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WIP: A Visual and Intuitive Explanation of Steady State in Feedback Control Systems

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Abstract

Teaching introductory Control Systems presents a common challenge: many students view it as a mathematical exercise rather than an engineering discipline grounded in physical reality. This perception stems partly from textbooks that emphasize analytical derivations while offering few intuitive, experience-based explanations. As a result, students often struggle to connect theoretical models to real-world systems. Even high-performing students may leave the course without a solid grasp of fundamental ideas such as modeling, stability, steady-state behavior, and the meaning of feedback.

This paper introduces an approach for teaching steady state and steady-state error through visual, intuitive, and engaging examples. The goal is to help students internalize the essence of steady-state behavior in closed-loop systems, beyond the formulas found in traditional textbooks. The discussion highlights situations in which feedback occurs naturally, even without an explicit sensor, showing how steady-state error can be understood directly from system behavior rather than formal computation.

The approach aims to help students experience the physics and engineering "aha" moment before engaging with mathematical formulation. Examples emphasize visual and experience-based feedback phenomena, where connections to standard block-diagram representations are not always obvious. This perspective encourages students to recognize feedback principles in both natural and engineered systems, fostering conceptual understanding before formal analysis.

The concept of steady state is clarified through demonstrations showing that steady does not mean static. A system may continue to move or oscillate in a balanced or repetitive way - as in sinusoidal steady state. Using simple time plots and first-order step responses, students clearly distinguish between transient and steady-state phases and visualize how the steady-state error forms and decays.

The examples in this paper are divided into several groups:
(a) Basic mechanical systems such as the roly-poly toy, and balancing bird, which return naturally to equilibrium; (b) Everyday analogies including the weighing scale, and bathtub - where inflow and outflow balance at steady state; (c) Centrifugal, density, and flow-based systems such as the governor, airship, cruise control, and windmill fantail, illustrating equilibrium through feedback; (d) Oscillatory systems - for example, the deer scarer, electric bell, or tipping-bucket rain gauge - where behavior repeats periodically rather than settling; and (e) Continuously unstable systems, such as the air dancer, included for contrast and engagement.

Together, these examples help students visualize the transition from transient to steady-state behavior, linking mathematical models with physical intuition and real-world feedback phenomena.

Following an initial qualitative assessment, a more rigorous extra-credit evaluation was conducted. Students identified steady-state phenomena from fields like chemistry, physics, and biology and rated this teaching approach. Scores showing strong support for intuitive, visual methods that students found exciting, practical, and memorable. Engagement scores indicated that adding real physical systems could enhance learning. Ratings for reducing heavy derivations suggest a preference for intuition and visualization before mathematical detail.

This work in progress does not aim to modify textbook chapters but to provide a supplementary resource that enhances the introduction of steady-state concepts and promotes intuitive understanding.

Key words: Feedback control systems, Error signal

1. Introduction

Teaching introductory Control Systems often presents a familiar challenge: many students approach the material as a collection of mathematical procedures rather than as an engineering discipline rooted in real physical behavior. This tendency is reinforced by traditional textbooks that prioritize analytical derivations and provide relatively few intuitive or experience-based explanations. As a result, students, sometimes even high performers, may struggle to connect theoretical models with the systems they are meant to describe, particularly when learning foundational concepts such as modeling, feedback, stability, steady-state behavior, and steady-state error.

To address this gap, we introduce an instructional approach that places intuition, visualization, and physical experience at the forefront when teaching steady state and steady-state error. The intent is to help students grasp the essence of steady-state behavior in closed-loop systems before encountering the corresponding formulas. Many of the examples illustrate feedback that emerges naturally in real systems, even when no explicit sensor is present. These cases allow students to understand steady-state error through the behavior of the system itself rather than solely through formal computation.

A key component of this approach is encouraging students to experience the "engineering intuition" moment early. Visual explanations and real-world analogies highlight feedback principles that may not be immediately obvious from standard block diagrams. This helps students recognize that feedback is not limited to engineered control loops; it also appears in natural, biological, mechanical, and everyday systems. In addition, we emphasize that steady state does not necessarily imply stillness, a system may move or oscillate in a balanced, repetitive pattern, as in sinusoidal steady state. Using simple time plots and first-order step responses, students learn to distinguish the transient phase from the steady-state regime and see how steady-state error emerges and stabilizes.

The instructional examples are organized into several groups: (a) **Basic mechanical systems**, such as the roly-poly toy and balancing bird, that naturally return to equilibrium, (b) **Everyday analogies**, including weighing scales and bathtubs, where inflow and outflow balance at steady state, (c) **Centrifugal, density, and flow-based systems**, such as governors, airships, cruise control, and windmill fantails (d) **Oscillatory systems**, including deer scarers, electric bells, and tipping-bucket rain gauges, where steady-state behavior is periodic rather than static; and (e) **Continuously unstable systems**, such as air dancers, included to highlight contrast and stimulate engagement.

Collectively, these examples help students visualize how systems transition from transient to steady-state behavior, providing a bridge between mathematical descriptions and physical intuition.

Following an initial qualitative assessment based on student reactions, a more rigorous evaluation was launched through an extra-credit assignment. Students were asked to identify steady-state phenomena from disciplines such as chemistry, physics, and biology, and to evaluate this teaching approach. Student ratings (1–10 scale) showed strong support for intuitive and visual teaching approaches, with most categories scoring 8–10. Students found the material highly exciting, practical, and memorable. Visuals and intuitive explanations were considered especially effective for understanding concepts. Engagement scores (7–10) suggested that incorporating real physical systems - not only simulations - could further improve learning. Interest in reducing heavy formula derivations reflects a preference for intuition and visualization before mathematical detail.

A variety of resources offer useful perspectives on how to introduce control systems, complementing the numerous excellent textbooks available on the subject. For instance, [1] provides an extensive set of feedback-system examples, many of them highly visual. Reference [2] offers an accessible introduction to key ideas and concepts in feedback control, and several of the illustrations used in the present paper are reproduced from it with permission. A rich historical survey - focused largely on mechanical feedback devices - is presented in [3]. The earliest Automatic Self-Regulatory Device is clearly documented in [4], while [5] offers detailed descriptions of systems such as the 1958 Chrysler cruise control and various centrifugal governors. Approaches that incorporate visual gaming and programming into feedback-control instruction are described in [6]. Of particular relevance to this paper is [7], which includes practical examples such as a liquid weighing station, chicken feeding station, spring-based mechanical scale, pressure-control mechanisms, and water-level regulation. In addition, [8] serves as a useful reference for visually introducing the foundational principles of control systems.

This work represents a supplementary teaching strategy rather than a replacement for textbook coverage. *is not meant to replace existing textbooks chapters.* Its goal is to enrich the introduction of steady-state concepts and provide students with a deeper, more intuitive understanding of feedback and system behavior before transitioning to analytical detail.

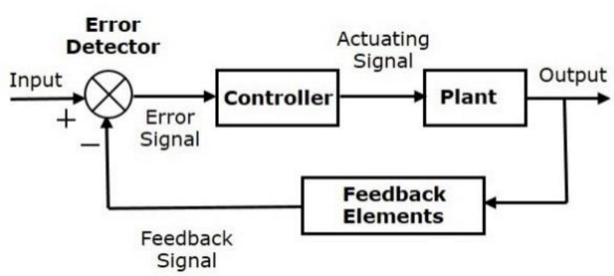

Figure 1: Typical textbook closed-loop diagram of a control system

This paper focuses on some elements of feedback control systems as seen in Figure 1. Specifically, it focuses on the meaning of the error signal which is the result of the subtraction element.

2. Class Examples

The examples in this paper are divided into several groups:

(a) Basic mechanical systems

Example 1: The Balancing Bird

The classic balancing bird toy provides a simple yet powerful illustration of a natural mechanical feedback control system that maintains the bird at a steady orientation (Figure 2).

Figure 2: Balancing bird – actual image

Its design places the center of gravity directly below the beak, creating a stable equilibrium. When the bird is disturbed from this orientation, the center of gravity rises (indicated by the orange arrow), generating a restoring moment. This moment automatically pushes the bird back toward its original balanced position.

A simplified block diagram of this self-correcting process is shown in Figure 3.

Notably, the system identifies the orientation error *implicitly*: it does not require measuring the bird's actual angle or knowing the exact equilibrium orientation. Instead, any displacement naturally produces a moment imbalance, which acts as the feedback signal. This moment drives the bird back toward equilibrium, completing the feedback loop.

Example 2: Roly-Poly Toy

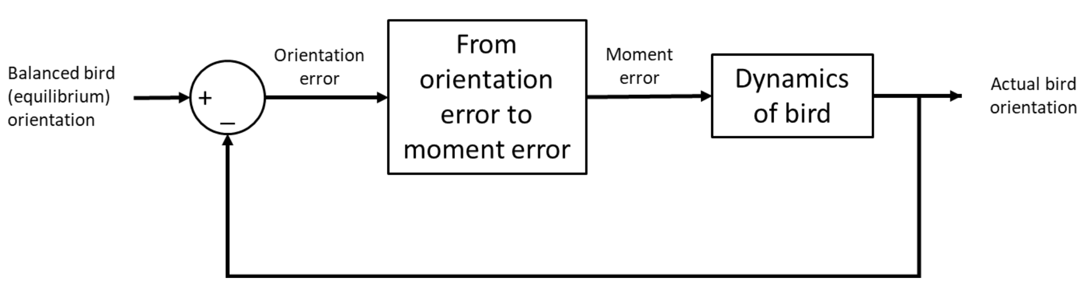

Figure 3: Block diagram of the balancing bird: note the orientation error

Refer to figure 4. A roly-poly toy is shaped so that its center of gravity (CG) is at its lowest point only when the toy is perfectly upright. If the toy is pushed and tilts, its CG rises and shifts away from the support point. This displacement creates a restoring moment that naturally works to bring the toy back toward the upright position. The toy rocks back and forth until it eventually settles.

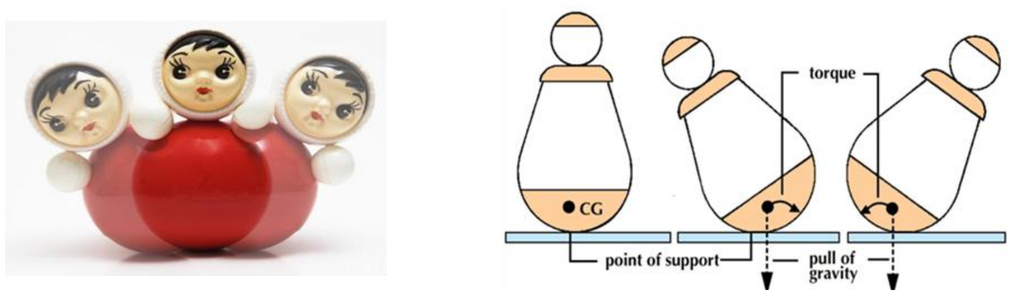

Figure 4: Roly-poly toy – relation to center of gravity

Image sources: https://fineartamerica.com/featured/roly-poly-toy-giphotostock.html
https://kids.britannica.com/students/assembly/view/53661

Refer to figure 5. In terms of feedback control, the desired position (reference input) is the perfectly vertical orientation. When the toy is disturbed, the actual angle becomes different from the desired angle. This difference, i.e., the error angle, automatically causes a shift in the CG relative to the contact point. The horizontal shift, denoted "d," produces a restoring moment proportional to "d" (by a constant factor "k"), which drives the toy back toward its equilibrium.

As the toy oscillates and loses energy, the moment gradually decreases. Finally, when the toy reaches its upright configuration, the steady-state error becomes exactly zero.

No explicit sensors or electronic feedback paths exist in this mechanical system. Instead, the toy's geometry, mass distribution, and natural mechanics perform all three functions simultaneously: sensing the deviation, generating the corrective action, and reducing the error to zero.

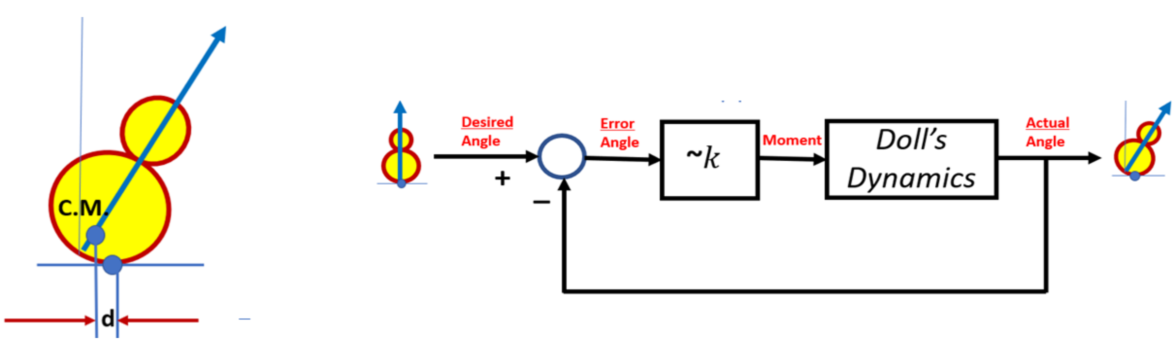

Figure 5: Roly-Poly system diagram: note the error signal

(b) Everyday analogies

Example 1a: Doctor’s scale

A doctor’s scale (Figure 6) works like a see-saw: your weight pushes one side down, and the sliding weights move until the bar balances, the tilt of the bar is the *error*, and when the see-saw finally sits perfectly level with no tilt, the *steady-state error* is zero and the positions of the weights tell your weight.

Figure 6: Doctor’s scale – an apparatus based on steady state balanced weight

Example 1b: Old-Fashion supermarket scale

An old-fashion supermarket scale (Figure 7) works like a see-saw with your produce on one side and known metal weights on the other: the tray tilts when the two sides don’t match, that tilt is the *error*, and weights are added or moved until the bar becomes perfectly level, meaning the *steady-state error* is zero and the total of the metal weights is exactly your produce’s weight.

Figure 7: Mechanical balance scale

Example 2: Flush toilet mechanism

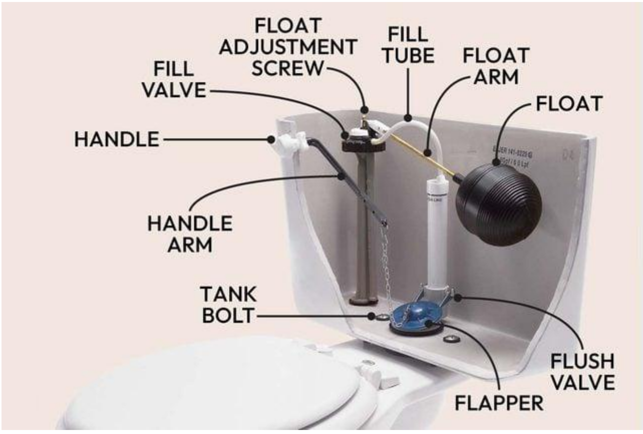

Figure 8: Flush toilet mechanism: at steady state the Fill valve is fully closed

Refer to Figure 8. After flushing the toilet, the water level drops, and the float drops with it. This lowering of the float creates an *error*, the tank is no longer at its desired water level, which causes the valve to open and let water flow in. As the tank refills, the rising float provides mechanical feedback by lifting the lever and gradually closing the valve. When the float reaches the exact height that corresponds to the desired water level, the valve fully shuts. At that point the *steady-state* is reached, the *steady-state error* is zero, and the water stays at the correct level until the next flush. Figure 9 shows the block diagram of the closed-loop system.

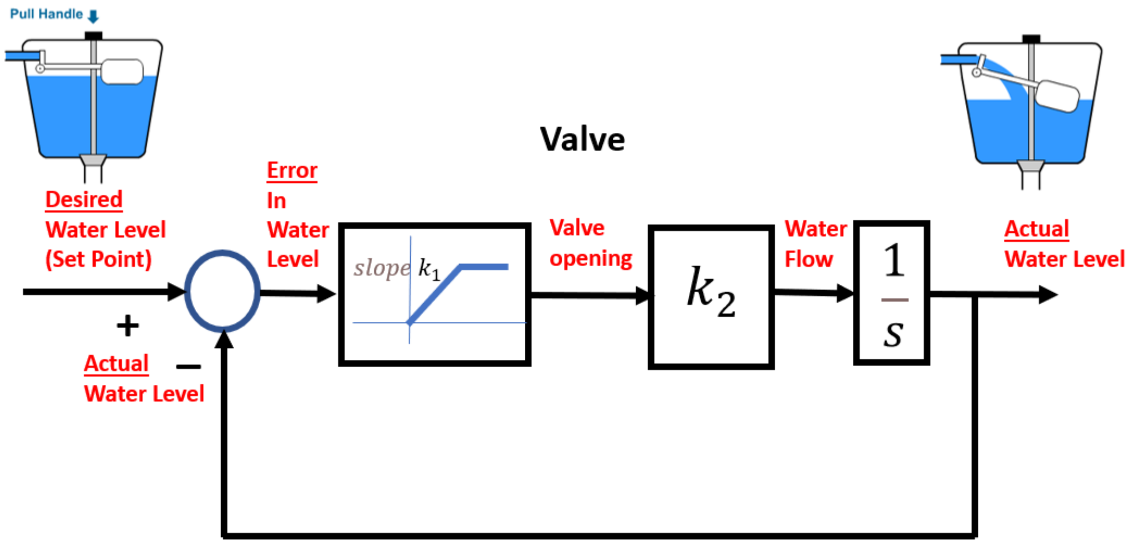

Figure 9: The Toilet: A mechanical closed-loop system. Note the error that eventually reaches steady state

(c) Centrifugal, density, and flow-based systems

Example 1: Universal governor

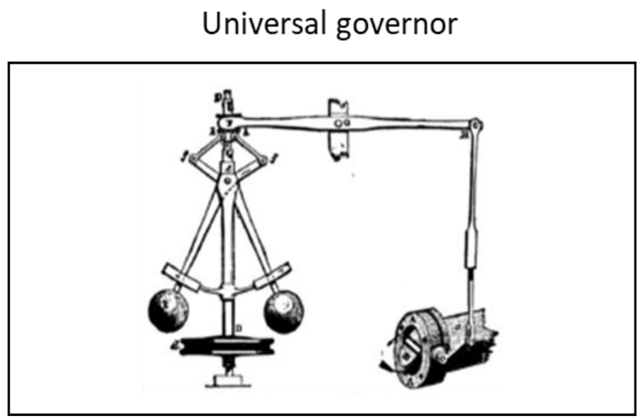

Figure 10: Universal Governor: At steady state the swing angle is constant

A centrifugal (flyball) governor (Figure 10) automatically regulates engine speed by using rotating masses to create a mechanical feedback signal. As the engine shaft turns, the two balls spin with it; higher speed produces greater centrifugal force, causing the balls to swing outward and lift a sliding sleeve on the central spindle. This sleeve is linked to the engine's throttle, so when the balls rise the throttle partially closes, reducing fuel or steam and slowing the engine. When the engine slows, the balls fall inward, the sleeve drops, and the throttle opens to increase speed again. The system settles at a steady angle where centrifugal force balances gravity, giving a stable operating speed.

Example 2: Farm windmill

Figure 11: Farm windmill achieves zero steady state error for wind speed and direction naturally

A farm windmill (Figure 11) reaches steady state when the aerodynamic torque produced by its spinning blades exactly balances the mechanical torque required to pump water. As wind begins to blow, the blades accelerate until the turning force generated by the wind equals the resistance of the pump mechanism and friction in the system. At this point the rotor spins at a nearly constant speed: not faster (because extra torque is absorbed by the pump load) and not slower (because the wind keeps supplying just enough torque). Most farm windmills also have a self-regulating tail-and-hinge system that turns the wheel slightly out of the wind at high wind speeds, reducing effective blade area so the rotation speed stays within a safe operating range. Together, this creates a stable steady state where blade speed, pumping rate, and wind direction remain in balance, despite fluctuations in wind speed.

Example 3: Cruise control

When you activate cruise control at a chosen speed, say 55 mph, the goal is for the car to settle into a stable condition where the speed stays constant. This stable condition is the **steady state**, where ideally the difference between the desired speed and the actual speed is zero. (See Figure 12).

Cruise control works by constantly measuring your real speed and comparing it to the target. The system looks at the *error*, i.e., the difference between "what you want" (55 mph) and "what the car is actually doing."

Now imagine you are climbing a long hill while cruise control is on. The car tries to maintain 55 mph, but you notice the speedometer shows 53 mph. That 2-mph drop is the *error* created by the extra load of the slope.

If the hill continues and the car is unable to fully eliminate that difference, the system may reach a new steady condition where the car stays at 53 mph instead of 55. The remaining difference, after the system has done all it can and the speed has "settled", is the *steady-state error*. In this case, with a target of 55 mph and a long-term actual speed of 53 mph, the steady-state error is 2 mph. The values change depending on the uphill slope.

Figure 12: Mechanical cruise control is slope-dependent steady state error

(d) Oscillatory systems
This is the case where behavior repeats periodically rather than settling,

Example 1: Shishi-Odoshi

The Shishi-Odoshi (Figure 13) is a simple water-powered mechanical oscillator that works by repeatedly shifting its balance as water fills and empties a small container on one end of a pivoted arm. As water slowly accumulates, its added weight creates an increasing imbalance, or "error," between the two sides of the arm. When this imbalance reaches a critical tipping point, the arm suddenly rotates, dumps the water, and becomes light again. Gravity then restores the arm to its original position, allowing the next filling cycle to begin. After a few initial cycles, the system naturally settles into steady-state oscillation, meaning that each cycle repeats with nearly constant timing: the same amount of water is needed to tip the arm, the same imbalance develops, and the arm flips back and forth in a uniform rhythm. In steady state, the inflow of water and the gravitational restoring forces become balanced in a repeating pattern, so the device continues its characteristic periodic motion without change unless the water flow or the counterweight is altered.

Figure 13: Shishi-Odoshi is a simple water-powered mechanical oscillator

Example 2: Buzzer

A buzzer (Figure 14) functions as a simple electromechanical oscillator in which an electromagnet repeatedly interrupts its own circuit. When power is applied, the circuit momentarily closes, energizing the electromagnet. The resulting motion of the contact arm immediately breaks the circuit, which turns the electromagnet off; the arm then relaxes and re-closes the circuit. This cycle of **on → off → on** continues automatically. Instead of reaching a constant steady state (like a system that settles to a fixed value), the buzzer settles into a **steady oscillatory state**, a repeating pattern in which the electrical and mechanical variables continually switch between two levels. The timing of these pulses becomes nearly regular, creating the familiar buzzing sound. The feedback diagram (Figure 15) reflects this behavior: the system generates a binary-type error that drives the electromagnet, and the repeated correction of this error sustains the ongoing oscillation.

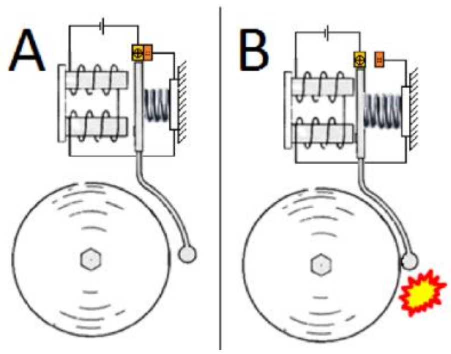

Figure 14: Buzzer: Oscillatory steady state

(e) Continuously unstable systems

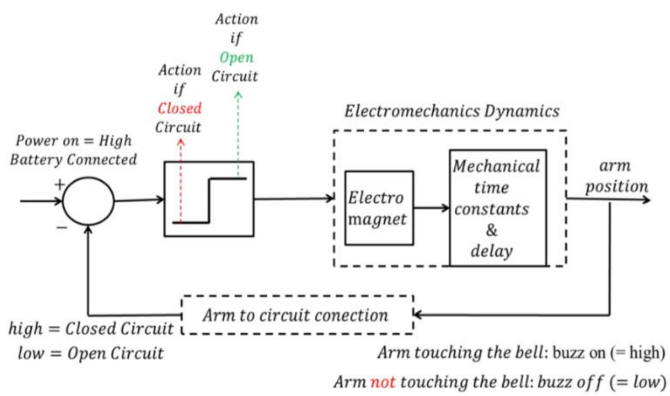

Figure 15: Buzzer system block diagram

Example 1: Air dancer. The case where steady state does not exist

An air dancer (Figure 16), the tall, flexible, inflatable "tube man" often seen at car dealerships, provides a vivid example of a system with *no steady state*. Instead of settling into a fixed equilibrium, the continuously streaming air creates ever-changing internal pressure patterns that make the tube bend, collapse, rise, and twist in a perpetual, irregular oscillatory motion. The airflow never allows the structure to stabilize; any brief upright moment is immediately followed by another deformation. In essence, the air dancer lives in a *dynamic, self-sustained oscillatory regime*, where instability is not corrected but *celebrated*, producing continuous, playful motion with no meaningful steady-state condition.

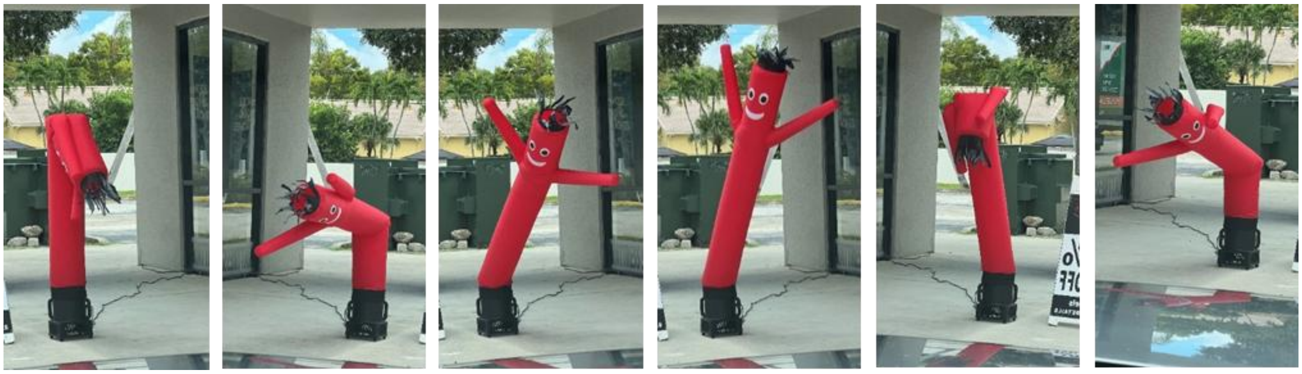

Figure 16: Air dancer: the case where is no steady state

3. Students' assignment

27 students were asked to develop well-explained examples, each from a different discipline such as medicine, electrical engineering, aeronautics, chemistry, physics, biology, nature, or computer science, that clearly illustrate the concepts of **steady state** and **steady-state error**. For each example, students were instructed to provide a title, a specific description, a clear explanation of its relevance to steady-state behavior, and to include a figure whenever appropriate.

In addition, students were asked to evaluate this intuitive and visual method of learning. Using a 1–10 scale (10 being the highest), they rated their **overall excitement level**, the amount of **intuition**, **visualization**, and **engagement** they prefer when learning new concepts, as well as their preference for **less formula derivation**.

4. Students' examples

This response reorganizes the information into a comprehensive table, incorporating a detailed description column to enhance the understanding of the mechanism and context of each example, as requested.

Detailed elaboration of steady state examples

The steady state (SS) is the final, stable operating condition of the system. The steady state error is the persistent, non-zero difference between the desired target (reference) and the actual stable output.

A. Sports and motion systems

Example Title	Detailed Example Description	Steady State (SS)	Steady State Error
1. Competing Runners	Two boys are running a race. The first boy is faster and maintains a lead. The second runner attempts to catch up by adjusting his speed to compete, but cannot entirely close the gap between them.	The second boy's speed eventually stabilizes, causing the distance (gap) between him and the faster runner to become constant.	The **constant distance** by which the second boy lags behind the faster runner, representing the persistent difference between the target (catching up) and the result.
2. Racing Cars	Two cars are racing on a highway. The second car attempts to go slightly faster to surpass the first car but is unable to increase its speed sufficiently to win.	The speed of the second car stabilizes at its maximum achievable value, and the distance between the two cars becomes constant.	The **constant distance** the second car lags behind the first, showing the persistent difference between the desired goal (winning the race) and the actual outcome.
3. Archery	An archer is aiming at a target. Despite repeatedly adjusting their aim, the arrow consistently lands slightly off the target. The shots stabilize around a point near the target but never achieve a perfect center hit.	The arrow's landing position eventually stabilizes at a consistent spot relative to the target.	The **persistent distance** between the target (goal) and the arrow's actual landing point, showing the unavoidable difference between the desired outcome and the actual result.
4. Football Goalkeeper Tracking	A football goalkeeper continuously observes the ball's lateral position (the setpoint) and adjusts their own position along the goal line to stay aligned with the ball's predicted impact point. The goalkeeper's visual system is the sensor, and their brain is the controller.	The goalkeeper successfully aligns with the ball's path and stops moving, or their position stabilizes in the corresponding proper position to the ball's attack angle.	A **persistent offset** between the goalkeeper's position and the set position, which may be caused by reaction delays or a conservative movement (low "gain").

B. Engineering and physical systems

Example Title	Detailed Example Description	Steady State (SS)	Steady State Error
5. Battery Charger	A battery is being charged using a standard charger. Due to internal resistance, efficiency losses, or charger limitations, the battery never reaches 100% charge.	The battery voltage eventually stabilizes at a nearly constant level, which represents the maximum charge the charger can provide.	The **difference** between the desired 100% charge and the actual final charge stabilized, representing the residual error that persists despite the charging process.
6. Ping Pong Ball Hovering	A ping pong ball is suspended above a hair dryer blowing upward. The ball hovers in the air, staying roughly at the same height, but continuously wobbles slightly due to small fluctuations in the airflow.	The ball's average height stabilizes at a certain level above the dryer.	The **small, persistent vibrations** or wobbles around the average height, showing residual deviations from the desired steady position despite continuous balancing forces.
7. RC Circuit (Ideal vs. Non-Ideal)	A capacitor charges through a resistor by a DC voltage source (e.g., 9V or 5V reference). The current decreases exponentially as the capacitor voltage builds up.	After a long time, the capacitor is fully charged, its voltage is constant (e.g., 9V), and the current is 0A.	**Zero volts (0V)** in an ideal circuit where the final voltage equals the reference. If non-ideal effects exist (like internal resistance), the voltage might settle at 4.95V instead of 5V, resulting in an 0.05V error.
8. Leaky Bucket	A bucket (with a small hole disturbance) is filled by a constant tap flow (input). The water level rises, increasing the pressure at the hole and thus increasing the leak rate.	A point is reached where the flow rate of water leaking out exactly equals the flow rate of water trickling in. The water level stops rising and stays constant.	The **difference in height** (e.g., 5 inches) between the desired full level (reference) and the actual settled water level (steady state).
9. River Level/Dam	A dam regulates river water level to prevent flooding. After heavy rain (input), the water level rises, and the dam releases water to	River level eventually stabilizes near the safe target height after compensating	The **small difference** between the target water level and the actual level, due to external disturbances.

	stabilize it. Inflow fluctuations can affect the stabilization.	for inflow fluctuations.	
10. CPU Temperature Regulation	A CPU adjusts its fan speed (control action) to maintain a safe operating temperature (target) during heavy processing. Response delays or environmental heat can act as disturbances.	CPU temperature stabilizes near the ideal target.	The **persistent difference** between the target temperature and the actual stabilized temperature.
11. Aircraft Autopilot Altitude	The autopilot's altitude-hold mode measures the current altitude (sensor) and compares it to the desired setpoint (e.g., 30,000 ft). The system commands elevator deflection (actuator) to counteract disturbances like wind gusts.	The aircraft maintains constant altitude (vertical speed = 0), flying level at a final, relatively constant value.	The plane settles at a **small, persistent offset** (e.g., 20 feet or 50 feet) below the desired altitude (30,000 ft) if the controller is simple (Proportional) and needs a constant error to generate corrective force.
12. Magnetic Hysteresis	The primary winding current establishes the required flux density (setpoint) in a transformer core. Due to magnetic hysteresis, the core's magnetization lags behind the AC input current.	The flux density settles into its required alternating pattern in response to the AC input.	A **persistent, non-zero magnetizing current** must flow to overcome residual magnetization (hysteresis)
13. Engine Thrust Asymmetry	The autopilot attempts to maintain a zero yaw rate, the setpoint) by adjusting the rudder (control action). A persistent thrust difference between engines (disturbance) creates a persistent moment.	The aircraft maintains a stable flight path, counteracting the engine thrust difference with a constant rudder deflection.	A **non-zero yaw offset** is required by a simple proportional controller to generate the necessary rudder deflection to hold the aircraft straight against the persistent disturbance.
14. Vacuum Chambers	A vacuum system's pumps attempt to achieve a perfect vacuum However, outgassing from chamber walls and micro leaks act as a constant gas load (disturbance).	The constant gas load is perfectly balanced by the pump's constant removal rate, leading to a fixed, non-changing residual pressure.	A **nonzero residual pressure** stabilizes, because the pumping system requires a nonzero pressure greater than zero to generate the flow

			necessary to carry away the constant gas load.
15. Robotic Stiction	A motor applies torque to position a robotic joint at a target angle. Stiction (static friction) is a non-linear force that prevents movement until a minimum breakaway torque is exceeded.	The motor stalls, applying a torque insufficient to overcome static friction, and the joint angle has settled to a fixed position.	An **unavoidable, fixed offset** occurs because the torque required to correct the small remaining error is less than the stiction torque, preventing the final actuation.
16. Cruise Control Speed	A car's cruise control is set to maintain a desired speed (e.g., 60 mph). When the car encounters an incline (load/disturbance), the system increases the throttle (control action) to compensate.	The speed settles to a constant value after reacting to the load and adjusting the throttle.	If the car consistently maintains 59 mph instead of 60 mph while on the incline, the error exists because a simple controller (Type 0) requires a persistent error to produce the constant control output (throttle) needed to counteract the constant load.
17. pH Neutralization	An automatic titration system aims to maintain the pH of a liquid at a neutral value (pH=7.0). An acidic waste stream (disturbance) is continuously added, and the system pumps a basic solution (control action) to neutralize the acid.	The pH of the liquid stabilizes and remains constant despite the ongoing acidic disturbance.	The system consistently stabilizes at a slightly acidic pH of 6.8. It is because the pump only works when there is an error, preventing it from reaching the exact setpoint.

C. Biological and medical systems

Example Title	Detailed Example Description	Steady State (SS)	Steady State Error
18. Insulin Regulation	The human body regulates blood glucose concentration (output) toward a target range (e.g., 90 mg/dL). After a meal (glucose input/disturbance), the pancreas releases insulin (control action).	In a healthy individual, the blood glucose level settles back to a stable, baseline level.	For a diabetic person, the blood sugar level stabilizes at a persistently **elevated concentration** (e.g., 110 mg/dL), resulting in a non-zero undesirable error.

19. Ventilator Oxygen Control	Mechanical ventilators use closed-loop feedback control to maintain a target arterial oxygen saturation. The ventilator adjusts the fraction of inspired oxygen to keep levels stable despite disturbances like coughing.	The patient's Oxygen level reaches and stays near the desired target set by the clinician (e.g., 96%).	The measured oxygen level stabilizes **below or above** the setpoint due to system limitations or inaccuracies in the patient's respiratory system.
20. Plant Water Balance	A potted plant continuously loses water through transpiration (evaporation from leaves). To survive, it replaces this water through root absorption. The roots try to compensate when loss rates increase (disturbance).	Water absorption and transpiration rates are balanced, and the plant's moisture content remains constant.	The plant stabilizes at a **slightly lower water level** than ideal (a persistent deficit) because, for example, limited soil moisture (low "gain") prevents it from perfectly matching the water loss.
21. IV Drip Rate Control	An IV drip delivers fluids or medication to maintain a patient's fluid volume or drug concentration at a stable, therapeutic level (setpoint). The nurse (controller) monitors vital signs (sensor) and adjusts the flow regulator (actuator).	The patient's condition stabilizes, and vital signs remain constant and within healthy limits.	When, despite a stable IV rate, the patient's measured condition remains **slightly off target** (e.g., stabilizing below target due to flow being slightly less than required, causing underhydration).
22. Presbyopia (Eye Focus)	The human eye's focusing mechanism attempts to bring light rays from an object into a sharp focus precisely on the retina (setpoint). With age, the lens loses elasticity and muscles weaken.	The eye's lens and ciliary muscles have settled into a fixed position while viewing an object held at a constant distance.	The **achieved focus power is persistently short** of the required focus power due to lens stiffening and muscle weakening. The final stable output is persistently short of the desired target.
23. Controlled Drug Delivery	A smart pump infuses a drug at a controlled rate (control action) to maintain a specific therapeutic concentration (e.g., 10 ng/mL, the reference) in the bloodstream, balancing elimination by the body (disturbance).	The drug concentration in the bloodstream stabilizes at a relatively constant level within the therapeutic window.	If the concentration consistently settles at 9.8 ng/ml due to suboptimal calibration or patient metabolism differences, there is a steady state error.

24. Body Temperature	The hypothalamus (controller) tries to maintain a core temperature setpoint (approx. 37°C). When entering a cold environment (disturbance), the body shivers (actuator) to generate heat.	The body reaches a new equilibrium where the heat generated by shivering equals the heat being lost to the environment, and the core temperature stabilizes.	A **persistent difference** (e.g., 0.2°C) between the 37°C setpoint and the actual stable temperature, because the controller requires a persistent error to maintain the necessary control action (shivering).

D. Economic, societal, and computing examples

Example Title	**Detailed Example Description**	**Steady State (SS)**	**Steady State Error**
25. Central Bank Rate Control	The central bank tries to maintain a target inflation rate (e.g., 2%). When inflation rises, the bank increases interest rates (control action) to make borrowing expensive and slow spending.	Inflation remains stable at or near the target level, neither rising nor falling.	When inflation consistently stays slightly **above or below** the target (e.g., stabilizing at 2.5% instead of 2.0%) despite corrective interest rate adjustments.
26. Student Learning	A teacher aims for a target performance level (setpoint). Students receive instruction (input), and the teacher measures output (assessments/sensor). The teacher provides feedback (control action) to reduce the gap.	The student consistently performs at or near the desired performance level, meaning learning has stabilized.	If 10 out of 100 students fail a course even after repeated review, it represents a 10% **steady state error** (the difference between the desired outcome, 0 fails, and the actual outcome).
27. Legal Enforcement	Laws regulate societal behavior (setpoint). When violations occur, law enforcement detects the deviation and applies corrective action (penalties/actuator) to restore order.	The rate of law violations stabilizes at a low, manageable level, meaning the legal system is effectively maintaining order.	A **persistent level of crime** or non-compliance remains despite enforcement, often due to weak or inconsistent penalties (low "gain").

28. Web Server Load Balancing	A load balancer distributes traffic (requests/disturbance) across a server cluster. The goal is to keep the average CPU utilization at a target level (e.g., 30% or 70%). The controller redirects traffic to the least busy server.	The servers' CPU loads hold steady after initial traffic spikes, settling to a stable percentage.	If the goal was 70% but the system stabilizes at 65%, there is 5% difference error. This persistent difference indicates suboptimal resource use but may ensure system stability.
29. Grocery Checkout Line	The manager aims for zero customers waiting in line (reference=0). Arriving customers are the disturbance. Cashiers process customers (actuator), and the manager opens new lanes (control action).	Cashiers process customers just as fast as they arrive, and the line length stops growing or shrinking.	The manager's goal was 0 people, but the system settles at an average length of **1 person per line**. This persistent, non-zero line length is the steady state error, often tolerated because achieving zero error is economically infeasible.
30. Floating-Point Error	The computer's arithmetic unit attempts to calculate and store the exact real number result. Due to the constraint of finite memory, the result must be rounded to fit the available precision.	The calculation is complete, and the machine has stored the final, stable floating-point representation of the result.	The **offset** between the exact real number and the stored floating-point number is due to inherent limitations of the computing system and rounding.
31. Bluetooth Latency	Wireless headphones transmit audio (output) which should ideally sync with the video frames (reference). Processing and transmission limits introduce a delay.	Once the Bluetooth connection stabilizes, the audio consistently plays back at a nearly constant delay relative to the video, meaning the delay does not fluctuate wildly.	The **persistent time difference** between the desired sync (0 milliseconds delay) and the audio reaching the ears (actual output). If the audio lags by 150 milliseconds after stabilization, there is a steady state error of 150ms.

E. Other dynamic systems

Example Title	**Detailed Example Description**	**Steady State (SS)**	**Steady State Error**
32. Maintaining Target Weight	A person aims to maintain a stable weight (e.g., 170 lbs, reference). They adjust food intake and exercise (control actions) based on their current weight (process variable/sensor).	The person's weight stops dropping, and their new lifestyle stabilizes their weight at a new "normal" average.	The **persistent 1 lb difference** (e.g., 171 lbs settled vs. 170 lbs goal), where the stable weight is not exactly the setpoint, indicating a persistent offset.
33. Predator-Prey Dynamics	In a closed ecosystem, a population of rabbits (prey) grows until it hits the natural carrying capacity (the maximum population the environment can sustainably support).	The population stops growing when it reaches the natural carrying capacity, where the birth rate equals the death rate, making the population stable.	If a park ranger wants to maintain a population of 800 rabbits (reference) but the natural carrying capacity is 1,000 (steady state), the steady state error is 200 rabbits (=1,000 - 800) between the goal and the system’s natural equilibrium.

5. Assessment

Quantitative assessment of the learning approach

The instructional methodology, which relies on intuitive, real-world, cross-disciplinary examples rather than focusing solely on mathematical derivations, received high marks from learners. This approach helps bridge the gap between mathematical formulation and practical intuition.

The following quantitative list summarizes the scores provided by students regarding the desired emphasis on different teaching elements (Scale 1–10, 10 being the highest emphasis):

Assessment Category	**Scores Reported (Average)**	**Interpretation/Feedback Summary**
Overall Excitement Level	9.5	The topic was genuinely engaging, memorable, practical, and creative.
More/Less Intuition	9.2	The current level of intuition introduced was considered **"perfect"** by some, making students understand the meaning rather than just memorizing.
More/Less Visual	9.2	Visuals help cement the ideas behind the theory and are highly valued.
More/Less Engaging	9.0	While good, the class could be greatly improved by providing learners access to **physical systems** rather than relying solely on simulations, which may not accurately mimic real responses.

6. Conclusion

This work introduced a collection of non-traditional, primarily non-textbook examples designed to convey the idea of steady state in a more intuitive and visual manner. The goal was to build conceptual understanding first, before engaging with formal mathematical treatment. These examples are intended to complement, not replace, standard textbook material. Interestingly, examples involving simple mechanical behaviors proved especially appealing and engaging for students. Early feedback has been highly positive, encouraging us to continue refining and expanding this approach. We hope that instructors incorporate selected examples to strengthen students' grasp of steady-state behavior. More broadly, this effort is part of our ongoing attempt to reimagine how feedback and other foundational control concepts are taught, aligning instruction with the ways students naturally learn and connect with the material.

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8. References

[1] Lewis, Frank. *Applied Optimal Control & Estimation: Digital Design & Implementation*. Prentice Hall and Texas Instruments digital signal processing series. Prentice Hall. 1992.

[2] Raviv, Daniel, G. Roskovich, and P. Noguera. *Understood: A Visual and Intuitive Approach to Teaching and Learning Control Systems*. Understood Series. CreateSpace Independent Publishing Platform. 2014.

[3] Bennett, S. and I. of Electrical Engineers (1993). *A History of Control Engineering*, 1930-1955. Control, Robotics and Sensors. P. Peregrinus.

[4] Normans, Jeremy. "*Ctesibius Builds the First Truly Automatic Self-Regulatory Device*". History of Information.com. https://www.historyofinformation.com/detail.php?entryid=2306.

[5] Åström, Karl. and Murray, Richard. *Feedback Systems: An Introduction for Scientists and Engineers*. Princeton University Press. 2010.

[6] Coller, B. D. *A video game for teaching dynamic systems and control to mechanical engineering undergraduates*. In Proceedings of the 2010 American Control Conference, pp. 390–395. IEEE. 2010.

[7] B. Karniel, G. Artzi, M. Barak. *Introduction to Control (In Hebrew).* The Centre for Educational Technology. The Open University. Ramat Aviv. Israel. 2009.

[8] Raviv, D. and G. J. Roskovich. *An intuitive approach to teaching key concepts in control systems*. In 2014 ASEE Annual Conference & Exposition, pp. 24–173. 2014.