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An intuitive approach to teaching key concepts in Control Systems

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An Intuitive Approach to Teaching Key Concepts in Control Systems

Abstract

As technology advances, newer generations are developing with quicker access to greater quantities of information than each one that precedes it. Congruently, research has shown a reduction in patience, while identifying the majority of the general populace as visual learners. This brings about the implication that conventional methods of text based instruction may not be as effective as they have been with previous generations. As technology brings about a paradigm shift in the way people perceive and learn new information, additional methods should be explored to adapt to new styles of learning.

This paper focuses on a mini-experimental reform to display topics in control systems in a visual and engaging manner before transitioning to traditional material. The method is designed to be purely supplemental to existing material in order to establish intuition before introducing deeper mathematical analysis. As this method is aimed at catering to visual styles of learning, it is also designed to engage the audience, retaining their attention. This strategy is also meant to foster an environment where students can feel un-intimidated by content with the hopes of boosting confidence while they establish intuition to apply to later analysis. As many efforts are currently being explored by many educators to achieve the same goal, it is the focus of this project to create a working manuscript for instructors to reference many key topics in control systems. This is part of a greater effort at Florida Atlantic University to apply this method to different subjects in engineering such as computer algorithms, calculus, and MATLAB. To gauge the receptiveness of the methodology, the techniques were applied over the course of a semester for a class titled “Control Systems 1”. The results, although preliminary, have been positive. A larger effort is presently being conducted re-assess the success of the method by monitoring the progress of a class and its individuals as the semester moves on.

1. Introduction

“Visual literacy in the classroom has become increasingly important as more and more information is accessed through technology. Students must maintain the ability to think critically and visually about the images presented to them in today’s society” [1].

With the advent of television, computers and all the engaging social media that the internet has to offer, the newer generations have developed primarily as visual learners. With the internet as a tool, there has been an explosion of knowledge and information which has this era appropriately deemed the age of information. With this overload of data, children are developing in a visual environment. On average a show on television changes camera angles once every 7-8 seconds [2]. Most people leave web pages within the first ten seconds of viewing. Only if they decide to stay longer than 30 seconds does the probability of them staying on longer than a minute level out [3]. This reduction in patience has been noted by Microsoft as they reported that users visit websites less if the site takes at least 250 milliseconds longer to load. “Two hundred fifty milliseconds, either slower or faster, is close to the magic number now for competitive advantage on the Web,” reported Harry Shum, computer scientist at Microsoft [4]. This is a statistic that advertisers have taken advantage of, with the majority of ads appearing as quick flashes of information for the purpose of sticking in the viewer’s memory. In a study by 3M Corporation, the brain processes visual information 60,000 times faster than text and that using visual aids in the classroom improve learning up to 400 percent [5]. The figure below illustrates the probability of a user leaving a web page in relation to the time spent visiting the page.

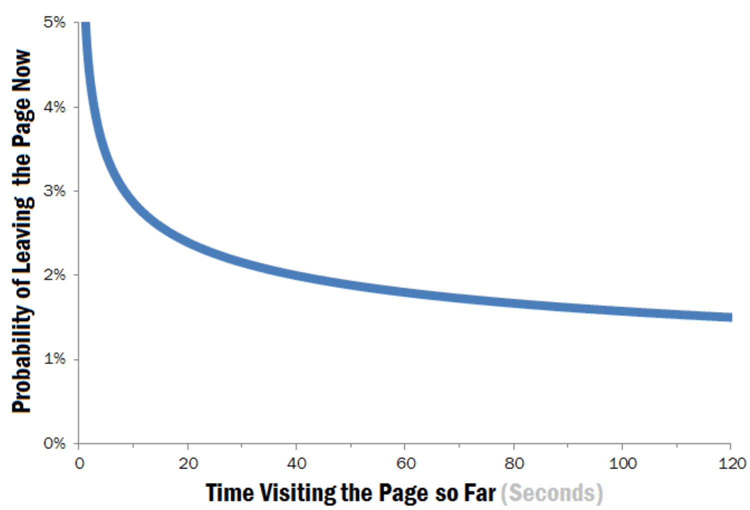

Figure 1.1: Probability of how long users likely stay on a web page [1]

With these facts in mind, it is no coincidence that as each year goes by, teachers notice a greater percentage of students having difficulty understanding key concepts from difficult coursework. With that said, it is not for lack of trying that students are failing to connect between what they learn and what is expected of them. Studies have shown that 65% of the population benefits more from visual learning than any other style [6]. As this can serve as a reflection of the changing world, it is up to educators to adapt to these changes to ensure that students are given the highest probability of success.

Addressing this growing trend, an approach has been developed to cater to students' increasing demand for teaching techniques that cater to visual learners. It is aimed at providing a "non-intimidating," "math-less" approach, by implementing a series of analogies and visual aids that relate everyday life to theories in difficult topics in engineering. It is important to note that this is not meant to be a replacement to existing textbooks, but supplementary material aimed at reinforcing understanding and enhancing intuition. This method was implemented through the creation of a supplementary book, to aid instructors in teaching students. The contents of the manuscript were presented over the course of a semester to senior level Electrical Engineering students in a class titled "Control Systems". A web-based questionnaire was then conducted to obtain feedback at the end of the course to gauge students' receptiveness to the techniques employed.

2. Methodology

An explanation of a concept starts off by presenting students with a familiar experience in their everyday life. The scenario is explained by employing analogy to help students understand and relate to the problem at hand. Once completed, the components of the analogy are compared to elements of a topic in engineering. Visual aids, such as illustrations and graphs, are used to reinforce the text and provide students with their need for a visual style of learning. Below are a couple of examples that utilize this method for various topics in Control Systems.

2.1 Example for Explaining the Concept of Time Constant

Imagine you were taking a trip from Florida to Maine. You have three vehicles to choose from: a sports car, mini-van or a truck. The sports car would offer performance and fun but requires high octane gas and offers little storage room. The truck would be roomy and provide storage space at the price of poor MPG and horrible acceleration. The mini-van is not necessarily the best at any one category but is well rounded and suited for the job. Based on the familiar letter grading system in figure 2.1 below, which vehicle would you choose?

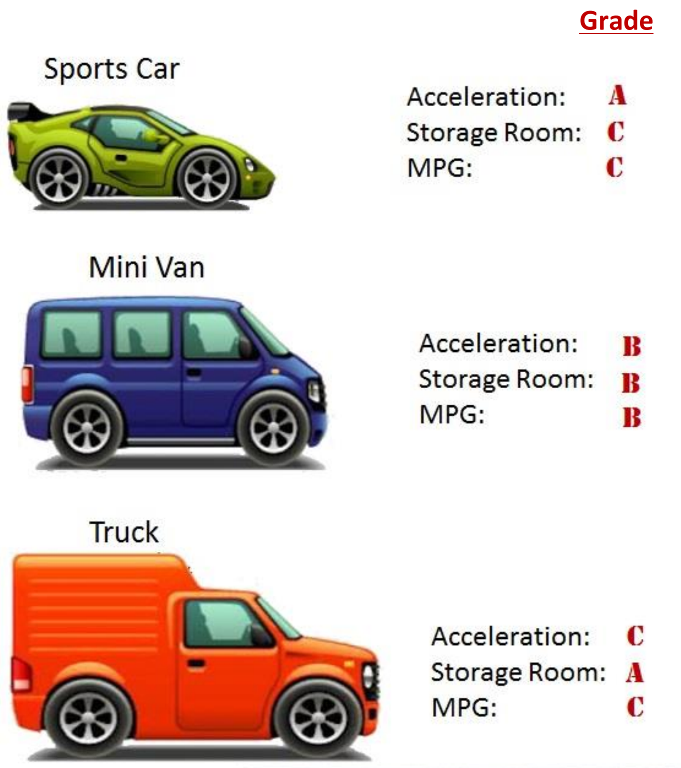

Figure 2.1: Automobiles displayed with graded attributes

You probably chose the minivan, since it has the highest average grade of the three attributes. These ***trade-offs*** are common in engineering. You cannot always afford to have the best of every world, so you must decide which solution fits your task best. As in engineering and most things in life, "there is no such thing as a free lunch."

On this trip, you encounter a red light on a three lane avenue. Coincidentally, stopped in each lane are the very cars you have at home. Which do you get behind? Most people would pull up behind the sports car. Its low profile allows you to sense more in front of it and its speed allows for little delay between the green light and your ability to take off.

You notice that each vehicle has a different acceleration once the light turns green. As each vehicle reaches the speed limit at different times, each system is said to have a different ***time constant***. In other words, the time constant serves as an indication for the time it takes the cars to reach a certain speed. In Figure 2.2, the lengths of the different arrows are an indication for the relative acceleration of each vehicle, and the color helps to indicate which one is "better," i.e., green is best and red is worst.

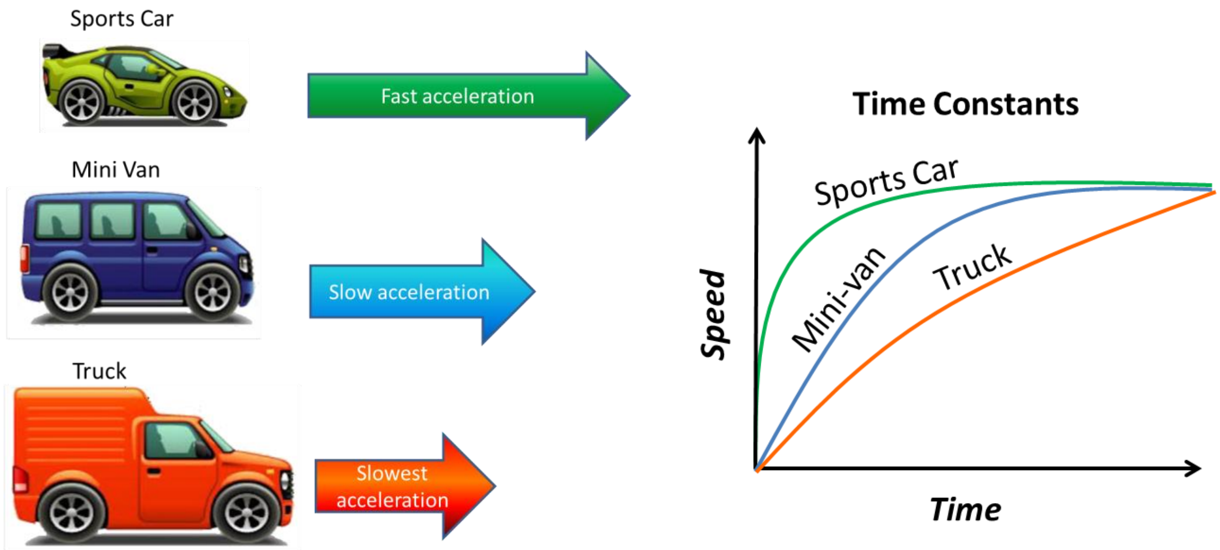

Figure 2.2: Automobiles acceleration with relation to their time constants

As the truck is the heaviest and the slowest of the three vehicles, it carries the largest time constant. The sports car is the fastest due to light weight, high horsepower and most likely a driver with a passion for speed, it carries the smallest time constant. The mini-van by default falls in the middle. This is clearly shown in the color matching graph in the left part of Figure 2.2.

2.2 Example for Explaining the Concept of Time Delay

While standing on the curb, you notice three vehicles of the same make and model, with very similarly behaving drivers. They are all lined up in the same lane at a red light. As the light turns green, they all accelerate at the same rate but at different times as illustrated in Figure 2.3.

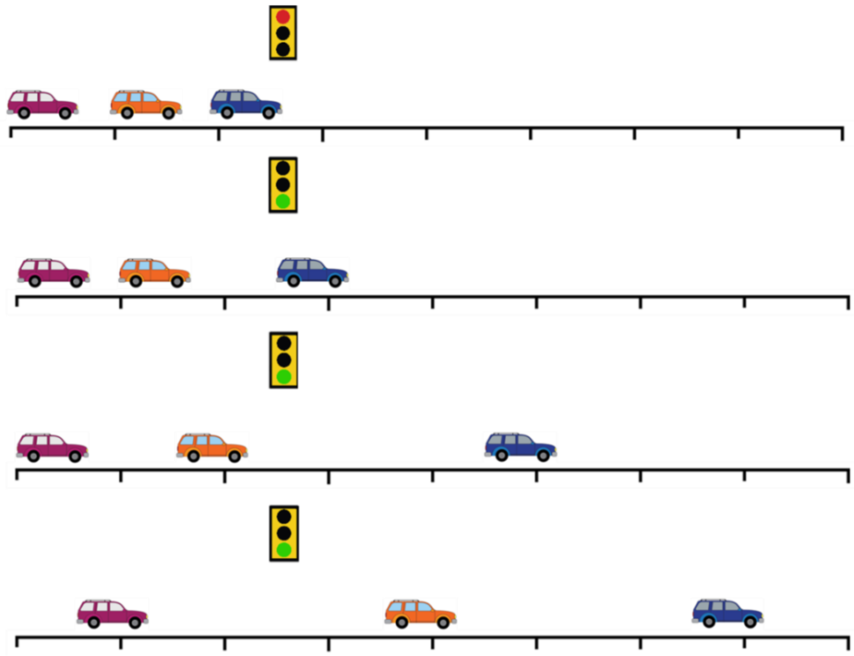

Figure 2.3: Position of all cars from totally stopping to full motion

The waiting time is considered a ***time delay***. Nothing was different from car to car except for the start time. Figure 2.4 illustrates that the cars have the same behavior with different time delays.

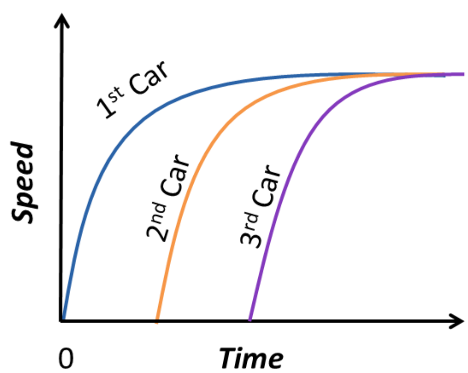

Figure 2.4: Graph representing behavior of similar systems with different time delays

2.3 Example for Explaining the Effect of Sensor Latency on Feedback System

It is not uncommon for Israeli engineers to use visuals and everyday examples for teaching concepts in engineering. The following example was inspired by a control systems book titled, “Introduction to Controls”, published in Hebrew [7].

A sensor's job is to feedback information to a system in order to correct errors that may exist. The quicker a sensor reports error to a system, the more accurately the system is able to compensate for it. For this reason, sensor placement is of great importance.

For example, imagine there is a factory that made cookies. The cookie dough is squeezed through a pump and on to a conveyer belt. To ensure the pump is squeezing out the right amount of dough, a sensor that measures the size of the cookies located below (Figure 2.7) is placed at the end of the conveyer belt. Do you see a problem with this?

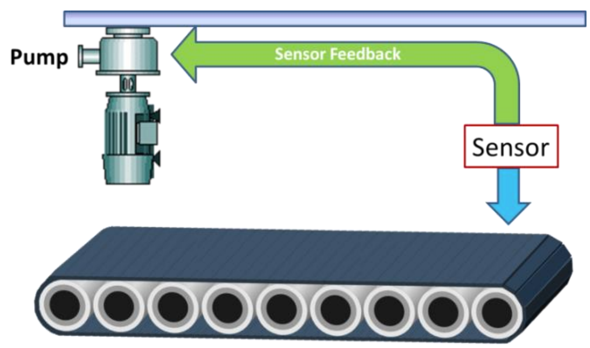

Figure 2.5: Conveyer belt with improper sensor placement

As you may have guessed, the sensor is placed too far from the pump. "So what?" one may ask. If the pump is making the cookies too big or too small, the pump would not find out until a number of cookies later. Suppose the example below, where the pump starts off making the cookies too small (Figure 2.8).

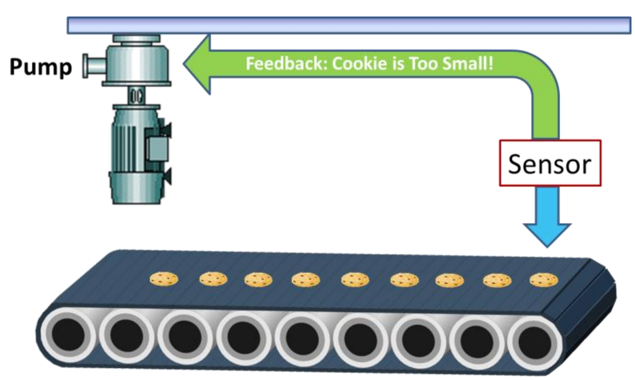

Figure 2.6: Conveyer belt producing cookies too small in size

In this scenario, the sensor would inform the pump of the wrong size after nine cookies were already made. At this point, the sensor would inform the system to increase the output, making the cookies bigger.

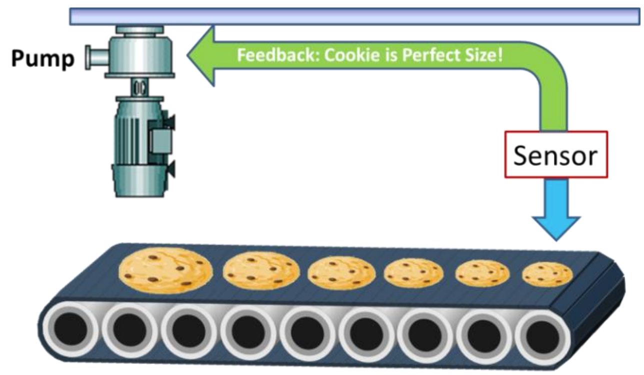

Figure 2.7: Conveyer belt producing cookies too large

Once the sensor reports to the system that the size is perfect, the pump has already increased the size much larger than desired. Once the sensor discovers the error, it will inform the system that it needs to decrease the size (Figure 2.10).

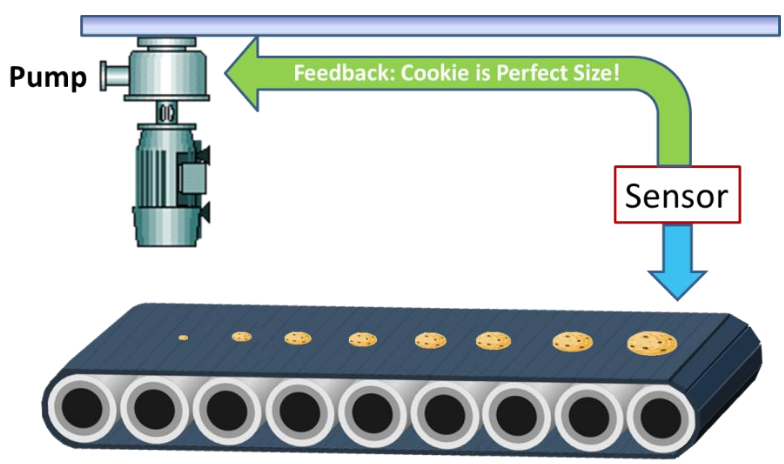

Figure 2.8: Conveyer belt producing cookies too small

Because the delayed response causes this back and forth, the system would continue to oscillate forever, never settling on its desired output. The graph below illustrates the changing cookie size as it goes from too small to too large, never settling on the desired size (Figure 2.11).

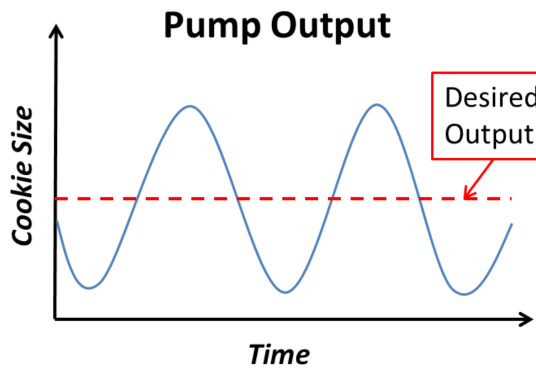

Figure 2.9: Graph displaying the size of the cookies being produced with time

A Solution:

Placing the sensor at the base of the pump, will ensure that the feedback is instantaneous, allowing the systems output to reach its desired settling point, i.e., the desired cookie size. The graph below titled "Pump Output", displays the size of the cookies over time when the sensor is placed at the base of the pump. Looking at figure 2.12, notice that the cookie size becomes constant once it reaches the desired output.

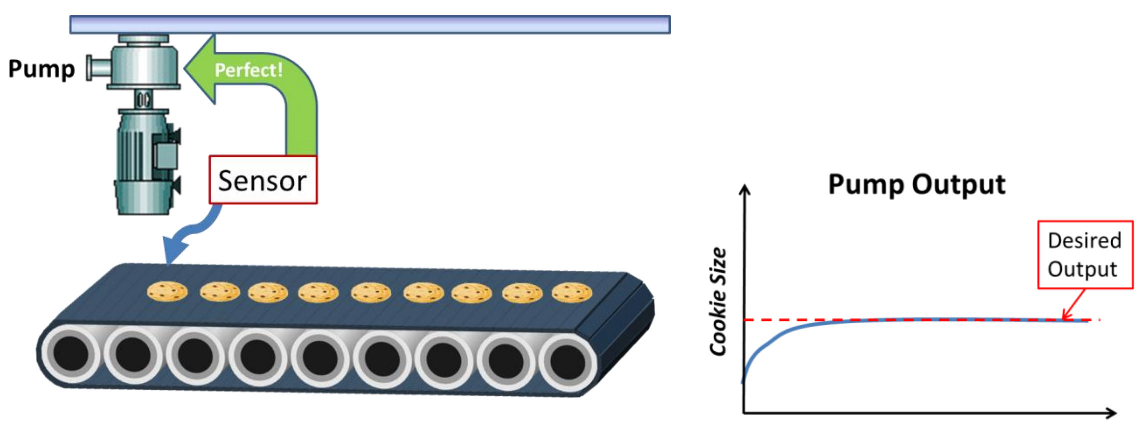

Figure 2.10: Conveyer belt with proper sensor placement with graph displaying desired behavior

2.4 Example for Explaining Design of a Closed Loop System

2.4.1 Armature Controlled DC Motor

Now observe the following DC motor. When we apply an input in the form of Voltage (v_a), we expect it to rotate. The angular velocity (ω) tells how fast the shaft is rotating at any given time. The angle theta tells the accumulated angle. The second image displays a DC Motor where inertia (J) and damping factor (b) are displayed.

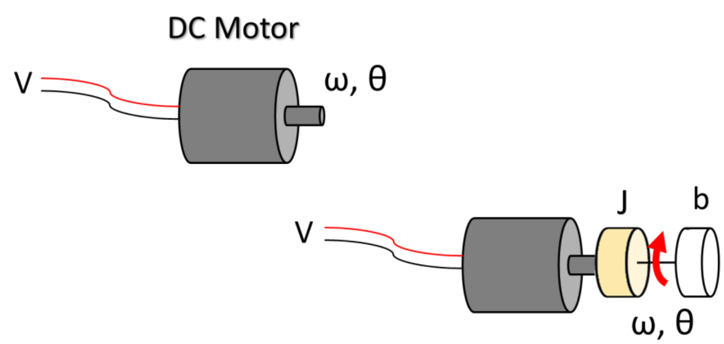

Figure 2.11: DC Motor with Variables

2.4.2 Armature Controlled DC Motor Equations

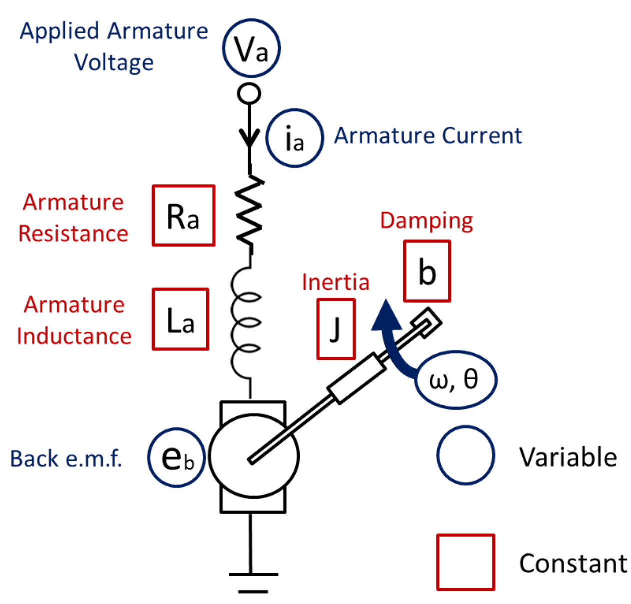

Figure 2.12: DC Motor Schematic

Writing the time domain equation leads to:

$$
\begin{cases}
\omega = \dfrac{d\theta}{dt} \\
e_b = K\,\omega \\
L_a \dfrac{di_a}{dt} + R_a i_a + e_b = v_a \\
J \dfrac{d^2\theta}{dt^2} + b \dfrac{d\theta}{dt} = K\, i_a
\end{cases}
$$

Figure 2.13: DC Motor Time Domain Equations

Note that: $\omega = \omega(t)$ $e_b = e_b(t)$ $\theta = \theta(t)$ $i_a = i_a(t)$ and $v_a = v_a(t)$

Taking the equations to the S domain (Laplace Transform) yields the following equations:

$$
\begin{cases}
\Omega(s) = s\,\Theta(s) \\
E_b(s) = K\,\Omega(s) \\
(L_a s + R_a)\, I_a(s) + E_b(s) = V_a(s) \\
(Js^2 + bs)\,\Theta(s) = K\, I_a(s)
\end{cases}
$$

Figure 2.14: DC Motor S-Domain Equations

From the equations above, and assuming L_a is very small, we obtain the transfer function for the DC Motor

$$
\frac{\Omega(s)}{V_a(s)} = \frac{K}{R_a J s + R_a b + K K_b} = \frac{\dfrac{K}{R_a J}}{s + \dfrac{R_a b + K K_b}{R_a J}}
$$

Figure 2.15: Transfer Function Equation for a DC Motor

By recognizing K_m as the DC Motor Gain constant and T_m as the DC Motor time constant, the transfer function can be simplified to become:

$$\frac{\Omega(s)}{V_a(s)} = \frac{K_m}{T_m s+1}$$

Figure 2.16: Simplified Transfer Function

Where:

$$K_m = \frac{K}{R_a b + K K_b} \qquad T_m = \frac{R_a J}{R_a b + K K_b}$$

Figure 2.17: Gain and Inertia Constants

With the transfer function, we can create a block diagram and include the input and output.

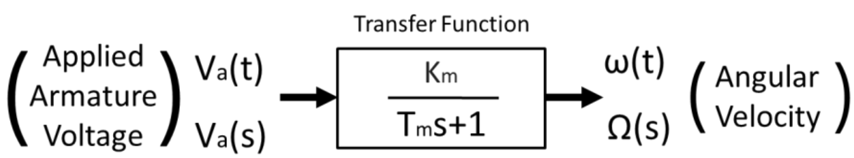

Figure 2.18: Block Diagram

This is how the input (v_a) and output (ω) looks when graphed in the time domain.

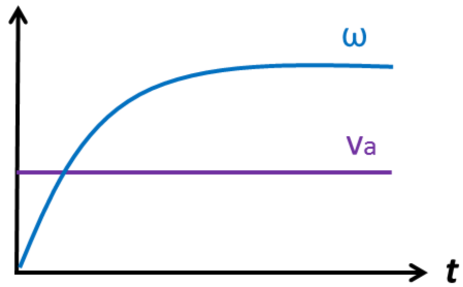

Figure 2.19: Graph Displaying DC Motor Input (Voltage) vs Output (Angular Speed) with Time

But let's say we want to determine the output by its angular position (θ). Since the angle θ(t) is the integration of angular velocity ω(t), multiplying ω(s) by 1/S (which in the S domain equivalent to integration) yields the angular position (θ(s)).

$$\frac{\theta(s)}{V_a(s)} = \frac{K_m}{s(T_m s+1)}$$

Figure 2.20: Transfer Function After Integration

Or in a Block Diagram:

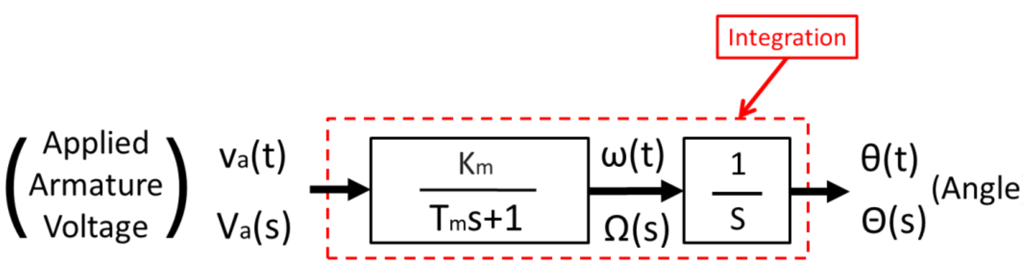

Figure 2.21: Integration in a Block Diagram

Which can be simplified to:

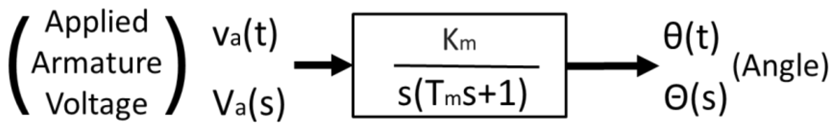

Figure 2.22: Simplification of Integration in Block Diagram

Taking another look at the time domain, we can see how the angular position θ has a constant slope (after some time) once the motor has reached a constant speed ω.

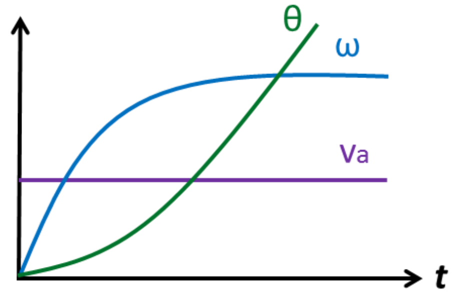

Figure 2.23: Graph Displaying DC Motor Input (Voltage) vs Output (Position and Angular Speed) with Time

2.4.3 Closing a Loop with a DC Motor

2.4.3.a Speed Control

But what is wrong with this picture? Observing the above block diagram, it is clearly an open loop system. Without feedback, we have no clue how ω or θ are behaving. So, in order to do so, we have to close the loop.

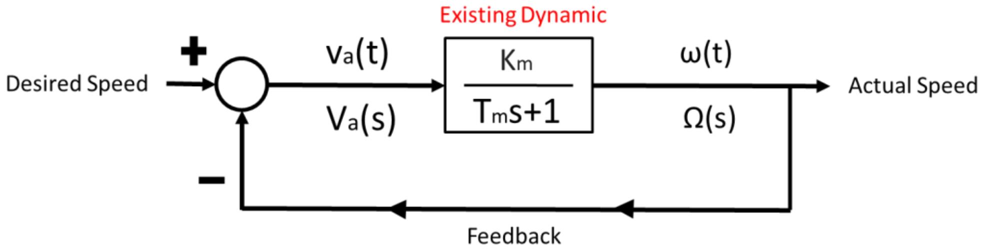

Figure 2.24: Block Diagram of Closed Loop System

Even with feedback, we may realize that the behavior of the system is unsatisfactory. For example, the closed loop system could not be reaching the desired speed as quickly as we would like. Simply put, the time constant may be too large.

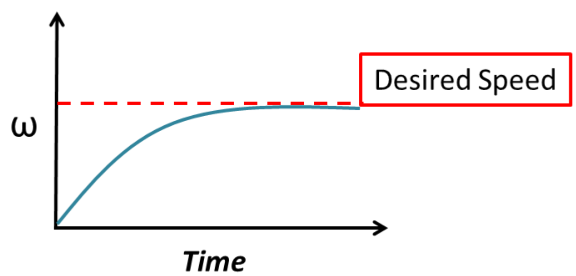

Figure 2.25: Graph Displaying DC Motor Behavior Without Controller

To speed things up, we need to add "dynamics" to the existing system in order to change its overall behavior. We do that by designing and adding a controller.

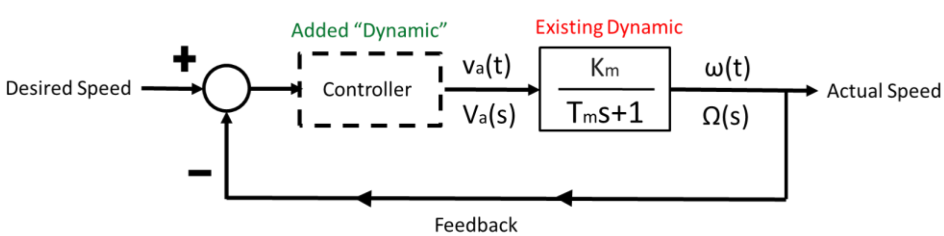

Figure 2.26: Block Diagram With Controller

Once we add the controller, the new closed loop system may have a smaller time constant. The controller can help go from a “slow” closed system to a “faster” one.

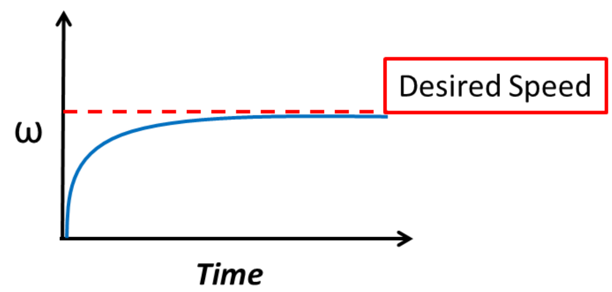

Figure 2.27: Graph Displaying Desired Behavior of Desired Speed

2.4.3.b Position Control

Now let’s say we want to control the angular position of the motor. We start off with the basics of the system.

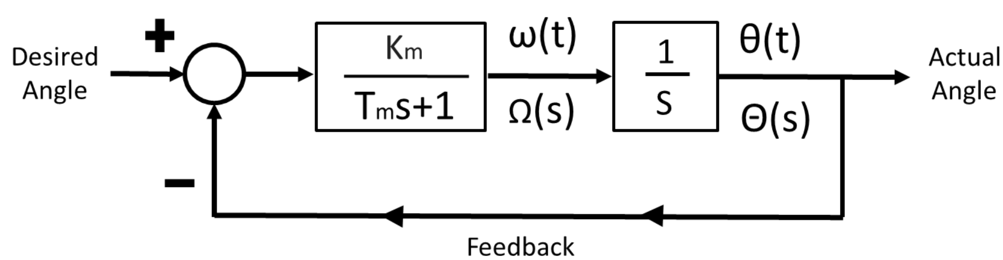

Figure 2.28: Block Diagram With Integrator

With the motor alone, the system may have an undesired response. This could mean that the position of the motor’s shaft is overshooting its mark and repeatedly over compensating by undershooting, much like a Yo-Yo.

For demonstrative purposes, let’s look at the side view of a DC motor as it behaves with time. The black arrow represents a reference line on the body of the motor which remains stationary. The orange arrow represents the actual angular position of the motor shaft at a given point in time.

Side View of Motor

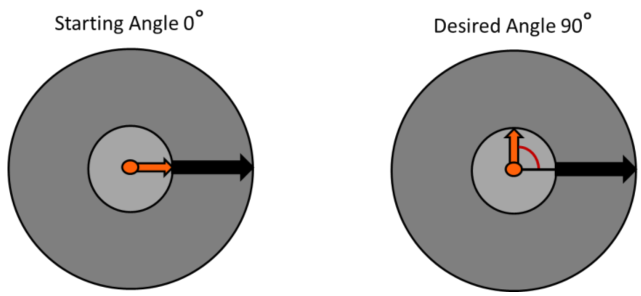

Figure 2.29: Side View of Motor With Starting and Desired Angle

In the above case, i.e., without a controller, the time response might be:

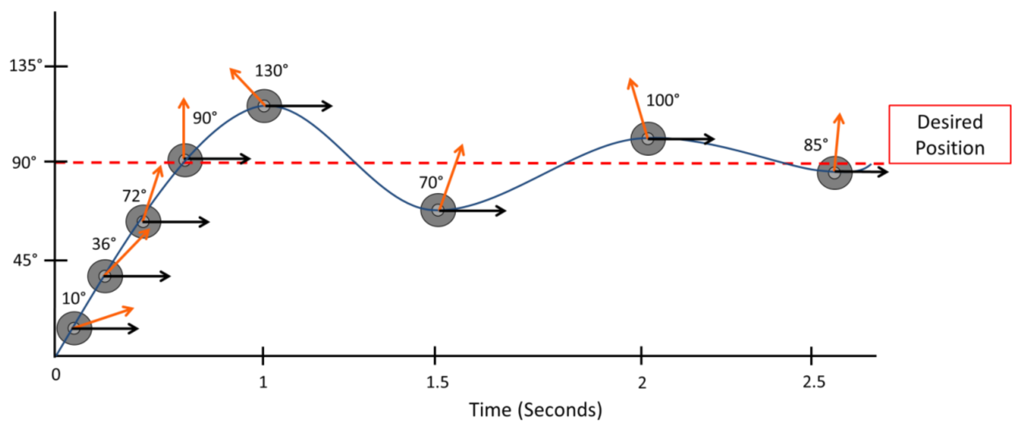

Figure 2.30: DC Motor Behavior Without Controller

Eventually, the shaft will settle on the desired position (90 degrees) but will not necessarily get there in a desired fashion. A desired behavior could look more like the graph below, where the motor quickly and smoothly reaches the desired angle.

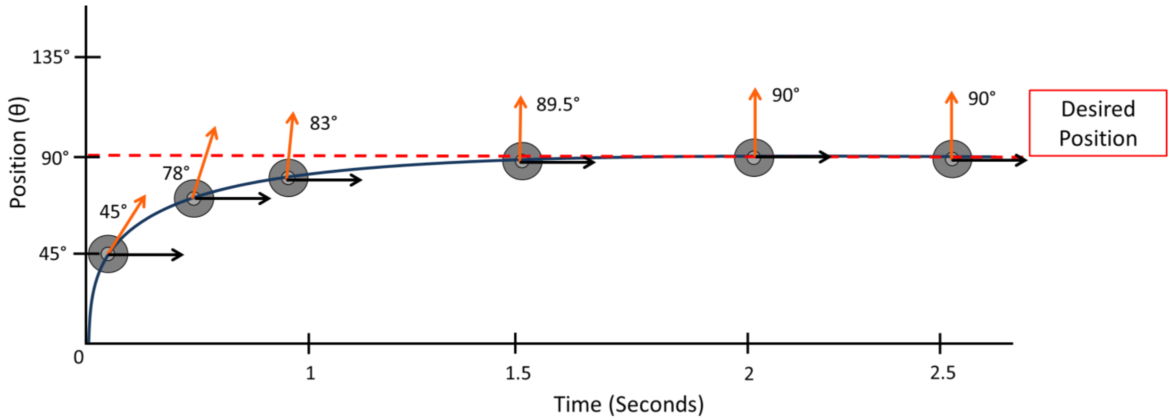

Figure 2.31: DC Motor Behavior With Controller

In order to achieve output with no overshoot (and with a small time constant, τ) above, we must add dynamics (a.k.a. controller) Once we know what we have (D.C. Motor Transfer Function) and what we want to achieve (closed loop response with no overshoot with small τ), we can design a controller to fill in the blank.

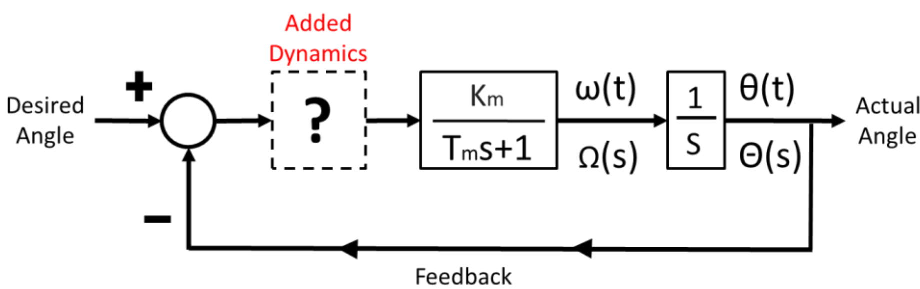

Figure 2.32: Block Diagram with Missing Component

2.5 Example of Engaging Activities for Teaching the Concept of Stability

Another technique used to clarify/explain concepts is to engage students during class by proposing a simple experiment meant to serve as positive reinforcement. This aids students in understanding concepts by fun, hands-on activities. The following is an example of how to engage students while reinforcing the concept of a topic in Control Systems called ***stability***.

Try on your Own!

If you want to see stability in action, start by making a paper airplane. Forget how to do it? Here is a sample instruction in Figure 2.13.

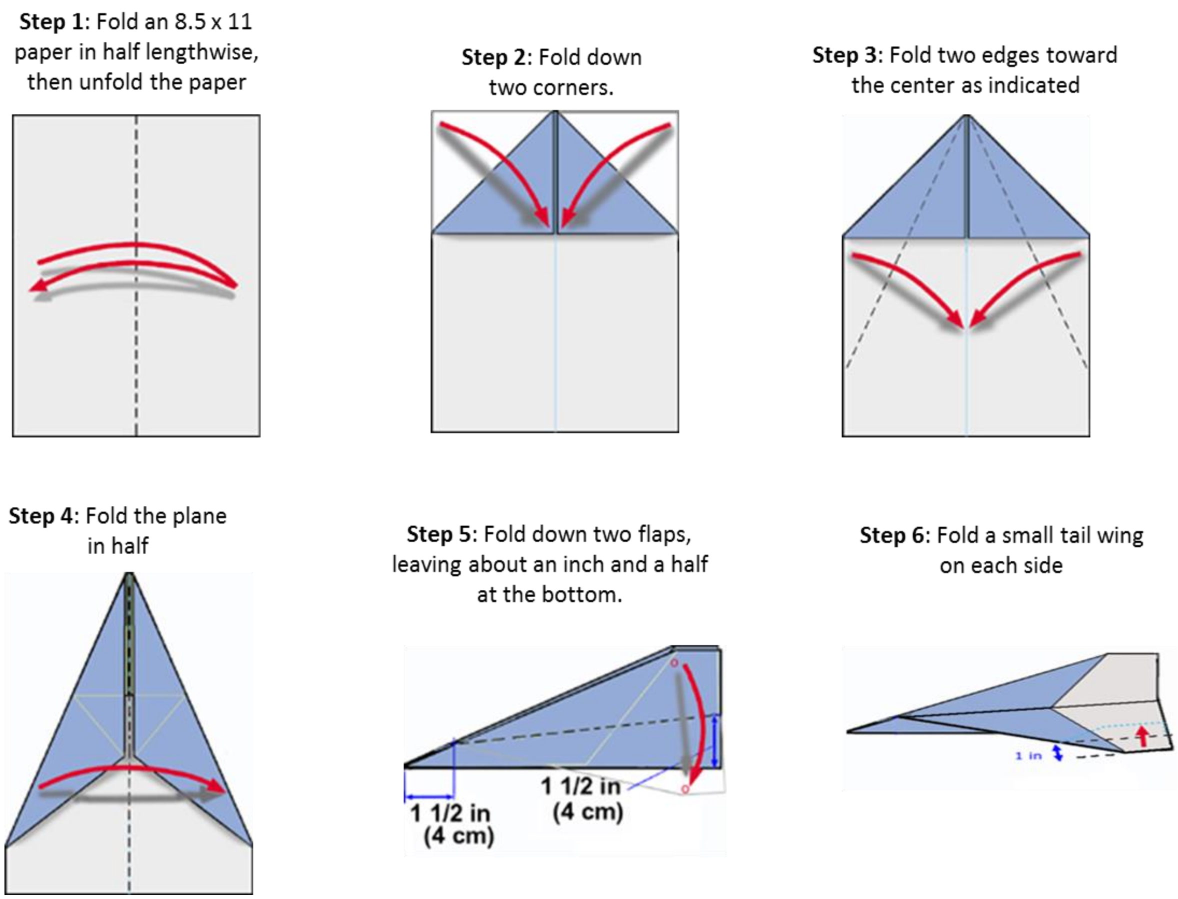

Figure 2.33: Instructions on building paper airplanes [8]

Now that you have a paper airplane, let's conduct a simple experiment. Place a paper clip on the front bottom edge of the plane. Now, fly it. The airplane should fly its normal, smooth pattern.

Figure 2.34: Stable Paper Airplane

Now, place that same pare clip towards the back of the plane. The path should be distorted.

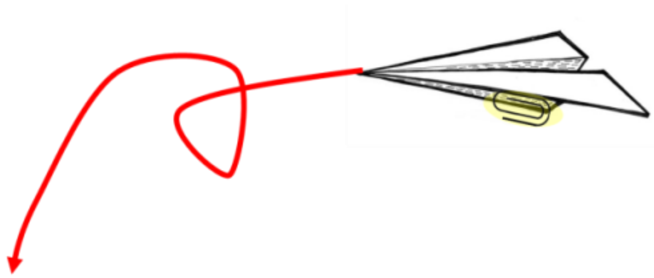

Figure 2.35: Unstable Paper Airplane

By adjusting the position of the paper clip, you are adjusting the pole of the system which in turn adjusts the stability of the airplane. Every object has a center of gravity. When the weight is shifted towards the front of a plane, stability is increased.

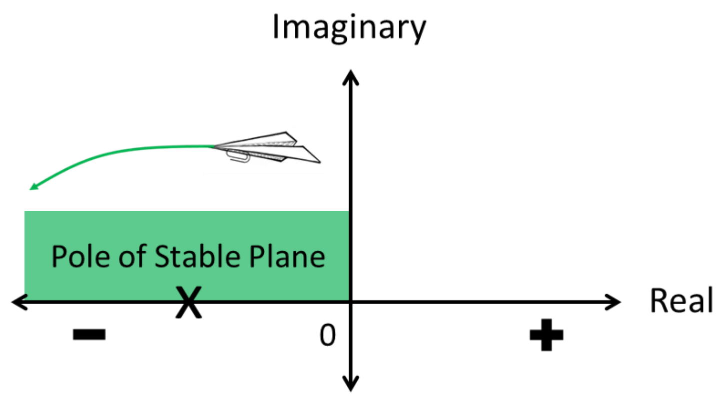

Figure 2.36: Pole of Stable Airplane

When the weight is shifted behind the center of gravity, a plane becomes more unstable.

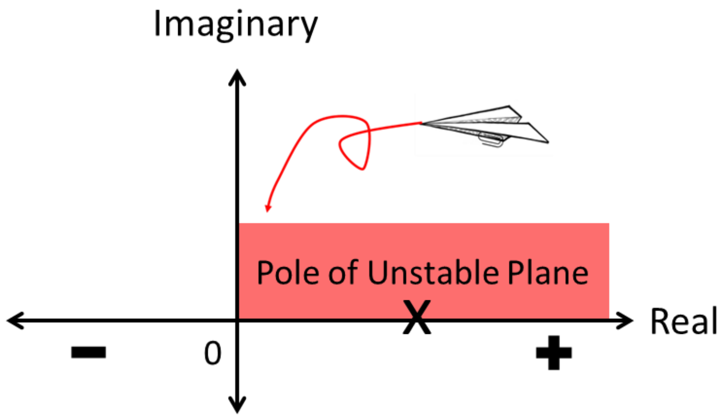

Figure 2.37: Pole of Unstable Airplane

When taught in a classroom environment, students are prompted to throw the paper airplanes at the teacher once the clip is moved to the back, making them unstable. Teachers can confidently stand firm as students try to hit them because the airplane will never have the proper trajectory to nail its target. The activity is followed by a class discussion. As this approach keeps participants engaged and entertained, it also provides them with a lesson they are not likely to forget. This strategy has been highly effective in increasing the attention of students while reinforcing the concept of stability.

Figure 2.38: Instructor demonstrating concept of instability

3. Assessment

The methods and examples highlighted in this paper were implemented in a Controls Systems class taught by a co-author of this paper at Florida Atlantic University. An online questionnaire was conducted in order to gauge how receptive the students were to various learning techniques. Out of 33 students, data was collected on each individual's demographics. The figures found in the appendix display the detailed results of the survey.

Figures A.1-A.3, located in the appendix, indicate the demographic breakdown of the students who participated. The demographic breakdown showed a fair amount of diversity. Although most of the students were between the ages of 21-25, the class represented most age groups, 21 and older.

Note that the feedback from each question was typically skewed towards the students agreeing or disagreeing with a particular learning strategy. On a scale of 0-4, zero being strongly disagree, four being strongly agree and two being neutral, the response towards the question, "I feel that developing intuition for control is important" (Figure 3.1) the average score was 3.66. While the students displayed their belief in the importance of intuition, they also displayed overwhelming support for the teaching styles implemented in the course that were designed to cater to visual learning. When asked the importance being able to visualize concepts as they learn, the total average score was above 3.6.

Q: I feel that developing intuition for control is important

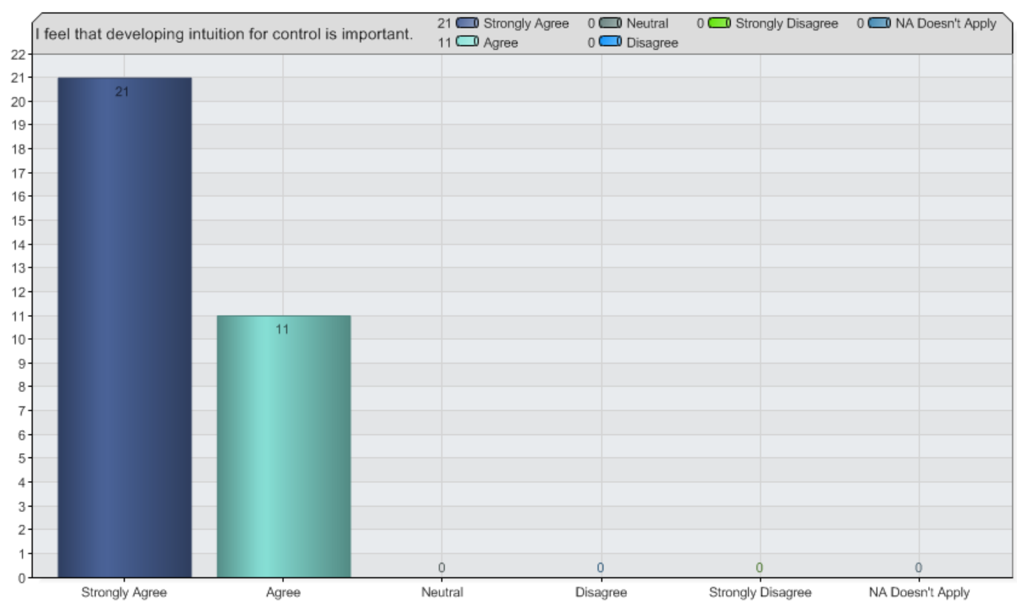

Figure 3.1: Student Feedback on importance of developing intuition for Controls

When asked questions on how the students preferred to be introduced to concepts in Control Systems, the results were in favor of engaging techniques such as visual, hands on activities, 3D puzzles, and communication-based exercises, as each of those scored above 3.4. When asked if they preferred to be introduced to new topics in Controls, by reading relevant chapters in a Controls text book, the total average was 1.9, which is below neutral. When asked whether they preferred to be self-taught, the total average was 1.3. This indicates that students prefer hands on engaging methods of learning difficult concepts to the conventional method of prescribed reading that is currently being employed.

Since the nature of the study is centered on a non-intimidating approach to Control Systems or more generally, topics in engineering, students were asked how they characterized their math skills. Out of 32 answers, only four students felt their skills were modest while the remainder felt their background was strong or extremely strong. This statistic highlights that even students with strong backgrounds in math still feel that they benefit from engaging, visual and intuitive-based learning. As Control Systems is a senior level Electrical Engineering course, the students feedback is significant as nearly all of them have had at least three years of math and science courses and at least one year of theory-based classes which utilize upper level calculus, differential equations, and physics. As these students are used to conventional methods of learning difficult concepts, they understand and denote the value of providing analogy and engaging examples to establish intuition before being taught the same concepts with math and physics. The figure below highlights the class' competency in mathematics.

Q: I would characterize my math background as…

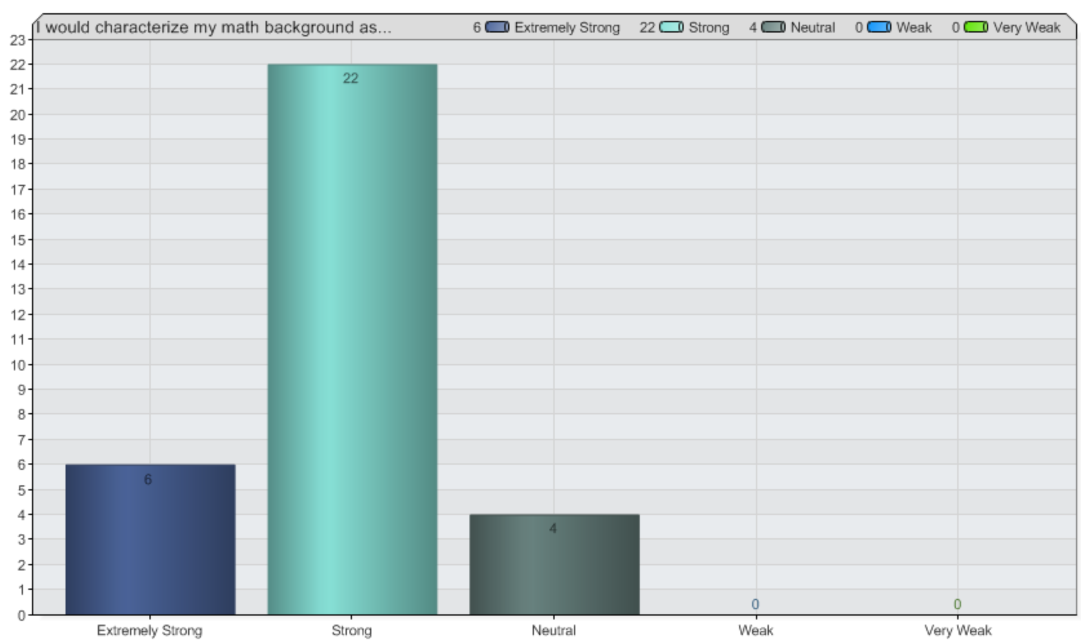

Figure 3.2: Student Competencies in Mathematics

As part of the questionnaire, students were also prompted to provide feedback to the question, “For future Control 1 classes, I would suggest to teach/learn in the following way:”

A1: “The way you teach the class is very good for learning.”

A2: “The same way. The lecture notes which are available online are really helpful and the in class examples which really helps to understand the material”

A3: “With more hands on examples or demonstrations in class”

A4: “The real life examples were essential for retaining the information. I liked the hands on demonstrations in class”

A5: “Examples that focus on the big picture ideas. I liked the fact that Dr. Raviv chose not to focus on material that Matlab or other software does for us (such as drawing Nyquist plots by hand), and instead focuses on the larger concepts.”

Based on the survey questions and comments, the author feels that this approach is worth pursuing.

4. Conclusion and Ongoing Work

As technology brings about a paradigm shift, changing the way people perceive and learn information, methods must be explored to improve the success of students in the classroom as well as encourage them to pursue difficult coursework in STEM. Conventional methods of teaching that fail to connect to the needs of the growing population of visual learners can only serve as a further deterrent of already intimidating topics in STEM-related fields. To curb this trend, the method of providing students with visual examples and engaging material aimed at solidifying intuition is proposed before the introduction of literature and math-based content. The methods described in this paper have been implemented as part of a senior level electrical engineering class titled “Control Systems.”

The approach was received with overwhelmingly positive reviews. As the students are no strangers to theory-based classes with heavy requisites in math and physics, their feedback to this evolving process is highly encouraging.

As this process is in preliminary stages, there are additional goals as part of a larger scope to enhance students’ understanding of difficult topics in STEM fields. In addition to creating a manuscript to serve as an introduction to existing materials in Control Systems, an effort is being made to convert the manuscript into an interactive, web-based manual. This will include videos, interactive activities, supplementary material, as well as links to relevant applications and existing math-based content once the reader has established intuition. An effort is also being made to do the same with other subjects such as “Calculus”, “Computer Algorithms”, “Estimation” and pertinent engineering software “MATLAB”.

Acknowledgements

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Appendix

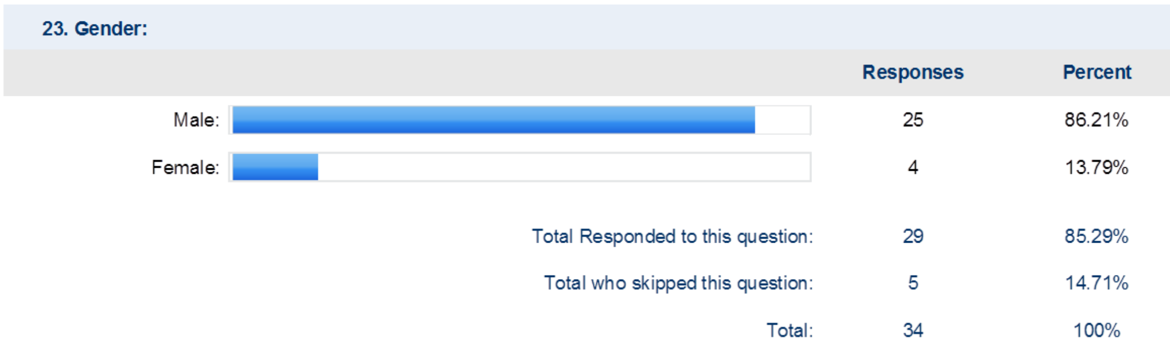
The following figures are graphs containing the results from the questionnaire discussed in the assessment section.

24. Race/Ethnic Origin:	Responses	Percent
White:	7	24.14%
Black:	6	20.69%
Asian or Pacific Islander:	6	20.69%
Hispanic:	10	34.48%
American Indian or Alaskan Native:	0	0%
If other, please specify:	0	0%
Total Responded to this question:	29	85.29%
Total who skipped this question:	5	14.71%
Total:	34	100%

Figure A.1: Ethnic Distribution

22. Age:	Responses	Percent
18-20:	0	0%
21-25:	18	60%
26-29:	9	30%
30-33:	1	3.33%
Above 34:	2	6.67%
Total Responded to this question:	30	88.24%
Total who skipped this question:	4	11.76%
Total:	34	100%

Figure A.2: Age Distribution



23. Gender:

		Responses	Percent
Male:		25	86.21%
Female:		4	13.79%
	Total Responded to this question:	29	85.29%
	Total who skipped this question:	5	14.71%
	Total:	34	100%

Figure A.3: Gender Distribution

Q: I feel that visualizing control ideas is important

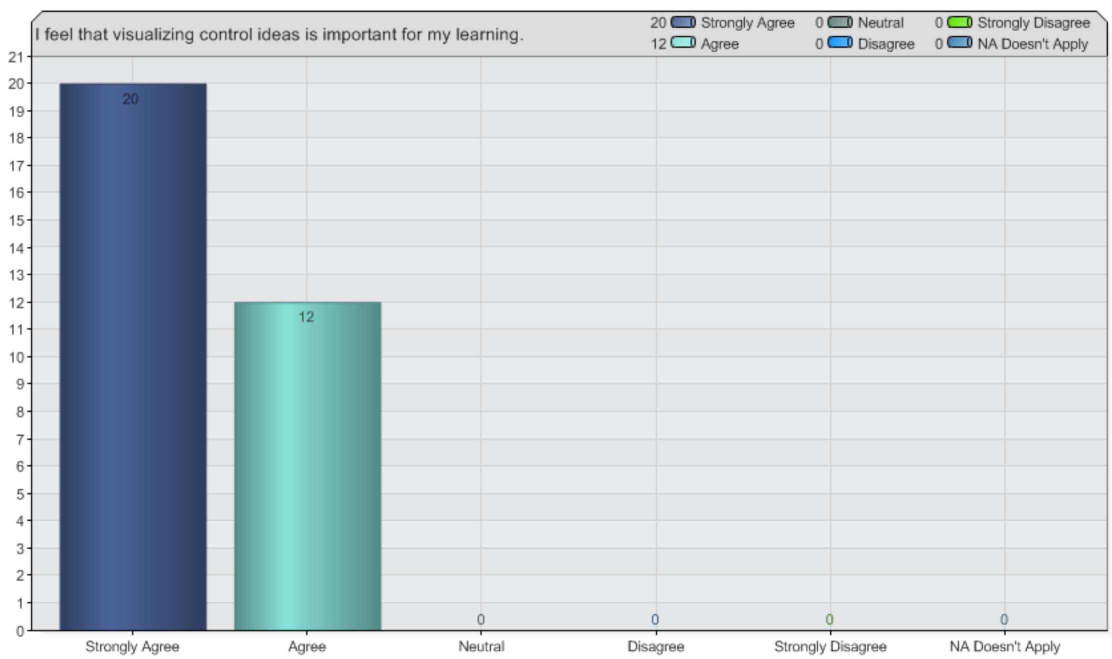


Figure A.4: Student feedback on Visualization of Controls

Q: I prefer to be introduction to new control concepts via visual hands-on activities

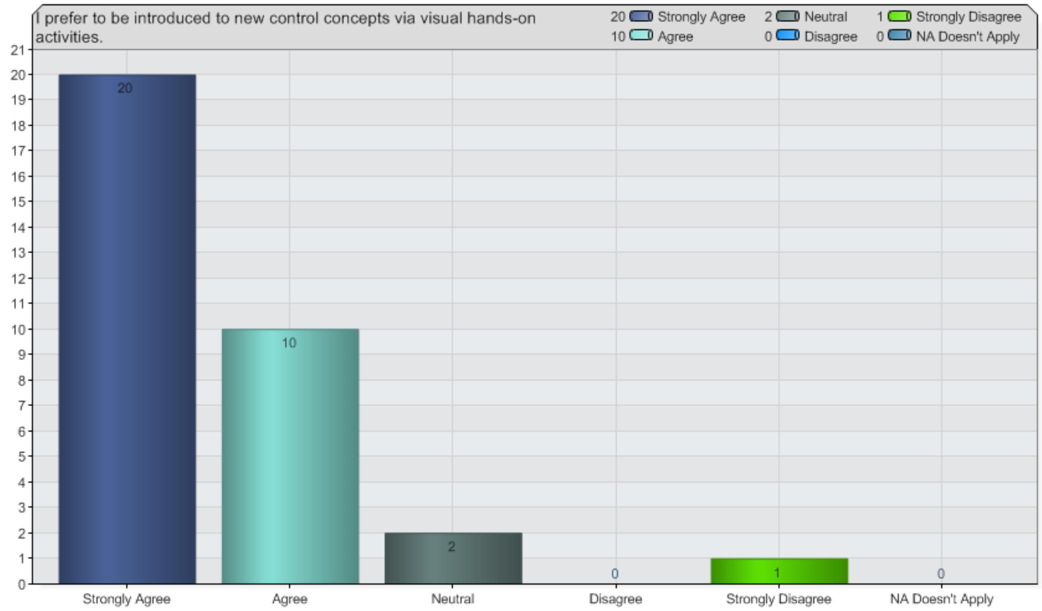


Figure A.5: Student feedback on visual hands-on activities

Q: I prefer to be involved in communication-based exercises to intuitively understand control system concepts

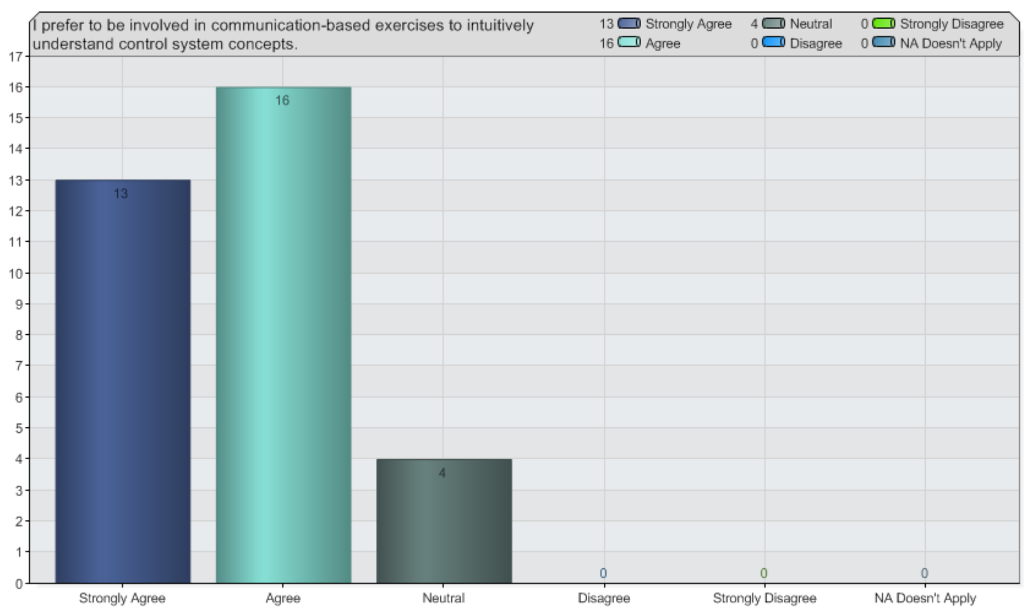


Figure A.6: Student feedback on communication-based exercises

Q: I prefer to learn control systems by reading class PowerPoint slides or transparencies

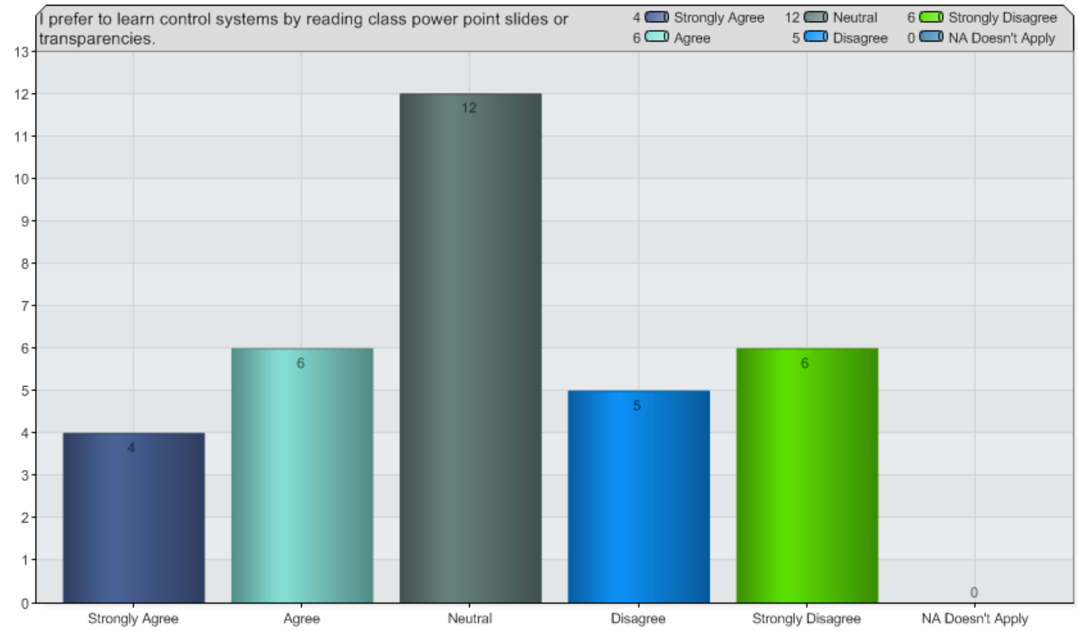


Figure A.7: Student feedback on learning by PowerPoint or transparencies

Q: I prefer not to be taught. I prefer to learn myself

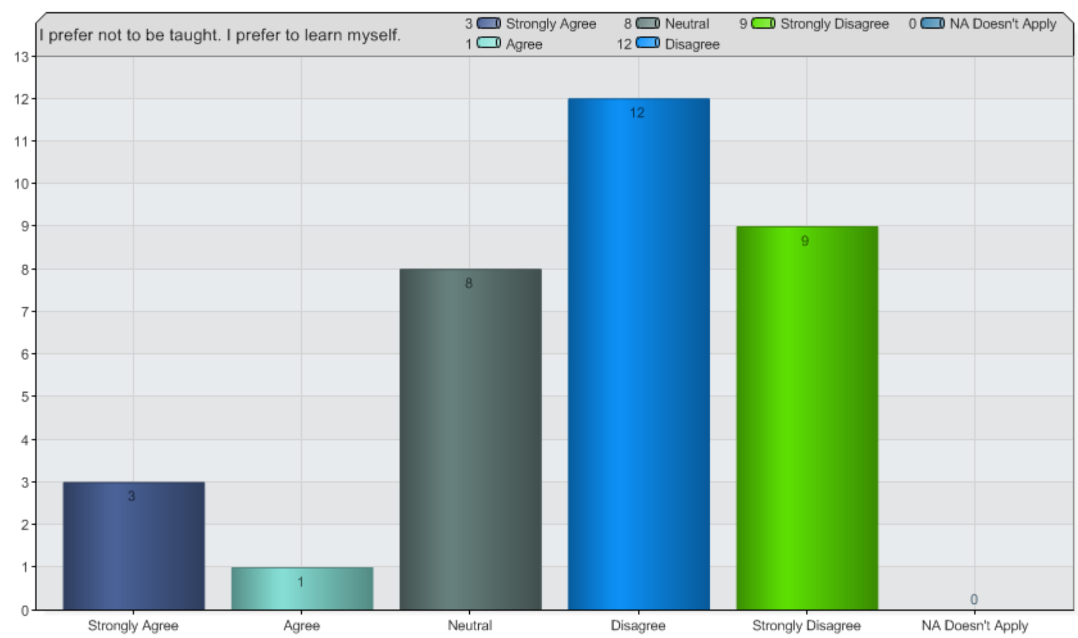


Figure A.8: Student feedback on self-teaching

Q: I prefer to learn about a control system topic by reading the relevant book chapter

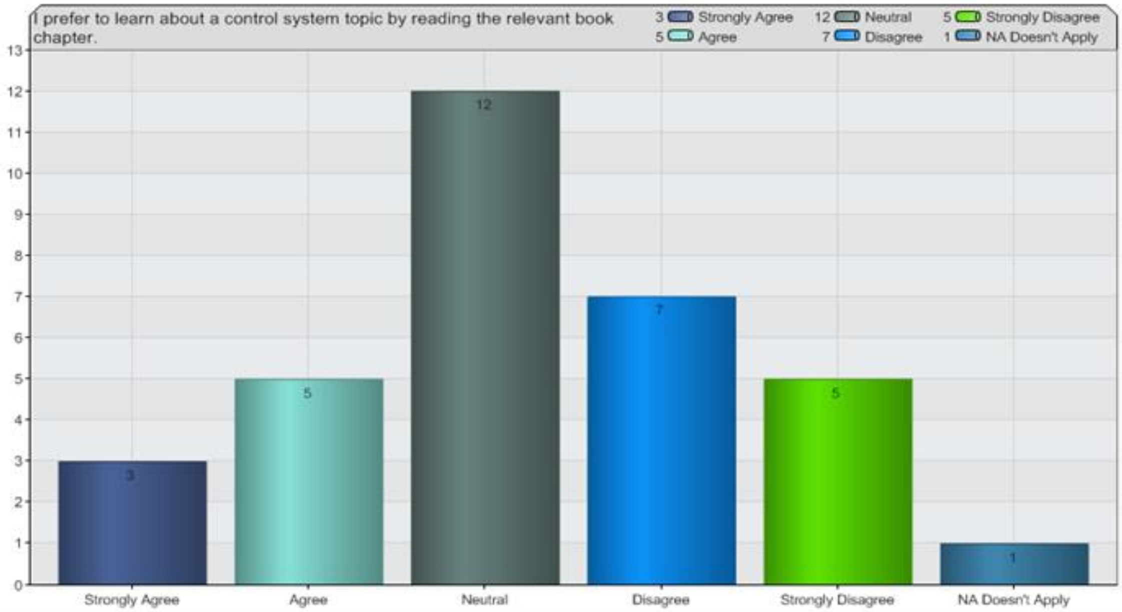


Figure A.9: Student Feedback on learning by reading relevant materials