Manual Tuning of a Discrete-Time PID Controller

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1.0 Learning Outcomes

After studying this ACE-Lab learning guide, you should be able to demonstrate the Learning Outcomes listed in Table 1. On completion of the ACE-Lab learning guide, revisit Table 1 and confirm whether each Learning Outcome has been achieved.

Table 1: *Learning Outcomes from the Manual Tuning of a Discrete-Time PID Controller Learning Guide*

ID	Learning Outcome	Achieved
	Explain how proportional, integral and derivative gains influence the measured system response during manual tuning.	☐
	Describe a systematic approach for manually tuning a discrete-time PID controller using measured responses.	☐
	Explain how selected controller gains can be evaluated against engineering requirements and how the benefit of derivative action can be assessed.	☐

2.0 Introduction

Manual PID tuning uses the measured response of the physical system to progressively select suitable values of K_P, K_I and, where required, K_D. The objective is not simply to adjust the controller gains, but to use measured evidence to identify settings that satisfy the defined system requirements.

The operation and discrete-time implementation of proportional, integral and derivative control are introduced in the *Discrete-Time PID Control* Learning Guide. Practical considerations, including sampling, measurement filtering, actuator saturation, anti-windup and derivative implementation are covered in the *Practical Considerations for PID Control* Learning Guide. These concepts are therefore not repeated here.

The figures in this learning guide provide illustrative examples of how controller gains can influence the system response and actuator command. The gain

values shown are specific to these examples. Suitable gains for a particular physical system should be established using its measured responses and evaluated against the defined engineering requirements.

3.0 Manual PID Tuning

A typical manual PID tuning process can be represented as:

define the requirements → prepare a repeatable test → tune P → add I → assess D → refine → evaluate against the requirements.

3.1 Define the Requirements

Before selecting the controller gains, define the requirements that the system must achieve. These should be measurable so that different controller settings can be compared consistently. Table 2 summarises the performance measures and limits that should be defined before tuning. These requirements provide the basis for evaluating the effect of each gain adjustment and, ultimately, determining whether the tuned controller provides acceptable performance.

Figure 1 illustrates the measures used to assess a response to a change in reference. Rise time describes the time taken for the output to move between 10% and 90% of the requested change, while overshoot describes the peak excursion above the reference. Settling time measures how long the output takes to enter and remain within the specified tolerance band. The steady-state error is estimated by averaging the tracking error over the final measurement interval, once the transient response has subsided. The lower plot shows the applied actuator command, allowing response performance to be assessed alongside actuator demand and saturation.

Table 2*: Requirements to Define Before Manual Tuning*

Requirement	Define before testing
Rise time	Required limit and convention, for example 10 - 90% of the commanded change.
Overshoot	Permitted peak above the reference.
Settling time	Required settling-time limit and settling band.
Steady-state error	Permitted error, units and final averaging interval.
Control effort	Actuator limits; acceptable saturation and control-signal variation; relevant current limits.

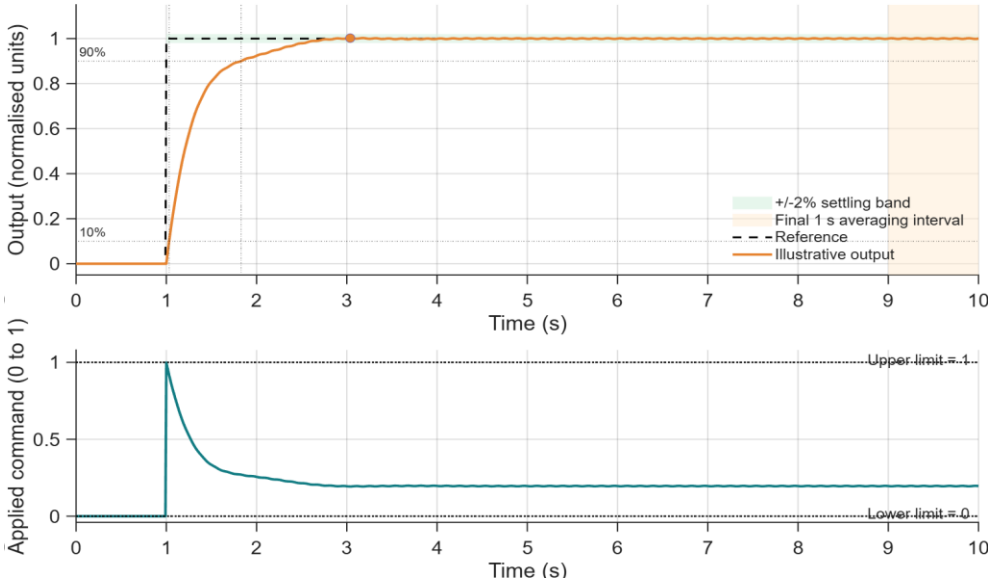


Figure 1*: Performance Measures Used to Assess the Controller Response*

3.2 Prepare a Repeatable Test

Manual tuning relies on comparing measured responses obtained using different controller gains. For these comparisons to be meaningful, the test conditions should remain consistent between trials.

Factors such as the setpoint change, starting condition, load and supply conditions should therefore remain unchanged wherever possible. Similarly, the sampling interval, T_s, measurement filtering, signal scaling and actuator limits should normally remain fixed while controller gains are being compared.

The reference, measured output and applied control signal provide the principal signals for evaluating each response. The control error and individual proportional, integral and derivative contributions may also provide useful information when interpreting controller behaviour.

3.3 Tuning Proportional Action

Manual tuning commonly begins with proportional action while the integral and derivative gains are set to zero. This allows the influence of the proportional gain, K_P, to be considered independently before the other controller terms are introduced.

Increasing K_P generally strengthens the controller response to the current error. This can produce a faster response, but an excessively large proportional gain may also result in increased overshoot, oscillation or unacceptable actuator activity. Conversely, a very small proportional gain may produce a slow response and leave a significant steady-state error. These general effects of proportional action are introduced in the Discrete-Time PID Control learning guide.

The purpose of proportional tuning is therefore to identify a gain that provides a responsive but well-behaved baseline from which integral action can subsequently be introduced. A steady-state error may remain when proportional control is used alone. Rather than continuing to increase K_P solely to reduce this error, integral action can subsequently be introduced.

Table 3 summarises typical changes in the measured response that may be observed when adjusting K_P. Figure 2 compares illustrative responses obtained with different proportional gains. The low-gain example responds slowly and retains a substantial steady-state error. The baseline example approaches the reference more quickly and reduces the remaining error. The excessive-gain example exhibits overshoot, oscillation and greater variation in the actuator command, including periods at its limits. These comparisons illustrate the balance between responsiveness and acceptable actuator behaviour. A suitable proportional gain should establish a controlled baseline response; any remaining steady-state error can then be addressed by introducing integral action.

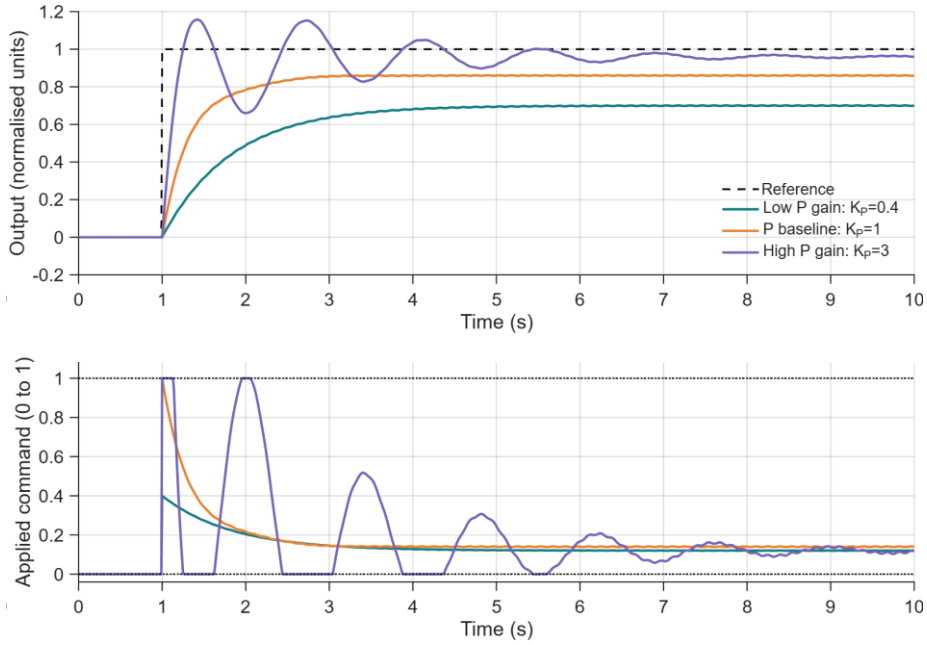


Figure 2*: Comparing Responses for Different Proportional Gains*

Table 3*: Typical Effects when Adjusting K_P*

Observed behaviour	Possible interpretation
Response remains slow	K_P may be too small, provided sufficient actuator authority is available.
Response becomes faster with acceptable overshoot	The change in K_P may be beneficial.
Overshoot or oscillation increases significantly	K_P may be too large.
Steady-state error remains	Integral action may be required.
Disturbance recovery	Permitted recovery time after a defined disturbance, together with the required tolerance band.
Actuator remains at its limit	Increasing K_P further is unlikely to improve the achievable response.

3.4 Tuning Integral Action

Integral action is typically introduced after a satisfactory proportional response has been established. Its principal role during manual tuning is to reduce or eliminate persistent steady-state error.

As K_I is increased, steady-state error can generally be removed more rapidly. However, excessive integral action may increase overshoot, increase settling time or introduce slow oscillation. The accumulated nature of integral action and its contribution to removing steady-state error are covered in the Discrete-Time PID Control learning guide.

Integral tuning therefore involves balancing improved steady-state accuracy against the resulting transient response.

Table 4 summarises typical changes in the measured response that may be observed when adjusting K_I. Figure 3 compares proportional control with two levels of integral action. The proportional-only example retains a positive tracking error, whereas the PI examples approach the reference and reduce the final error towards zero. The balanced integral setting achieves this with little overshoot. The larger integral setting produces greater overshoot and oscillation before settling. In the lower plot, a negative error indicates that the output has exceeded the reference. The comparison demonstrates why integral gain should be assessed using the complete transient response and actuator command, rather than final accuracy alone.

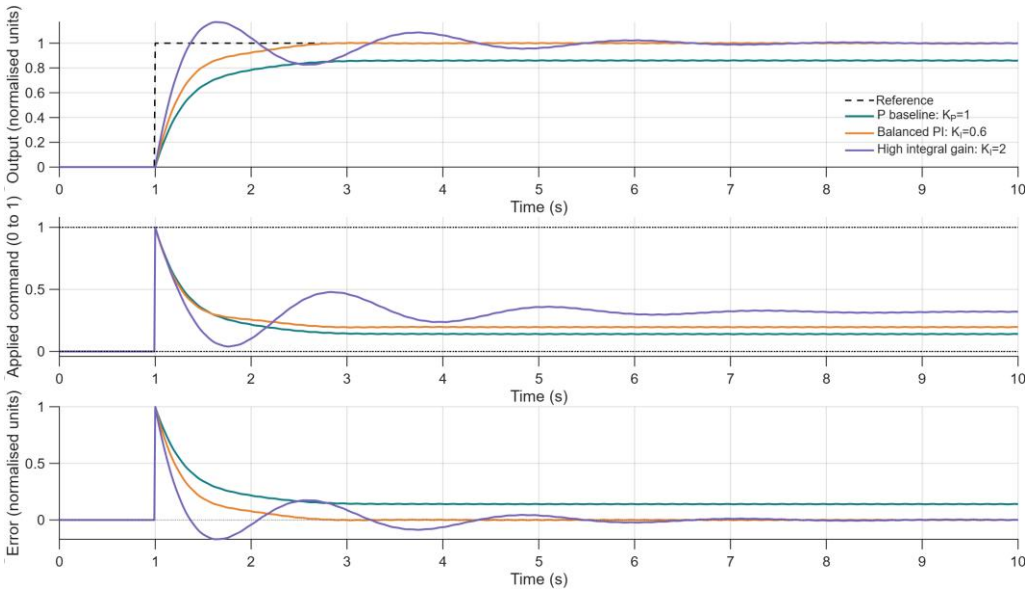


Figure 3*: Effect of Integral Action on Tracking Error and Transient Response*

Table 4*: Typical Effects when Adjusting* K_I

Observed behaviour	Possible interpretation
Steady-state error reduces slowly	A larger K_I may improve error removal.
Steady-state error is removed with acceptable transient behaviour	The integral gain may be suitable.
Overshoot increases substantially	K_I may be too large.
Slow oscillation develops	Integral action may be too aggressive.
Error remains while the actuator is saturated	The limitation may be physical rather than a lack of integral gain.

Actuator saturation is particularly important when integral action is present because it can lead to integral windup. Anti-windup and actuator limits are considered separately in the *Practical Considerations for PID Control* learning guide and should be accounted for when interpreting tuning results.

The proportional and integral gains should therefore be considered together. Introducing integral action may reveal that the previously selected proportional gain also requires some refinement.

3.5 Tuning Derivative Action

Derivative action is not required in every control application. It is generally considered after a suitable PI response has been obtained and where additional damping or a reduction in overshoot would be beneficial.

Increasing K_D can provide additional damping as the system approaches the reference, which may reduce overshoot and oscillatory behaviour. However, excessive derivative action can make the control signal sensitive to rapid measurement changes and measurement noise.

The purpose of derivative tuning is therefore to determine whether the addition of derivative action provides a measurable improvement over the PI controller.

Table 5 summarises some of the response characteristics that can be used to assess whether derivative action provides a useful benefit. Figure 4 compares a PI baseline with moderate and excessive derivative action. All three examples approach the reference, but the derivative cases have slower initial responses and provide little visible improvement in overshoot because the PI baseline already has a well-controlled response. The actuator-command plots reveal increasing variation as derivative action becomes stronger, particularly in the enlarged time interval. This example illustrates the need to establish a measurable benefit before retaining derivative action. Where PI control already satisfies the requirements, additional derivative action may introduce actuator activity without a worthwhile improvement in output performance.

Measurement filtering and derivative kick should also be considered when derivative action is used. These practical issues are covered in the *Practical Considerations for PID Control* learning guide.

A three-term PID controller does not require all three gains to be non-zero. If a PI controller provides the required performance without the additional sensitivity

associated with derivative action, retaining $K_D = 0$ may be the preferable solution.

Table 5: *Assessing the Effect of Derivative Action*

Observed behaviour	Possible interpretation
Overshoot or oscillation is reduced	Derivative action may be providing useful damping.
Settling behaviour improves	K_D may be beneficial.
Actuator command becomes noisy	K_D may be too large or measurement noise may be significant.
Little change in the system response	Derivative action may provide limited benefit.
PI control already satisfies the requirements	Derivative action may not be necessary.

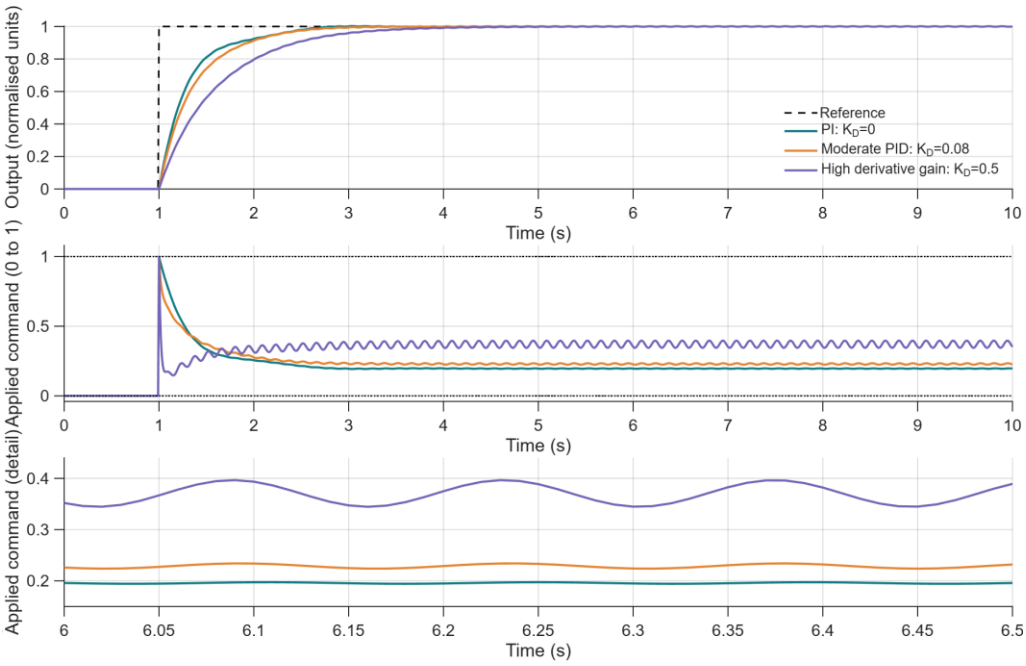


Figure 4: *Comparing PI and PID Responses and Actuator Command Variation*

3.6 Refining the Controller Gains

Although proportional, integral and derivative actions can initially be considered separately during manual tuning, their effects interact when combined within the closed-loop system. Changing one gain can influence several characteristics of the response, including rise time, overshoot, settling behaviour, steady-state error and actuator effort.
Once suitable initial values have been established, the complete controller can therefore be refined using small changes to the gains. During refinement, one gain should normally be adjusted at a time, with the gain values and resulting performance recorded for each trial.

Figure 5 compares three candidate controller settings against six performance criteria. Both the bar heights and numerical labels represent each performance value divided by its acceptance limit. A ratio at or below one satisfies that requirement. All three settings meet the limits shown. The refined PID example has the shortest rise time, while the PI example has the lowest command activity. The comparison illustrates why the final gain selection should consider the balance between response speed, accuracy and actuator behaviour, rather than a single measure.

Command activity is the sum of the absolute changes in the applied actuator command over the test record. The “at limits” measure is the percentage of post-step command samples at an actuator limit. These measures help compare actuator behaviour alongside the output response.

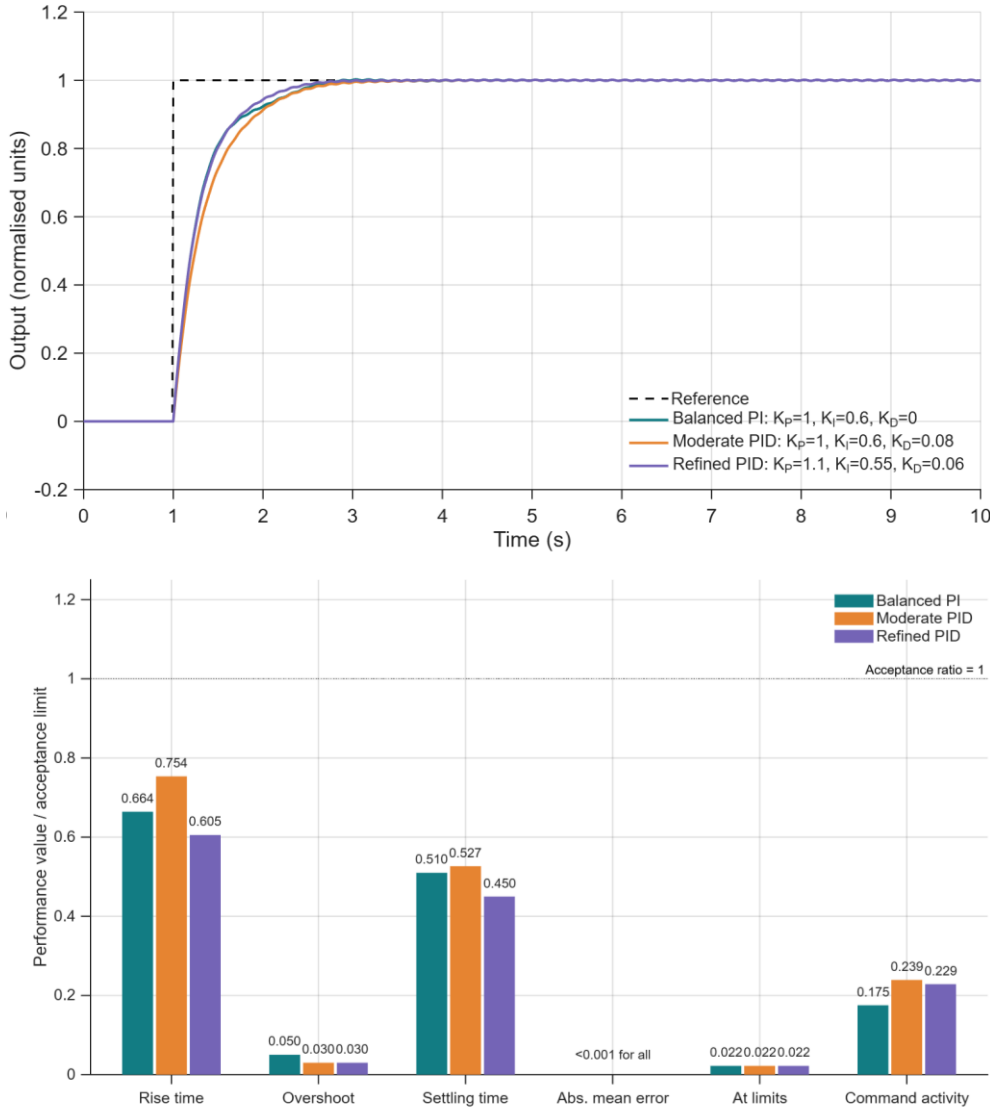


Figure 5*: Comparing Controller Settings Against Performance Requirements*

Table 6 summarises some of the measured behaviours that may guide further refinement of the controller gains.

Table 6*: Measured Behaviours and Possible Tuning Considerations*

Measured behaviour	Possible tuning consideration
Response is too slow	Consider increasing K_P, provided actuator authority remains available.
Steady-state error disappears too slowly	Consider increasing K_I.
Overshoot is excessive	Consider reducing K_I or K_P, or assessing whether derivative action provides useful damping.
Repeated oscillation occurs	The controller gains may be too aggressive, although sampling, filtering and delays should also be considered.
Control signal is excessively noisy	Consider the derivative gain, measurement quality and filtering.

Performance varies significantly with operating conditions	A single set of gains may not provide the required performance across the complete operating range.

The effect of each change should be assessed against the complete response rather than a single performance measure. An improvement in rise time, for example, may not be worthwhile if it produces excessive overshoot or prolonged actuator saturation.

Manual tuning is therefore an iterative process in which the controller gains are progressively refined until an acceptable balance between the different performance requirements is obtained.

3.7 Evaluating the Tuned Controller

The final stage of manual tuning is to evaluate whether the selected controller gains satisfy the original system requirements. This closes the tuning process by returning to the performance measures and operating conditions defined at the outset.

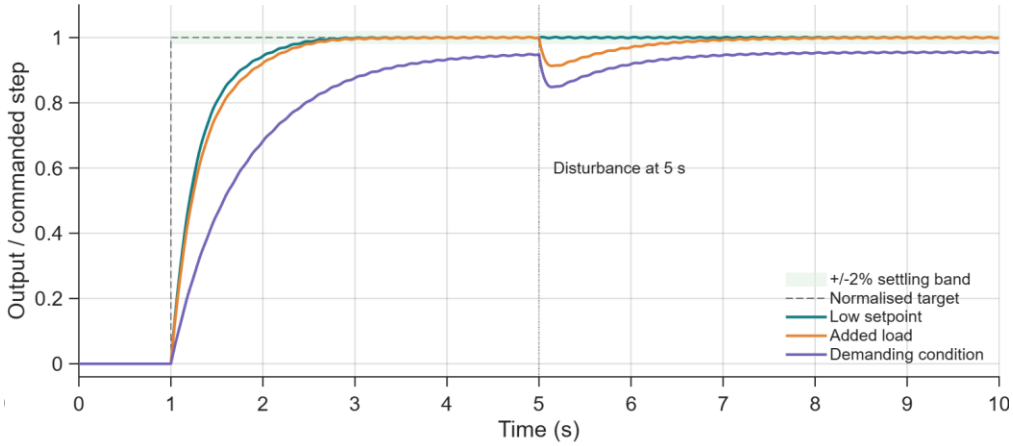
Evaluation should consider both the measured system response and the associated control signal. Meeting a rise-time or steady-state-error requirement, for example, may not represent satisfactory performance if it is accompanied by excessive overshoot, prolonged actuator saturation or an unnecessarily variable control signal.

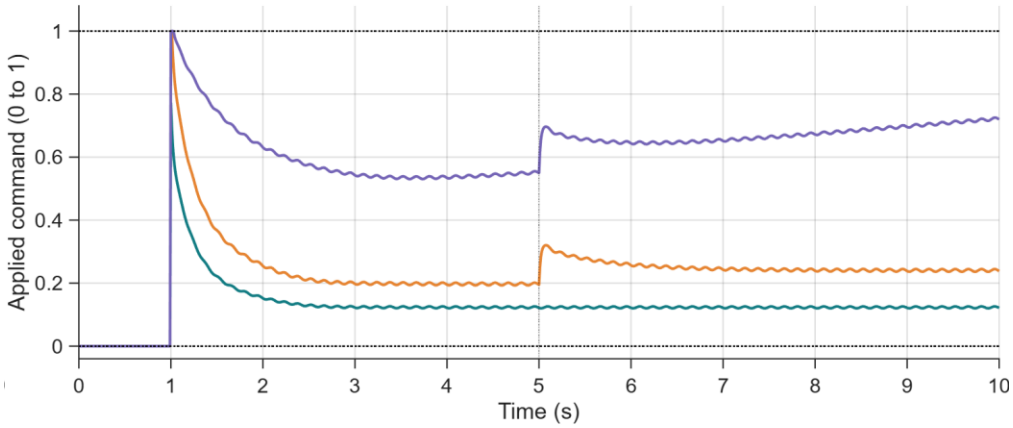
The selected gains should also be evaluated across the required operating conditions. A controller that performs satisfactorily for one setpoint or load may not necessarily provide the same performance elsewhere within the required operating range.

Practical verification, including actuator saturation, integral behaviour and control-signal activity, is discussed further in the *Practical Considerations for PID Control* learning guide.

A manual tuning process can be considered complete when measured evidence demonstrates that the selected controller provides acceptable performance against the defined engineering requirements.

Figure 6 compares the selected controller across different operating conditions. The low-setpoint example meets the stated requirements. The added-load example meets the initial response requirements, but its disturbance recovery time of 1.29s exceeds the one-second limit. The demanding-condition example fails the rise-time, initial-settling, final-error and disturbance-recovery requirements, while requiring a larger sustained actuator command. The output is normalised so that one represents the target for each trial. These comparisons demonstrate that acceptable performance under one operating condition does not establish acceptable performance across the full operating range.





Low setpoint: PASS | All displayed requirements met

Rise: 0.73 s | Initial settling: 1.35 s

Disturbance recovery: N/A (no disturbance) | Mean final error: <0.01% in magnitude of step

Added load: FAIL | disturbance recovery

Rise: 0.85 s | Initial settling: 1.48 s

Disturbance recovery: 1.29 s | Mean final error: +0.02% of step

Demanding condition: FAIL | rise time, initial settling, final mean error, disturbance recovery

Rise: 2.20 s | Initial settling: Not settled before disturbance

Disturbance recovery: Not settled within record | Mean final error: +4.53% of step

Limits: rise <=1.2 s; overshoot <=5%; initial settling <=3 s; |mean error| <=2% of step.

Recovery <=1.0 s after disturbance; at limits <=5%; command activity <=12 over 0-10 s.

Figure 6*: Evaluating Controller Performance Across Operating Conditions*

4.0 Summary

Manual tuning of a discrete-time PID controller is an iterative process of adjustment, measurement and evaluation. Proportional action can first be used to establish a suitable baseline response, after which integral action can be introduced to address persistent steady-state error. Derivative action may then be considered where additional damping provides a measurable benefit.

The complete controller can subsequently be refined through small changes to the gains, with each adjustment evaluated against the engineering requirements. The final gain selection should be supported by measured evidence across the required operating conditions and should consider both system performance and actuator behaviour.

Return to the Learning Outcomes in Table 1 and consider whether you can now confidently demonstrate each one.

Recommended Citation

If you have used this learning guide in your teaching, learning or research, please cite it using the reference below, adapting the format as required by your preferred referencing style.

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