

# Instrumentation and Control Assignment 2

*by* Ralph Whittaker

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# **Instrumentation and Control Assignment 2**

by

**RALPH WHITTAKER**

UWTSD

STUDENT ID: P148322

**TEST RANGE ENGINEERING**

**MODULE:** Instrumentation and Control

**M5X00940**

**LECTURER:** DR STEPHEN MOSEY

**UNIVERSITY OF WALES**

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## Abstract

The following report is an evidential record and summary of the practical investigation into a variety of electronically driven controllers that were used to independently power and control a DC motor, dependant on a stepped input.

The aim of the task was to physically demonstrate and evaluate the characteristics of a *Proportional (P)*, *Proportional – Integral (PI)*, *Proportional – Derivative (PD)* and *Proportional – Integral - Derivative (PID)* controller with a practical investigation using Positional Control apparatus (Fig.1). Throughout the report the advantages and disadvantages of each of the types of controllers will be explored and recorded.

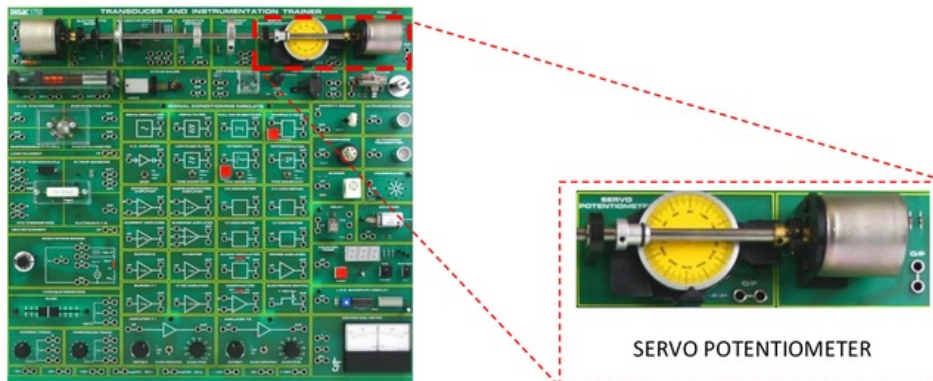


Fig.1

The performance of the controllers was judged on the accuracy of the physical control of a DC powered motor using the measurements of a Servo Potentiometer directly attached to the motor via a drive shaft. Observations were then made of the motors rotational displacement (in degrees), speed and behaviour. Depending on how large the angle of movement, what direction, speed and how long the servo potentiometer took settle, directly relates to the behaviour of the motor being controlled. This in turn correlates to the accuracy of the control method in terms of speed of response, overshoot and settling time. Critical analysis could then be conducted of the range of responses produced by the different control system scenarios built from the subsequent instrumentation and allowed development of solutions to specific problems that arose.

The task was completed using an *LJ Create 1750 Transducer and Instrumentation Trainer* (Fig.2) [1] of which enabled the easy interchange between controller types and stepped input by amending the setup of the apparatus and therefore circuitry arrangement using jumper leads, depending on the selection of control type. The instructions and task queries within sections 18.3 to 18.6 of the *LJ Create Curriculum manual* [1] were used as a guide for this report, aiding the selection of necessary research literature and supporting the development of knowledge on the subject.

The LJ Create 1750 Transducer and Instrumentation Trainer

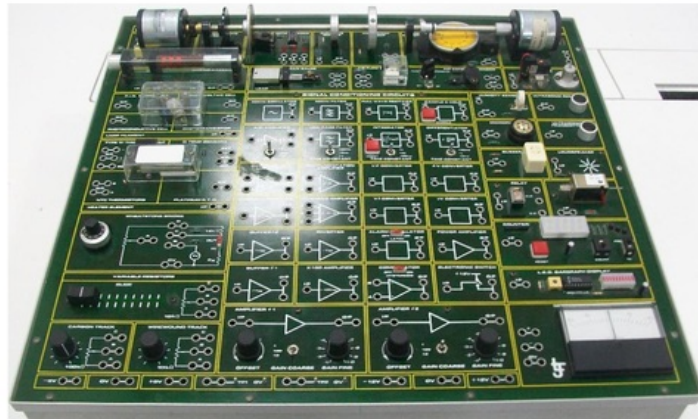


Fig.2

Throughout the sequential progression of the tasks, the document will present the observational findings and results in tabular and graphical form ready for analysis and discussion. To conclude the document, a comparison will be made between the different control methods, summarising the benefits and disadvantages of each. Evidence will prove how the PID controller is the most suitable method of control for the stabilisation of a DC motor.

## Introduction

A controller is a management system of sensory and calculative instrumentation that can be implemented into any man-made process that only requires very little, if any, human interaction. If a system requires an element of detection and automatic correction, a feedback controller can be designed and applied to evaluate feedback from process conditions and use this information to calculate the necessary adjustment measures for an actuator (Plant) to action for the process to stay within set specifications (set points).

Controllers exist in many different forms, depending on the design and requirement of application. For this assignment, the focus was on variations of the most common type of control method, the Proportional-Integral-Derivative controller (PID). A PID controller is a closed loop control method that can be used in such a way that its main elements (Proportional, Integral and Derivative) can be selectively turned on or off, therefore used individually or together to form either *P*, *PI*, *PD* or full *PID* control. The electronic controllers for this task were each in turn, individually produced in accordance to the schematics below and their electronic circuitry (component and construction) varied depending on what each specific system required.

### Proportional control

Proportional control (P), works by proportionally adjusting the output of the system depending on the error feedback, to an appropriate level (voltage) that works to try and correct the error of under or over damping. Therefore, the error is directly proportional to the control input. For this task the error is the difference between the **set point voltage (AMP #2)** and the process variable (wire wound track potentiometer). The difference is calculated by the error detector (instrumentation amplifier) throughout the duration of the process. The proportional adjustment is calculated within the proportional control algorithm (multiplication of error x gain within the proportional gain amplifier) of AMP #1 and in this instance, will determine whether the rotation of a motor will be controlled steadily, be under damped and rotate uncontrollably fast or be over damped and not rotate at all.



P control is mathematically represented by:

$$A(t) = K_p \times e(t)$$

A(t) is the proportional controller output,  $K_p$  is the controllers set gain and e(t) is the error signal.

The voltage across the motor was proportionally increased or decreased by varying the resistance of the wire wound 10k potentiometer. The differential amplifier (DIFF AMP) supplied the step input voltage based on the potential difference (voltage) between the wire wound track, process variable (PV) and the offset variable Amp #2, set point, that is initially manually set to a predetermined voltage. The 10K wire wound resistor acted as the command input and was manually amended throughout the duration of the process, varying the control of the motor according to Ohm's Law (set point voltage across the motor).

The practical set up for this system (see Fig. 1) [1] required only error calculation and proportional adjustment using an instrumentation amplifier (INST AMP) and a summing amplifier (see Fig. 2). The process variable (PV) is subtracted from the set point (SP) to find the error, this is then multiplied by the control actions, the proportional gain ( $K_p$ ) to produce the control system output in the form of a control signal to the plant (motor). This process then starts again with the error being calculated and fed back into the system in what is known as a closed loop (feedback) system. Care should be taken when setting the gain for this system for it to respond quick enough but to avoid under and over shooting, and achieve the set point without introducing large unnecessary instabilities due to oscillations about the set point. If too high a gain is set, response time can be quick but the system can become unstable with excessive oscillations occurring. A lower gain can still produce oscillations that overshoot the set point but will be less aggressive. A steady state error will always be present however, with the system never reaching or maintaining the set point. No integral or derivative control is included within this system.

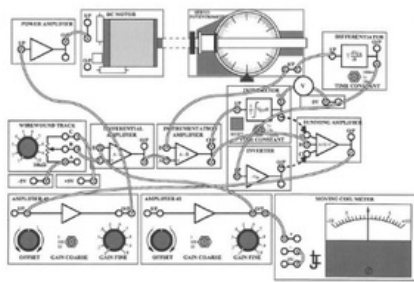


Fig.1

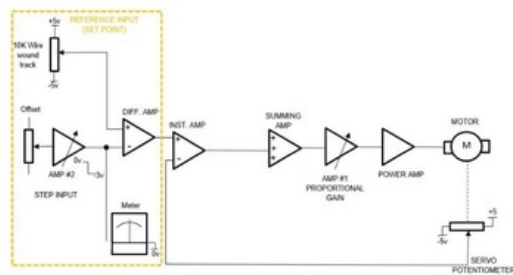


Fig. 2

### Proportional-Integral control

A Proportional-Integral (PI) controller requires the same system as previously but with the addition of Integral control using an Integrator (see Fig. 3 & 4). The integration can be added to the system with an input into the summing amplifier from the integrator. The integrator collects the errors (potential differences) from the instrumentation amplifier and calculates 'the sum of all the instantaneous values that the signal has been' [2] for the set duration period, it therefore jointly considers the history of error and works against the P controller to eliminate the steady state error. The integral is also multiplied by the error value and the P and I functions are added together to form the PI controller algorithm to tune the system further, eliminating offset, a common weakness of P only control. Control action is both determined by and proportional to the error, gain and the integral of the previous error signals.

Mathematically PI control is represented by:

$$A(t) = K_i \int_0^t e(t)dt + K_p e(t)$$

The integral of errors over time  $K_i$  multiplied by system gain  $e(t)$  is added to the Proportional gain  $K_p e(t)$ .

For this task the integrator adds the potential difference to the average sample for each loop of the process, this further progresses the output towards the desired set point at a faster rate. If sampling rates are set too high, previous error spikes can introduce unintentional responses of overshooting and oscillations. No derivative control is included in this system.

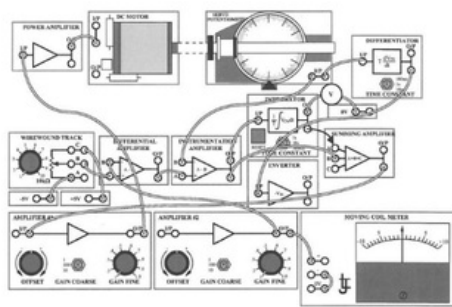


Fig. 3

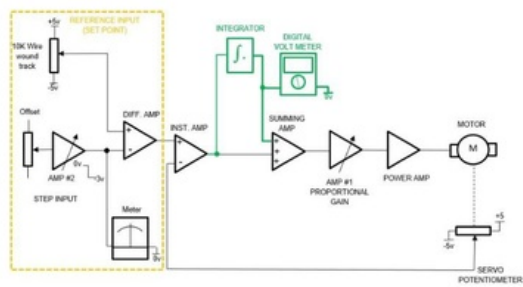


Fig. 4

### Proportional-Derivative control

Proportional-Derivative control was the same set up as the Proportional control system but with the addition of a Differentiator and inverter connected between the negative port of the instrumentation amplifier, the Servo Potentiometer and the summing amplifier (see Fig. 5 & 6). The differentiator has the effect of reducing overshoot by calculating and using the previous rate of change of the error signal to predict the future rate of change. This reduces and minimises the transient response of the output (deviation from steady set point state).

Mathematically PD is represented by;

$$A(t) = K_d \frac{de(t)}{dt} + K_p e(t)$$

Controller output  $A(t)$  is equal to the derivative gain,  $K_d$  multiplied against the rate of change in error, along with the addition of proportional control.

The inverter in the circuit inverts the differential value (to provide negative feedback) so that this differential error can be subtracted (by the addition of a negative value) from the process signal within the summing amplifier before it has any gain applied to it and sent to the plant (power amp) that powers the motor. This allows for the use of a higher gain and time constants, reducing the response time of the control system. A drawback is that any noise or disturbances [3] within the system can affect the algorithmic response and produce spikes in the control signal. No integral control is included in this system.

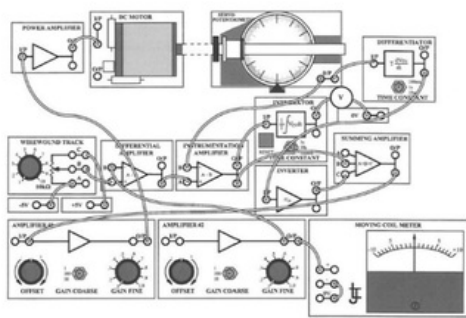


Fig.5

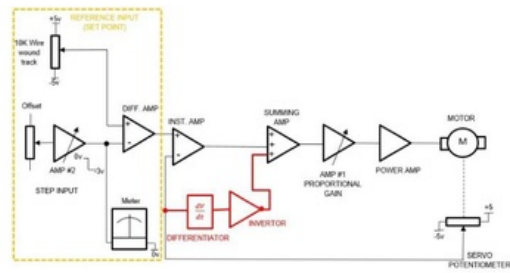


Fig.6

### Proportional-Integral-Derivative control

Full PID controller incorporates all three of the variable elements of proportional, integral and differential control. Combined it can form a well all-round controller (see Fig 7 & 8).

The output of control  $A(t)$  can be mathematically represented by;

$$A(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt}$$

$e$  = setpoint - Input

For the task, it required the basic proportional closed loop set up with the addition of the integrator and differentiator (and inverter) to be added to the summing amplifier so that all three elements could be implemented and used to counterbalance the weaknesses that each individually introduce to the control loop feedback system. However, the accuracy and reliability of this full system is still dependent on the noise level within the system.

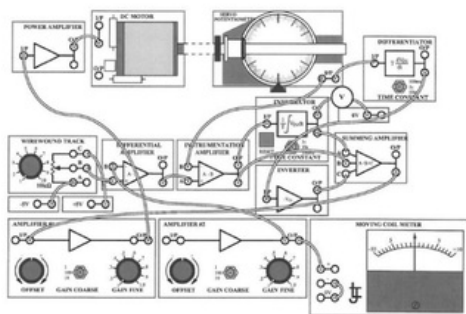


Fig.7

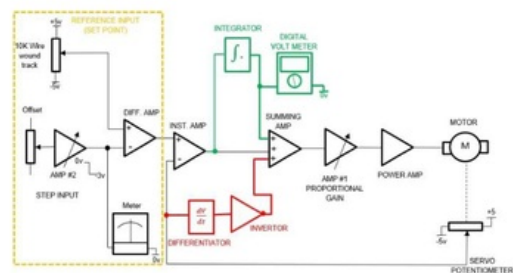


Fig.8

## Method

For this investigative task, the four individual control methods were created by forming the corresponding electrical circuits depending on the control method under investigation. Observations and recordings were made of the different combinations in order to understand how and why the amendments of the control construction can produce a variation in control system (motor) responses.

The procedure for the task corresponds to that set out in the IT02 Practical Control Systems Curriculum Manual, chapter 18 (pg. 18-322) document [1]. The step by step guide was logically followed to produce the previously given set ups and controller circuitry (see above) on the *LJ Create 1750 Transducer and Instrumentation Trainer*.

The first task was to create the basic set up of a P controller, followed by a PI controller, a PD controller and finally a PID controller. Each chosen element of the PID control will be connected using jump leads from the component to the summing amp in order to analyse the behaviour and effectiveness of the systems. The power supply to the motor was disconnected each time a new controller was set up.

## Apparatus

The following equipment was used for the experimental investigation;

- LJ Create 1750 Transducer and Instrumentation Trainer with built in:  
10k $\Omega$  wire wound resistor (variable potentiometer), Amplifier #1, Amplifier #2, Differential Amp, Instrumentation Amp, Integrator, Differentiator, Inverter, Summing Amp, Power Amp, DC motor, Servo-Potentiometer, Moving coil meter
- Digital Voltmeter
- Jumper leads

## Results

### **Task 1: P Controller**

With Amp #1 gain set to 1.0, rotation of the 10k $\Omega$  wire wound resistor (from central 0V position to full travel in both directions) produced the following full displacement on the Servo Potentiometer dial. (Table 1)

| Amplifier #1 Gain = 1.0     | Positive | Negative |
|-----------------------------|----------|----------|
| Maximum Dial Reading (deg.) | 140°     | 213°     |

Table 1

The results reflect a clear imbalance (of 7°) on the maximum range from 0V to 10V (140°) and 0V to 1V (213° - 360° = -147°)

It was also noted that when carrying out the same procedure but with a higher setting of gain control (5.0), the Servo-Potentiometer followed the input closely with the system having a prompter response.

With Amplifier #1 gain set to 5.0, rotation of the 10k $\Omega$  wire wound resistor from 1 to 10 (positively to full travel) produced the following displacement on the Servo Potentiometer dial (Table 2). Counter-clockwise movement (dial movement to the left of 0/360 $^{\circ}$  starting point) is denoted by a negative rotational value in degrees. Continuous rotation occurred on both procedures when the control was set to 1.

**Clockwise turning of wire wound resistor fully from 1 to 10**

| Control setting                         | 1                   | 2    | 3    | 4   | 5   | 0V    | 6  | 7  | 8   | 9   | 10  |
|-----------------------------------------|---------------------|------|------|-----|-----|-------|----|----|-----|-----|-----|
| Servo-Potentiometer Dial reading (deg.) | Continuous rotation | -155 | -115 | -72 | -30 | 0/360 | 12 | 58 | 103 | 148 | 165 |

Table 2

With amplifier #1 gain set to 5.0, rotation of the 10k $\Omega$  wire wound resistor from 10 to 1 (negatively to full travel) produced the following displacement on the Servo Potentiometer dial (Table 3).

**Counter-clockwise turning of wire wound resistor fully from 10 to 1**

| Control setting                         | 1                   | 2    | 3    | 4   | 5   | 0V    | 6 | 7  | 8  | 9   | 10  |
|-----------------------------------------|---------------------|------|------|-----|-----|-------|---|----|----|-----|-----|
| Servo-Potentiometer Dial reading (deg.) | Continuous rotation | -155 | -125 | -87 | -43 | 0/360 | 2 | 48 | 92 | 142 | 160 |

Table 3

The following is a graph comparing the two eventualities (results in degrees) of the clockwise and counter-clockwise turning of the wire wound resistor with a gain setting of 5. Hysteresis within the procedure displays the noticeable deadband of the P control system.

**A graph to show the Deadband of the control system  
(Clockwise Vs Counter-clockwise)**

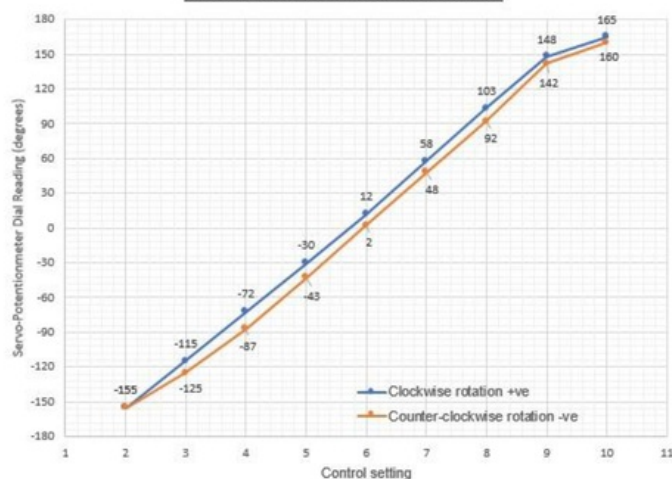


Table 4 below provides results of a deadband test and signifies the total range of which the dial of the Servo Potentiometer can be moved manually by hand without the system responding and moving the dial back to the original position. This was done by rotating the Hall effect disc and enabled observation of the systems deadband over which the system does not respond.

| Amplifier #1 Gain | $10 \times 1.0 = 10$ | $10 \times 0.5 = 5$ | $10 \times 0.1 = 1$ |
|-------------------|----------------------|---------------------|---------------------|
| Deadband (deg.)   | 8°                   | 15°                 | 80°                 |

Table 4

The range of degrees over which the dial could move without the system responding and correcting the disc back to its starting position was a varied response, depending on the Amplifier #1 gain setting. A Higher gain gave a smaller deadband, a lower gain gave a larger deadband.

To further observe the effect of gain on the response of this system, Amp # 2 was used (-3V) to provide a stepped input and Amp #1 was used to provide a variation of gain settings (1.0, 5.0, and 10.0). The effect of gain on the response to a stepped input was that the speed of the response was greatest with high gain and that the overshoot was greatest with high gain. When the Proportional control system is set to have a low gain in the feedback loop, it will have a large deadband and an overdamped response to a step input (The motor was completely stopped from rotating).

#### **Task 2: PI Controller**

With the addition of an Integrator to the Proportional system to form a PI controller with time constant set to 1s, it was noted that when applying a 3V stepped input by switching the Amp #2 gain coarse to 100 (on) and then back to 1 (off), the effect on the Servo-Potentiometer and the Integrator voltage reading on the digital voltmeter varied depending on the gain settings selected (either, 1.0, 5.0 or 10.0).

With a gain of 1, the Integrator output voltage displayed on the voltmeter (across the motor) continued to vary even after two minutes and the Servo-Potentiometer dial reading moved rapidly towards the target, overshoot then returned. With the Amp #1 gain set to 5, when compared to a gain of 1, the effect on speed of response was faster and there was continuous oscillation of the dial. With the Amp #1 gain set to 10, when compared to a gain of 5, the effect on speed of response was about the same and the dial again oscillated continuously.

Carrying out the procedure two more times with the integrator time constant set to 10s and then again at 100ms it was noted that the time constant setting of 10s produced the smallest number of overshoots.

Using a time constant of 100ms and Amp #1 gain set to 5.0, it was noted that the effect of manually displacing the output from its stable position by moving the Hall effect disc around 10° on the dial and then releasing it, produced a build up to continuous running of the motor.

### Task 3: PD Controller

With the gain of Amp #1 set to 1, the following results were observed for a 3V stepped input (from Amp #2) when the differentiators time constant was varied between 1s, 10ms and 100ms; The Servo-Potentiometer dial reading did not return to zero setting (original position) after the step input had been applied in both directions. When the differentiator time constant was set to 10ms, the effect of manually moving the output from its stable position (using the Hall effect disc) by about a quarter of a turn, the PD control system had no tendency to re-adjust and correct the error. The derivative control only affects the response during change of output. Increasing the time constant of the differentiator increased the damping effect.

### Task 4: PID Controller

With the addition of all three P, I and D control elements to form a PID controller, the effect of applying a 3V step input to the system with all variations of Integrator and Differentiator time constants was observed and noted in the following table (Table 5).

| Test | Integrator time constant | Differentiator time constant | Continuous running YES/NO | Response time SLOW/MEDIUM/FAST | Number of Oscillations |
|------|--------------------------|------------------------------|---------------------------|--------------------------------|------------------------|
| 1    | 10s                      | 1s                           | No                        | Slow                           | 0 (vibrating)          |
| 2    |                          | 100s                         | No                        | Medium                         | 0                      |
| 3    |                          | 10ms                         | No                        | Fast                           | 2                      |
| 4    | 1s                       | 1s                           | No                        | Slow                           | 1                      |
| 5    |                          | 100s                         | No                        | Medium                         | 1                      |
| 6    |                          | 10ms                         | No                        | Fast                           | 2                      |
| 7    | 100ms                    | 1s                           | No                        | Slow                           | 6                      |
| 8    |                          | 100s                         | No                        | Fast                           | 1                      |
| 9    |                          | 10ms                         | YES                       | Fast                           | 0                      |

Table 5

It was noted that the combination giving the optimum response (with a smallest overshoot) was Test 8 (100ms integrator time constant, 100s differentiator time constant, no continuous running with a fast response time and only 1 oscillation). The most desirable characteristic for a positional control system is a ***fast response time with no oscillations***.

## **Discussion**

By analysing the results of the investigation, it was possible to define the characteristics and behaviours of the various control methods. Completing the clockwise and counter-clockwise full range test of the wire wound resistor during the P controller set up enabled us to identify that it is the gain that allows the system to be tuned and that the higher the gain is set, the smaller the deadband within the system, lesser overshooting and faster the response time between command input and motor response. With a lower gain setting, the output of the system had a slower overdamped response and sluggishly followed the command input and the Servo-Potentiometer, often failing to return to the starting position.

The deadband was also increased with lower gain, which could result in the loss of small (increments of) input signal. From the Table 4 it can be seen that an increase in system gain successfully reduces the deadband of the P controller by 90%.

Addition of the Integrator introduced an improvement to the system response time (faster) but the disadvantage is, more overshooting occurred. Alternatively introducing a Derivative to the system instead, resulted in the output (dial) failing to return back to the original zero position due the system only affecting the response when a change in the output itself occurs.

When all three methods are combined into a PID controller, it was evident that the system can be selectively tuned through amendment of the integral and derivative time constant parameters, depending on the requirements of the process. Results of Test 2 (Table 5) prove that the best settings for this PID system are an Integrator with time constant of 10s and a differentiator with time constant 100ms. This enabled a medium response time with no oscillations. The fastest response time is ideal but 1 oscillation occurred as a result of this setting. It is undesirably possible that with certain settings (Test 9) that the motor continuously runs uncontrollably.

## **Conclusion**

Concluding the results of the investigation, found that for the positional control of the motor, the PID control system was the best suited method for the role, with an Integrator time constant setting of 10s and Differentiator time constant setting of 100ms. The PID controller can be tuned and implemented with suitable characteristics such that the ideal response time is produced with no oscillations present, providing suitable stability.

The advantages of Proportional control are that it helps stabilise a system by reducing the steady state error, where the input control signal that is sent to the plant to actuate the process of proportional gain is directly related to the speed and value of the output fed back into the error detector at the start of the system. The error is the difference between the set point value and the sensed value fed back in from the output of the process. The system's deadband can be reduced by increasing the gain. The disadvantages of this method are that there is noticeable offset and overshooting still occurs.

Proportional-Integral control has an even faster control response (than P) but more overshooting occurs. Overshooting can be reduced by increasing the integrals time constant but this impacts the response time of the system.

Proportional-Derivative control is usually only used in combination with other control methods for support due to the introduction of its own disadvantages. PD only comes into action when there is a change in the output and there is noticeable offset within the system control. It can be used to introduce damping by increasing the derivatives time constant, of which is useful for underdamped systems.

The full PID system takes the advantages of all three methods of control and enables full tuning of the process by amending the integral and derivative time constants to suit the tolerances of control. This can result in the system having an ideal damping effect and response time. However, if the time constants are not of the correct rate, an unstable system can occur. This method proved that the motor can be quickly controlled without overshooting.

The task itself went well, having used reliable equipment, the results and conclusion matched that of existing literature found during initial background research on controllers [4].

## References

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# Instrumentation and Control Assignment 2

## GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

**Instructor**

62/100

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PAGE 2

PAGE 3

PAGE 4



### Comment 1

Your abstract should also include a brief statement of your results. "It was found that the proportional controller gave more overshoot and a faster response when the gain was higher..." etc.

PAGE 5



### Comment 2

Set point voltage comes from the wire wound track. The process variable is the angle of the servo pot

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GRADING FORM: SMU GENERIC\_GJ

**RALPH WHITTAKER****61.60****RESEARCH-INFORMED LITERATURE**

Inclusion of a range of research-informed literature, including sources retrieved independently. Referencing conventions mostly consistently applied.

**13.75****KNOWLEDGE AND UNDERSTANDING**

Knowledge is extensive. Exhibits understanding of the breadth and depth of established views.

**18.6****ANALYSIS**

Sound, logical, analytical thinking; synthesis and evaluation. Ability to devise and sustain persuasive arguments, and to review the reliability, validity & significance of evidence. Ability to communicate ideas and evidence accurately and convincingly. Sound, convincing conclusions

**19.5****PRACTICAL APPLICATION AND DEP.**

A very good application of a range of methods,

**6.5**

materials, tools and/or techniques. Very good consideration of the context of the application.

#### SKILLS FOR PROFESSIONAL PRAC.



Can communicate well, confidently and consistently in a suitable format. Work is coherent and fluent and is well structured and organised.

**3.25**