# A Visual Approach to Introducing Concepts in Control Systems

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***Abstract*– *Along with the technological advancements of this decade, a growing number of students have somewhat turned away from textbook-based traditional learning, while relying more on visual methods, such as web-based videos from other universities and learning platforms (e.g., The Khan Academy). Based on experience at Florida Atlantic University, we noticed that many students seek relevance of complicated and intangible heavy-math content to real life applications. In addition, after many years of teaching Control Systems courses, we observed that some students, while doing well in class assignments and exams, are missing understanding of basic key concepts. More specifically, they are all too often perplexed by the concept of stability. To address the question of how this became a pitfall for a grand majority of our students, we decided to introduce the material differently, i.e., to first establish the "aha" moment in students' minds, giving students something tangible to which they can relate - based on their own daily experiences. We have been trying to accomplish it in part using a 21-minute YouTube video. This video is also available to students and instructors at other universities, with the hope that they will use relevant parts in their learning and teaching. The video includes demonstrations, experiments, animation, stories, and real life examples, constantly connecting them to the concept of stability, while relating them to other concepts such as negative and positive feedback, and closed loop control. The concept of stability is introduced gradually, making sure there are no "discontinuities" in the presentation. In the first few days we noticed more than 200 viewers and a lot of highly encouraging feedback. In this paper, we list the activities with the take-away for each. They are organized in the following way:***

1. High level understanding (e.g., experimenting with Jenga-like tower)
2. Bounded Input Bounded Output (e.g., hearing screeching noise; story-telling)
3. Qualitative understanding of pole location, effects on stability and Connection to the s-plane(e.g., in class building and flying a paper airplane)
4. Connection to open and closed loop and feedback (e.g., performing in class broom balancing acts)
5. Quantitative measurement of degrees of stability and instability (e.g., jumping a rope; driving in a narrow street)

The video and this paper end with a challenge to the viewer to make sure he/she experience and further inquire about the concept of stability. We should notice here that this paper reports on larger scale on-going project that aims at explaining basic control system concepts in a similar manner.

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## I. INTRODUCTION

Why are concepts in a Control Systems course so difficult for students to comprehend? A great insight that can help answer this question is given by B.D. Coller, a Professor of mechanical engineering at Northern Illinois University [1]:

"Cognitive science, however, paints a different picture of how learning actually works. One of the most widely accepted and empirically confirmed models of how people learn is that of Constructivism. That is, human learning is constructed. Learners build new knowledge, based upon the foundation of previous learning."

Essentially, new information is filtered through mental structures which rely on things such as prior knowledge. Without consistency between the structures and the new information, the new information will probably not be fully incorporated [2]. This creates an inconsistency. This inconsistency coupled with the "rapid-fire" succession of equations thrown at students is often overwhelming [1].

There is however a unique advantage that present students have: the information age. There is a wealth of web-based information at their disposal. This encourages teaching methods to be supplemented with dynamic and innovative means [3]. In this age, more and more students are looking for increasingly unconventional and intuitive ways of comprehending concepts from lectures. This is why Neil DeGrass Tyson encouraged educators to wear a "cultural utility belt" [4] just as he did to supplement his teaching methods.

When it comes to conceptual understanding of Control Systems, there seems to be a disconnect. This is where a valuable opportunity arises: giving students the "aha" moment by way of easy, visual and intuitive examples has become a popular notion. Books have been published on the premise of taking advantage of the growing trend of visual learning in order to create intuitive analogies [5]. There are also many experiments in which this idea is tested. We have even seen encouraging preliminary results when teaching a Dynamics course using a video game [6], [7]. Given the vast amount of innovations that make the web more available to people, we begin to see new developments spring forth from this new environment. For instance, YouTube, a video-sharing website, allows users to create their own channel. A particular channel created by Brian Douglas [8] has had a great success in creating videos that supplement a controls course. With almost 7 million views, close to 90,000 subscribers, and a library of over 100 videos (and counting), this platform and its tremendous success could easily become a great example for others to follow.

The 21-minute YouTube video [9] that is detailed in this paper provides another avenue to supplement and enhance traditional teaching methods (but not meant to replace them). The target audience of the video are engineering students who are either taking or planning to take a basic Control Systems course. By using YouTube as a medium of communication we can reach students as well as professors who may decide to adopt part of the activities in order to enhance their teaching as well as students' learning.

In this paper, along with the video, readers and viewers alike are exposed to many different examples that introduce the concepts and different aspects of stable, marginally stable and unstable systems. They include examples based on daily experiences, such as a Jenga-like tower that many play at a young age, screeching noise heard in concerts, people behaviors (e.g., Power Lotto, troubles with adjusting shower temperature), and flying paper airplanes. The key feature is that of tangibility, putting on the 'cultural utility belt' and demonstrating something that students may relate to in order to become a building block in their foundation for the knowledge to come.

## II. HIGH LEVEL UNDERSTANDING

The following demonstration is an intuitive way to comprehend the very basic idea behind the concepts of stability and instability.

### A. *Using Jenga-like Tower*

A way to explain the meaning of stable, marginally stable and unstable systems is by using a Jenga-like tower, a familiar game for the vast majority of students. When analyzing the different phases of the tower throughout the progression of the game and correlating them to stability, students may be able to gain some tangible understanding.

In our video, we show a home-made giant Jenga-like tower made out of many 1.5" x 1.5" x 6" wooden blocks. It is constructed in a very fast motion to show different levels of stable systems, frozen at an "almost falling" position, and then falling in slow motion. This is followed by discussion referring to the different acts as stable, marginally stable and unstable phases of the tower.

As seen in Fig. 1, the tower is in a "stable" state. Even a quick shake of the table in which the tower is on does not cause it to fall over. However, during the progression of the game the tower becomes increasingly vulnerable to falling to a "just before instability" point and then reaching instability, i.e., it collapses.

Fig. 1 Stable Jenga-like Tower

In Fig. 2 the tower is "marginally stable." The tower is clearly not as stable as before but still not unstable. It is now at the borderline between stability and instability.

Fig. 2 Marginally Stable Jenga-like Tower

Finally, in Fig. 3, there is no question about the state of the tower. It is clearly "unstable."

Fig. 3 Unstable Jenga-like Tower

By incorporating such basic, yet tangible demonstrations, students may now have a better understanding and an "anchor" on which to base their knowledge of stability. This is an "aha" moment as the connection between the tower's balance and stability is made (Fig. 4).

Fig. 4 Jenga-like Tower at Different States

## III. Bounded Input Bounded Output

Once students have gained the understanding of a closed loop transfer function they can visualize the meaning of Bounded Input Bounded Output (BIBO) Stability. At first it may seem daunting to understand, but it boils down to a simple explanation: if for any bounded input, the system has a bounded output, then the system is BIBO stable. The following example is a special case that hints at unstable BIBO systems.

### *A. Hearing a Screech from Speakers Using Animation and an Experiment*

We all attend concerts or events that have a microphone and speakers. In the video, we show a case in which a pleasant situation becomes not-so-pleasant.

When the speakers are faced away from the microphone (not shown) all is fine and the audience enjoys the event. However, when the speakers face the microphone a familiar screech is heard (Fig. 5).

Fig. 5 Concert with Speakers Facing Microphone

This same idea is also demonstrated through an interactive animation. In the animation, music is played in the background while the user has full interactive control over the orientation of the speakers. By rotating the speakers to face the microphone (Fig. 6), the familiar screech is heard until it becomes unbearable.

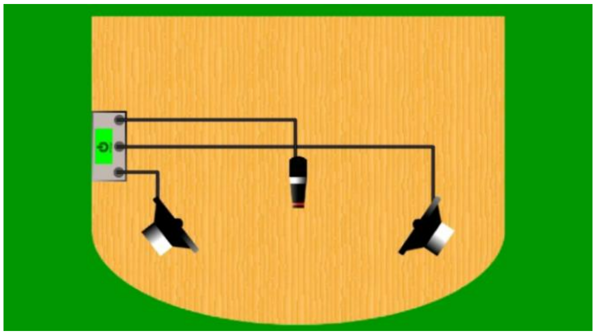

Fig. 6 Interactive Animation with Speakers Facing Microphone

We show the same idea using a real microphone and speaker, and suggest to the viewers to "try it at home." The microphone is waved around (Fig. 7), occasionally facing the speaker to produce a screech like the one heard in the animation.

Fig. 7 Microphone Waved Facing Speaker

As explained in the video, at first, when the system is "stable," the microphone picks up one's voice (input), which is amplified to be heard via the speakers (output). However, in the "unstable" case – when the "unbounded" noise is heard – the output of the speakers is picked up by the microphone, amplified and output by the speakers to commence the closed loop until the eventual screech is heard. This means the bounded input results in an "unbounded output." This of course is only theoretical, due to practical saturation of the screechy signal.

This phenomenon is also known as "positive feedback." It happens when the speakers are facing the microphone. It is clear that the system is not BIBO stable since the output (at least theoretically) is not bounded.

### *B. Adjusting Water Temperature While Taking a Shower*

Likewise, in the video we narrate a story common to us all: adjusting water temperature in a shower to a comfortable level.

We know that most showers are set up having the traditional two knobs. Turning one in a counter clockwise direction adds cold water, while turning the other in a counter clockwise direction results in added hot water. At first the water temperature is usually either too hot or too cold. Depending on the starting temperature one would either increase (or decrease) the hot or cold water by turning the corresponding knobs. After a few iterations, one can reach the desired temperature (Fig. 8).

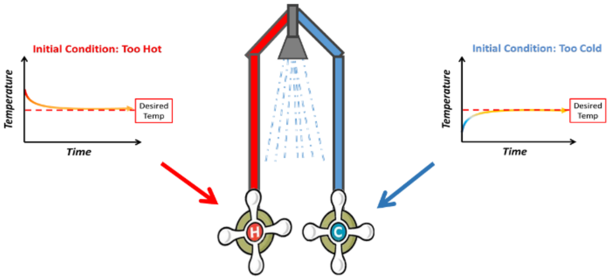

Fig. 8 Shower Temperature Control

Suppose a plumber arrives to fix a leak and accidently switched the colors of the knobs. Then, if the starting temperature is too cold, a person taking a shower would turn the "hot knob" to increase the temperature. Instead the water becomes colder and colder up to the point where he/she will eventually run out of the shower. No matter what the starting temperature is, the water temperature moves further away from the desired temperature (Fig. 9). This shower will therefore behave as an unstable system with the ever increasing or decreasing water temperature.

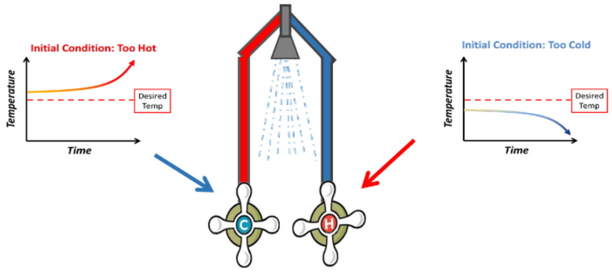

Fig. 9 Shower Temperature Control with Switched Knobs

## IV. QUALITATIVE UNDERSTANDING OF POLE LOCATION AND EFFECTS ON STABILITY

At this point we introduce the concept of pole placement and the effects on stability utilizing a qualitative example while varying the center of mass' location.

### *A. In Class Building and Flying of Paper Airplane with Varying Locations of its Center of Mass*

This example leads into pole placement and its effects on stability of a given system. We start by asking the students to build paper airplanes. Once constructed, we pose a question: what would happen if we place paperclips at the frontend of the airplane (Fig. 10)?

Fig. 10 Paper Airplane with Paperclips Placed at Frontend

After adding the clips and throwing the paper airplane for a "test flight" the students and viewers notice that the flight is indeed smooth (Fig. 11). This is an indication for stability. There is no stalling of the airplane.

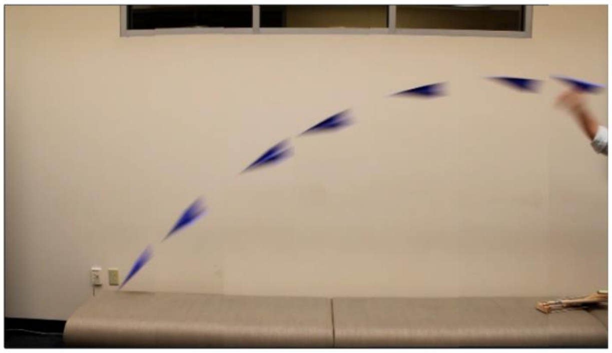

Fig. 11 Video Snapshots of a Flight Path with Paperclips Placed on Nose

Now we pose a second question: What would happen if the paperclips are in the rear of the airplane (Fig. 12)?

Fig. 12 Paper Airplane with Paperclips at the Rear-end

This time, when the students throw the airplane for a "test flight" they notice a completely different flight trajectory! The airplane is "tumbling," an indication for instability (Fig. 13).

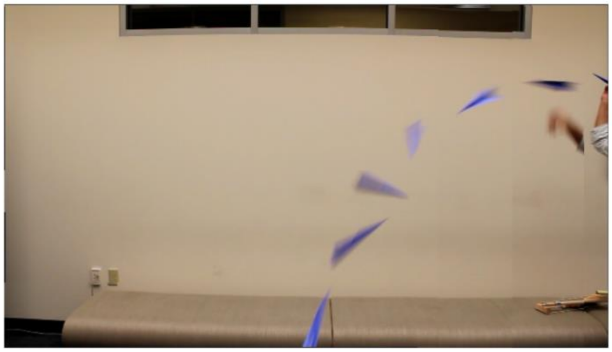

Fig. 13 Video Snapshots of a Flight Path with Paperclips Placed at the Rear-End

But why is there such a difference in stability stemming from paperclip placement (Fig. 14)?

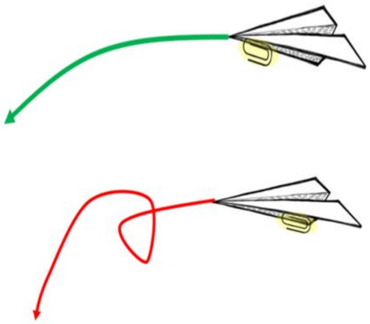

Fig. 14 Different Flight Patterns Based on Clip Location

A basic and intuitive explanation uses the relationship between center of pressure and center of mass of the airplane. For paper plane to be stable, the center of mass needs to be in front of the center of pressure. However, when the center of mass is behind the center of pressure we have an unstable flight (Fig. 15).

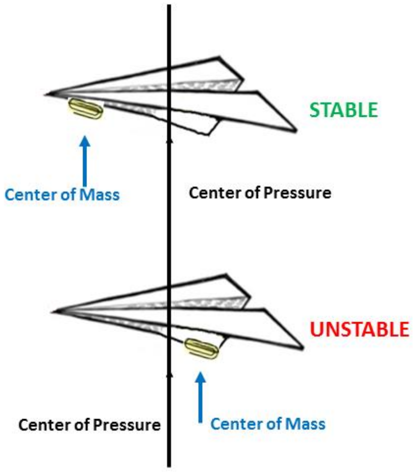

Fig. 15 Paper Airplane Stable/Unstable Comparison

## V. RELATING PAPER AIRPLANE STABILITY TO THE S-PLANE

Up to this point in the video, examples consist of “stable” or “unstable” systems. This section delves into a qualitative example of “levels” of instability.

### *A. Visually Relating Pole Locations to Paper and Actual Airplanes*

Following the demonstration and relation to stability/instability we relate the case to the location of the system pole to the s-plane. When we place the paperclips at the front of the airplane, (i.e., stable system) the pole of the system is on the left-hand side of the s-plane (Fig. 16).

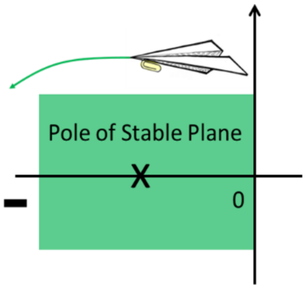

Fig. 16 Pole of a Stable System

In the second case where the paperclip is placed behind the center of pressure, the system has a pole in the right-hand side of the s-plane (Fig. 17).

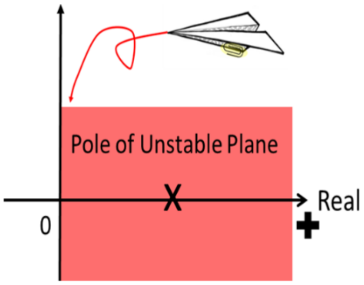

Fig. 17 Pole of an Unstable System

This allows students to tie together the concept of stable and unstable systems along with pole placement. As the pole moves to the right-hand side of the s-plane, the airplane becomes unstable.

Not only can the airplane “just” be stable or unstable, it can also be shown how “moving” the paperclip affects the location of the system’s pole, resulting in “levels” of stability and instability (Fig. 18).

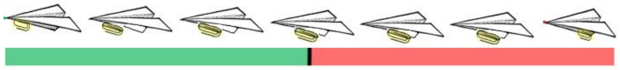

Fig. 18 Qualitative 'Levels’ of Stability

We then relate the concept to real life examples, this time not with paperclips, but by drawing comparisons to airplanes such as the Boeing 747 and the X-29.

The Boeing 747 (Fig. 19) is a large commercial airplane with the purpose of transporting passengers and/or cargo around the world. It is designed and built with the safety of its passengers and cargo in mind. Should all engines fail, the plane is stable and is able to glide in mid-air even without a pilot.

However, when looking at the X-29 (Fig.20), being an experimental aircraft with the purpose of testing forward-swept wings and canard control surfaces meant its design is deliberately aerodynamically unstable.

Fig. 19 Boeing 747 [10]

Fig. 20 X-29 [11]

Due to this unstable design, we know the plane is not able to glide without a pilot closing the loop to make it stable in closed loop.

## VI. CONNECTION TO OPEN LOOP AND CLOSED LOOP

As discussed earlier with a few examples, it was noted how "positive feedback" could make a system unstable. We now tackle "negative feedback" which we refer to as just "feedback." Feedback allows us to (sometimes) bring an unstable system back to stability. By having a set position or value (like in the shower temperature example), we can use feedback to provide information about a system's output. A controller then uses this information to adjust the systems output to the desired position or value.

Many students have a difficult time understanding the fundamentals of open and closed loop systems. In many books the qualitative difference is a line connecting the output to the input; clearly confusing for some readers. In the words of B.D. Coller, "The subject is very mathematical and the mathematical framework is unfamiliar to novice students." [1] A tangible explanation is needed for students to make the connection. Fortunately, such a connection can be seen with the following Broom Act.

### *A. Performing in Class Broom Act*

Many students have seen a street performer attempting to balance a stick at a carnival or fair. The performer needs to provide constant feedback by readjusting the broom's position in order to keep the stick in place and in a "stable" manner, i.e., he/she needs to "close the loop." In the video, we use this example to illustrate a closed loop system and its corresponding open loop.

To get a balanced broom the performer must constantly look at and "feel" the broom's angle as well as angular change to provide feedback to balance the broom. In other words, the system needs feedback. The error signal provides the performer with information on how to compensate appropriately in order to maintain balance (Fig. 21). With appropriate feedback the system behaves as desired and is usually "stable."

Fig. 21 Balancing Broomstick

What happens if the performer were to become tired or distracted? Without constant readjustment, the stick will not be balanced appropriately and become increasingly "unstable," eventually falling to the ground (Fig. 22).

Fig. 22 Unbalanced Broomstick Falls

To control an unstable system, in this case an upside-down stick, feedback is necessary. This example makes a clear-cut connection between open and closed loop systems. A simple daily example makes a difference!

## VII. RELATING TO NEGATIVE AND POSITIVE FEEDBACK

A simple demonstration in the video deals with a broom stick, this time oriented horizontally. Starting with forefingers outstretched as in Fig. 23 (a).

(a) (b) (c)

Fig. 23 (a, b, c) Forefingers Outstretched on Horizontal Broom Stick

Then we show the motion of the fingers moving toward each other. In this demonstration, the fingers eventually come together at the center of mass, and therefore, the stick is balanced (Fig. 23 (b)).

The experiment can be repeated several times, even with different initial position of the fingers. The end result will always be the same, no matter whether it is a broom stick, or any stick-like object.

By closely analyzing the experiment, one can notice that only one finger at a time moves. It may seem as if both move simultaneously, but in reality, because of different friction forces (that are alternating with time), only one finger moves at any given moment. This happens until the friction force between the broom and the finger in one hand exceeds the friction force between the broom and finger in the other; the finger motion keeps switching roles. This continues until the fingers meet at the stick's center of mass. This is an example for *negative feedback*.

A very different scenario occurs when we try to move the fingers away from the center of mass as shown in Fig. 23 (c). Surprisingly only one finger moves away from the center of mass. This occurs due to a slightly greater friction force initially exerted on one finger which causes the other finger to move away from the center, therefore, causing even more friction force between the stationary finger and the broom. Thus, the other finger moves more smoothly, i.e., as the moving finger progresses, less and less friction force is exerted on it.

It is here where the connection to *positive feedback* is made. Contrary to the first experiment with the horizontal broomstick where there is a clear negative feedback, this case exhibits a growing difference in friction forces exerted on the two fingers. This is positive feedback! Due to this difference in friction growing, the intended outcome of having both fingers move relatively simultaneously becomes impossible.

As it turns out, the experiment can even be repeated, leading to the same results even when the center of mass is located at a different place on the broomstick due to added weight at one end. In the video, we attach a broom head at the end of the stick and repeat the experiment (Fig. 24).

Fig. 24 Negative Feedback and Positive Feedback Demonstrations with Attached Broom Head

## VIII. QUANTITATIVE MEASUREMENTS OF DEGREES OF STABILITY

We continue with stability, this time we discuss levels of stability, i.e., how close a system is to instability. In the case with the paper airplane, a qualitative example is given by seeing the pole of the plane "move" from one side of the s-plane to the other just by moving the paperclip (Fig. 18). In this part of the video we explore a more quantitative aspect.

This concept is demonstrated by loosely holding a stick vertically at different places (Fig. 25).

Fig. 25 Demonstration of Levels of Stability and Instability with Broomstick

From Fig. 26, we show the stick going from "very stable," to a bit "less stable," to "unstable," and to even more "unstable."

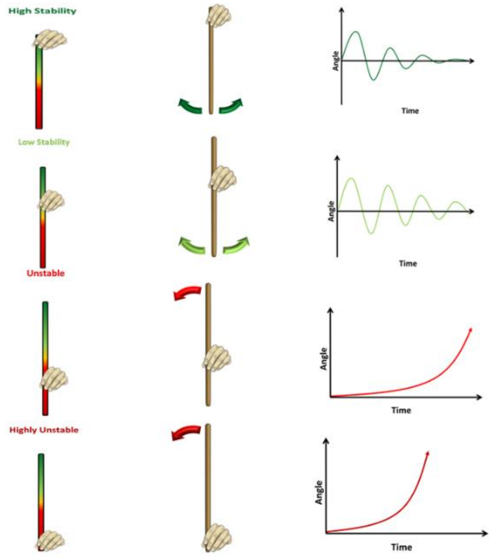

Fig. 26 Levels of stability and Instability with Broomstick

Another example to visually explain levels of stability and instability is of two cars coming toward each other using varying road widths (Fig. 27).

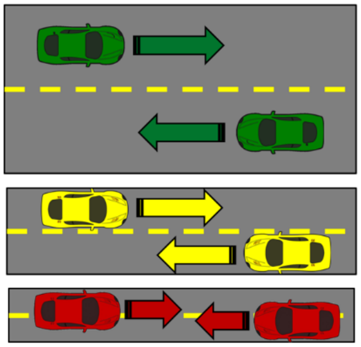

Fig. 27 Levels of Stability and Instability –Cars and Road Size Example

The approaching green cars are shown metaphorically as a stable case (since they do not collide), yellow for marginally stable (borderline case), and red for unstable (due to imminent collision). Clearly, as the width of the road shrinks, the situation approaches "instability."

Similarly, we use the example of jump rope (Fig. 28). When the rope is far away from one's legs, there is no chance of it getting caught with them. However, when decreasing the length of rope, we go from a very safe case all the way to a very unsafe case, i.e., from "stable" to an "unstable" situation.

Fig. 28 Levels of Stability and Instability –Jump Rope Example

In Fig. 29 we refer to a quantitative measure of degrees of instability, i.e., phase margin.

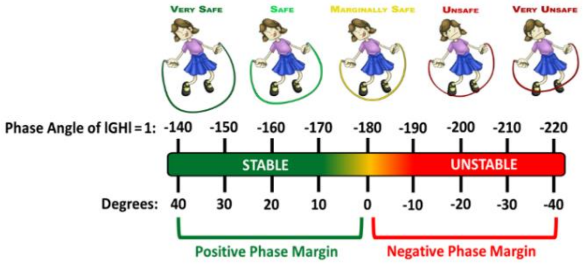

Fig. 29 Degrees of Instability – Visually Relating Jump Rope and Phase Margin

We can calculate the phase margin (for gain $GH = 1$) as a measure of stability. Showing that for a phase larger than $-180°$ (i.e., less negative), we have a positive phase margin resulting in a stable system. However, for a phase more negative than $-180°$, we have negative phase margin and an unstable system.

## IX. OPEN CHALLENGE

Toward the end of the video, the viewer/reader is left with an engaging take-home challenge in order to further spark curiosity and interest, just as it is done in class. Starting with two distinct cup arrangements, one joined at the rims and the other at the ends of the respective cups we allow them to roll down an incline (Fig. 30).

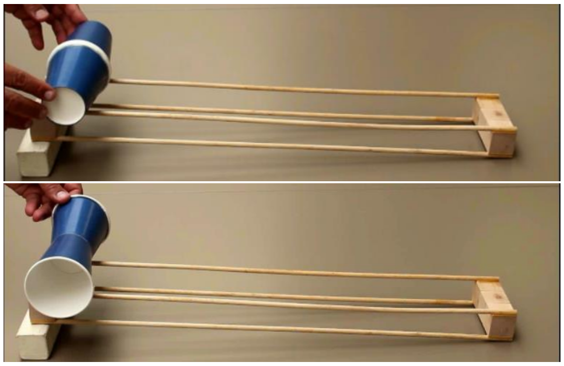

Fig. 30 Open Challenge Side View

The video continues by showing a top view of the experiment (Fig. 31).

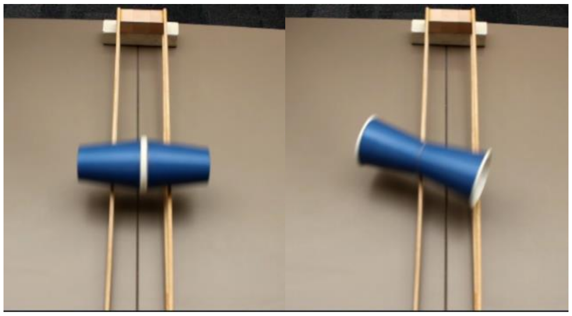

Fig. 31 Open Challenge Top View

Shown from both angles, the viewer/reader can clearly see the trajectories of both experimental sets. The cup arrangement joined at the rims rolls down, always staying directly at the center of the incline until the end with any deviation being self-corrected. In the second experiment, in which the cup arrangement is joined at the bottoms ends, it quickly deviates and comes off of the incline before the end of the path. The viewer/reader is asked to come up with explanations of the matter based on what they have seen in the throughout video.

## X. ASSESSMENT

The video has received very encouraging feedback from students and professors. It has also been broadcasted throughout the university to all electrical and computer engineering students. Within the first week of sharing the video it received over 200 views and very many "likes." Due to the nature of this medium, traditional assessment methods cannot be used. Rather, it is based on crowd-based feedback received, i.e., number of video views and "likes." It should be noted that statements from some engineering professors such as "I wish I had learned I this way when I was a student…" have also been received. Some professors who do not teach control surprisingly said: "I finally understand stability."

The contents of this video and corresponding paper are a work in progress. We plan to release more videos with more comprehensive content and assessment.

## XI. CONCLUSION

We have taken up a challenge of introducing a specific concept in Control Systems, namely stability, in more visual, intuitive and engaging ways.

This video is not meant to replace conventional teaching methods. Rather, it demonstrates new options that may help the many inundated and/or bewildered students who face this concept every semester. By providing tangible connections, engineering students taking Control Systems or any other person interested in learning may indeed benefit from the content provided. To explore the subject of stability of Control Systems with a firm, tangible foundation on concepts covered (such as BIBO stability, levels of stability, the s-plane, open and closed loop, negative and positive feedback, and quantitative measurements of degrees of stability and instability) may very well clear up any cloudiness associated with the subject. We hope that the video (part of which explains class demonstrations) will produce “aha” moments for many students, allowing them to spend less time struggling to understand fundamental concepts.

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