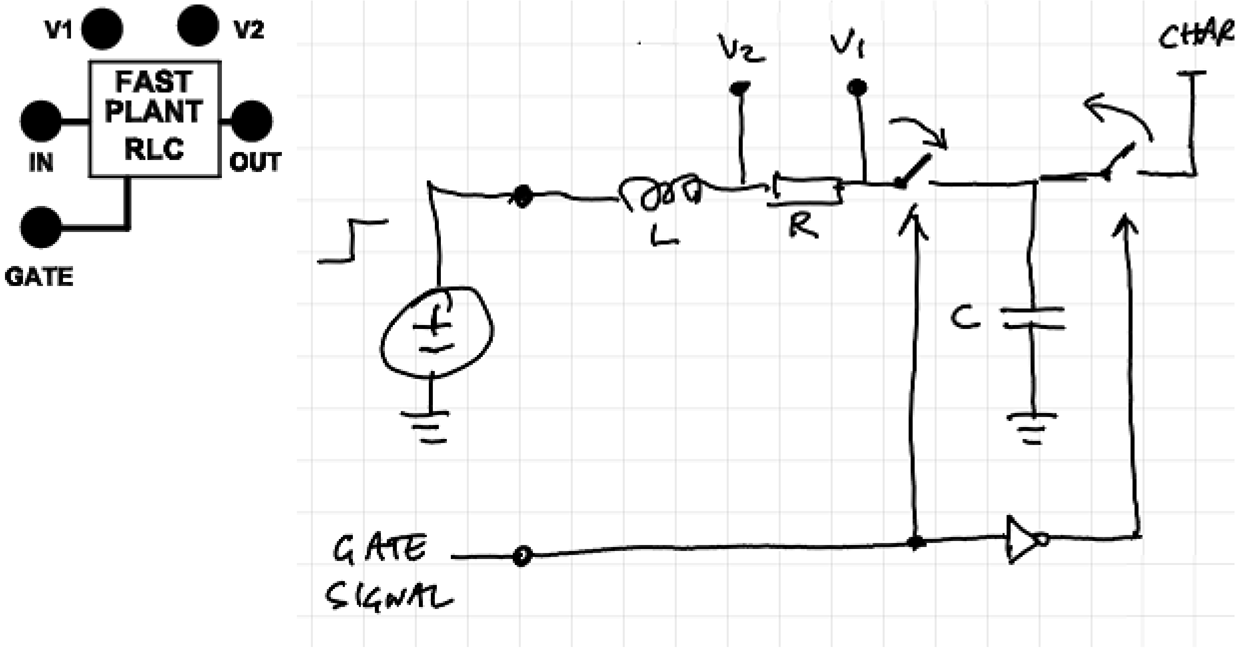


Figure 7: 2nd order RLC "FAST" plant block and circuit

This LPF block has one input IN and one output OUT from the output capacitor in the RLC series circuit.

The GATE input serves to switch the output capacitor between in-circuit and being charged from a +5V source and separated from the RLC circuit.

“0” or no-connect on GATE will put the capacitor into charging state, separate from the RLC circuit..
“1” (>=1V) will put the capacitor into series circuit, no longer charging

Output terminal V1 and V2 are connected to the series 1kohm R and enable the measurement of voltage across this resistor (using a MATH channel in the Scope instrument and hence the current through the series resistor.

Terminals V1 and V2 can also be short circuited to force R=0

BASIC SPECIFICATIONS

IN typically DC to 20 kHz
Gain 1
GATE: input logic signals from 0V to 1-10V level signals
R: 1kohm +/- 5%
L: 100mH +/- 10%
C: 10nF +/- 10%

0-2 What is the current through the circuit in terms of V1, V2 and R ?

2.4 SLOW plant

A 2nd order RLC filter block with underdamped characteristics and a “slow” response time.

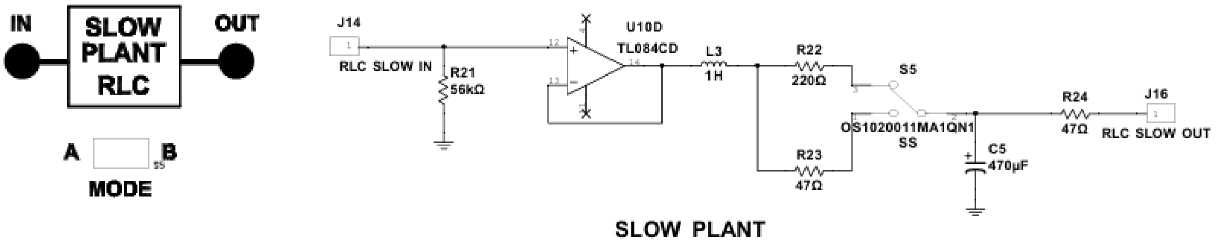


Figure 8: 2nd order RLC "SLOW" Plant block and circuit

This LPF block has one input IN and one output OUT from the output capacitor in the RLC series circuit and has a response time in the order of fractions of a second making it useful for “human-speed” operations.

MODE enables selecting different response characteristics.

BASIC SPECIFICATIONS
IN typically DC to 20 kHz
Gain 1
MODE A: R=47
MODE B: R=220

0-3 What is the resonant frequency for each mode of this circuit ?

2.5 4th Order RLC plant

Two 2nd order RLC filter blocks in series

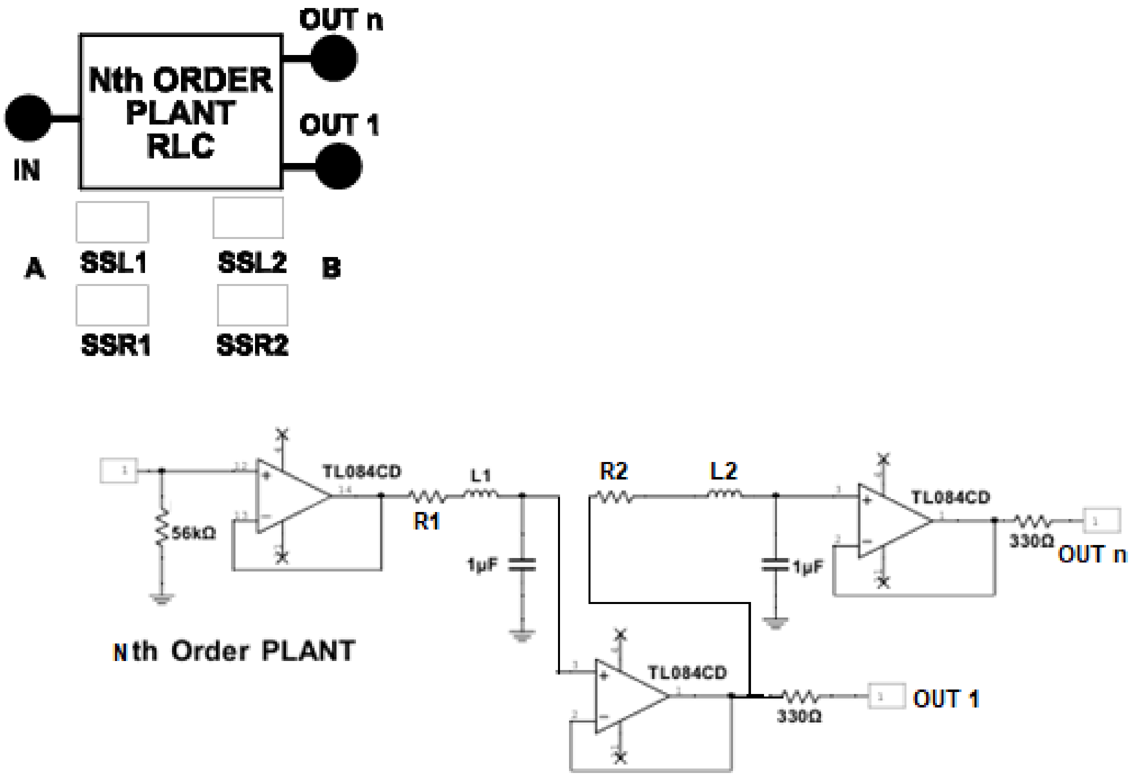


Figure 9: Nth order RLC Plant block and circuit

This LPF block has one input IN and two outputs. One output after the first 2nd order stage and the second output after the second stage..

Each stage can have its R & L components varies using the slide switches.

As follows:
SSR1: A= 1000Ω; B= 0 Ω;
SSR2: A= 1000Ω; B= 0 Ω;
SSL1: A= 100mH (180 Ω); B= 1mH (25 Ω);
SSL2: A= 100mH (180 Ω); B= 1mH (25 Ω);

2.6 VARIABLE DC

Manually adjusted DC voltage output. Acts as a real-time voltage source.

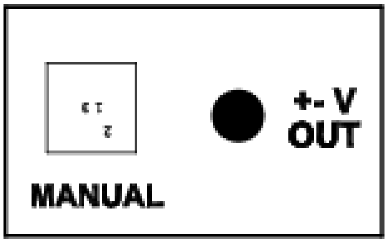


Figure 10: Variable DC block

A user can manually adjust the DC voltage between a fixed range to act as a slow speed input signal.

BASIC SPECIFICATIONS
+-V range: approx. -2 < V < +2

0-3 What is the voltage range available ? Use the scope to determine this.

2.7 DIFFERENCE JUNCTION

Triple input ADDER with positive unity gain on two input and negative unity gain on the other input. Resulting in an output signal of the difference between the inputs.

The D input can be used to inject externally generated Disturbances into the primary Set Point signal.

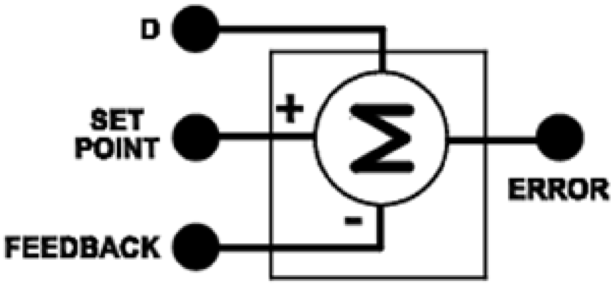


Figure 11: Difference Junction block

BASIC SPECIFICATIONS

SET POINT input: positive unity gain; typically DC to 20 kHz
FEEDBACK input: negative unity gain; typically DC to 20 kHz
D input: second positive unity gain: typically DC to 20 kHz

ERROR output: typically DC to 20 kHz

0-4 What is the transfer function for the differential amplifier circuit shown ?

2.8 PID CONTROLLER

Manually adjusted 3 branch analog PID controller block. The PID CONTROLLER input is hard-wired directly to the ERROR output form the DIFFERENCE JUNICTION block. A single output from the CONTROLLER block is available as PID OUT.

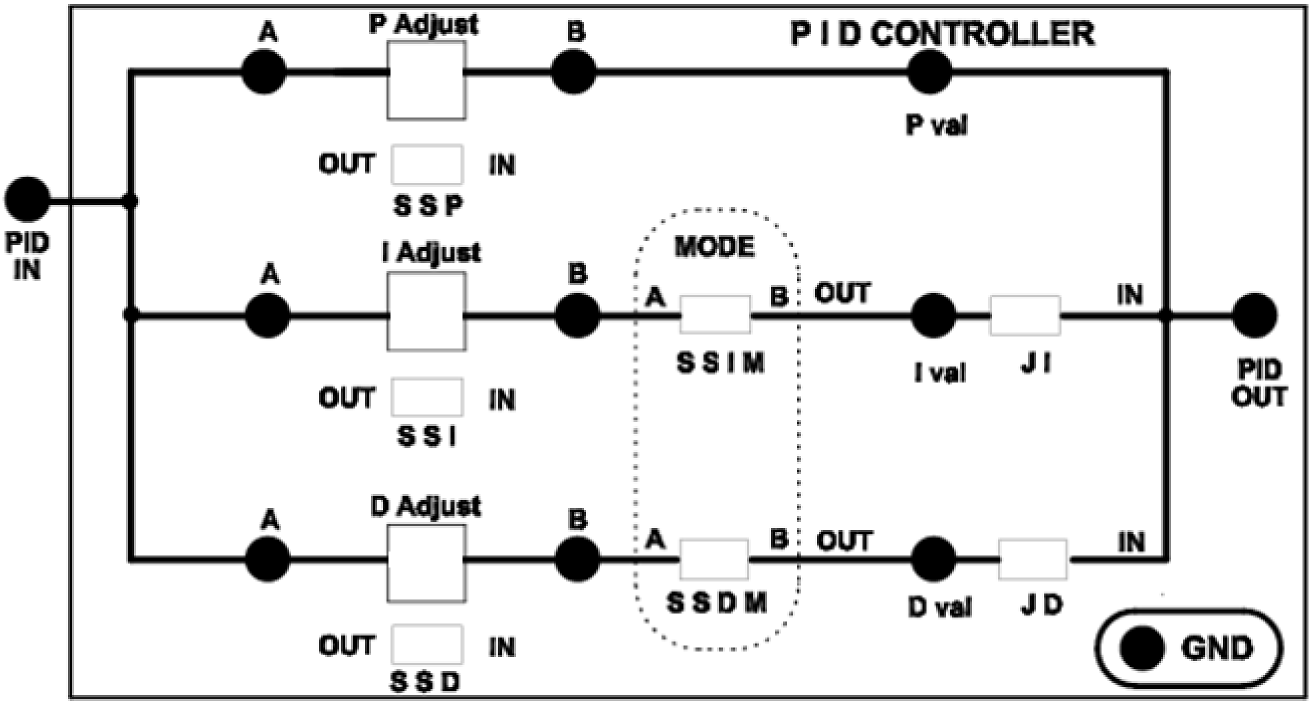


Figure 12: PID controller block diagram

The CONTROLLER block takes an ERROR signal and enables Proportional, Integral and Differential adjustment to that error signal in real time. The contribution from each branch can be viewed at Pval, Ival and Dval output terminals.

ALL P,I and D gain levels are manually adjustable,(using P/I/D adjust trimmers).

I & D branch can be taken out of circuit using the respective JI and JD slide switches set to IN or OUT –of-circuit position.

MODE A or B switches enable the changing of response range for the I and D branches using SSIM and SSDM switches.

To enable the measurement of the gain trimmer, each Adjust trimmer can be taken out of circuit using the SSP/SSI/SSD switches respectively. The trimmer value can be measured at its respective A-B terminals using an Ohm Meter (DMM Instrument)

Normal operation of the PID CONTROLLER requires all slide switches to be set to IN position and MODE switches set as required.

Proportional Gain: Kp = Padjust / 4k7

Integral Gain: Ki = 1/RC; R = Iadjust; where C = 100nF/10nF in A/B mode

Differential Gain: Kd = RC; R = Dadjust; where C = 10uF/10nF in A/B mode

BASIC SPECIFICATIONS

Padjust trimmer: 100k
Iadjust trimmer: 100k
Dadjust trimmer: 10k

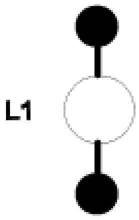
SSIM MODE:
A position: Slow
B position: Fast

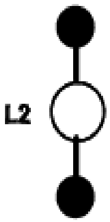
SSDM MODE
A position: Slow
B position: Fast

0-5 What is the maximum gain for the P branch?

2.6 INDUCTORS

Two sample inductors from the FAST and SLOW plant available for out-of-circuit measurement..





These sample inductors, typical of those used in the FAST and SLOW RLC circuits are available for their inductance and series resistance to be measured. The ADS Max DMM can be used to measure resistance.
An inductance meter is required to measure inductance: not provided.

BASIC SPECIFICATIONS

L1 (SLOW): typical 1H; 880 ohms ; +/- 15%
L2 (FAST): typical 100mH; 180 ohms ; +/- 10%

0-6 Why does the inductor have a resistance ?

2.7 Breadboard area

A powered single-strand breadboard area is provided for users to incorporate their own circuits into the experimental setups.

Single-strand wire connectors are available to supply power and GND to the circuit.

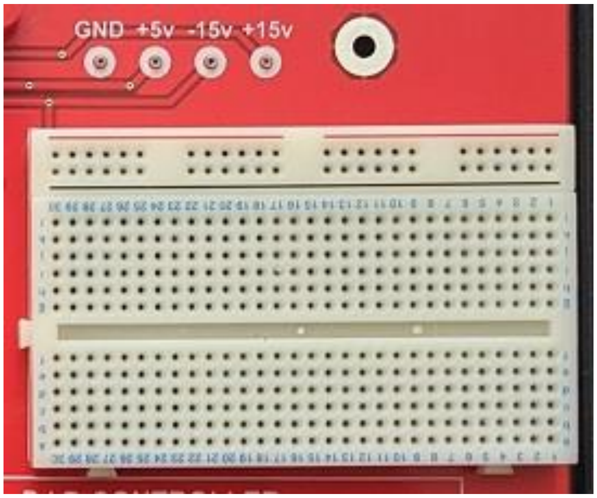


Figure 13: Breadboard area for custom circuits

3.1 ADS MAX instruments used with the EMONA Controls Explorer board

The ADS MAX has numerous virtual instruments included in its platform. Below we will only describe the instruments used with the EMONA Controls Explorer board. The other instruments are described in the respective ADS MAX User Manual for use via the DIGILENT WAVEFORMS software.

3.2 OSCILLOSCOPE

Four high speed oscilloscope inputs are provided on the righthand side of the ADS MAX unit. These are connected to via BNC connectors.

For use with the EMONA board, the four supplied BNC to 2mm-plug cables can be used.

These 2mm plugs are stackable, so that multi-point connections can be made at the same 2mm terminal.

When used with the EMONA SFP software, all required oscilloscope controls are provided in the software which is run on LabVIEW ONLY.

BASIC SPECIFICATIONS
See the DIGILENT ADS MAX User manual

3.3 FUNCTION GENERATOR

Two high speed outputs are provided on the righthand side of the ADS AMX unit. These are connected to via BNC connectors.

For use with the EMONA board, the two supplied BNC to 2mm-plug cables can be used.

These 2mm plugs are stackable, so that multi-point connections can be made at the same 2mm terminal eg you may need to connect the FUNCTION GENERATOR to an input AND view that input with the OSCILLOSCOPE lead at the same time.

When used with the EMONA SFP software, all required FUNTION GENERATOR controls are provided in the software which is run on LabVIEW ONLY.

BASIC SPECIFICATIONS

See the DIGILENT ADS MAX User manual

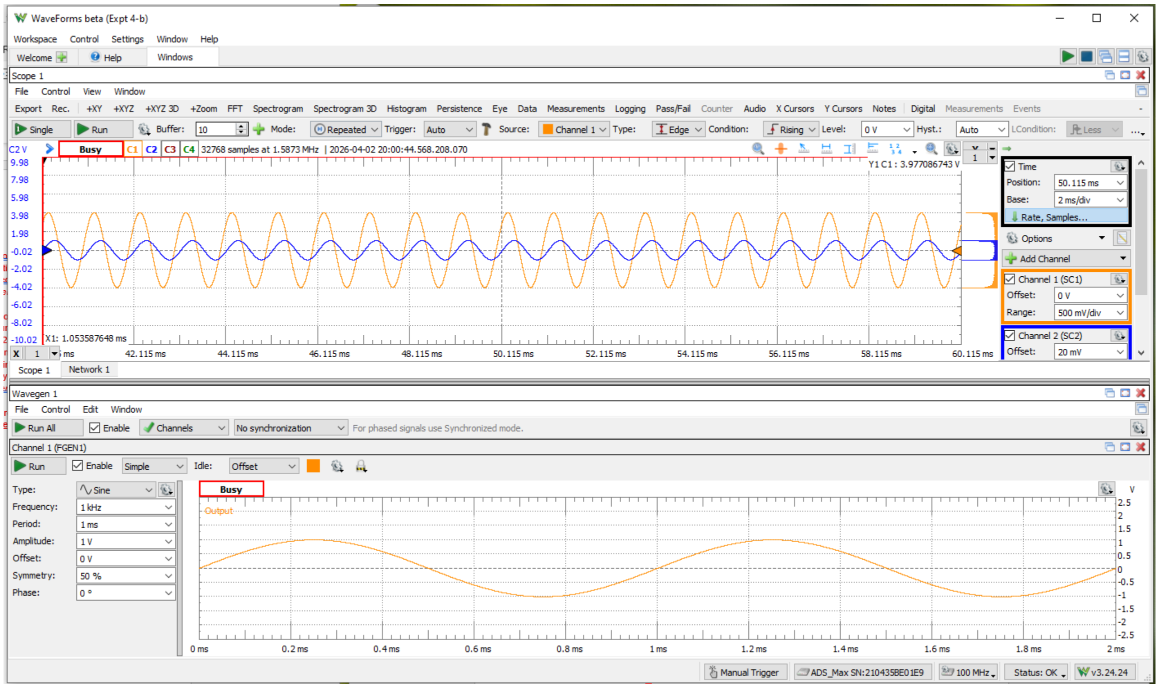
3.4 WAVEFORMS software

The WAVEFORMS software from DIGILENT is a powerful suite of virtual instruments which operate from the ADS Max platform.

There are over a dozen instruments available from the ADS Max via the WAVEFORMS software panel.

For convenience, every experiment in this Lab manual is accompanied by a loadable WORKSPACE file, with suffix ".dwf3work" which when loaded sets up the required instruments for that particular experiment procedure.

This can be easily modified and saved by the user if changes are required or preferred.



Buffer: 10

Mode: Repeated

Trigger: Auto

Source: Channel 1

Type: Edge

Condition: Rising

Level: 0 V

Hyst.: Auto

LCondition: Less

32768 samples at 1.5873 MHz | 2026-04-02 20:00:44.568.208.070

Y1 C1 : 3.977086743 V

X1: 1.053587648 ms

☑ Time

Position: 50.115 ms

Base: 2 ms/div

☑ Channel 1 (SC1)

Offset: 0 V

Range: 500 mV/div

☑ Channel 2 (SC2)

Offset: 20 mV

☑ Enable

Channels

No synchronization

For phased signals use Synchronized mode.

Channel 1 (FGEN1)

☑ Enable

Simple

Idle: Offset

Type: Sine

Frequency: 1 kHz

Period: 1 ms

Amplitude: 1 V

Offset: 0 V

Symmetry: 50 %

Phase: 0 °

ADS_Max SN:210435BE01E9

100 MHz

Status: OK

v3.24.24

Figure 14: Sample WAVEFORMS instrument panel from a workspace file

CONTEX-30 Lab Manual References

Norman S. Nise “Control Systems Engineering”; Wiley; 8th edition

CONTEX-30 System specifications

CAUTION: ELECTROSTATIC SENSITIVE PRODUCT
The Controls Explorer inputs/outputs can be damaged if subjected to Electrostatic Discharge (ESD). To prevent damage, industry-standard ESD prevention measures must be employed during transportation, installation, maintenance and operation.

ELECTROMAGNETIC COMPATIBILITY (EMC)
The Controls Explorer board must only be installed in the ADS MAX-Series base unit, powered only via the NI supplied power supply, which is CE and FCC marked. The controlling PC must be CE marked and FCC compliant. EMC tests have been performed in a selection of typical Controls Explorer experiment configurations. Should the system be affected by external interference, the degradation of any experimental waveform due to interference in normal use may be observed and interpreted by the trainer/student as an unusual response. If deemed necessary the affected experiment or test can be repeated without harm to the user.

PC-CONTROL MODES
The ADDER gains can be controlled via PC-control.
PC-control can only be implemented by NI LabVIEW via ADS MAX edge connector

STANDARD ACCESSORIES
Patch Cords 10 x 2mm-2mm stackable patch cords
Scope leads 6 x 2mm-to-BNC coaxial oscilloscope leads
DMM leads 2 x 4mm to 2mm patch cords
Documentation 1 x User Manual; 1 x Experiment Manual; 1 x Instructor Manual
Software Controls Explorer SFP, Manuals in soft format.
COMMON ELECTRICAL SPECIFICATIONS
Input impedance: typically 50kohm
Output impedances:
- **Analog signals:** 330 ohm
- **Digital signals:** 47 ohm

Maximum allowable input voltage: +/- 12V
Maximum output voltage : +/- 12V
Functional Displayed Tolerances : +/- 10% under Controlled EM environments, or +/- 2 divisions otherwise.
POWER SUPPLY

Power Source supplied via ADS MAX edge connector: +5V, +15V, -15V rails consume <500mA each

ENVIRONMENTAL

Operating Temperature Range 10 to 30 degrees C

Storage Temperature Range 5 to 40 degrees C

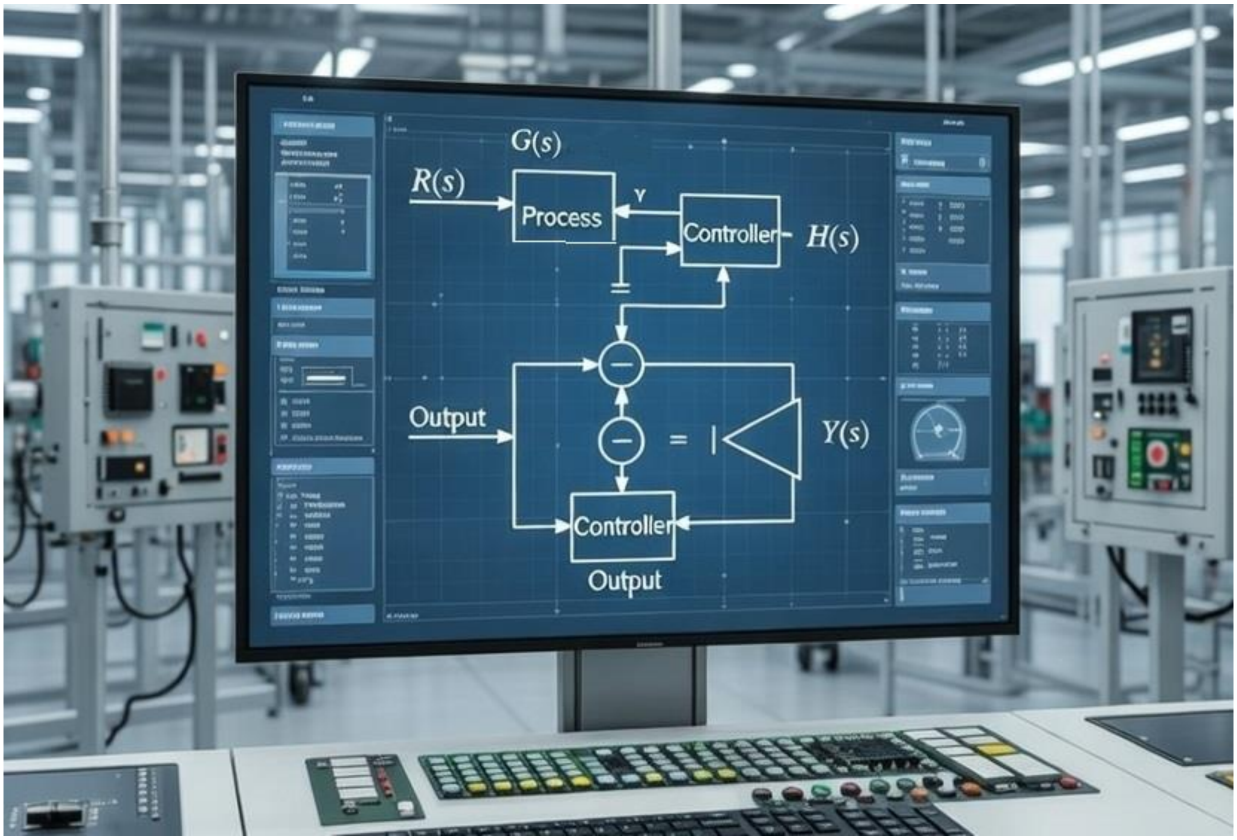
Humidity up to 90% RH, non-condensing

PHYSICAL

Dimensions front panel 280 x 215mm

Lab Manual:
Introduction to Controls Theory
for EE & ECE courses

Using the EMONA Controls Explorer board for ADS MAX



Lab 5: Designing for PID control of plant

Experiment 5

Designing for PID control of plant

Authors / Contributors

Carlo Manfredini, B.Eng; EMONA TIMS Pty Ltd, Australia

Achievements in this experiment

To examine the benefits of feedback in a control loop.
Consider mathematical computation of controller values.
To understand the 3 parts of a PID controller
To introduce a manual tuning methodology.
To develop intuitive understanding for the effects of feedback

Background: -
In many situations we have a desired outcome we wish the “plant” to follow but we find that due to many external influences, that plant is unable to track the desired outcome accurately when used in an open loop situation. That is, when the input is simply applied to the plant and the output of the plant is not modified in any way.

A simple example is driving to a destination using pre-set commands with no adjustment for any changes along the route, like traffic, wind, etc. Open-loop is like driving blind (simple, cheap, fast to "set", but fails if anything unexpected happens). Introducing feedback enables the system to be informed of any deviations and to adjust in order to better meet the desired outcome. This is known as Closed-loop, that is, driving with eyes open (a bit more effort/hardware like sensors giving you feedback information, but way more accurate and reliable in the real world).

Most precise everyday things (like cruise control on a car, room thermostat, or even how you balance while walking) work closed-loop style — that's why they're reliable! By inserting a PID Controller into the path and closing the path into a closed loop, we are able to have the output of the system more accurately follow the desired input.

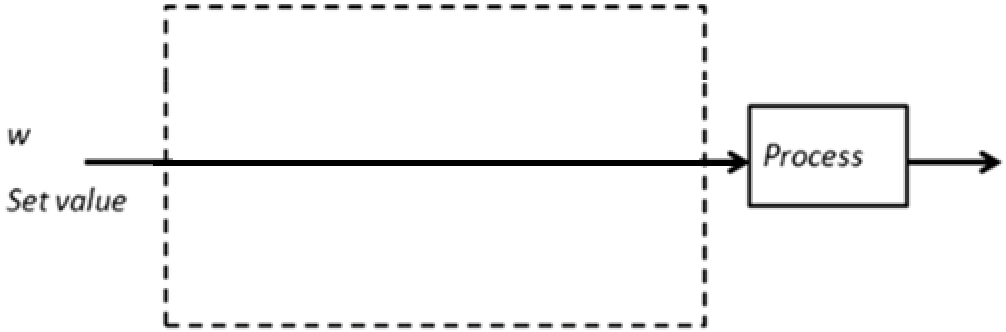


Figure 64: Open-loop process control

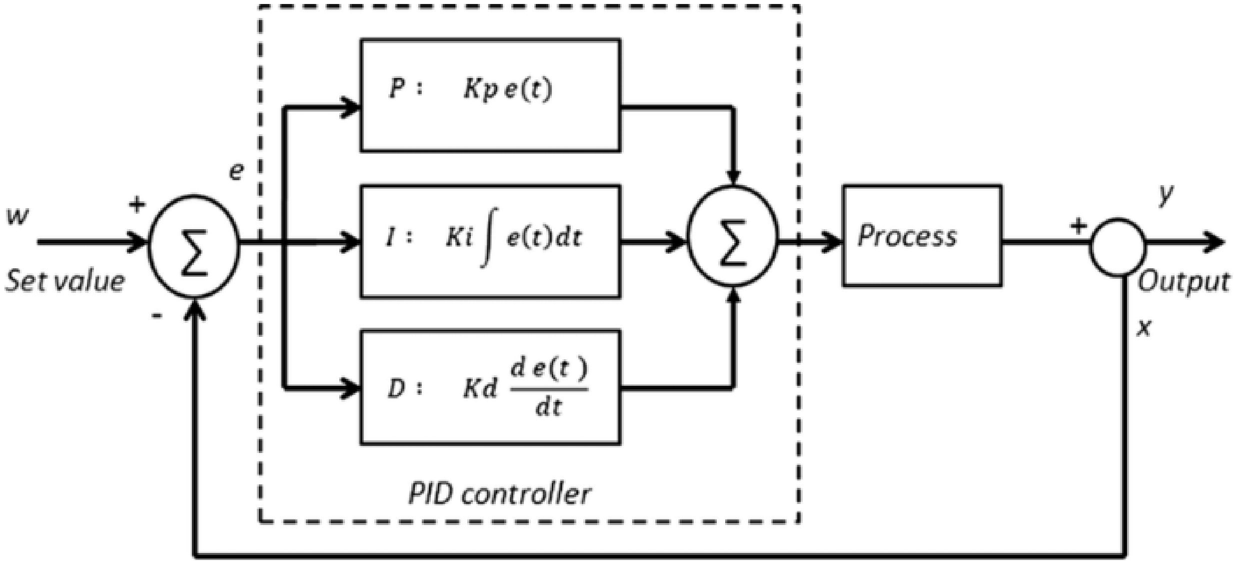


Figure 65: Closed-loop process with PID control

https://www.researchgate.net/figure/Block-diagram-of-PID-closed-loop-control-system_fig1_326068417

In simple terms, if the desired output of the plant is a more rapid response, then the PID controller “drives” the plant harder to meet the desired criteria of the Set Point.
In most cases we aim to achieve the “ideal” output response from the plant.

The “ideal” output response of a well-tuned PID controller (to a sudden step change in setpoint, like turning up the thermostat) is usually described as:

- Fast rise to the target (quickly gets close without being sluggish).

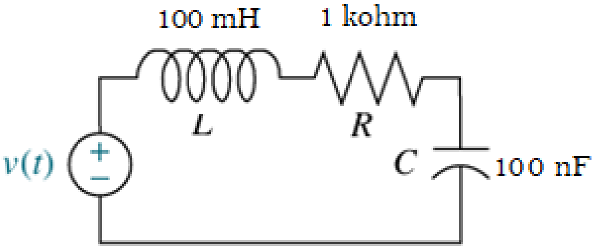
- Little or no overshoot (doesn't go noticeably past the setpoint before settling).
- No oscillations or just very mild damped ones that die out quickly (no ringing/back-and-forth).
- Zero steady-state error (settles exactly at the desired value, not slightly off).
- Smooth, stable approach (critically damped or slightly overdamped behavior is often preferred in real applications for robustness).

The perfect step response looks like a smooth, quick "S-curve" that rises rapidly toward the target, barely (or never) overshoots, then settles cleanly and stays rock-solid at the setpoint — no wobbling afterward. Many textbooks aim for something close to critically damped (fastest possible without overshoot) or allow a small overshoot (e.g., 5–10%) if you want even quicker rise time, as long as it doesn't oscillate. Real-world "ideal" often trades a tiny bit of overshoot for faster response, but stability and no endless ringing come first.(If the process has lots of delay or is noisy, you might accept slower settling to stay ultra-stable — there's no single universal "perfect" curve, but the above traits are what every control engineer chases!)

You can imagine that the controller for a robotic surgery tool will have more strict criteria than for a parking gate controller.

It is interesting and informative to calculate the PID controller branch settings mathematically. Below is outlined an example computation process for the plant used in this experiment. Be sure to read it and follow the steps involved…. you will be implementing this theory into practice next.

The plant to be used is the “FAST PLANT RLC”. It has a circuit and transfer function as follows:



$G(s)=1/LC/(s^2+sR/L+1/LC)$
$G(s) = 10^8/(s^2 + 10^4 s + 10^8)$
$G(s) = K/s^2+as+b$
$G(s) = w^2/(s^2 + 2\zeta ws + w^2)$

This is a lightly damped second-order system with:

Natural freq $\omega_n = 10^4$ rad/s
Damping ratio $\zeta = 10^4/2\omega_n$ =0.5
Open loop settling time of 0.8 ms
Overshoot of 16% and some oscillatory ringing

Our design objectives are:

Overshoot < 5%
Settling time = 0.5 ms (0.0005 sec)

These objectives are stricter than what the plant would naturally operate to in open loop ie without being in a controller loop. So we are using the loop to force the plant to respond more rapidly but in a controlled manner.

Step 1: Translate specs to define the dominant closed-loop poles

Percent overshoot (%OS) ≈ 5% (0.05) → damping ratio $\zeta \approx 0.69$
using the formula:

$$\zeta = -\frac{\ell n(\%OS)}{\sqrt{(\pi^2+\ell n\,(\%OS)^2)}} = 0.69$$

Settling time $t_s \approx 4 / (\zeta\,\omega) \approx 0.5$ ms → $\zeta\,\omega \approx 4 / 0.0005 = 8000$ rad/s

Thus desired closed-loop natural frequency: $\omega_n \approx 8000 / 0.69 \approx 11{,}600$ rad/s
(nb: 11,600 rad/s is $11{,}600/2\pi = 1{,}846$ Hz)

So dominant poles $\approx -\zeta\,\omega \pm j\,\omega\,\sqrt{(1-\zeta^2)} \approx -8000 \pm j\,8300$ (approx.)

We have now determined poles required for a 2nd order system to be able to perform according to the specifications we set earlier.

Step 2: Choose the third pole position

The third pole arises naturally in the closed-loop system when using a PID controller on your second-order plant, and we explicitly place/design it (rather than letting it "happen" randomly) to achieve good performance while keeping the response predictable. The PID controller adds a pole to the 2 poles from the 2nd order plant when they are combined into a loop.

The desired characteristic polynomial, with an extra pole :

$(s^2 + 2\,\zeta\,ws + w^2)(s+p)$
$s^3 + (2\,\zeta\,w + p)s^2 + (w^2 + 2\,\zeta\,wp)s + w^2p$

We select the pole to keep the third pole non-dominant (fast dynamics, minimal influence on overshoot/settling). A rule of thumb is to place real pole
at $p = 4 \times \zeta\omega$ to $8 \times \zeta\omega$l
So a common practical choice: $p \approx 5 \times 8000 = 40{,}000$ rad/s (5× real part of dominant poles)

Why is the pole placed far to the left on the negative real-axis ? One reason is to make its effect negligible on the transient response.

Given $\zeta = 0.69$; $w = 11{,}600$; $p= 40{,}000$

So we can calculate the coefficients of s2, s and constant in the desired char equation above to be:

- s^3 coeff: 1
- s^2 coeff $\approx 2\zeta w + p = 2\times0.69\times11600 + 40000 \approx 16000 + 40000 = 56000$
- s coeff $\approx w^2 + 2\zeta wp = 11600^2 + 2\times0.69\times11600\times40000 \approx 1.35\times10^8 + 6.4\times10^8 \approx 7.75\times10^8$
- const coeff $\approx w^2p = 11600^2 \times 40000 \approx 5.38\times10^{12}$

Step 3: define the closed loop equation for Plant and PID

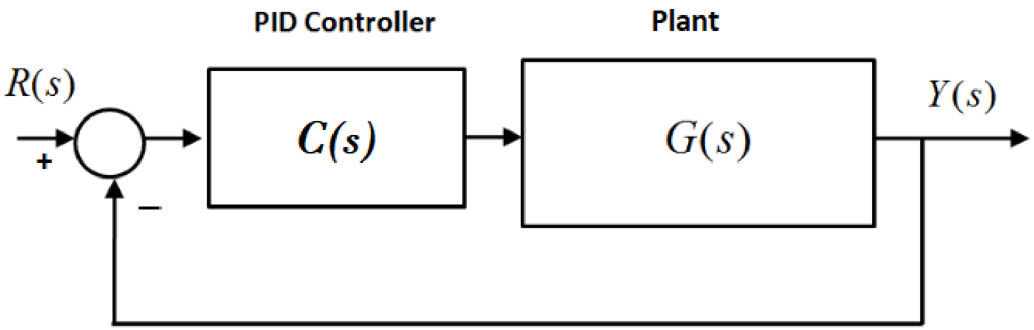


Figure 66: Block diagram for PID loop with plant

Closed loop transfer function $T(s) = \dfrac{C(s)G(s)}{1+ C(s)G(s)}$

We select the pole to keep the third pole non-dominant (fast dynamics, minimal influence on overshoot/settling). A rule of thumb is to place real pole
at $p = 4 \times \zeta\,\omega$ to $8 \times \zeta\,\omega l$
So a common practical choice: $p \approx 5 \times 8000 = 40{,}000$ rad/s (5× real part of dominant poles)

Why is the pole placed far to the left on the negative real-axis ? One reason is to make its effect negligible on the transient response.

$C(s) = Kp + Ki/s + Kd.s$	$G(s) = 10^8/(s^2 + 10^4 s + 10^8)$

Using the functions C(s) and G(s) above in the T(s) formula, and then viewing the denominator only, known as the characteristic equation.

We study the denominator of the closed-loop transfer function T(s) — specifically, we set it equal to zero to form the characteristic equation — because its roots are precisely the closed-loop poles of the system. These poles completely determine the most important dynamic properties of the feedback-controlled system, especially:

- Stability (asymptotic, marginal, or unstable)
- Transient response characteristics (settling time, overshoot, ringing/oscillation frequency, damping)
- Natural modes of behavior (how the system responds to disturbances, initial conditions, or setpoint changes over time)

This approach is fundamental in classical control theory (transfer function / frequency-domain method).

For linear systems, the transient (natural, unforced) response is determined by the poles of T(s) — i.e., the values of s where the denominator becomes zero (and the transfer function becomes infinite).
Mathematically: Poles of T(s) ⇔ roots of $1 + C(s)\,G(s) = 0$
This equation:$1 + C(s)\,G(s) = 0$ called the characteristic equation of the closed-loop system.

Solving for this gives:
$s^3 + s^2(a + K.Kd) + s(b + K,Kp) + K.Ki = 0$

- s^3 coeff: 1

- s^2 coeff: a + K.Kd ≈ $10^4 + 10^8$.Kd
- s coeff: b + K,Kp ≈ $10^8 + 10^8$.Kp
- const coeff: K.Ki ≈ 10^8.Ki

Step 4: relating characteristic equation to give PID design values

Correlating the two sets of equations and solving for the PID values gives:

• s^2 coeff: a + K.Kd ≈ $10^4 + 10^8$.Kd • s coeff: b + K,Kp ≈ $10^8 + 10^8$.Kp • const coeff: K.Ki ≈ 10^8.Ki	• s^2 coeff = 56000 • s coeff ≈ 7.75×10^8 • const coeff ≈ 5.38×10^{12}

Resulting in :

Kp = 6.75; Ki = 54000; Kd = 0.00046

Kp = 6.75	Rf = 6.75 x Ri
Ki = 54000	Ki = 1/RC; where C = 10nF R = 1.8 kohm
Kd = 0.00046	Kd = RC, where C = 10nF R = 46 kohm

This is good starting point and we will see how well it works once implemented in a real world circuit on the actual CONTEx board.

https://www.ni.com/en/shop/labview/pid-theory-explained.html?srsltid=AfmBOoqTPXPGgFDGSSOulszk9b9R7L97MgVcPjztYTthNZx7kjGj-g3t

Preparatory Questions

Question 1

Calculate the closed loop transfer function T(s), Show your working.

Required Tools and Technology

Platform: ADS MAX

Instruments used in this lab:

- Oscilloscope-Time
- Function Generator
- DMM: Ohm Meter

Hardware: Emona Controls Explorer Board (CONTEx)

Components used in this lab:

- Six BNC to 2mm banana-plug leads
- Assorted 2mm banana-plug patch leads
- Two 4mm to 2mm patch cords for Ohm Meter usage

Software: DIGILENT WaveForms
V3.23.72 or later

Files used in this lab:
Expt 5-a.dwf3work

Expected Deliverables

In this lab, you will collect the following deliverables:

- ✓ Calculations
- ✓ Data from measurements
- ✓ Observations

Your instructor may expect you to complete a lab report. Refer to your instructor for specific requirements or templates.

Implemention

Powering up the ADS MAX + EMONA CONTEx Board

9. Ensure that the ADS MAX Application Board power button at the top left corner of the unit is OFF (not illuminated).

10. Carefully plug the Emona CONTEx into the ADS MAX ensuring that it is fully engaged both front and back.

3. Ensure that you have connected the ADS MAX to the PC using the USB cable and that the PC is turned on.

4. Turn on the Application Board *Power* button by pressing it once and confirm that it is illuminated. The LEDs on the CONTEx should also be illuminated. If they are not, then switch the unit off immediately and check for connection or insertion errors.

5. Open the WAVEFORMS software on your PC.
Open the supplied workspace file for this experiment.
The instrument panel will open into a convenient configuration relating to this experiment. You can modify and save the workspace configuration to suit yourself

6. RUN each of the tabbed instruments when needed and when switching between tabs. Refer to the WAVEFORMS User documentation for details about each instrument.

Experiment Procedure

Part 1: Manually determining the PID values for OVERdamped plant

In this part of the experiment, you will select the simple 1st order overdamped circuit to investigate. Using a step response to manually tune the PID control values to achieve a critically damped response.

1. Load the following workspace for convenience of the ADS Max setup:
   Expt 5-a.dwf3work

Function Generator Configuration

Waveform	Squarewave
Frequency FG1	50 Hz
Amplitude	500mVpk
DC Offset	500mV

DMM: Ohm Meter Configuration

Mode	Auto

Scope Configuration

Channel Voltage range CH1, CH2	2V/div
Horizontal Timebase	1ms/div
Trigger	Type: Analog edge, Source: Channel 1 input, Rising
Probe Attenuation	1x

2. Patch together the Open-loop version of this experimental setup. Have the FUNCTION GENERATOR go directly to the 1st Order plant and view both the input and output of the plant. Plot the step response in the graph below.

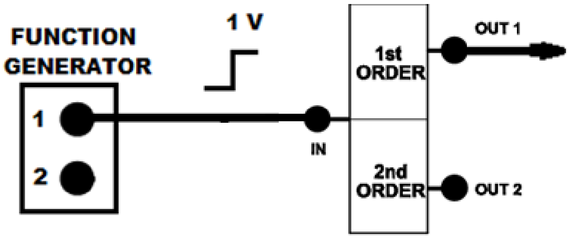


Figure 67: Block diagram for underdamped plant in open loop

3. Patch together the Closed PID loop experiment setup according to the patching diagram. Since we are using this plant in a static zero-initial condition arrangement, the GATE signal is set to 0.

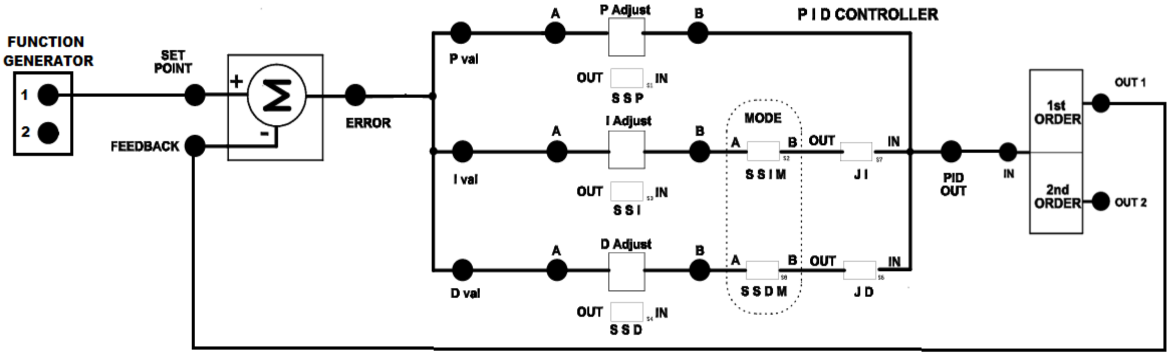


Figure 68: Block diagram for overdamped plant with PID controller…with FG and OHM in PID loop

Figure 69: Patching for PID loop with underdamped plant

4. Set up the PID Controller to only have the Proportional branch activated as follows:
   Set switch JI and JD to OUT: Open circuit I & D branch
   Set switch SSP, SSI and SSD to IN: Close all resistors
   Set MODE SSIM to B position
   Set MODE SSDM to position B

5. Use the 4 channel scope to view the following points:
   Setpoint input
   PID output signal
   Plant output signal
   Various other points: Error, Pval, Ival,Dval

Remember that each branch contribution is added with unity gain to produce the PID Controller PID OUT signal. Confirm for yourself that this is indeed happening.

Also, confirm that the ERROR signal is indeed the difference between in the SET POINT input and the fed-back signal, at FEEDBACK. In a sense the PID CONTROLLER loop is aiming to minimize the ERROR signal.

6. Adjust the Pval trimmer whilst viewing the Plant output until you get the best result possible. View the Pval output and confirm the ERROR signal is as expected.

5-1 Was the Prop only controller able to give an ideal response ?
Explain your findings ?

Now introduce the Integral branch.
Set the JI switch to ON to introduce the Integral branch into the controller.

7. Adjust the Ival trimmer whilst viewing the Plant output until you get the best result possible. View the Ival output and confirm the ERROR signal is as expected.

5-2 Was the P + I only controller able to give an ideal response ?
Explain your findings ?

Now introduce the Differential branch.
Set the JD switch to ON to introduce the Differential branch into the controller.

8. Adjust the Dval trimmer whilst viewing the Plant output until you get the best result possible. View the Dval output and confirm the ERROR signal is as expected. You don’t need to include the use of the Differential branch if its contribution is not significant to your design requirement.

5-3 Was the P + I +D controller able to give an ideal response ? Explain your findings ?

Return to make subtle adjustments to the 3 variables to try and improve the output signal. You are aiming to achieve close to a critically damped output response in most but not all cases. If you DO make adjustments, then you will need to re-measure the resistance for that branch and update your table.

9. View each of the Pval, Ival and Dval output signal points to see the contributing components of each branch, as well as their total , PID out, which is simply their sum.. Plot these 4 signals in the graph along with the Set point input, error, and Plant out.

5-4 Compare your best PID response with the open loop response of the plant. DIscuss

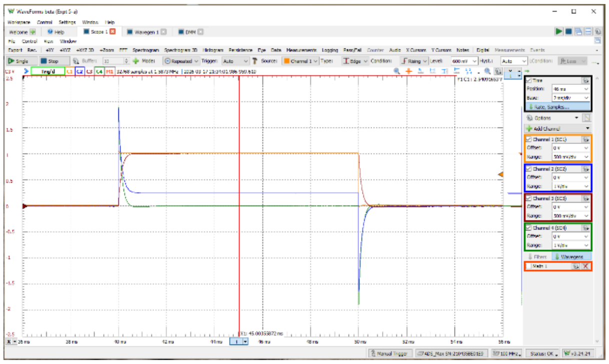


Figure 70: Example of PID enhanced response

21.3886 kΩ

Figure 71: Example reading from Ohm Meter in DMM instrument

Now you will need to measure the actual trimmer resistance value for each branch as follows.

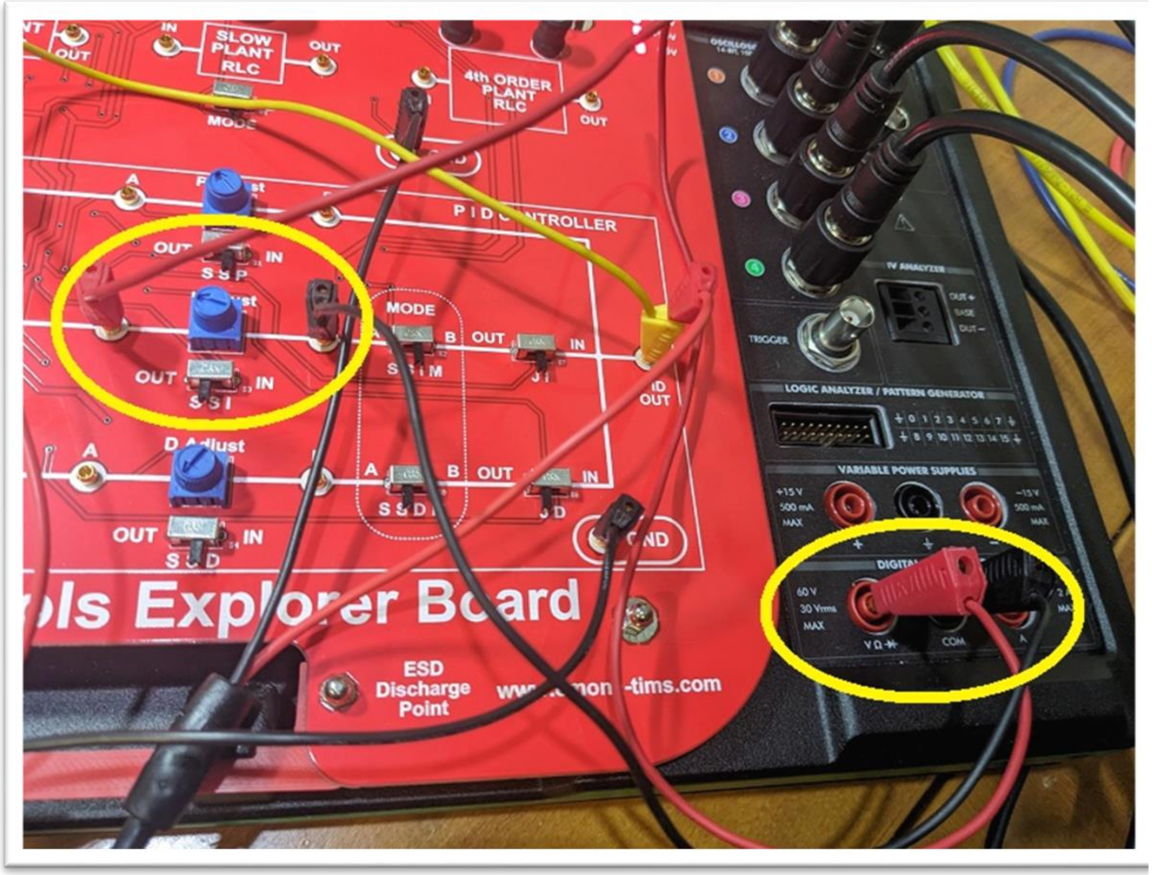


Figure 72: Patching for DMM Ohm Meter usage

10. Open the Pval switch (set SSP to OUT) and measure the resistance of the trimmer at its optimum position using the OHM METER from the ADS MAX at the two points A and B on either side of the trimmer. Enter the value into the table. Close the SSP switch (set to IN) when done to place it back into the circuit

11. Repeat this measurement for both the Ival and the Dval trimmer, using switches SSI and SSD respectively. Enter these values into the Table as you go. Take care to not change the trimmer position whilst doing this.

12. Calculate the K gains for each branch in the table.
Pval = (R/4700)
Ival = 1/(R*C) where C = 10 nF (MODE B)
Dval = R*C, where C = 10 nF (MODE B)

Branch Value	**Resistance (ohm)**	**K gain value**	
Pval resistance			
Ival resistance			
Dval resistance			

Graph 1: Response and components

Part 2: Manually determining the PID values for UNDERdamped plant

In this part of the experiment, you will select the second order FAST Plant RLC circuit to investigate. Using a step response to manually tune the PID control values to achieve a critically damped response.

In the introduction to the Experiment we discussed the various decision metrics involved in choosing an optimum output response. This will depend on the type of plant you are actually controlling.

1. Load the following workspace for convenience of the ADS Max setup:
   Expt 5-a.dwf3work

Function Generator Configuration

Waveform	Squarewave
Frequency FG1	50 Hz
Amplitude	500mVpk
DC Offset	500mV

DMM: Ohm Meter Configuration

Mode	Auto

Scope Configuration

Channel Voltage range CH1, CH2	2V/div
Horizontal Timebase	1ms/div
Trigger	Type: Analog edge, Source: Channel 1 input, Rising
Probe Attenuation	1x

2. Patch together the Open-loop version of this experimental setup. Have the FUNCTION GENERATOR go directly to the FAST plant and view both the input and output of the plant. Plot the step response in the graph below. Measure accurately all the relevant parameters.

.

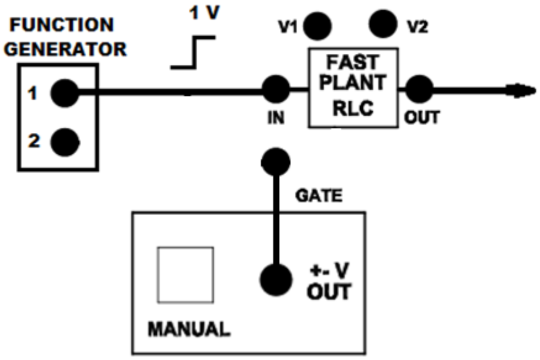


Figure 73: Block diagram for underdamped plant in open loop

3. Patch together the Closed PID loop experiment setup according to the patching diagram. Since we are using this plant in a static zero-initial condition arrangement (non charging), the GATE signal is set to 1.

.

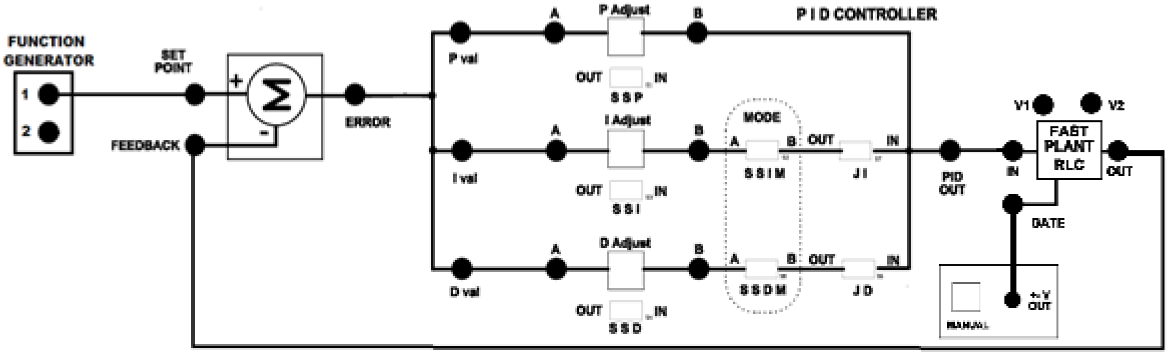


Figure 74: Block diagram for overdamped plant with PID controller

Figure 75: Patching for PID loop with underdamped plant

4. Set up the PID Controller to only have the Proportional branch activated as follows:
   Set switch JI and JD to OUT: Open circuit I & D branch
   Set switch SSP, SSI and SSD to IN: Close all resistors
   Set MODE SSIM to B position
   Set MODE SSDM to position B

5. Use the 4 channel scope to view the following points:
   Setpoint input
   PID output signal
   Plant output signal
   Various other points: Error, Pval, Ival,Dval

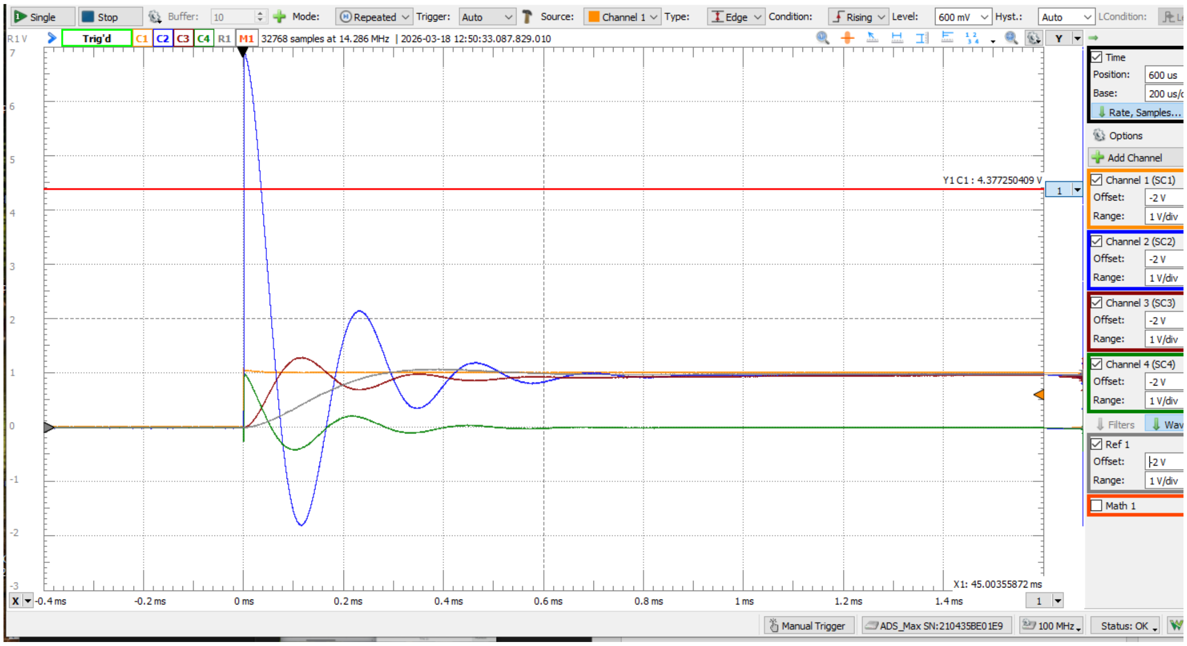
Remember that each branch contribution is added with unity gain to produce the PID Controller PID OUT signal. Confirm for yourself that this is indeed happening.

Also, confirm that the ERROR signal is indeed the difference between in the SET POINT input and the fed-back signal, at FEEDBACK. In a sense the PID CONTROLLER loop is aiming to minimize the ERROR signal.

6. Adjust the Pval trimmer whilst viewing the Plant output until you get the best result possible. View the Pval output and confirm the ERROR signal is as expected.

5-5 Was the Prop only controller able to give an ideal response ? Explain your findings ?

No. It cannot have the output reach the full value. It has a constant error.



Single | Stop | Buffer: 10 | Mode: Repeated | Trigger: Auto | Source: Channel 1 | Type: Edge | Condition: Rising | Level: 600 mV | Hyst.: Auto | LCondition:

Trig'd | C1 | C2 | C3 | C4 | R1 | M1 | 32768 samples at 14.286 MHz | 2026-03-18 12:50:33.087.829.010

☑ Time
Position: 600 us
Base: 200 us/

Channel 1 (SC1): Offset: -2 V, Range: 1 V/div
Channel 2 (SC2): Offset: -2 V, Range: 1 V/div
Channel 3 (SC3): Offset: -2 V, Range: 1 V/div
Channel 4 (SC4): Offset: -2 V, Range: 1 V/div
Ref 1: Offset: -2 V, Range: 1 V/div
☐ Math 1

Y1 C1 : 4.377250409 V

X1: 45.00355872 ms

Manual Trigger | ADS_Max SN:210435BE01E9 | 100 MHz | Status: OK

Figure 76: Example signals with P branch only with Open Loop response as grey Reference signal

Now introduce the Integral branch.
Set the JI switch to ON to introduce the Integral branch into the controller.

7. Adjust the Ival trimmer whilst viewing the Plant output until you get the best result possible. View the Ival output and confirm the ERROR signal is as expected.

5-6 Was the P + I only controller able to give an ideal response ? Explain your findings ?

____

____

____

____

5-7 Why does the system become unstable when the Iadjust trimmer is set very low ?

____

____

____

____

Now introduce the Differential branch.
Set the JD switch to ON to introduce the Differential branch into the controller.

8. Adjust the Dval trimmer whilst viewing the Plant output until you get the best result possible. View the Dval output and confirm the ERROR signal is as expected. You don’t need to include the use of the Differential branch if its contribution is not significant to your design requirement.

5-8 Was the P + I +D controller able to give an ideal response ? Explain your findings ?

____

____

____

____

____

Return to make subtle adjustments to the 3 variables to try and improve the output signal. You are aiming to achieve close to a critically damped output response in most but not all cases. If you DO make adjustments, then you will need to re-measure the resistance for that branch and update your table.

9. View each of the Pval, Ival and Dval output signal points to see the contributing components of each branch, as well as their total , PID out, which is simply their sum.. Plot these 4 signals in the graph along with the Set point input, error, and Plant out.

5-9 Compare your best PID response with the open loop response of the plant. Discuss

____

____

____

____

Now you will need to measure the actual trimmer resistance value for each branch as follows.

10. Open the Pval switch (set SSP to OUT) and measure the resistance of the trimmer at its optimum position using the OHM METER from the ADS MAX at the two points A and B on either side of the trimmer. Enter the value into the table. Close the SSP switch (set to IN) when done to place it back into the circuit

11. Repeat this measurement for both the Ival and the Dval trimmer, using switches SSI and SSD respectively. Enter these values into the Table as you go. Take care to not change the trimmer position whilst doing this.

12. Calculate the K gains for each branch in the table.
    Pval = (R/4700)
    Ival = 1/(R*C) where C = 10 nF (MODE B)

Dval = R*C, where C = 10 nF (MODE B)

Branch Value	Resistance (ohm)	K gain value	
Pval resistance			
Ival resistance			
Dval resistance			

Graph 2: Response and components

Appendix A: EMONA CONTEx Lab to Textbook chapter mapping table

This table aims to direct users to sections of the selected reference textbook containing theory and further practical exercises related to experiments currently documented and implementable with the ADS Max/ CONTEx Explorer bundle

Norman N. Nise “Controls Systems Engineering” ; Wiley

CONTEx Lab Manual Section	**Nise: Text Chapter**
1: 1st & 2nd order systems	4: Time Response
2: State Space analysis	3.3 The general state-space representation
3:Stability & Routh-Hurwitz criterion	6: Stability
4: Frequency & Phase response	10: Frequency response techniques
5: Designing for PID control of plant	9.4 Improving Steady-State Error and Transient Response / PID Controller Design
6: Gamifying PID design for optimum performance	9.6 Physical Realization of Compensation

EMONA ETT-511 CONTEx CONTROL THEORY EXPERIMENTS

Emona Instruments Pty Ltd
78 Parramatta Road
Camperdown NSW 2050
AUSTRALIA

web: **www.emona-tims.com**
telephone: +61-2-9519-3933
fax: +61-2-9550-1378