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| PID: AUTONOMOUS CONTROL  **Year 13 Computer science project**  **LUKE WALTON** | |

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# Requirements Analysis

## Introduction of project/scope

PID is a closed feedback loop using Proportional, Integral, and Derivative calculation, designed to meet a numerical goal without overshooting. This is often used in automatic systems, for high speed and accuracy.

Some terms that I will be using and are important to understand for this are:

* Set Point – The desired numerical value to be reached
* Process Value – The current numerical value, read in by a sensor
* Error – The difference between the Set Point and Process Value
* Output – The calculated PID output, often an acceleration
* kP, kI, kD – The constants used in each individual calculation

I intend to build a teaching tool able of demonstrating mathematical principles, like Integration and Derivation, in a fun and interesting way for the students to see. I think to be able to see calculations being ran and used in real time will really help them develop an interest in what’s happening behind the screen, boosting their focus, and hopefully helping them remember and recall what they are learning.

Alternately, the PID module could be separated and used for robotics, such as autonomous control systems. I’ll get onto more examples of this later. The PID algorithm itself is usable in any given context, that can be broken down to a numerical goal, and acceleration, provided it is tuned correctly via the passed in parameters, like P, I and D constants, or clamping and scaling values.

## Identification of problem

Imagine a thermostat. When you set it to a particular temperature, you want it to reach that exact point quickly and accurately. Behind the screen there will be a PID module controlling the heating, turning it up and down perfectly so that it reaches the set temperature, without overshooting. If the thermostat fully applied the heating until it reached the correct temperature, and then turns off, the room will continue heating up for a bit afterwards still, as the signal to turn off will not happen instantly. And then after this, it will only slowly cool down again, so some extra control is necessary, including shutting off before the point is reached.

This is where PID comes in. There’ll be a PID model reading the Process Value from the temperature sensor and giving its output to control the heating. Now imagine those exact same principles but controlling a servo or piston to reach a distance or angle, and now you have a robotic arm, picking up a can of cat food off a conveyor belt, sorting it, and putting it onto another belt or box.

## Identification of the prospective user(s)

Usable in maths for demonstrating the uses of Proportional, Integral and Derivative relationships, Maths teachers and students alike could use and benefit from this tool, being able to see the process that must be done, then watching how the calculations work, what they do for the system, and being able to influence it themselves.

However, it is also applicable to Mechanics in Maths and Physics as the models demonstrate a physical autonomous system moving and compensating for momentum and air resistance. The models representing these systems - keeping a rocket upright, or automatically driving a car - would be very helpful to study how the system compensates for these outside factors that the students will be studying.

When put into a program, it becomes open to Computer Science students and teachers, demonstrating autonomous systems and feedback loops. The PID module itself being useful in robotics, which has strong ties to computer science, but also the programming principles demonstrated by using the one module in multiple front-end models.

## Interview with Sponsor

The purpose of an interview with the sponsor is to determine the [User Needs](#_User_Needs), which will be used to establish [Requirements and Limitations](#_Requirements_and_Limitations) and then [SMART Objectives](#_Objectives_(SMART)) to aim for throughout production.

|  |  |
| --- | --- |
| **Question** | **Purpose** |
| What teaching methods are currently used for teaching Maths, Physics and Computer Science? | The point of this question is to learn more about the current options that can be replaced by this project. |
| How engaged with the lesson do you find students using these teaching methods? | This question helps us know more about the current teaching methods, to see what needs changing more |
| Do you think having an interactive tool demonstrating the taught principles would help? | This gets a teachers opinion on how much this tool will help with engagement and recollection. |
| What do you want to get out of the program? | This and the next one help form the [User Needs](#_User_Needs) and [Requirements And Limitations](#_Requirements_and_Limitations) |
| What limits will you have for running it? |  |

## Sponsor Interview – Mr Maher

**Me:** What teaching methods are currently used for teaching Maths, Physics and Computer Science?

***Mr Maher:***Often I will put a PowerPoint up on the board, talking through it and answering anyone’s questions. Later I’d provide worksheets for the students to try, and occasionally put a video on the board.

**Me:** How engaged with the lesson do you find students using these teaching methods?

***Mr Maher:*** Often students will ask a lot of questions that either I or the PowerPoint have already gone over, so they clearly either don’t take in the information, or they stop paying attention. I’d say overall there’s about 5-10% of students not paying attention in a lesson.

**Me:** Do you think having an interactive tool demonstrating the taught principles would help?

***Mr Maher:*** Absolutely, just a video alone helps grab their attention, and often the taught principles stay in their mind better, so a program that they can interact with and see how it reacts would likely help a lot.

**Me:** What do you want to get out of the program?

***Mr Maher:*** I want my students to be able to interact with the program, see how that interaction is affecting it, and see what is happening in the background. Most importantly I want it to hold their attention, but still actually teach them.

**Me:** What limits will you have for running it?

***Mr Maher:*** It will likely be running on school computers or laptops, so it can’t require extremely heavy processing power. Ideally, we’d also have it ready for next year’s students, or even by this year’s revision period.

In conclusion, the program should hold the user’s attention, so that they aren’t bored, but not to a level they just aren’t learning. It should be interactable to properly demonstrate the principles being used, be quick and light to run so that it will be able to run on school laptops and computers and be ready for this year’s revision period.

## Research into current or alternate methods

### PowerPoints

All three subjects are currently taught by putting a PowerPoint on the board, and the teacher talking through it. This is often boring, as it will just be a block of text or a single image for either the student or teacher to read and will lead to the students stopping paying attention and not learning what is being taught.

PowerPoints can be helpful for demonstrating some things in diagrams or small animations, and often these are projected onto white boards, so the teacher can easily annotate it, describing processes in more detail if required.

This could couple well with my project, as the teacher can teach the principles and then demonstrate them easily by either projecting the program, or having students run it and interact with it themselves. If projected, the teacher will be able to control the process, demonstrating the processes in the best way possible, before letting the class get on with the program themselves, using their curiosity to fuel their learning.

### Worksheets

Worksheets are good checkpoint tests to see if a student understands what they’ve been taught, however if they don’t understand it, often the worksheet does nothing to help them learn what they need to know. They are forced to ask either another student or the teacher for help. This often leads to many students not learning, as they are too afraid to ask for help, as they think it will reflect a poor image onto them.

Due to this last point, the project would work well with this method, as they would not need to ask another person for help, they can simply run the program and see what it is doing, and hopefully learn from it. This cuts out the fear of being judged, even if they likely wouldn’t be in the classroom environment anyway.

### OneNote Work

Using OneNote, the teacher is able to send out pages of work and the lesson PowerPoints to the students. This means that it is a lot easier for students to individually take notes or look back at the slides while doing the work, as they can do this themselves rather than getting the teacher to do it and stalling the entire class.

This will also work well combined with the program, as it can be put onto a page and distributed so that the students can run it on their devices, and interact with it themselves, once again rather than every student interfacing with it through the teacher projecting it once onto the screen.

## Interview end users

The purpose of an interview with end users is to get the flaws of the current system and how we can increase the student’s engagement from the students’ point of view

|  |  |
| --- | --- |
| **Question** | **Purpose** |
| How easily did you learn Differentiation and Integration? | Identify the students’ ability with standard methods, how much could they have improved with this project? |
| Did you find yourself engaged with the lessons? | See if they were engaged from their point of view, was it possible for them to me more engaged? |
| Do you think an interactive tool, demonstrating these principles and uses, would help with engagement? | This gets the students’ opinion on how much this tool will help with engagement |
| Do you think said tool would help with remembering the methods? | This gets the students’ opinion on how much this tool will help with recollection |
| What kind of computer system do you have at home, if any? OS and power wise | This helps establish the [Limitations](#_Requirements_and_Limitations) of the project, as it will have to run on every students devices. |

### End User Interview 1 – Alex E

**Me:** How easily did you learn Differentiation and Integration?

***Alex:*** I learnt it just fine, it made logical sense and after some worksheets, it stuck well in my mind.

**Me:** Did you find yourself engaged with the lessons?

***Alex:*** No, they were often very boring, with a lot of reiterating the same thing that I learnt quickly. After a weeks’ worth of worksheets, more worksheets don’t help anymore.

**Me:** Do you think an interactive tool, demonstrating these principles and uses, would help with engagement?

***Alex:*** Massively. Any interactive tool that I can play around with, and see how it reacts, especially with feedback of what is happening inside, would deeply benefit my learning.

**Me:** Do you think said tool would help with remembering the methods?

***Alex:*** Same as above, I will more easily recall something if I enjoyed learning it, or an experience closely tied to something, as it will be more stuck within my memory. I feel an interactive tool would massively help.

**Me:** What kind of computer system do you have at home, if any? OS and power wise

***Alex:*** I have a moderately powerful gaming PC, running windows 11 currently.

From Alex’s point of view, it isn’t a necessary tool as he was fairly strong anyway, however it would strongly benefit his attention to the lesson and possibly help him catch something he might have missed. There is not a low barrier for computer power, for Alex, but he is a perfect example of why this should be done by the start of the next school year.

### End User Interview 2 – Jakub W

**Me:** How easily did you learn Differentiation and Integration?

***Jakub:*** I was quick at understanding what each one did, like finding area or gradient, but it took me a lot longer to understand how to do it myself. I found myself often mixing up which one to add or subtract the power, or multiply or divide by etc.

**Me:** Did you find yourself engaged with the lessons?

***Jakub:*** Maybe the first lesson on each, but after that it was just many worksheets, trying to figure out what to do for each as I went through them. This meant I was often losing focus, not having the mental effort to push over this hurdle.

**Me:** Do you think an interactive tool, demonstrating these principles and uses, would help with engagement?

***Jakub:*** Probably yes, it would be a lot less boring than just working through worksheets, yet I probably wouldn’t just mess around with the tool, I’d actively try to learn.

**Me:** Do you think said tool would help with remembering the methods?

***Jakub:*** It would depend on how well the program demonstrates it. If it was just hidden in the code and I had to scour through to find it, then no, but if there was an easily accessible explanation and demonstration, then it would help a lot, it would be a lot more memorable than text on a whiteboard.

**Me:** What kind of computer system do you have at home, if any? OS and power wise

***Jakub:*** I do have a computer at home, but not very powerful. Windows Operating system.

From Jakub’s point of view, the program would have heavily benefitted getting the method stuck into his head, seeing it in action whenever he needs. The program will have to be light to suit to Jakub’s use and must demonstrate it well in the program and UI, rather than running something and trying to figure out what it is doing in the background.

## User Needs

After all the interviews, it seems clear that everyone thinks that this program would really help engagement and recall of information. I do need to ensure that it isn’t a program that can just be played around with endlessly, meaning actual work won’t be done.

I need to ensure the program is light to run, as although Alex has a stronger device, Jakub doesn’t, and the school provided devices aren’t strong. So, people should be able to run it on school devices and weaker home computers. If it can’t be easily run on these devices, it leaves only people with their own stronger devices able to run it, at which point I am limiting the opportunities of people with disadvantaged backgrounds, which I don’t want, so it must be easy to run.

Although none of the interviews brought up accessibility requirements, my program has no apparent need for a keyboard control, only a mouse or touchscreen would actually be required. This will be a good goal to aim for to help not restrict the possible users, as outlined in the previous paragraph.

The program must give a lot of feedback clearly, without the need to look through the code. It should be easily accessible and give a wide range of information on what is actually happening, including equations for the Derivative and Integral, as well as feedback on the current values and what is currently happening in the program. This is so it can actually be learnt from.

Finally, it wants to be finished by this year’s exam period, so that the models can be used for revision. Although the tool will be a lot more useful for initial learning rather than revision, it will still hopefully help, and Spring 2022 is still a good goal to have it ready for next year’s students learning differentiation and integration for the first time.

## Requirements and Limitations

Using these user needs, I am able to outline the requirements and limitations for the project. This should encompass all three interviews and their needs. It should also start to incorporate programming principles of how some of these can be achieved or what restrictions will do for the program.

### Requirements

* Able to hold the user’s attention
  + Interactive
  + Interesting range of scenarios
* Helps cement the information into the user’s head
  + Information on the process easily available
  + A demonstration where you can see what is happening as it goes.
* Follows laws of physics
  + Air resistance and momentum modelled

### Limitations

* Finished before this year’s revision period
  + Spring 2023
  + If not possible, aim for September 2023   
    for next year’s students
* Simple and light to run
  + O(nk) at worst
  + Simple, light graphics
  + Physics abstracted to simpler degrees
  + Proportional relationships

## Objectives (SMART)

Using these [requirements and limitations](#_Requirements_and_Limitations), we can form a list of objectives to aim towards throughout production. These should follow SMART principles (Specific, measurable, achievable, realistic, time based) to ensure the programming process can go quickly while still delivering the product that the sponsor and end users need.

1. Interactive and intuitive user interface (A,R)
2. Contains a control panel to interact with the PID model (S,M,A,R)
3. Includes feedback of calculations and current values (M,A,R)
4. Has expandable menus detailing the processes behind each part of PID (S,M,A,R)
5. Three detailed models should be available (M,A,R)
6. Rotation, extension, and velocity control should be demonstrated (S,M,A,R)
7. Relationships should aim to be proportional or polynomial (A,R)
8. Must be light enough to run on light computer systems, running windows (S,M,A,R)
9. Must be finished before Spring exams 2023 (S,M,A,R,T)

# Technical Analysis

## Technology comparisons

Using these Objectives, I can now start to compare different programming languages, and tools within the language, to each other. This helps me decide which language I should use, and which would be definitively best for the program.

|  |  |  |  |
| --- | --- | --- | --- |
| Objective | Python | C# | Scratch |
| Interactive and intuitive user interface (A,R) | TKInter is a useful tool for UI design in python, however it is primitive for rotating and changing objects | WPF is extremely helpful for this project, as it has built in functionality for changing length, position, or rotation of an object | Scratch is simple and has inbuilt functionality for animating sprites, however it is primitive in its design due to its simplicity |
| Contains a control panel to interact with the PID model (S,M,A,R) | TKInter seems to have functionality for interactive controls, however it is unintuitive and difficult to learn, from my research | WPF has inbuilt buttons, as well as an easy Function menu to create On Click Events. | Scratch has simple When Key Pressed or When Sprite Clicked blocks, so could make a UI with ease |
| Includes feedback of calculations and current values (M,A,R) | Python has a simple console Print() function, and Tkinter has a Text item, and so feedback can be easily returned as text. There is also a helpful library called MatPlotLib for plotting graphs. | With sliders, colour control and text blocks, WPF is a great option for returning feedback | Scratch has limited text return options, and so would not be a good choice. |
| Has expandable menus detailing the processes behind each part of PID (S,M,A,R) | TKInter has dropdown menus, however they look old and unappealing visually. This would not help hold the user’s attention | While there is the ability to create custom drop-down menus, it isn’t entirely intuitive, so WPF isn’t the best choice here, but it works. | Scratch has changeable textures on sprites. With these texture changes being able to be attached to any trigger, Scratch is very useful for changeable, expandable menus |

|  |  |  |  |
| --- | --- | --- | --- |
| Three detailed models should be available (M,A,R) | I could use Functions to store different models and navigate between them through a menu. Returning after the PID module won’t be difficult either. | C# uses Object Orientated Programming (OOP) so having different models call one PID module will be simple | Scratch will easily be able to make 3 different models, and run a different one based on a menu selection, but the PID model would mean the structure ended up messy quickly |
| Rotation, extension, and velocity control should be demonstrated (S,M,A,R) | Python does not easily handle rotation, extension, or position change in TKInter | All three are really easy and simple to implement with WPF | Scratch has really simple blocks for movement, rotation, and extension. It also has variable functionality to store velocities |
| Relationships should aim to be proportional or polynomial (A,R) | As it’s a text-based programming language, the maths will be as simple as I make it. | As it’s a text-based programming language, the maths will be as simple as I make it. | Scratch has a variety of maths blocks, however due to the block nature it will actually be a lot slower to run a small and simple algorithm. |
| Must be light enough to run on light computer systems, running windows (S,M,A,R) | Due to the difficult nature of changing TKInter UI, the program will be more complex than it has to be, slowing it all down. It also requires a python interpreter to run on windows, which creates unnecessary complexity | Although a very easy language to compress the algorithms into simpler statements, WPF can thoroughly slow down if too many updates are required. Fortunately, this shouldn’t be an issue for the three models. | Scratch would be entirely illogical to use, as it requires an internet connection to access the site and encourages students to browse games made available on the site. |
| Must be finished before Spring exams 2023 (S,M,A,R,T) | I already know how to program in Python, however some functions in TKInter make take some time for me to learn and use efficiently. | I am near fluent in C# and WPF, so I will be able to produce the program very quickly without a need for much more research or sacrificed quality of the product. | Being a block-based language, it would take a ridiculous time to code the complex algorithms into scratch, and so wouldn’t be a fit choice. |

## Chosen Technology

### Python

I am already well versed in Python, but not so much TKInter or MatPlotLib. This would mean the program would be slow to develop as I am spending time learning the ins and outs of these libraries. From the research I’ve done so far on these libraries, the tools they contain are simply not suited for the required needs of this project – the functions either don’t exist, are sloppy and difficult to use, or they are not visually appealing. When it comes to actual algorithms and such, Python would work as well as any text-based programming language, with most of the same functions for what I need. Overall, Python wouldn’t be a good choice, but it would be doable provided there wasn’t a better option available for me to use for the project.

### C#

With WPF and OOP, C# is an extremely reliable choice for a program. I already know the language well, including the extra libraries I might need like WPF, and these libraries give me extensive control over the UI, feedback to the user and ensuring it is all visually appealing throughout. OOP also opens the door for an interesting structure to allow the connection between all three models and a single PID controller module, that they could all call in different contexts, and get the result they want from it. With a wide diversity of methods available, it is quickly apparent than C# is an outstanding choice for this project, and most likely the best one.

### Scratch

While Scratch is an amazing tool for people first learning programming, or to throw a quick simple demonstrative tool together – it isn’t a good choice at all for something that requires complicated code. Its UI and feedback system is extremely simple, and amazingly controllable, however due to this simplicity and its limited functionality or blocks available, the moment you want to code a serious program with heavy algorithms, it simply doesn’t stand up to other programming languages. In conclusion, Scratch is a fantastic UI tool, and likely better for it than TKInter in python (which really says something about TKInters quality, that it can be beaten by a toy for children) but when it comes to the actual functionality and coding aspect, it falls flat on its face.

### Chosen Technology

After reviewing each Language, C# with WPF is clearly the best choice for this program, with Scratch and Python barely holding a candle to its ability to provide what I need for the program. Scratch and C# both provide the intuitive and appealing UI, while Python and C# hold the algorithmic diversity I need, and so to have the best of both worlds, C# is the clear choice for this project.

## Architecture overview

My UI will consist of three models navigable between through a small heading. They will be controlled via a panel with sliders to control the kP, kI and kD, and a feedback system. These will be required for all three models, and so will be persistent.

The first model will use PID to control the rotation of a rectangle to maintain an upright position. The user will be able to adjust the rotational velocity of the rectangle, before enabling PID with their selected values for the constants. The model will involve air resistance, and the Output will be linked to Rotational Acceleration, so that the automatic system will try reach an upright position, without overshooting.

The second model will still control rotation; However, it will be in three different points, and two of them will actually be controlling a distance. This is because the model will be of a Robotic Arm able to move to any point within a circular range. One of the rotations will be controlling the base, deciding what direction the base of the arm is pointing. The next rotation is controlling the angle between the horizontal and the first length of the arm. The final rotation control is between the first and second length of the arm, acting as the elbow of the arm. These last two will form a triangle between the two lengths of the arm, and the level of the floor modelled. This will not account for vertical movement, so the desired value for these two can be calculated using trigonometry, and passed into the SP.

The third model will control both rotational velocity, and standard velocity. The rotational model will be used on the front wheels of a vehicle, and the velocity model will be used to control the engine and thus velocity of the vehicle. This effectively creates a self-driving car, that can navigate to a point. However, there will be no obstacles or other cars that must be avoided; It is only the very core functionality of an automatic car system. Similar to the previous model, the user will select a point on a canvas that they want the vehicle to navigate to, and the PID system will do the rest.

## Mathematical model

At the core of all three models will be the PID controller. I spoke briefly on this earlier, so you already know a bit of how this works.

Here are the definitions for some of the important terms again:

* Set Point – The desired numerical value to be reached
* Process Value – The current numerical value, read in by a sensor
* Error – The difference between the Set Point and Process Value
* Output – The calculated PID output, often an acceleration
* kP, kI, kD – The constants used in each individual calculation

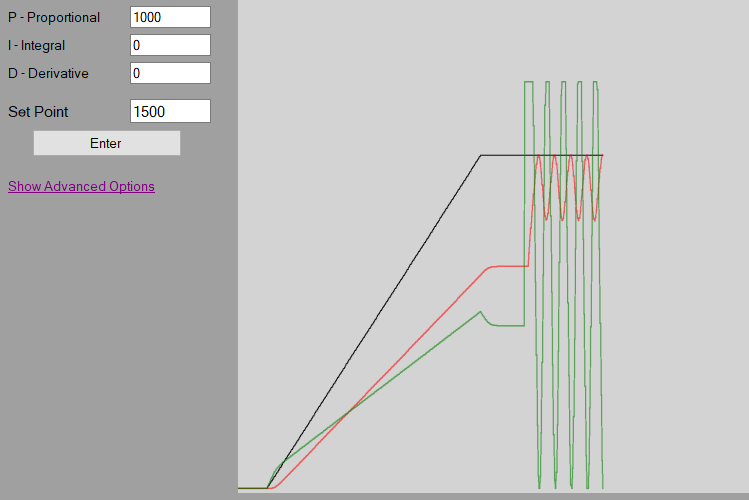
The controller can be broken down into four calculations: Proportional, Integral, Derivative and Output. All of these can be nicely demonstrated as graphs between the Set Point (Black), Process Value(Red) and the Output (Green), with time across the X axis and value on the Y axis.

### Proportional

The proportional calculation forms a linear, proportional relationship between the Error and the output. This is done just by multiplying by the kP constant, as such:

P = Err \* kP

This creates a relationship that simply approaches the target with constant acceleration, so that at an error of zero, there is no acceleration. However, because of momentum, the process value will not stop exactly when the output is zero, it will keep going at the highest speed it reached, and only then will it start to decelerate and turn around. This causes an entropic loop of oscillating back and forth, when used alone.



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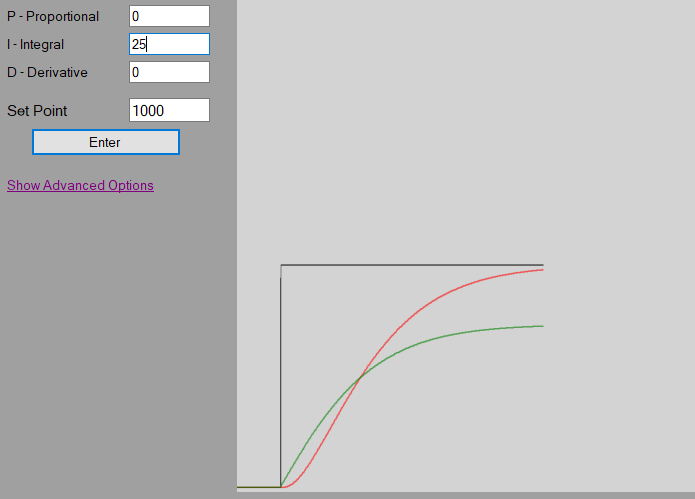
### Integral

The integral calculation creates a relationship of slow increasing acceleration. It will do fairly little at the beginning, but as it takes more and more time to reach the Set Point, the Output will slowly increase by more and more each time. This means that the longer it takes to reach the set point, the faster and faster it will increase acceleration (Jerk increases)

I = kI \* Err \* Δt

It = It + I

These calculations come together to form this relationship through the accumulative total, added to every time the PID controller is called. This would increase really quickly and uncontrollably, however in the initial calculation there is a delta time, so regardless of the time period between calculations, it will increase at the same rate. Over two seconds, whether the PID controller is called one time, or ten, the integral total will still be the same at the end of the two seconds. Due to the increase over time, integral becomes useful for counteracting resistive forces.



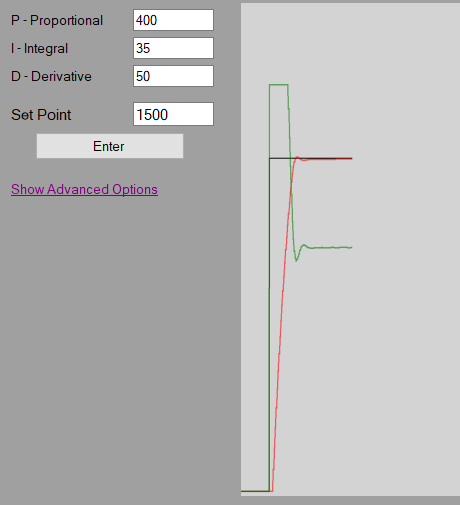
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### Derivative

The Derivative calculation is actually the only relationship that turns negative before reaching the set point. This means that on its own, it is actually terrible at reaching the set point, it will just quickly and smoothly come to a stop. Only once we introduce an amount of Proportional or Integral will it actually start to reach the goal.

D = kd \* (Err – pErr) / Δt

The derivative works in the same way as the integral calculation, as it has delta time involved in the calculations, to help account for the time taken between the previous PID calculation, and this one. This is required in derivatives as the calculation involves subtracting the previous error from this one. This means if the error is reducing, because the PV is approaching the SP, then D will be negative, and it will slow down to a stop. If the PV is going away from the SP, and thus the error is increasing, the derivative will become stronger to pull it towards the SP.



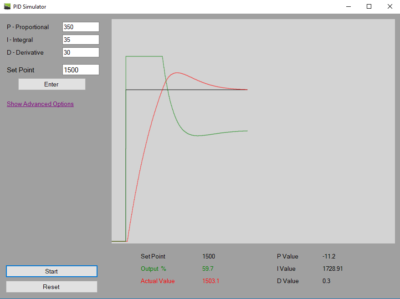
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### Output

Altogether, the combination of these three relationships creates a controlled algorithm, able to reach a numerical goal accurately and precisely without overshooting.

Output = P + It + D

However, it isn’t always perfect. PID controller tuning is a fine and delicate process, where the kP, kI and kD values need to be at the right ratio to each other, and the right scale compared to your PV and SP.



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## Gap Analysis

MVVM? Multi-Threading? Pre-saved Constants with JSON?

## Prototype

E

# Functional Design

# Technical Design

# Technical Solution

# Systems Testing

# Evaluation