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WIP: An analogy-based approach to explaining the controllability and observability concepts

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WIP: An analogy-based approach to explaining the controllability and observability concepts

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Abstract

The concepts of controllability and observability are essential for understanding and designing control systems. Textbooks often explain them thoroughly using mathematical approaches, such as matrix manipulation and the concept of matrix rank. However, these explanations can sometimes lack the intuition necessary for students to fully grasp the ideas. In the Modern Control class that we currently teach, we noticed a gap in students' ability to visualize and intuitively understand these concepts. To address this, we decided to use a non-engineering approach: explaining the concepts through well-known examples from medicine. Surprisingly, the students found this explanation very helpful, which led us to share it with other instructors who teach these topics. In this paper, we share some ideas related to controllability and observability.

Controllability: Medical doctors can influence or affect patients in various ways through non-invasive methods such as looking, talking, or touching, which can have both psychological and physiological effects. For example, a doctor can achieve psychological influence through eye contact and body language, building trust, empathy, or reassurance, and may also utilize the placebo effect to influence a patient's belief in the efficacy of treatment. Through tone, choice of words, and empathy, a doctor can help calm anxiety or fear, and the way a doctor discusses a condition or pain can shape how a patient perceives it. Using positive language and framing outcomes optimistically can reduce the perception of pain or discomfort. Finally, gentle, intentional touch can help reduce stress, pain, and anxiety.

Observability: Medical doctors can observe several key signs and symptoms through basic interactions by looking at, talking to, or touching a patient. These observations often provide crucial clues for diagnosis. By looking at the patient, a doctor can assess overall health, body posture, and comfort level - signs of fatigue, distress, or pain may be apparent, while rashes, lesions, or abnormal movement could indicate underlying conditions such as neurological issues, like Parkinson's disease or a stroke.

Verbal interaction can reveal slurred speech, difficulty finding words, or unusual tone and pitch, which may indicate neurological problems like stroke or brain injury. Doctors also assess memory, orientation, and concentration to evaluate mental status, identifying conditions such as dementia, while a hoarse voice or cough can suggest respiratory issues or heart failure. Through touch, temperature differences in the skin can indicate fever, inflammation, or poor circulation. These simple yet critical observations allow doctors to narrow down potential diagnoses and determine which further tests or examinations might be necessary.

Following an initial, limited-scope assessment based on students' reactions and enthusiasm, we decided to pursue a more rigorous quantitative evaluation. To achieve this, an extra credit assignment was introduced, requiring students to identify primarily non-engineering examples of controllability and observability from fields such as chemistry, physics, biology, and computer science. Students were also asked to evaluate this teaching and learning approach, share their level of excitement, and propose ideas for further improvements. The results were highly encouraging. Some of their ideas are shared in this paper. They also shared their ideas regarding this teaching and learning approach and found it highly effective in bridging the gap between abstract mathematical concepts and practical intuition. Students expressed enthusiasm for the method, with many rating it 8/10 or higher for engagement. They highlighted the value of connecting theory to relatable real-world examples, emphasizing the need for more interactive, visual, and engaging teaching methods to reinforce understanding.

This work should be viewed as a <u>work in progress</u>. This paper does <u>not</u> propose altering or modifying existing chapters in control textbooks. Instead, the material presented here is intended to serve as a supplementary resource that can be used to enhance the introduction of the topic.

1 Introduction

Teaching Control Systems has long been a challenging endeavor due to the abstract nature of its concepts. Students often struggle to connect the mathematical formulations, such as matrix manipulations and transformations, with real-world applications. The disconnect between theory and practical understanding can leave students feeling disengaged and overwhelmed [1], particularly when faced with rapid successions of equations that lack context or intuition.

One promising way to address this challenge is to draw on familiar experiences and relatable analogies to make abstract concepts more tangible. Learning is most effective when new information builds on prior knowledge and lived experiences, allowing students to form meaningful connections. Without such connections, even well-structured mathematical explanations can fall short of fostering true understanding [2] [3]. Educators have unprecedented opportunities to explore innovative teaching methods. Online platforms like YouTube have revolutionized how students access information, with engaging visual content supplementing traditional lectures [4]. By incorporating creative, everyday examples into teaching materials, including, for example, video games, we can bridge the gap between the abstract and the intuitive, providing students with memorable insights that resonate far beyond the classroom [5] [6].

This paper introduces a novel teaching strategy that leverages relatable analogies from different disciplines and simple real-world examples to explain the fundamental concepts of controllability and observability in Modern Control Systems [7]. For instance, the concept of controllability can be illustrated through the familiar experience and knowledge from medicine, and the concept of observability are made relatable through behaviors in human interactions. By grounding these abstract ideas in everyday life, we aim to foster deeper student engagement and comprehension. This approach not only enhances learning but also aligns with the growing demand for creative and dynamic methods in modern education.

The examples presented in this paper are intended to provide a toolkit for educators, inspiring them to adopt intuitive and accessible methods in their teaching practices.

The concepts of controllability and observability are central to understanding and designing control systems. While textbooks often explain these ideas in detail through mathematical methods such as matrix manipulation and rank analysis, these approaches can sometimes fail to cultivate a deep, intuitive understanding in students [8] [9].

In control classes, a significant gap often exists between solving equations and developing a genuine conceptual grasp of these principles. To address this, we adopted a non-engineering perspective, using relatable examples from medicine—a context students found particularly enlightening.

For example, when discussing controllability, we compared it to how medical professionals influence or affect patients through non-invasive methods such as communication or physical touch. These actions can produce both psychological and physical outcomes. Similarly, in the context of observability, we explored how medical professionals detect critical signs and symptoms through basic interactions, such as observing, speaking with, or touching a patient.

This material should be regarded as a work in progress. It is not designed to replace conventional textbook chapters but rather to complement them as a valuable supplementary resource. Our aim is to support educators in teaching and to help students grasp intricate control concepts in a more interactive and impactful way.

1.1 Why controllability and observability are not intuitive?

Consider the continuous linear time-invariant system:

$$\begin{aligned} \dot{\mathbf{x}}(t) &= A\mathbf{x}(t) + B\mathbf{u}(t) \\ \mathbf{y}(t) &= C\mathbf{x}(t) + D\mathbf{u}(t) \end{aligned}$$

where:

$\mathbf{x}$ is the $n \times 1$ **state vector**,

$\mathbf{y}$ is the $m \times 1$ **output vector**,

$\mathbf{u}$ is the $r \times 1$ **input (or control) vector**,

A is the $n \times n$ **state matrix**,

B is the $n \times r$ **input matrix**,

C is the $m \times n$ **output matrix**,

D is the $m \times r$ **feedthrough (or feedforward) matrix**.

The $n \times nr$ controllability matrix is given by:

$$R = \begin{bmatrix} B & AB & A^2B & \cdots & A^{n-1}B \end{bmatrix}$$

The system is controllable if the controllability matrix has full row rank (i.e., $\text{rank}(R) = n$).

If and only if the column rank of the **observability matrix**, defined as:

$$\mathcal{O} = \begin{bmatrix} C \\ CA \\ CA^2 \\ \vdots \\ CA^{n-1} \end{bmatrix}$$

is equal to n, then the system is **observable**.

The rationale for this test is that if n columns are linearly independent, the system's states can be uniquely determined from the output.

It is evident that examining this set of matrices, as they are typically presented in control textbooks, makes it difficult to develop intuition.

Following the initial success in introducing the topics in the classroom, the students were suggested an extra credit assignment. Some of their examples may be used by instructors who choose to add intuitive understanding to their teaching assignments.

1.2 The assignment

For extra credit the students have been asked to come up with examples for the analogy-based approach to explaining the controllability and observability concepts. To avoid biased feedback, we assured the students that the grade of the extra credit is not based on their feedback.

Extra Credit Assignment

General

The purpose of this extra credit assignment is to find 10 examples (5 for controllability and 5 for observability) that can help future students better understand these concepts. Each example should be drawn from a different discipline, for example:

- Medicine (1+1)
- Electrical Engineering (1+1)
- Aeronautics (1+1)
- Chemistry (1+1)
- Physics (1+1)
- Biology (1+1)
- Computer Science (1+1)

What do you need to do:

1. Title of the example.
2. Description. Each example must be very specific.
3. Clear relevance to controllability or observability.
4. Assessment:
   (a) Clearly write in bullet points your opinion about this approach to learning and teaching.
   (b) Your excitement level on a scale of 1 to 10 (10 being the highest) for being introduced to the topic in this manner.
   (c) What would you like the instructor to emphasize when teaching new concepts? Use a scale of 1 to 10 for aspects such as:
      - More/less intuition?
      - More/less visual?
      - More/less engaging?

2 Examples shared by the instructor in the classroom

2.1 Controllability Examples

Medical doctors can influence or affect patients in various ways through non-invasive methods such as looking, talking, or touching. These interactions can have both psychological and physiological impacts. Here are some examples:

a) Therapeutic Touch and Relaxation

By touching the patient, therapeutic touch has been shown to reduce cortisol levels, decrease blood pressure, and slow heart rate, particularly in stressful situations. In some cases, it can also provide pain relief. Touch can activate the parasympathetic nervous system, promoting relaxation and reducing stress. This, in turn, positively affects various bodily functions, including blood pressure, digestion, and heart rate.

b) Specific Touch Techniques

Many examples of touch-based methods come from practices such as acupressure, reflexology, or general therapeutic massage. For instance, applying pressure to the LI-4 acupressure point can help relieve headaches, while applying pressure to the B23 point can alleviate lower back pain. These simple techniques, which involve applying pressure to specific points, can significantly alleviate physical discomforts such as headaches, stress, nausea, or muscle pain. They are non-invasive and can often be performed anywhere, providing immediate relief for minor issues.

c) Lifestyle Modifications

Several external measures and actions can positively affect the health and function of internal organs or help manage diseases. These measures range from lifestyle modifications to medical interventions. Examples include making dietary changes, engaging in regular exercise, maintaining proper hydration, and ensuring sufficient sleep.

d) Medical Interventions

Using prescribed medications and getting vaccinations can also help control health outcomes effectively.

2.2 Observability examples

Medical doctors can observe several key signs and symptoms through basic interactions, such as looking at, talking to, or touching a patient. These observations often provide crucial clues for diagnosis.

a) Visual Inspection

Doctors gather information about a patient through visual inspection of their general appearance, skin color and condition, swelling or edema, breathing patterns, facial expressions, movement and gait, and overall body habitus.

b) Verbal Interaction

Through verbal interaction, doctors can assess a patient's speech patterns, cognitive function, and the quality of their cough or voice.

c) Touch (Palpation)

By using palpation, doctors can obtain valuable information such as the patient's skin temperature, pulse, and any signs of organ enlargement.

d) Non-Invasive Diagnostic Tests

In addition to direct interaction, non-invasive diagnostic tests provide valuable insights into the health and function of internal organs. Common examples include ultrasound, magnetic resonance imaging (MRI), computed tomography (CT scans), echocardiograms, and endoscopy.

3 Summary of examples by students

For more details please refer to the Appendix.

Category	**Controllability**	**Observability**	**Total**
Medicine	12	11	23
Engineering (Electrical, Mechanical, etc.)	15	16	31
Aeronautics	8	8	16
Sciences (Physics, Chemistry, Biology)	17	13	30
Computer Science and Cybersecurity	3	5	8
Environmental and Ocean Sciences	4	4	8
Other Fields	6	5	11
Total	**65**	**62**	**127**

Table 1: Summary of Controllability and Observability Across Fields

4 Sample of students examples titles

Titles of Controllability Examples
Controlling Patient Heart Rate Through Medication (**Medicine**)
Voltage Control in Power Grids (**Electrical Engineering**)
Aircraft Flight Control System (**Aeronautics**)
Gene Expression Control via CRISPR (**Biology**)
Manipulating Reaction Rates via Temperature and Pressure (**Chemistry**)
Adjusting Water Temperature in a Shower (**Mechanical Engineering**)
Robot Path Planning for Navigation (**Computer Science**)
Controlling Pollutants in Waste Water (**Environmental Science**)
Managing Traffic Flow with Signal Control Systems (**Traffic Management**)
Producing Salt by Reacting HCl and Na (**Chemistry**)

Table 2: Highlighted Examples of Controllability Across Domains

Titles of Observability Examples
Monitoring Blood Glucose Levels via Continuous Glucose Monitoring (**Medicine**)
Observing Power System Stability via Phasor Measurement Units (**Electrical Engineering**)
Monitoring Aircraft Health Using Onboard Sensors (**Aeronautics**)
Monitoring Cell Activity Through Microscopy (**Biology**)
Monitoring Molecular Structures and Reactions in Real-Time (**Chemistry**)
Sensors on Bridges for Identifying Strain or Displacement (**Mechanical Engineering**)
Real-Time Performance Monitoring in Cloud Systems (**Computer Science**)
Tracking Climate Change Using Satellites (**Environmental Science**)
Monitoring Patient Vital Signs in ICU (**Medicine**)
Analyzing Distant Stars with Space Telescopes (**Astronomy**)

Table 3: Highlighted Examples of Observability Across Domains

5 Assessment

To assess the effectiveness of the new approach, we asked students in question 4 of the assignment.

a. Opinion

- *"Helps in understanding controllability in biological systems. Provides a real-world, relatable scenario."*
- *"Highlights the interaction between technology and biology. A powerful tool in real applications."*
- *"I believe this approach is very effective because it addresses a common challenge for students: connecting theoretical concepts to real-world applications."*
- *"Using relatable, real-world examples that are widely understood can give students a more intuitive grasp of theory, forming a solid foundation for deeper learning."*
- *"This style gives an intuitive approach to understanding controls and gives the learner a chance to relate to something they have more familiarity with."*
- *"Real-time performance monitoring provides a practical analogy for observability in computer systems. This example bridges theoretical concepts with real-world computing practices."*
- *"I found that this method is highly effective in bridging the gap between abstract mathematical concepts and practical intuition."*
- *"More relatable: Connecting abstract concepts like controllability and observability to real-world examples makes the material easier to digest."*
- *"Seeing how controllability and observability apply in other fields helps me see how control system topics can be associated with the field that I feel stronger with."*
- *"This method encourages active participation rather than passive listening, which improves retention and understanding."*

b. Excitement Level (Summary)

Most students rated their excitement level highly, with the majority giving scores of 8/10 or above. Many found the teaching method engaging and appreciated the use of real-world examples, noting that these made the material more accessible and intuitive. A few students specifically highlighted their excitement for future lessons and deeper understanding.

c. Desired Emphasis (Summary)

Students emphasized the importance of balancing intuition, visuals, and engagement. Many requested more interactive and hands-on activities, such as simulations and real-world applications, to reinforce concepts. Visual aids like graphs, diagrams, and animations were frequently mentioned as crucial to improving clarity and understanding.

6 Conclusion

The concepts of controllability and observability are foundational to understanding and designing control systems, yet their mathematical explanations often fail to provide the intuitive grasp needed for meaningful comprehension. By introducing analogy-based teaching strategies, such as relatable examples from medicine, we believe that instructors can introduce topics in a more clear and intuitive ways, helping students visualize these abstract ideas in a practical and engaging manners. Our classroom experience and initial student feedback suggest that this approach fosters a deeper understanding and enthusiasm for the subject. Although further quantitative evaluation is needed, the positive reception of these examples highlights their potential as valuable tools for educators. By grounding theoretical concepts in real-world analogies, we aim to inspire broader adoption of intuitive teaching methods,thereby advancing the effectiveness of modern control systems education. This paper is not suggesting to modify or replace textbook chapters, instead is an add on material instructors may use.

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Appendix: Samples of extra credit examples

Controllability Sample of Examples

Controllability Example: Controllability in Gene Expression Regulation

Title: Controllability in Gene Expression Regulation **Description:** In cellular biology, controlling gene expression is essential for understanding and treating diseases. Scientists influence gene expression through:

- Gene Editing Tools: Using CRISPR-Cas9 to activate or suppress specific genes.
- Chemical Inducers: Applying molecules like tetracycline to turn genes on or off.
- Environmental Changes: Altering temperature or nutrient availability to influence gene expression.

For example, in research on diabetes, scientists can use CRISPR to control insulin gene expression, helping to study its effects or develop treatments.

Relevance to Controllability:

- The system is the gene expression pathway.
- The inputs are gene editing tools, chemical inducers, or environmental factors.
- The desired state is the targeted activation or suppression of specific genes.

This illustrates controllability by showing how external interventions can drive biological systems toward desired gene expression patterns.

Controllability Example: Managing Traffic Flow with Signal Control Systems

Title: Managing Traffic Flow with Signal Control Systems

Description: At intersections, traffic lights are programmed to regulate the movement of cars and pedestrians. To reduce congestion, traffic management systems modify signal timings in response to real-time traffic data. It is possible to dynamically control traffic flow by:

- Varying the lights' length.
- Adjusting the sequence of signals.

Relevance to Controllability:

- The ability to adjust traffic signals to manage vehicle flow demonstrates controllability.
- Inputs (signal timings) influence the state of traffic congestion.

Observability Sample of Examples

Observability Example: Analyzing Distant Stars with Space Telescopes

Title: Analyzing Distant Stars with Space Telescopes
Description: Space telescopes, like the James Webb Space Telescope, collect data on distant stars and galaxies. By analyzing the light spectra, scientists can deduce the composition, temperature, and motion of these celestial objects without direct interaction.
Relevance to Observability: The light spectra serve as outputs that allow scientists to infer the internal characteristics of distant objects, demonstrating observability.

Observability Example: Monitoring Aircraft Health Using Onboard Sensors

Title: Monitoring Aircraft Health Using Onboard Sensors
Description: Modern aircraft are equipped with numerous sensors to monitor critical components such as engines, hydraulic systems, and structural integrity. These sensors measure variables like temperature, pressure, and vibration, generating large volumes of data that are continuously analyzed in real time for anomalies or impending failures. This enables early detection, facilitating effective maintenance and enhancing safety.
Relevance to Observability: This example demonstrates observability as the internal health of the aircraft is inferred from external observations made by onboard sensors. Real-time monitoring allows operators to assess the condition of various subsystems without requiring direct physical access.