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An Alternative Method to Teaching Design of Control Systems

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ABSTRACT

As technology advances, newer generations of students are being exposed to greater quantities of instantaneous information and media. As researches have noted an increase in visual media usage, they have correlated a reduction in academic performance. It may be for this reason that a greater number of instructors are noticing that students are finding it increasingly difficult understanding and retaining difficult concepts in STEM programs. As conventional methods of lecturing and prescribed reading do not always cater to students' styles of learning, a method is being developed at Florida Atlantic University to create a manuscript that provides students and instructors with visual and engaging material aimed at establishing intuition before transitioning into difficult concepts and deeper mathematical analysis. The manuscript is not meant to be a replacement to existing textbooks but to serve as supplementary material to aid in the teaching and understanding of difficult concepts in STEM. This paper highlights the methods employed, with examples and explanations.

1. INTRODUCTION

Over the last couple decades, the internet has provided the general populace with instant access to multiple forms of media. This instantaneous access has taken on a new meaning with the advent of tablets and smart phones. As newer generations develop with the increasing availability of media, the way they perceive and prefer to view information is changing. A study conducted by the Keiser Family Foundation showed that visual forms of media between children, ages 8-18, are on the rise. Visual forms of media include movies, video games television programming, and computer usage. Over the last five years, children have increased visual media usage from 6:21 hours a day to 7:38 hours a day. This means that over the course of a week, children spend more time with visual media than most adults do at work. While these numbers are on the rise, text based media is on the decline. Instant access may play a role as 20% of media is done by the use of mobile phone. The number of children with mobile devices rose from 39% in 2005 to 66% in 2010. In comparison, youths who spend more time with media report lower grades than other children as 47% of heavy users (3-16 hours a day) report low grades and behavioral issues while only 23% of light users (under 3 hours a day) report the same short comings (Rideout, 2010). This statistic does not necessarily mean that visual media is to blame for a students lack of success. It could imply that educators are not making a strong enough effort to cater to students changing styles of learning.

As childrens' preference for visual media has increased, instructors are noticing a larger disconnect from students to difficult concepts being taught in the classroom. Tyler DeWitt, high school teacher and Ph.D. student at MIT, noticed this phenomenon occurring with his high school chemistry students. As he taught the class some of his favorite topics in chemistry, he noticed students did not understand the content, regardless of prescribed book reading and well thought out lectures. It came to his attention that even his top students were failing to understand key concepts. In response, he developed a style of teaching that is designed to engage students, making the subject matter more fun for the audience. Mr. DeWitt's plea to educators is that although there is an importance for scientists to communicate on a higher level, more must be done to introduce young students to the same material in a less intimidating manner. This dialogue can be found in the TED Talk titled "Hey Science Teachers: Make it Fun!" (DeWitt, 2013)

American astrophysicist Neil deGrasse Tyson, made a similar claim during a key-note speech given to the American Association of Physics Teachers. In it, he highlighted the importance of educators making an effort to relate to students during lecture. He states that being a lecturer and being an educator are two different things. As children spend more than 30 hours a week watching television, teachers have a powerful tool by using pop culture to relate topics in lecture to situations students can relate to. “You know how much physics goes on in a football game? Transfer of momentum and moving coordinate systems — a moving ball plus a moving person intersect with a parabolic trajectory of a spiral, of a spin-stablized projectile? There's a lot of physics there, you don't even know how to go there, because you're not watching the same game they are,” (Holmes, 2010). In addition to hosting an educational science television program, NOVA ScienceNOW on PBS, he has been an active proponent of increasing general awareness and interest in STEM programs.

As educators such as Tyson and DeWitt stress the importance of making greater efforts to reach out to students, an approach has been developed at Florida Atlantic University to cater to students’ increasing demand for teaching techniques which focus on visual and engaging styles of learning. It employs visual, analogous examples that provide a smoother transition from concept to deeper mathematical analysis. The goal is to foster a non-intimidating learning environment, while keeping students interested and engaged. The contents have been compiled into a manuscript for a senior level electrical engineering course titled control systems.. Although similar approaches have existed among educators, there seems to be a lack of literature supporting this alternative methodology, especially in the areas of STEM and engineering. The following section contains an excerpt from the manuscript. As control systems material carries heavy components of math and physics, the manuscript is unique in the sense that it offers students and instructors with examples that require little to no pre-requisite in STEM. It is important to note that material developed is not meant to be a replacement to existing textbooks, but to serve as supplementary material aimed at reinforcing understanding and enhancing intuition.

2. METHODOLOGY

A typical example starts off with an idea or concept students are familiar with. Once a familiar scenario is played out, the components of the analogy are switched with components of concepts in control systems. This is typically achieved using little to no math.

The following examples come from an excerpt from the last chapter of the manuscript. This section differs from the majority of the text as it starts to introduce mathematical formulas in connection with the concepts taught throughout the preceding chapters. It differs from existing literature on control systems because it attempts to bridge the gap between mathematical representations of systems to their actual physical representation.

2.1 EXCERPT OF MANUSCRIPT

The Art of Design

Imagine you are an artist and you want to use the color green but you only have primary colors, red, blue and yellow. Yellow is already on the palate. What primary color would you add to create green?

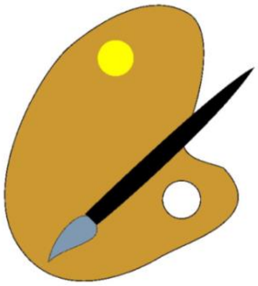

Figure 1: Palate

You undoubtedly learned from grade school that mixing blue with yellow results in green. If you wanted darker or lighter shades of green, you would just simply add more or less blue to the mixture.

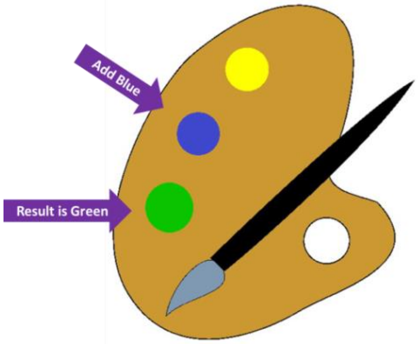

Figure 2: Palate with Additional Colors

The idea behind design of control systems is analogous to art. We modify existing “system dynamics” to obtain a better desired behavior. This is because every piece of hardware provides a specific performance given a specific input. Unless by some profound coincidence this piece of hardware has the exact behavior you desire right out of the box, you need to design another component to plug into the system in order to make it perform in a desired manner. Practically, when designing a control system, the existing “system dynamics” is modified. In this simple analogy, yellow is the existing “system dynamics” and blue is added to the mix to give the desired result, the color green. In design, we add dynamics to improve the system behavior just like adding color to improve the color.

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.

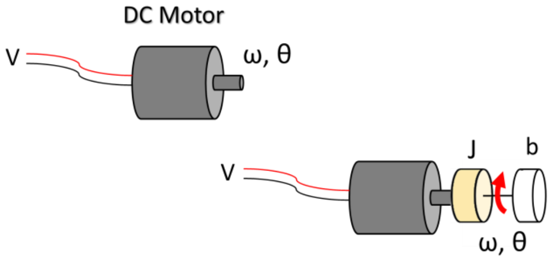

Figure 3: DC Motor with variables

Armature Controlled DC Motor Equations

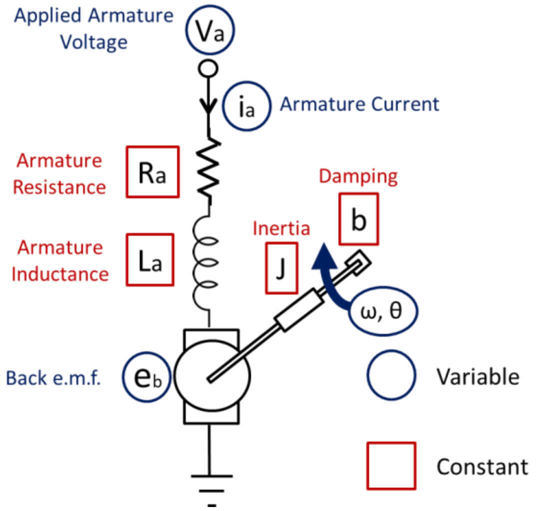

Figure 4: DC Motor Schematic

Writing the time domain equation leads to:

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

Figure 5: Time Domain Equations for DC Motor

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 6: S Domain Equations for DC Motor

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

$$\frac{\Omega(s)}{V_a(s)} = \frac{K}{R_aJs + R_ab + KK_b} = \frac{\frac{K}{R_aJ}}{s + \frac{R_ab + KK_b}{R_aJ}}$$

Figure 7: Transfer Function Equation for 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 8: 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 9: Gain and Inertia Constants

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

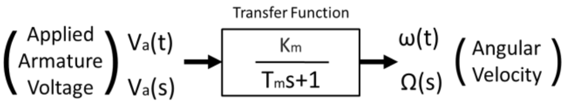

Figure 10: Blcok Diagram

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

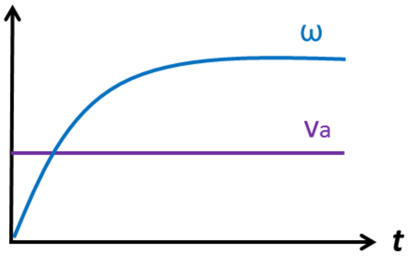

Figure 10: Graph Displaying DC Motor Input (Voltage) vs Output (Angular Speed) with Time

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 11: Transfer Function After Integration

Or in a Block Diagram:

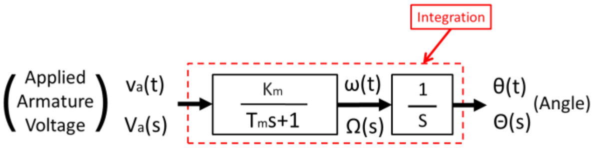

Figure 12: Integration in a Block Diagram

Which can be simplified to:

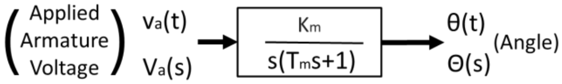

Figure 13: Simplification of Integration in Block Diagram

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.

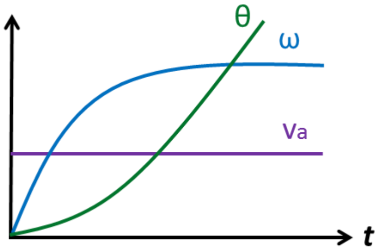

Figure 14: Graph Displaying DC Motor Input (Voltage) vs Output (Position and Angular Speed) with Time

Closing a Loop with a DC Motor

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.

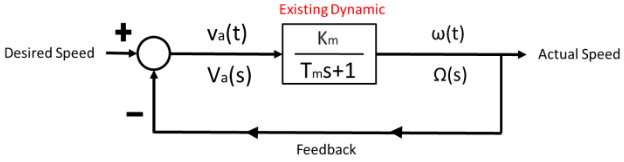

Figure 15: Block Diagram of Closed Loop System

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.

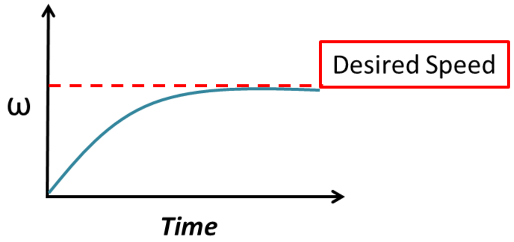

Figure 16: Graph Displaying DC Motor Behavior without Controller

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.

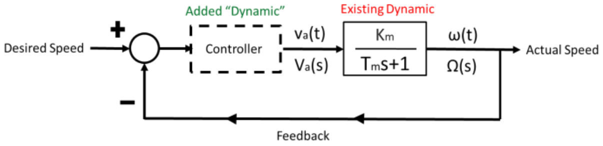

Figure 17: Block Diagram with Controller

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.

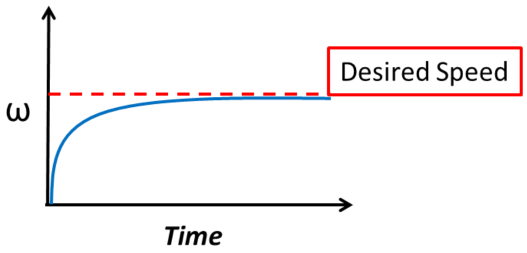

Figure 18: Graph Displaying Desired Behavior of Desired Speed

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.

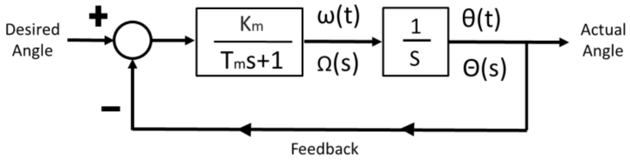

Figure 19: Block Diagram with Integrator

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

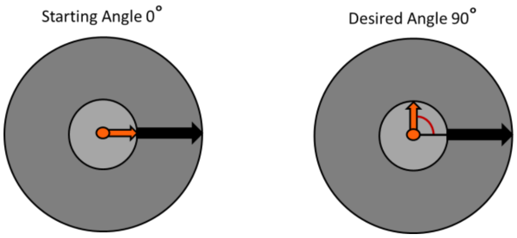

Figure 20: Side View of Motor with Starting and Desired Angle

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

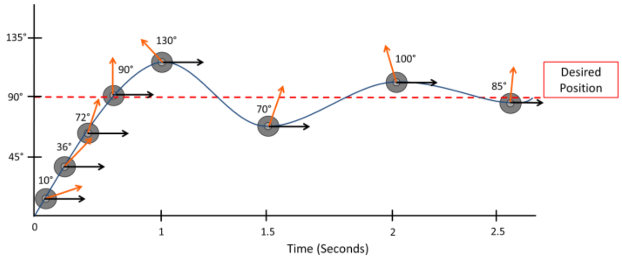

Figure 21: DC Motor Behavior without Controller

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.

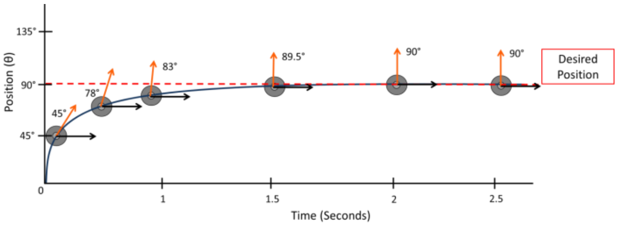

Figure 22: DC Motor Behavior with Controller

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.

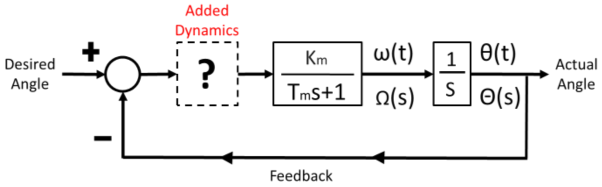

Figure 23: Block Diagram with Missing Component

Basics of Closed Loop Design

Let's observe the closed loop process!

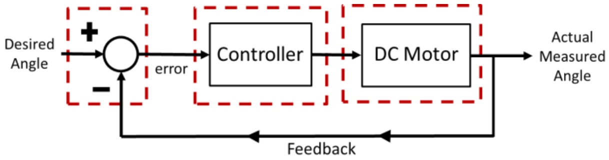

Figure 24: Simple Block Diagram

Note the "Desired Angle" and "Actual Measures Angle" output of the DC Motor. First, we set a value or function for the "Desired Angle". Using "Feedback" the "Actual Measured Angle" is subtracted from the "Desired Angle" to result in an "Error" signal. This error signal is manipulated by the controller to be fed to the DC Motor. As a result, the DC Motor rotates accordingly to provide a new Actual Angle. The Actual Angle is then measured and fed back to be subtracted again from the "Desired Angle".

Practically it looks like

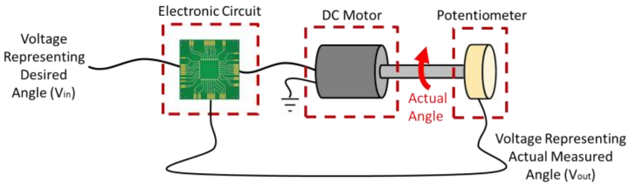

Figure 25: Physical Representation of DC Motor System

Voltage representing the Desired Angle of the DC Motor and the voltage representing the Actual Angle (i.e., the Actual Measured Angle) are fed into an electronic circuit (consisting of subtraction, controller, and power amplifier circuits). The output of the power amplifier circuit is the input voltage to the DC Motor circuit.

More Details

Taking a deeper look into the above closed loop system we find that the Actual Measured Angle (v_{out}) is subtracted from the voltage representing the Desired Angle (v_{in}) (by adding the inverted voltage of the Actual Measured Angle). This is followed by a Proportional-Integral (P-I) Controller. The output signal is enhanced via a Power Amplifier to allow enough current to the DC Motor. The Actual Angle (θ (t)) is measured by a potentiometer, which in turn is fed back.

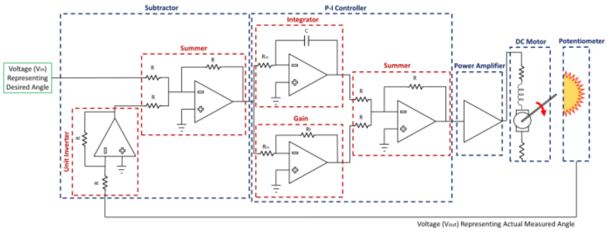

Figure 26: Electronic Schematic of Closed Loop System

For a while, engineers had to rely solely on hardware to change system dynamics. As hardware can be expensive, inflexible and sometimes with parameters that can change over time, designing complex systems could be difficult. The advent of software has made the implementation of a CPU based controller, more reliable and less costly. This works by inputting an analog signal into an A/D converter. Software that is coded to change the system dynamics (resulting in a similar effect as the hardware-based controller) sends the desired digital signal to a D/A converter, which in turn outputs an analog signal to the DC Motor.

The digital controller works by digitizing an analog signal using an A/D converter.

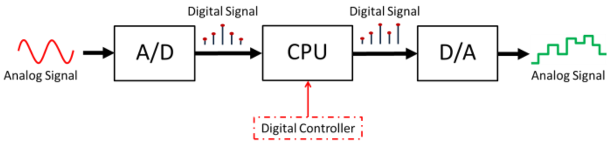

Figure 28: Digital Controller Block Diagram

Where are the Equations?

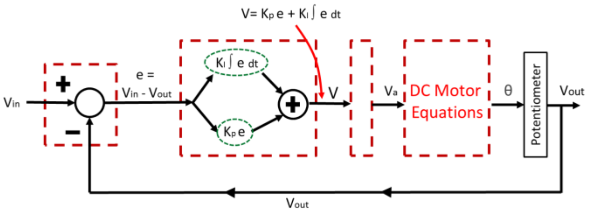

Figure 29: Block Diagram with Equations

Where are the Transfer Functions?

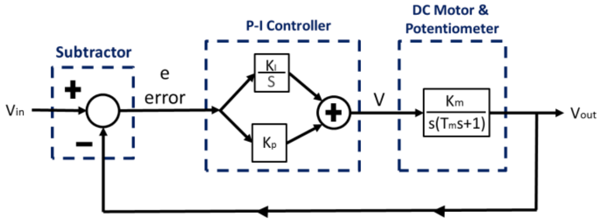

Figure 30: Block Diagram with Transfer Functions

…Or Simply

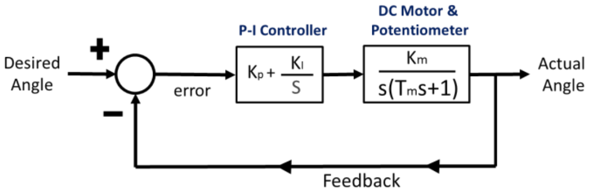

Figure 31: Block Diagram with Simplified Transfer Functions

The following is a summary of tools for analyzing and synthesizing a controller for a closed loop system. They help answer the following questions:

- Is this system stable? (R.H.)
- Where are the C.L. poles? (R.L.)
- What's the frequency response? (Bode)
- How does the frequency domain affect the stability? (Bode)
- Another Look (Nyquist)
- What's the time response? (Compare to original C.L. without controller)

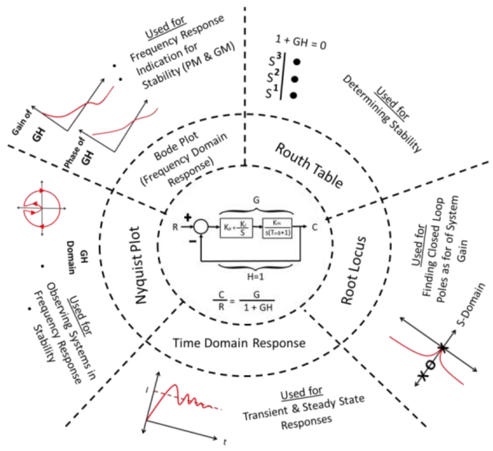

Figure 32: Diagram Displaying Analysis Tools for Control Systems

3. CONCLUSION

With the advent of mobile technology and applications that provide streaming media, the usage of visual media has increased among youths. This increase is correlated to a decrease in academic success. To mend the growing disconnects between students and lesson plans, educators must find alternative ways to increase students' understanding of the material and overall success academically. At Florida Atlantic University, an alternative method is being created to teach a course titled Control Systems. Breaking from tradition, the method focuses on providing visual examples that employ analogy to reinforce intuition. The approach is aimed at catering to students' needs for visualization while keeping them engaged. As educators have employed similar methods in the past, this manuscript is an attempt to provide literature that could serve as a reference to instructors. Other efforts are currently being made to create similar manuscripts for multiple topics in STEM such as Calculus, Algorithms and MATLAB.

4. REFERENCES

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