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Model-Based Control Systems with Intermittent Feedback: Conceptualization and Insights for the Teaching and Learning Process

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I. Introduction

The field of engineering education has grown considerably over the past two decades, with the majority of the research focusing on empirical results or statistical studies. Alongside this growth, it is important for researchers to develop increasingly intuitive and useful conceptual models for educational processes. In this paper we present a conceptual framework for the teaching and learning process based on a concept familiar to most engineers: feedback control systems. Feedback control has long been a staple of engineering curricula, primarily in electrical engineering, but also across other disciplines such as mechanical and chemical engineering. This is largely due to the diversity of applications of control theory.[1] Feedback control concepts have also been applied in areas outside of engineering, such as psychology and human behavior, particularly in the areas of goal setting and performance.[2,3] However, in the field of engineering education, the concepts from control theory have been underused. We build upon the ideas presented in the related literature by providing a novel control systems-based conceptualization framework applied to the teaching and learning process, particularly in undergraduate engineering.

We begin by presenting a “traditional” setup using classical control theory. We map the fundamental elements of the process (instructor, student, tasks, etc.) to key aspects of the control diagram (controller, plant, sensors, actuators, communication pathways, etc.). While this framework provides us with an initial conceptual mapping, we outline various limitations in its ability to capture real-world applications to teaching and learning.

Next, we refine our model by turning to a more recent field of research for controls engineers: Networked Control Systems (NCSs). We provide an introduction to networked control systems and identify the various challenges in their analysis and design.

Having introduced NCSs, we then present our main contribution: a conceptual framework based on a system architecture known as Model-Based Networked Control Systems (MB-NCS).[4] The study of MB-NCS has developed in an attempt to analyze and design control systems in the presence of real-world constraints such as network usage, information delays, and limited bandwidth. Through thorough analysis, we explain how these constraints map accurately to the reality of various educational processes, such as the way students learn and their interaction with faculty. In particular, the case of MB-NCS with Intermittent Feedback becomes especially relevant.[5] We provide an in-depth explanation of this conceptualization framework. Once the model is presented, we provide tangible examples of how lessons from MB-NCS theory apply to teaching and learning.

It should be pointed out that most of our models for the signals and systems involved are of a qualitative nature and that, similarly, the insights we derive should be treated as guidelines rather than steadfast rules. After all, one of the more tempting mistakes in Systems Engineering is to try to arrive at a solution that is neat and elegant, but which may not accurately capture the reality of the situation. Because teaching and learning processes deal with complex interpersonal interactions between instructor and student, as well as internal personal dynamics which may be extremely difficult to model, we feel that an attempt to rigidly quantify each variable would fail to capture the experiential dynamics of real-world interactions. We believe that our application of MB-NCS theory to engineering education provides valuable insights while maintaining sufficient flexibility, and thus it could help faculty members develop useful insights into their own teaching practice.

II. Feedback Control Systems

A. Introduction to Feedback Control Systems

The concept of a "feedback control system" is probably familiar to most engineers. While the exact presentation may vary from discipline to discipline, applications of feedback control systems are ubiquitous throughout the engineering world. Indeed, the study of feedback control systems (sometimes also referred to as "automatic control systems, "control engineering", or simply "control systems") is often referred to as a "stealth science," due to its widespread prevalence in a behind-the-scenes role of how engineering systems and devices may work. Although many readers are probably familiar with many of the concepts that will be discussed in this section, we nevertheless wish to provide a simple conceptual base so as to 1. remind the reader of basic terms and definitions that we will continue to use throughout the paper and 2. serve as a conceptual foundation for the more complex models discussed in subsequent sections. With this in mind, let us consider the block diagram in Fig. 1:

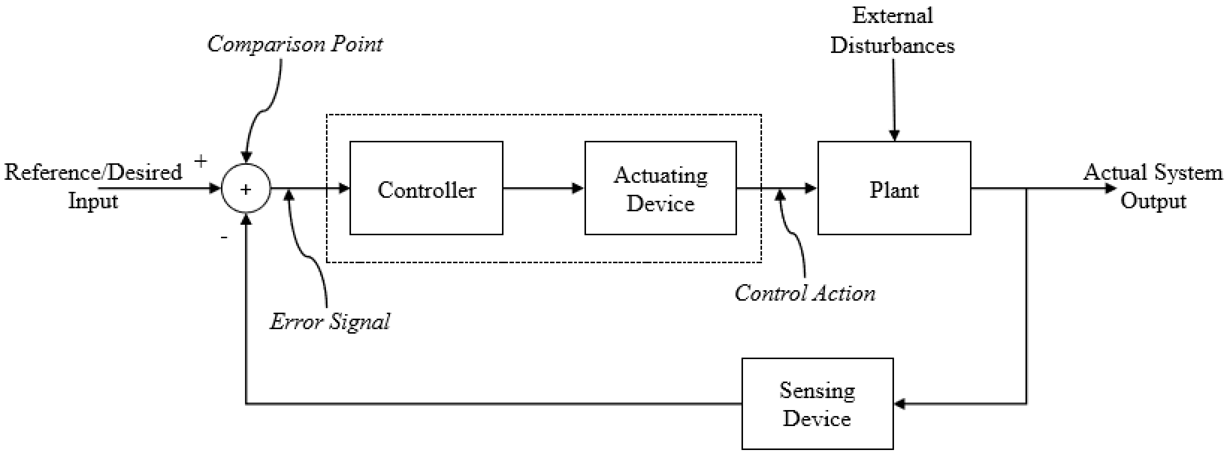

Fig. 1. Classical Control System

This block diagram provides a general topology of a control system and may serve as an initial point to model a wide variety of automated processes, from a room temperature system in a home to an automatic pilot tracker in an airplane. Regardless of the technical application, feedback control systems can often be simplified to slight variations of the block diagram above. Let us now clarify some of the key terms pertaining to this block diagram.

The main role of a control system is perhaps best explained by first considering its input signal (on the far left of the diagram) and its output signal (on the right). The input signal is typically a "desired" or "reference" input, which the user sets with the goal that the system will automatically try to "track" or "follow" this signal. Thus, ideally, the output signal (the actual system response) will be as close as possible to the reference signal. The block labeled as "Plant" refers to the system whose output we are actually trying to control. Notice that the plant may be susceptible to external disturbance signals. The only way to ensure that the output will be able to track the reference input while in the presence of disturbances is through the concept of feedback. Feedback is accomplished by using a "sensing device" (or simply "sensor") to measure the current actual output. The data from the sensor is fed back to a comparison point, where it is compared to the reference signal. The difference between the reference signal and the measured signal result in an error signal. This error signal is then processed by the "Controller," which processes the error signal to produce a control instruction. This instruction is then provided to an "actuating device" (or simply "actuator") which takes the corresponding control action on the Plant. Depending on the application, several of these blocks (such as the Controller and Actuator) may be collocated and part of the same physical device.

If the system is well designed, this closed-loop feedback process will allow the actual output of the Plant to closely follow the reference input, even in the presence of external disturbances. There are key control objectives that arise in the analysis and design of feedback control systems, such as stability (ensuring the output or internal signals within the plant will not diverge or deviate excessively from the input), robustness to external disturbances or system parameter uncertainties, and performance (speed and accuracy considerations). While these controls objectives may be defined in very precise, quantitative terms, for the purposes of this paper, we wish to focus on an intuitive understanding of the concepts.

B. Feedback Control Systems Applied to the Teaching and Learning Process

Variations of the block diagram showed in Fig. 1 have been prevalent in a wide variety of engineering applications, such as electromechanical systems or chemical processes. It might seem appealing, however, to model other, non-engineering processes through a traditional control model. For example, we may intuitively think of the teaching and learning process as a relationship between instructor and student where feedback is present. We therefore develop an initial model of this process with a fairly straightforward conceptual mapping, depicted in Fig. 2.

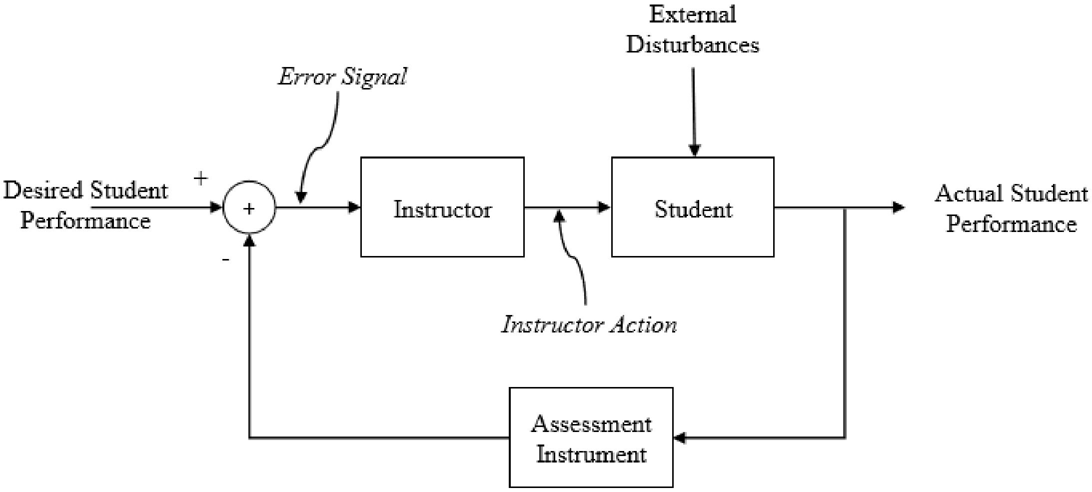

Fig. 2. A Classical Control Model of Teaching and Learning Process

In this case, the student represents the role of the "Plant," that is, the system whose behavior or response one is attempting to control. While the specifics of the system output may vary, most faculty members would agree there are certain key learning objectives they would like their students to meet in their course. The actual system output or response represent the degree to which the student has achieved those learning objectives. That performance must be measured via some sensing device or instrument. In the educational setting, this usually takes the form of an exam, written report, or other graded assignment. The results of the assessment instrument are there fed back and compared to a reference signal, usually corresponding to desired student performance. This error signal is then processed by the instructor who, performing the role of Controller and Actuator, provides a new, adjusted set of input signals (instructor actions) that the student receives. Just as any other plant, the student is susceptible to external disturbances. In the student's case, these disturbance signals may take the form of social distractions, work from other courses, extracurricular activities, or learning difficulties.

C. Challenges and Limitations of this Model

One might hope that, with the above model, one could then use the robust results from classical control theory to develop insights and recommendations for the teaching and learning process. Appealing as that may be, the model from Fig. 2 is replete with oversimplifications and challenges that make it an inadequate depiction of an actual teaching and learning process. The following are some of the glaring challenges or limitations associated with this model:

The illusion of continuous feedback: In the diagram, the signals appear to be continuous in nature, and the feedback process itself appears to be continuous as well. However, given our conceptualization of sensors as assessment devices, the reality is that the loop is open most of the time, giving the controller only a discrete number of opportunities to make adjustments and take corrective actions.
Imperfect communication channels: The model assumes that the signal produced by the instructor is received and processed by the student. However, in practice, we know that the

information the instructor hopes to deliver is often misinterpreted or misunderstood by the student, or delivered by the instructor in unclear ways.

Unidirectional Communication: The model suggests a largely unidirectional interaction between student and faculty, with the faculty member providing corrective action when needed based on assessment instruments. The realities of bidirectional communication between instructor and student are ignored.

Lack of Consideration of the Affective Dimension: The model considers achieving of learning objectives as the only output signal. However, in practice, the student's ability to reach these objectives are often shaped by the affective, emotional, and interpersonal dimensions of the student's experience. None of these are considered in this initial model.

Sensing devices: While our choice of sensing devices may match the output signal we are trying to measure, "sensor noise" will inevitably be introduced, as the results from the assessments can never quite fully capture the exact learning the student has achieved.

One plant vs multiple plants: In reality, faculty members must make decisions that affect an entire class, not just a single student. Modeling a single-instructor, multiple-student control system would require a more detailed diagram. Furthermore, even when the faculty member receives reasonably accurate feedback, it is unclear how then to process the error signal as to generate a suitable control action for an entire class (e.g. whether to speed up or slow down the pace of coverage of material if some students are performing well above the desired level and others well below).

While some of the above challenges may be inevitable even with a more accurate model, the quantity and severity of the limitations listed above raises the question: is it possible to develop a model that more accurately captures the reality of teaching and learning? In the next section, we use this motivation to explore a specific field of study in control systems.

III. Networked Control Systems as an Improved Approach to Teaching and Learning Process

One particular field of study within the area of Control Systems which has been particularly active over the last two decades is Networked Control Systems (NCSs).[6-9] NCSs are control systems where the feedback occurs in the presence of a data network (typically, a digital or wireless communications channel). Fig. 3 provides a typical architecture for an NCS. The blocks marked "S" and "A" represent sensors and actuators, respectively. Notice an NCS may be a large, spatially distributed system comprised of a collection of plants, controllers, actuators, and sensors, sharing information via the communications network.

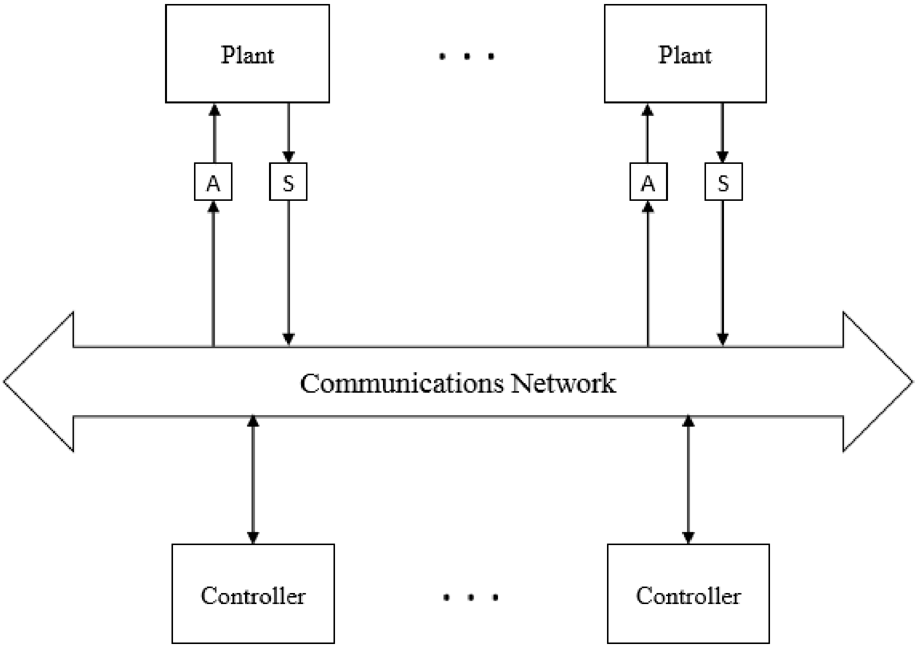

Fig. 3. Typical NCS architecture

The study of NCS has flourished due to the increasingly widespread use of wireless communication channels in varied applications, such as chemical or industrial processes. NCS have the potential to provide benefits in terms of cost, ease of use, flexibility, and efficiency. However, the presence of the network complicates the analysis and design of NCSs. In particular, the following characteristics of NCSs present with unique challenges when compared to classical control systems:

-*Band-limited communication channels:* Perhaps the most notable challenge of NCSs, the communication network is a shared medium which the various subsystems all need to use. However, the channel has a limited capacity, so it cannot be used by all subsystems at once. It is thus imperative to try to meet control objectives while at the same time making efficient use of the network.
-*Delays in the network*: One of the most damaging effects to control systems are delays. If the information does not arrive instantaneously, by the time a corrective action is taken, the output signal may have already deviated so much from the reference input that system performance or stability may be compromised.
-*Information corruption or loss:* Unlike classical control systems, signals sent from one device to another may be prone to becoming corrupted in the communication network. In other cases, information may be dropped or lost, never arriving at the next system.
-*Complex system architecture:* The analysis of systems with multiple plants necessitates more complex mathematical models.

To simplify the analysis, controls researchers often focus on the relationship between the signals pertaining to a single controller and a single plant, such as depicted in Fig. 4.

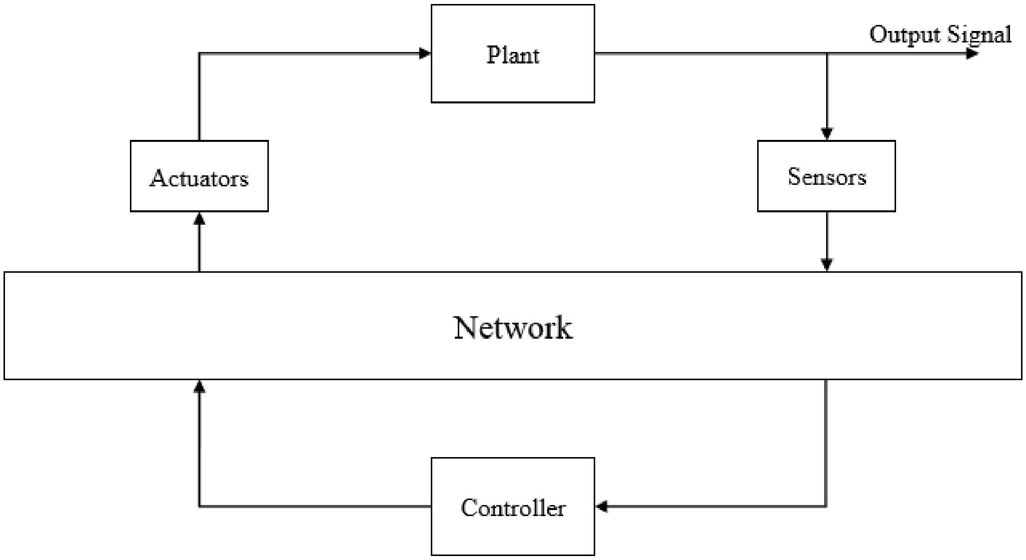

Fig. 4. Simplified NCS architecture

The reader may have noticed some striking similarities between this list of challenges and that of the limitations associated with the classical model in the previous section. Indeed, most of the complications associated with NCSs map very closely to the realities of the teaching and learning process.

In an educational setting, we as faculty members certainly operate with a "limited capacity channel," where it may not always be possible to give full attention to every student. Inside the classroom, whether in a lecture, laboratory, or discussion-based course, it is extremely difficult for the faculty member to instantly gauge the current state of each student and which actions to take accordingly. Faculty time outside the classroom is limited, with many factors vying for attention, from course preparation to grant-writing.

The process has delays embedded throughout its various steps: whether considering the case when an instructor delivers an assignment or instruction and a student takes several days before acting on it, or the time lapse between when an assessment instrument is initially put to use and when the instructor either receives that information, finishes decoding it, or makes use of it, these delays may prove crucial in maintaining overall system performance.

As mentioned in the previous section, the information that the instructor shares with the students may not be fully comprehended by the students (resulting in information corruption) or may be ignored or forgotten (resulting in information loss). Just as importantly, students may often try to reach out or communicate feedback information to instructors that instructors may ignore or misinterpret. To clarify, this kind of communication may take place both inside or outside the classroom and is not restricted to the information carried by the assessment instruments that we assigned as our formal "sensing devices." In fact, this information may pertain to affective, emotion, or other interpersonal matters or to academic factors which may influence student learning but which may not be captured by the instructor-designed assessment instruments.

Finally, the system architecture which models student-faculty interaction, as discussed in the previous section, is indeed more complex, as it is rare to find a case where an instructor is teaching only one student. Nevertheless, as with the NCS literature, it may be useful to proceed with a simplified architecture and gather insights on how a faculty member can generate suitable "control actions" that may benefit each student.

Based on the parallelism of these challenges, we therefore surmise that an existing approach for achieving control objectives in NCSs may also be valuable in modeling the teaching and learning process.

IV. Model-Based Networked Control Systems: Basic Architecture

One approach to analyzing NCSs is known as Model-Based Networked Control Systems (MB-NCSs). MB-NCSs were introduced by Montestruque and Antsaklis[4], and further results about their stability and performance in various modes of operation were developed in [10-11]. The basic idea of the MB-NCS architecture is to use partial knowledge about the plant so as to reduce communication needs, and thus network usage. To achieve this, consider an NCS architecture where the actuator nodes are configured as in Fig. 5.

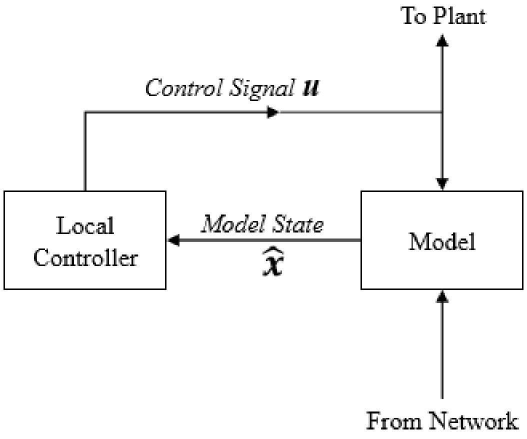

Fig. 5. Actuator node in MB-NCS

This results in the MB-NCS architecture depicted in Fig. 6.

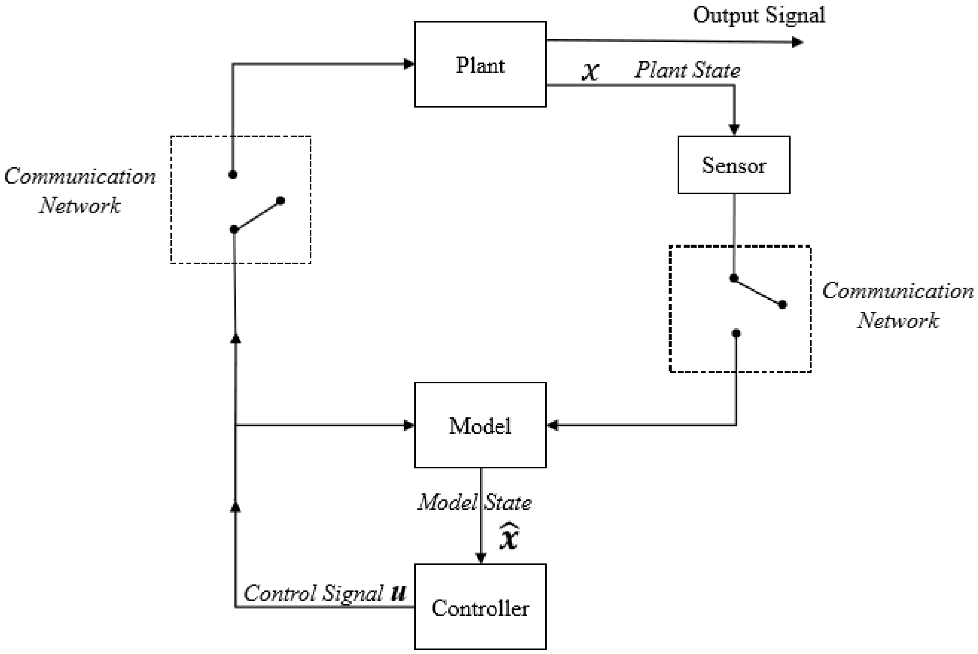

Fig. 6. MB-NCS Architecture

As the name would suggest, the use of the model is central to the MB-NCS approach. The model consists of an approximation of the plant dynamics, i.e. an educated guess as to how the plant actually behaves and will process inputs. Notice that the information that is being fed back is not the output, but the plant's state. The state is usually a vector which contains several internal variables that capture the current condition of the plant, and how it will respond to input signals. If the model of the plant is accurate enough, then the MB-NCS architecture may provide significant advantages. Notice that, when the system does not have access to the network communication channel (i.e. network communication channel switches are in the open position), the system may nevertheless generate control signals based on the state of the model. While these control signals may not be the ideal ones that would be generated if one had continuous access to the communication channel (switches closed), they will nevertheless help preserve stability and performance (once again, provided the model is "good enough"). The control actions are then provided to the model and (whenever available) to the plant. The model state is updated with the new information, and new control instructions are thus generated. Often in MB-NCS, the actuator nodes are not included since they are assumed to be collocated with the controller.

The model is updated with the actual state of the plant when the switches are closed. Depending on whether these switches may close only an instant before relinquishing network usage or for finite intervals at a time, we say that the system uses either "instantaneous feedback" or "intermittent feedback," respectively. The latter case is particularly applicable to educational settings.

V. MB-NCS Model for the Teaching and Learning Process

Having considered the theoretical foundations of MB-NCS in the previous sections, let us now turn our attention to how such an architecture may be applicable towards the educational setting. We begin by modeling the teaching and learning process as an NCS, with a similar architecture to the one shown in Fig. 3. The reasoning from Section III exemplifies the numerous and important parallelisms between the realities of the teaching and learning process and the NCS architecture. The resulting mapping is displayed in Fig. 7.

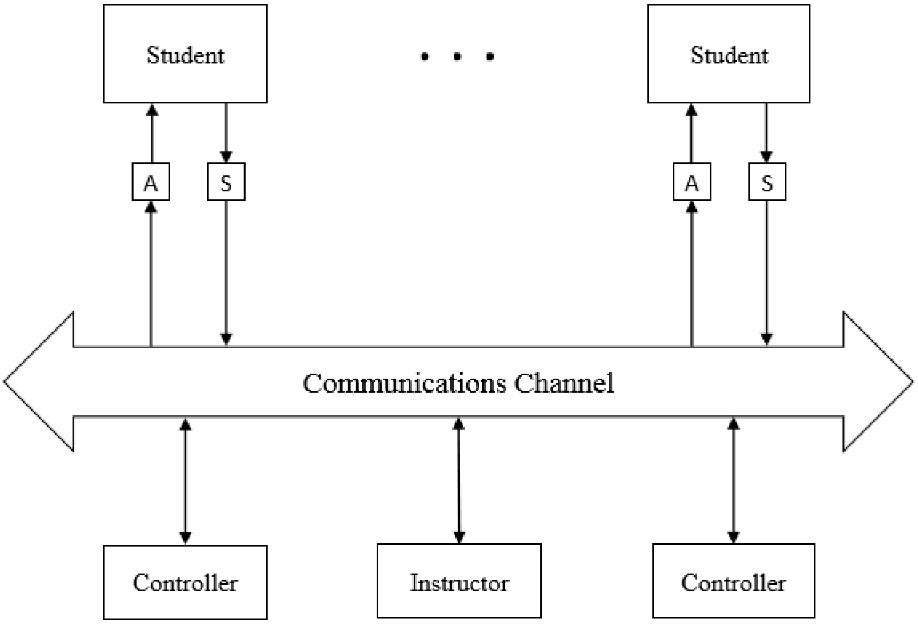

Fig. 7. NCS Conceptualization of Teaching and Learning Process

Notice that the instructor shares the communications channel with several other "controllers." We have only labeled one of the blocks as "instructor" to emphasize that the diagram is conceptualized from the point of view of one faculty member attempting to improve the performance of his or her students. Nevertheless, there may be other "controller" elements attempting to use the communication channels to send signals to the students (some of these other "controllers" may of course be other instructors). Unlike the more precise definition of the digital communication network in NCS theory, here our communication channel is considered in a broader sense, including both electronic and non-electronic communications with the student.

The diagram from Fig. 7 provides an important step towards conceptualizing the teaching and learning process more clearly. However, we need to dig deeper to yield a model that will prove valuable from a practical standpoint. To do so, we take advantage of the MB-NCS architecture introduced in Section IV. Mapping the elements from the teaching and learning process to this architecture in more detail, we arrive at the diagram shown in Fig. 8.

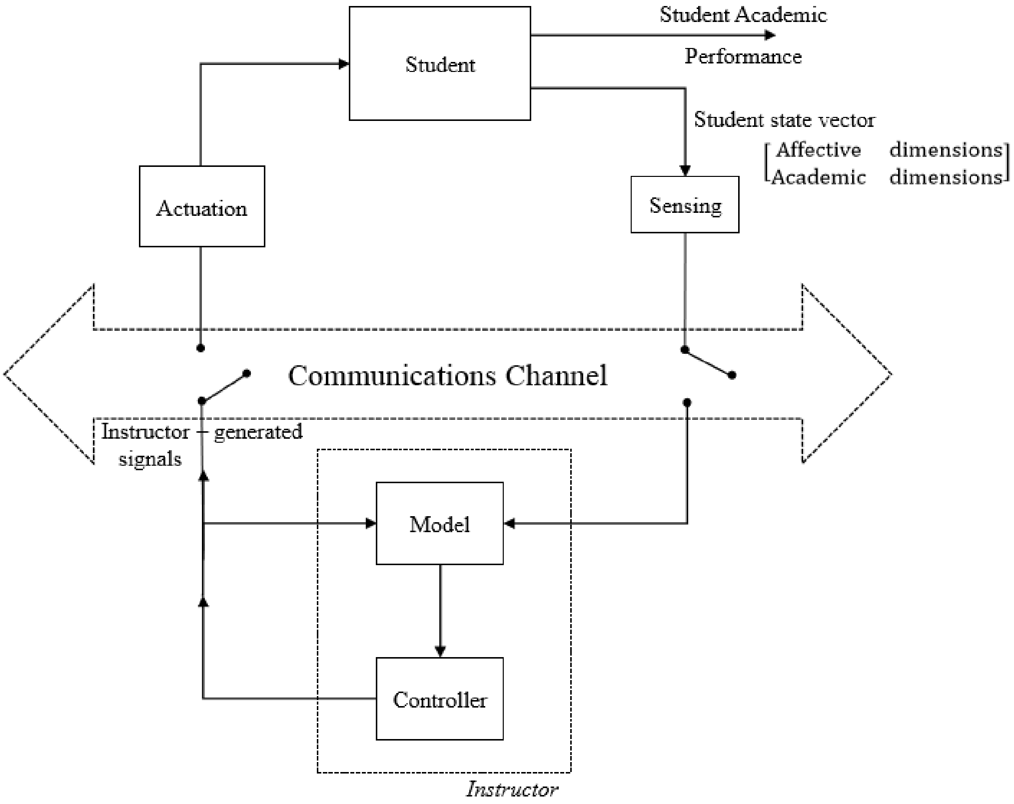

Fig 8. MB-NCS Conceptualization for the Teaching and Learning Process

While this conceptualization has its limitations, we nevertheless believe this conceptualization very effectively captures the realities of teaching and learning. Before we move on to outlining some of the insights from MB-NCS theory that we can employ to our advantage, let us briefly review the operation of the conceptualization. Let us recall that the student remains the plant, or system whose behavior or response is of interest. The output signal is still the academic performance of the student in the course. If the course is well designed, the quantitative outcome of this signal should measure the degree towards which the student met the learning objectives set out by the faculty member.

Notice, however, that the information fed back is not this output signal, but the state of the student. As a vector of multiple dimensions, this state can capture internal variables that may be hard to track, but which, should the instructor dedicate enough personal resources to exploring, will result in a more effective teaching and learning process. We explain this set of internal variables in more detail in the next section, but, as indicated in the diagram, we should make the key distinction between the affective and academic dimensions of the state. Both are going to be important in determining the student's overall state and therefore the student's performance output.

We model the instructor's role in this conceptualization through the controller/actuator role. Fig. 9 depicts the instructor block in more detail. Notice the instructor block contains an instructor-generated model. This model should be informed by previous knowledge the instructor may have about the student. Using the student model state, which is periodically updated through the sensing devices, the instructor then generates control actions which are transmitted to the student via the communication channel.

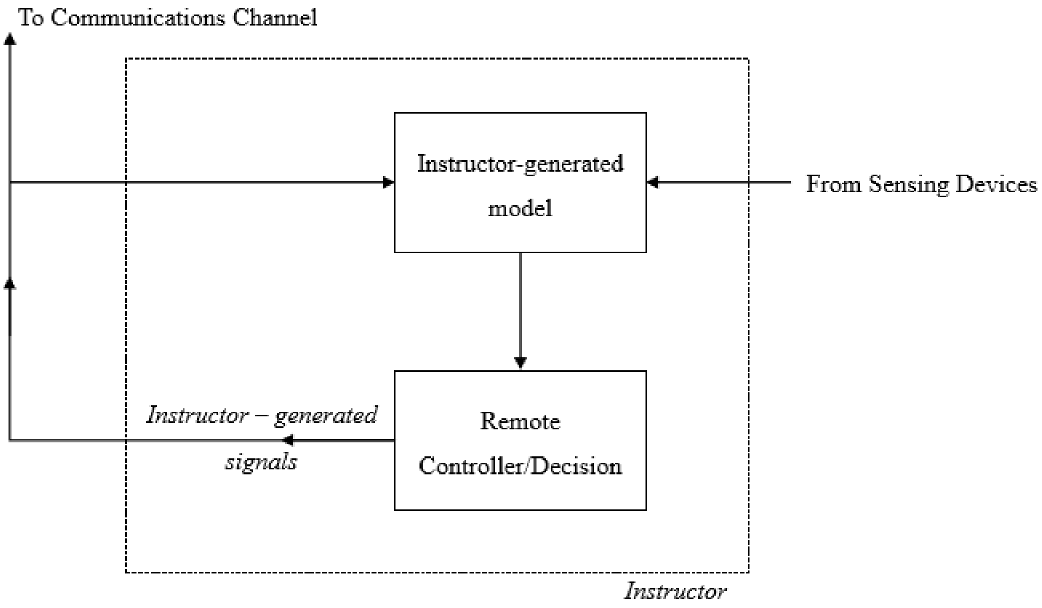

Fig. 9. Instructor as Controller/Actuator

The reader may have observed that the communication channel displays two switches, one from the sensors to the instructor block, and the other from the instructor block to the student actuation. Separating these switches more closely matches the realities of student-faculty interaction. The communication channel may of course be subject to delays, usage by other controllers and fellow students, and saturation due to limited capacity.

There are two distinct modes of operation that are of particular importance, closed loop operation and open loop operation. The switching between these two modes is reminiscent of MB-NCS with intermittent feedback from control theory. In closed loop operation, both switches are closed, meaning there is a complete loop for communication signals to flow. So what exactly constitutes closed loop operation? Notice that these are the cases when student and faculty are mutually engaged and sharing information. The signals in this mode can take various forms, such as material-specific instructions from faculty member to student, comments or visual cues from the student during a class or office hour session, or mutual engagement in the academic topic (e.g. student and instructor attempting to solve a problem together). When either of the switches in the communication channel opens, the system operates in open loop mode. In open loop mode, the instructor updates the control actions to be taken based on the model of the student, not on the direct student information. Our experiential observations of student-faculty interactions suggest that intermittent feedback captures the communication dynamics far more accurately than the models based on classical control systems.

VI. Insights and Recommendations

Having now explained the MB-NCS conceptualization of the teaching and learning process, we can focus on insights about the teaching and learning process informed by results in MB-NCS theory. We hope this section provides the reader with practical recommendations that may be valuable in the reader's own teaching practice.

-*The better the model, the longer the system may run in open loop mode.*
Let us recall that one of the major advantages of the MB-NCS architecture is allowing for effective control while making economical use of the network. Similarly, here, both from the student and faculty perspective, the architecture allows for the desirable objectives of maintaining a stable student state (and satisfactory student performance) without needing to be in closed loop mode and thus using communication channel resources. This is desirable both for the faculty member who wants to help the student but has other students to attend to (and other tasks as well) and for the student who wishes to maintain strong academic performance without excessive dependence on the instructor.

The results from MB-NCS theory suggest the intuitive notion that a more accurate model will allow the student to run open loop for a longer period of time while still meeting control objectives. Therefore, for the faculty member who seeks to foment independent students and free up his own communication channels, it becomes of paramount importance to craft an accurate model of the student. In other words, while it may be seem time consuming, devoting additional effort to getting to know one's students well may have a wealth of benefits in the long run.

-*The state is more important than the output.*
In most systems, the output signal is easiest to measure and may yield the quickest way to diagnose whether performance is satisfactory or not. However, whether in engineering applications or in the teaching and learning process, the state vector carries far more important information. The state vector contains all the internal variables based on which the output and future evolution of the system are determined. As a reminder, the state vector should include both academic dimensions (student preparation, work ethic, achievement level, etc.) and affective dimensions (student emotional state, physical challenges or disabilities, participation in athletics, etc.). The latter are often a mystery to the instructor (particularly in large classes), but insights into these domains can often give the instructor valuable insight into how to best help a student move towards his or her goals.

-*The sensors should be designed to accurately measure the state.*
Faculty members typically dedicate abundant time to developing assessment instruments (sensing devices) attuned towards particular learning objectives. While this is of course valuable, it is recommended to similarly develop one's sensing devices to pick up on the other dimensions of the state vector mentioned above. This may translate to making a deliberate attempt to be more perceptive to student reactions in class, rather than simply disseminating information. It may also mean paying more attention to student's tone and body language during office hour visits, rather than just the specific questions they may raise.

-*Information is prone to getting corrupted.*
This point may be confirmed experientially by any faculty member. Oftentimes an instructor may feel that he or she delivered a very clear message in the classroom, only to realize it was drastically misinterpreted by a student. The knowledge that information can indeed be corrupted (or lost) suggests that the faculty member may benefit from repeating the important points of a lecture or an assignment. Additionally, the recognition of information loss or corruption an inherent part of the process may allow the faculty member to be more patient when a student needs information repeated.

-*It is paramount to make the most of closed loop operation.*
In order to augment student independence, in addition to a good model, it is important for the faculty member to make the closed loop operation particularly meaningful. If, in an MB-NCS, the opportunity to close the loop is wasted, performance is likely to degrade very rapidly. This implies that whenever student and faculty member are mutually sharing a communication channel (whether during a class lecture or discussion, office hours, or other interactions), the faculty member should not take these interactions cursorily. Real engagement and commitment on the part of the faculty member will benefit the student even long after the switch has opened and the system is running in open loop mode.

Additionally, theoretical results from MB-NCS suggest that the duration of the closed loop periods play a positive role in maintaining stability and performance. These results suggest to the faculty member that making the effort to spend more time with a student (for example, through office hours) may have very positive effects over time.

-*It is impossible to operate in open loop mode forever.*
While we may encourage students to become more independent, it would be naive of a faculty member to believe that he or she may allow a student to work wholly alone, without any guidance. While some students prefer to work alone, the faculty member should not be surprised when, if the system is left open loop for an excessive amount of time, student performance may degrade (often for reasons that could have been predicted by more closely monitoring the state vector). Even in situations, periodic interventions by the faculty member may make a very significant difference in restoring a student's state and be conducive to improving their academic performance.

-*Improving the model on-the-go leads to improved performance*.
It is clear that a better model leads to better performance and a more independent student. But can a faculty member change the model of the student during the course of a semester? The answer is that, yes, the faculty member can and should periodically update the model. By using information gained from previous experiences (whether about a student's academic profile or psychological makeup), a faculty member may make the best use of open loop periods by refining the model. This will allow the student to meet performance objectives even with progressively longer open loop periods.

-*The student block features a local actuation node.*
We have mentioned our intent for student's to become more independent learners and be able to maintain high academic performance while in open loop mode. How is this possible within the

framework of the MB-NCS architecture? The main observation here is that the student features a local controller/actuator node, as depicted in Fig. 10.

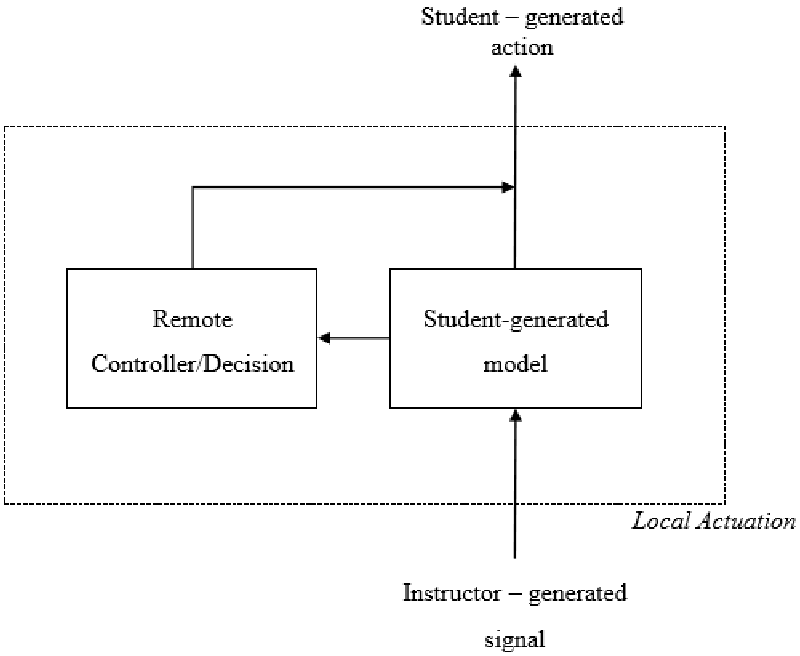

Fig. 10. Student's Local Actuation Node

When the switch on the left side of the communication network is open, the student may still be able to generate effective control decisions by using a student-generated model to inform these decisions. Unlike the model in the instructor block, this model captures the student-perceived dynamics of the assignments and expectations from the faculty. Naturally, increased accuracy of the model in this local actuation node is conducive to better performance and longer allowable open loop times. Therefore, it is paramount that instructors communicate their expectations (of what an assignment entails, of what work outside of class a student should do, etc.) to students very clearly. It is not possible for a student to generate efficient control actions during open loop operation if the student is confused as to the expectations of the instructor.

-*The challenges of multiple plants make the control problem harder, but not impossible.* Throughout most of this analysis, we have proceeded with the simplified architecture featuring one plant and one controller. Both from a theoretical and practical standpoint, the process becomes much harder to analyze when considering a controller seeking to simultaneously maintain control objectives for multiple plants. However, while more difficult to quantify, it is still possible to maintain stability and performance objectives, although it may be under more restrictive conditions.

We encourage the instructor's approach to interactions with students to follow that of this paper. In other words, it is recommended that the focusing on the single-plant case, treating each student as an individual rather than as a member of a class. Doing so will provide the maximum benefits for long-term student development and independence. The reader may hypothesize that this approach runs the risk of saturating the capacity of the communication channel, as generating an accurate model for every plant can be time-consuming. However, there are ways to streamline this process: while every student is unique, there are general traits of a student cohort's academic profile that an instructor can reasonably expect (e.g. level of preparation from previous courses), which may lead to general pedagogic approaches that can work for the majority of the class. Similarly, during class time, an instructor may utilize the communication channel effectively to reach a large number of students. It is important to bear in mind, however, the importance of classtime representing a fully closed loop case: both communication switches need to allow for communication. This means that the instructor should still make an effort to pay attention to the responses and visual cues from as many students as possible. While initially challenging, this may be achieved through a variety of techniques, such as periodically scanning the room, using clickers to receive immediate student feedback, and encouraging students to perform active learning exercises in small groups.

We hope the above conceptualization may prove useful for faculty members in encouraging a more effective teaching and learning process in their courses. Like all conceptual models, however, our approach has its limitations and is no substitute for an intuitive understanding of the realities of student-faculty interaction, both in and outside the classroom. While the goal of this paper was to provide a thorough conceptual analysis, in the future we hope to complement this approach with empirical data that may lead to newer insights.

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