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Teaching Mechatronics Effectively in a Mechanical Engineering Program Under Limited Time

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Abstract

Mechatronics is a well defined multidisciplinary engineering design philosophy that draws knowledge from mechanical engineering, electronics, computer science, and control systems. Undergraduate mechanical engineering programs in many institutions often find it difficult to comprehensively cover all principles of mechatronics because of its wide spectrum and limitations in the available instruction time. The mechanical engineering program at North Dakota State University offers mechatronics education in one semester as a three-credit undergraduate course. Due to the spectrum of its contents, the allocated three credit time is inadequate for this course, as such it was necessary to carefully develop the teaching materials so that it effectively meets its educational objectives, yet without overloading the students. This paper discusses experiences gained in preparing and teaching this course over a time span of three years.

1 Introduction

It is a well known fact that most of modern products are an integration of mechanical systems, electronic systems, control systems, and computer systems; they are often referred to as mechatronic systems. The term mechatronics began as a patented special type of technology by Japanese companies in the early 1970's[1]. At that time, its focus was on application of electronic computers in controlling mechanical systems. Since then it has grown into an engineering design philosophy that integrates traditional engineering disciplines in the design of products. Although many definitions of the term mechatronics have been proposed, the widely used definition treats mechatronics as a multidisciplinary engineering philosophy that synergistically combines traditional mechanical engineering with electronics, controls and computing[2]. All modern systems that integrate computer technology into mechanical systems fall in the category of mechatronics systems.

Fueled by recent rise in global market competition coupled with rapid advancement in sophisticated engineering systems, the demand for mechanical engineers with mechatronics skills has become very high. The knowledge of mechatronics not only provides mechanical engineers with the highly needed multidisciplinary skills but also helps them to better develop concepts that can easily be communicated to all members of multidisciplinary teams[3]. For that reason, there has been a steady growth in integrating mechatronics training into the mechanical engineering curriculum[4–11]. While there is no clear global definition of the course content for mechatronics education, a good dose of mechatronics education should cover control systems design, microprocessor/microcontroller programming and interfacing, digital logic systems, transducers and actuators and the standard mechanical engineering education[12–15].

There are many institutions that have introduced mechatronics as a separate undergraduate degree program[8–10]; however, most institutions offer mechatronics training as an integrated package of the mechanical engineering degree program. Unfortunately, this approach of embedding mechatronics training as an integral part of mechanical engineering tends to result in a highly compressed program that may not sufficiently meet the core objectives of mechatronics training, for example by only focusing on PC based data acquisition systems and their use in control of mechanical systems.

Regular annual program evaluation results in the Department of Mechanical Engineering and Applied Mechanics at NDSU have shown an increase in the number of students with interest in courses that cover mechatronics and robotics[16]. On the other hand, these results have also shown that the current course load of 130 credit points must be maintained while keeping all existing courses. To address these student concerns, the department decided to introduce a technical elective that focuses on mechatronics design principles without significantly disrupting the existing educational structure. A comprehensive one semester curriculum that effectively covers the necessary elements of mechatronics education in a minimal class time of three credit hours was developed. Since the course topics were well known, the the challenge was on developing an instruction method that enables all intended topics to be covered without overwhelming students in their learning process.

It is known that most students approach the learning process through one of the following methods[17,18]: (a) surface approach, which relies on memorization of the facts; (b) deep approach, which deeply probes into the facts and their limits; and (c) strategic approach, which mixes both surface and deep approaches with the purpose of scoring highest in the examination. Based on review results of[17,19], it was decided to design a curriculum that will lead students into using the deep learning approach, which needs students to be highly *motivated* to develop *interest* in the subject matter. Popular teaching methods that have been proven to motivate students are based on the *learn-by-doing* philosophy[20]; these include the *problem-based learning (PBL) approach*[17,21], and the *inquiry based learning (IBL) approach*[17,22]. These are inductive methods that introduce the topic by using a problem which can be either a real-life problem, a theoretical problem or even a case study; subsequently, theories are taught around that problem, and students may be required to actually solve that problem. They are very effective in motivating students especially when the central problem is a is derived from real life experiences that students can relate to, as opposed to hypothetical problems that students may not be able visualize. IBL is effective in natural sciences[17], while PBL is more effective in applied sciences such as medicine [21] and engineering[19]. Despite their effectiveness in motivating students, these methods require a longer time to cover a specified amount of material in comparison to conventional methods; hence, they can be inefficient in terms of time[17,23].

Several schools have attempted the PBL approach in offering mechatronics education, and each may had encountered different experiences depending on their course structure, see for example[4–6,24,25]. This paper presents a brief description of the course structure that was developed and offered in one semester at NDSU for instruction of mechatronics principles using PBL; its also discusses some of the experiences gained in two years of running this course. The combined weekly instruction time for the course was four hours which covered both formal lectures when necessary and hand-on PBL sessions.

2 Mechatronics Instruction Program at NDSU

2.1 Program Prerequisites and Course Outline

There are several core courses in the NDSU's mechanical engineering curriculum that teach the necessary preliminary material for Mechatronics course. These courses include combined 10 credit hours on fundamentals of Electrical Engineering, 3 credit hours of Engineering instrumentation and measurements, 12 credit hours of mechanical and fluid power systems. Additionally, a 3 credit hour course in automatic control theory is offered as a technical elective. Students were assumed to have taken all of these courses before enrolling in the Mechatronics course; therefore, the course enrollment involved only graduating seniors and starting graduate students.

As would be expected from the standard content of mechatronics course, the new course was designed to cover the following topics:

- A overview of analog and digital automatic control systems.
- Elements of automated systems: sensors, actuators, and motion transmission units.
- Digital logic systems: combinatorial and sequential logic components.
- Microprocessor/microcontroller programming.
- Microprocessor/microcontroller based mechatronic systems and interfacing: DC motor drive systems, stepper motor driven systems, and pneumatic/hydraulic driven systems.
- Problem analysis, mechatronic system design and integration.

It is worthy noting again, that all of these topics are taught in many existing mechatronics programs elsewhere; however, because of time limitations, it is not common to have all of them covered under a one semester package. For example, some schools put more emphasis on PC-based control topics[5], and there are those that put more emphasis on microcontroller topics[6]. Some programs break these topics into two or more courses[25].

After considering the contents of the course prerequisites and these topics, it was decided the break the program into three levels with a total of ten modules as illustrated in Figure 1. The first level comprised of four modules that focussed on the basic elements of mechatronic systems; students learned how the core prerequisite courses come into play in the development of mechatronic systems. In general, this level provided students with both a theoretical review of facts learned elsewhere in the prerequisites and simple practical activities that enhanced their understanding of those theoretical facts; more emphasis was placed on major characteristics and limitations of sensors, actuators, motion transmission systems, analog signal conditioners, and digital logic circuits. Eventually students were introduced to the basic structure of microcontrollers, and features that distinguish them from the well known personal computers.

The material covered in the second level combined various elements learned in the first level into more meaningful microcontroller based mechatronic systems. Students were subjected to

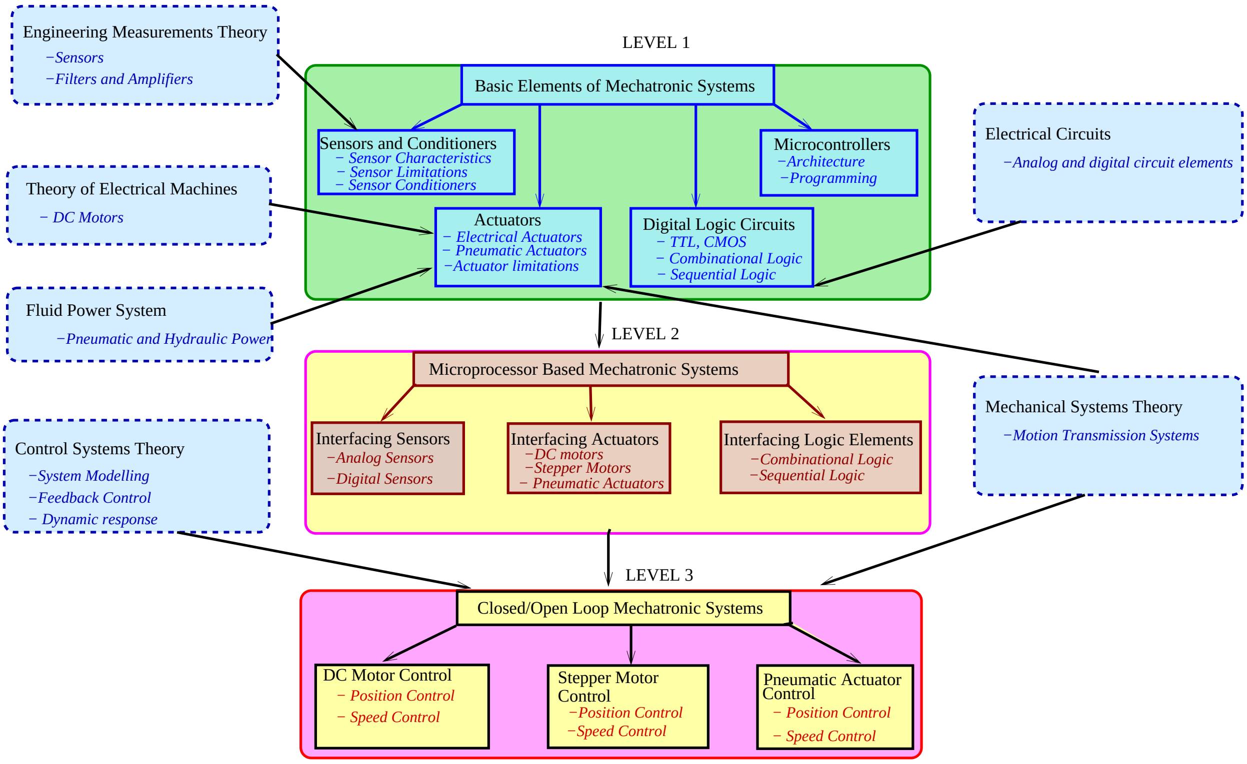

Figure 1: The Educational Structure of the Mechatronics Program at NDSU

activities that taught them how to use microcontrollers in reading sensor data and driving actuators. These activities focused on both interfacing techniques and programming the microcontroller. Students were taught principles of power electronics using transistor switches and optocouplers: high and low switches were discussed for two types of transistors: Bipolar junction transistors (BJT) and Metal Oxide Silicon Field Effect Transistors (MOSFET). Given the time limitations, Insulated Gate Bipolar transistors (IGBT) were not experimented with although they were introduced to students. The HIGH and LOW siwtches were combined in Half bridge, H-Bridge and inverter circuits, which were later used in interfacing various types of motors. The objective of this level was to prepare students for designing and building simple open loop and event driven mechatronic systems. Activities in this level were covered in sessions of three modules.

In the final level, students were required to use the knowledge gained in the second level along with control systems theory and mechanics of machinery into developing mechatronic systems that perform specific tasks based on closed loop control architecture. Students were subjected to activities that taught them how to build specific feedback mechatronic systems. It was expected that after this level, students should have been able to design and develop more complex closed loop systems with specific dynamic features. This level had three modules.

2.2 Program PBL Instruction Design

As it has been mentioned in the pevious subsection, the PBL approach for this program was broken down into a total of 10 modules grouped in three levels. Although these modules were crafted and worded in a way that students can relate the intended objectives to normal daily things, each module had specific educational objectives. In implementing the module, each student group had access to at least the following instruments: an OTE HY3005-3 Triple Output DC Power Supply, a Victor VC 9805A Digital multimeter, an Instek GDS-2204 Digital Oscilloscope, Solderless Breadboards and other instruments as illustrated in Figure 2. Students were organized into groups of three students, semi-independently working as group on each of these modules. The grade on each module was based on getting the module to work as intended, and for students being able to clearly show that they understood the module. To stir up competition among groups, there was a grading component that was determined how fast the group finished and understood their module relative other groups.

Figure 2: Typical lab instruments available to each student group per module

The details of each module are as follows:

MODULE 1: Characteristics of analog sensors/transducers and their signal conditioners:

1. **Objectives:** The main objective of this module was to teach students on how to handle various sensor/tansducer signals. Although the module was directly derived from the measurements and instrumentation course, it only focused on characterizing sensors and transducers based on their response signals and their dynamics. The module also covered methods of modifying sensor/transducer signals by signal conversion, amplification and filtering.
2. **Approach:** Three types of response signals were considered : electrical charge signals, electrical resistance signals and electrical potential difference signals. The module also considered two types of response dynamics in the linear range: the DC dynamics and the AC dynamics. The module was designed to use piezoelectric accelerometers as representatives of the charge dependent sensors, resistance strain gauges and pressure transducers as representatives of the resistance dependant sensors, and thermocouples and linear variable differential transformers (LVDT) as potential difference dependent sensors. In terms of the signal dynamics, the LVDT

was characterized as having AC dynamics while the rest had DC dynamics. First, in groups, students were allowed to play with and examine how these sensors respond to their target quantities. After students were familiar with how each group of sensors respond to their stimuli, they were guided to learn by experimenting on how to convert the non-voltage sensor signals to voltages. Finally a discussion on the application of AC signals was held and students were further guided though the conversion of the LVDT AC signal to DC by AD578 signal processors. Students were also reminded of the presence of capacitive transducers which were not covered in this module but they are resistance-like sensors with AC dynamics. This module was covered in one week of instruction.

MODULE 2: Characteristics of Actuators and Motion Transmission Systems:

1. **Objectives:** This module was focussed on exposing students to some of the popular types of actuators, their actuation motions and how these motions can be transformed by using motion transmission systems. The objective of the module was to teach students the basic structures and dynamics of various actuators and transmission systems; it was hoped that at the end of this module, students should be able to select an appropriate actuator for any given application.
2. **Approach:** This was a one week module in which students were asked to, first, study the internal structure of brushed DC motors, brushless DC motors, unipolar stepper motors, bipolar stepper motors and pneumatic cylinders by disassembling them. This PBL module did not include linear DC motors, AC motors nor rotary pneumatic actuators although there was a short lecture discussing them. After understanding the internal structure of those actuators, students were then asked to manually run the motors while changing their drive signals. DC motors were driven using variable voltage DC power supplies while stepper motors were driven using DMD808-P808 stepper motor diver unit and a function generator. Students were given an opportunity to examine how these motors respond to their drive signals and hence learn how their motion can be controlled. Pneumatic cylinders were controlled by using simple solenoid valves and they responded only by either retracting to extending; precise motion control for pneumatic actuators was not covered in this module although students were taught through a brief lecture on how such control can be achieved.

   Finally students were given an opportunity to transform actuation motion using mechanical motion transmission systems such as gears; belt and pulley drives; leadscrews and ballscrews; and pinion and racks. Plastic motion transmission systems from Lego Mindstorm kits were used for this purpose.

MODULE 3: Behavior of Combinational and Sequential Logic Circuits:

1. **Objectives:** This module explored the major principles of digital logic circuits: both combinational and sequential logic circuits were studied. The objective of the module was to equip students with the necessary skills for designing and developing digital electronic circuits using standard logic gates. Students already had the basic understanding of digital logic gates as covered in the core courses on principles of electrical engineering.

2. **Approach:** After a brief lecture on digital circuit design principles, students were provided with a variety of digital logic gates. Combinational gates included the AND, OR, NAND, NOT, and XOR gates; and, the sequential logic gates included the J-K flip flops, latches, counters, registers, and the 555 timer. Additionally, students were also provided with dip switches, push buttons, and light emitting diodes (LED) for use in studying the behavior of various logic gates. There were several predesigned group activities that lead students into examining the characteristics of these logic gates. Activities included simple combinational logic gates as in the open-door alarm system found in cars to complex digital signal patterns such as pulse width modulation (PWM) and others similar to those used in driving stepper motors. This module was completed in two instructional weeks.

MODULE 4: Architecture and Programming of Microcontrollers:

1. **Objectives:** This module was for teaching students the core element of most mechatronic systems, i.e., the microcontroller. The main objective of this module was equip students with sufficient knowledge on the structure and features of various microcontrollers; with this knowledge students can use manufacturers data sheets to identify and understand the key structure and features of any given specific microcontroller. The module closed by teaching students how to program microcontrollers using the assembly language instructions that are included in the manufacturers data sheets.
2. **Approach:** Since this module covered something that was completely new to students, one full lecture on microcontrollers and their common features was presented at the beginning of the module. Students were provided with a sample of various types of Microchip's PIC and Freescale Semiconductor's HC microcontrollers along with their datasheets. Finally the module focused on the HCS12 microcontroller, which is built in the Wytec Dragon12-Plus evaluation board. This is the board that was used throughout the course, it has many visual I/O interfaces that simplify the leaning process. Students were guided on using the instruction set to program the microcontroller for reading and manipulating its I/O ports. In doing so, students learnt various programming techniques ranging from simple straight line programs to complex programs that use subroutines, conditional branches and interrupts. The module was covered in two and half instruction weeks putting more emphasis on assembly language instructions that are most relevant for automatic control applications such as accessing input and output ports, looping and branching operations, arithmetic and logical operations,subroutines, and handling of interrupts.

MODULE 5: Microcontroller Interfacing of Logic Elements:

1. **Objectives:** In this module, students were taught on how to extend the functionality of a microcontroller by interfacing with external logic gates. The main objective of the module was to make students aware of the possible practical problems that might arise in hooking different logic units and how to address such problems.
2. **Approach:** Students were given both TTL and CMOS logic gates, and were asked to connect them as inputs and outputs of the microcontroller; dipswitches and LEDs

were used to assist in providing input and output signals. A simple continuous loop microcontroller program was used to read the input and write the result at the output. Different input and output signals were tested and students were able to see and learn some of the limitations in digital interfacing; i.e., some of the input digital signals were not understood by the microcontroller and sometimes the microcontroller output signal was not properly received by the output digital network. After these observations, students were taught on how to address those limitations by using pull-up resistors, Schmitt trigger gates, and optocouplers. The whole module was covered in one instruction week.

MODULE 6: Microcontroller Interfacing of Analog Sensors:

1. **Objectives:** The main objective of this module was to teach student various methods of interfacing analog sensors to a microcontroller. The module combined the knowledge gained in modules 1 and 5 in building a meaningful mechatronic subsystem that uses a microprocessor to read sensor data for possible use in closed loop control system.
2. **Approach:** Students were provided with single chip instrumentation amplifiers, a variety of calibrated analog sensors, and analog to digital converters (ADC) ICs. They were led to learn the process of scaling and converting an analog signal to a digital signal and its resolution, by building a system that translated the sensor signal into a digital signal at the input port of the microcontroller. The microntroller digital value of the sensor signal was compared to the actual analog value of the sensor and students were asked to verify the Aanalog-to Digital conversion theory in terms of the analog scaler and the digital resolution. Students were further taught that the analog input function of standard data acquisition systems is based on the same principle. After students were familiar with the analog interfacing process using ADC, they were focussed to the ADC functions built-in the HCS12 microcontroller chip by learning how to set them up and use them with various analog sensors.

MODULE 7: Microcontroller Interfacing of Actuators:

1. **Objectives:** The principal objective of this module was to teach students on the power limitations of microprocessors in comparison to power requirements of most physical actuators, and how these actuators can be hooked to and controlled by a microcontroller. Additionally, students were taught on the effects of the back emf generated by most electric motors to the performance of the microcontroller and how to suppress these effects.
2. **Approach :** In this two week module, students were provided with a DC motor, a stepper motor, power transistors, logic gates, digital-to-analog converters, optocouplers and a microcontroller evaluation board. First, students were asked to connect a DC motor directly to the microcontroller output port and program the microcontroller to turn on the motor. Following the obvious fact that the microcontroller was unable to drive the motor, students were taught why microcontrollers may not be able to directly drive most electric motors and other actuators. After learning the power

limitations of the microcontroller, students were further taught on how to address this limitation by using power transistors. Students learnt how to build DC motor drivers using both the linear and the switching (PWM) power transistors; after discussing advantages of each of these two methods, students further learnt that similar switching power transistor drivers can be used to drive stepper motors and hydraulic/pneumatic actuators. Finally, students were asked to monitor the microcontroller switching signals as the DC motor is driven by PWM driver; spiky signals were observed, which was an indication of the effects of backemf. These effects were then eliminated by connecting the microcontroller signals to the motor drive through optocouplers.

MODULE 8: Microprocessor Control of a DC Motor:

1. **Objectives:** The focus of this one and a half week module was to teach students how to build a closed loop control system for a DC motor to attain predefined speed and angular displacement values. The objective is to enable students develop both hardware and software system for closed loop DC motor control using a PID control algorithm, an H-bridge motor driver and an incremental optical encorder.
2. **Approach:** Along with the microcontroller evaluation board, students were also provided with an LMD18245 standard full bridge circuit, a 2140.937-61.112-050 Maxon 25V DC motor equipped with 2 phase optical encoder of 100 transitions and a gearhead reducer with a transmission ratio of 6:1, an unlimited supply of digital logic gates and passive components as the student may request. Students were challenged to build the closed loop system by completing the PWM motor drive unit and the encoder counter circuit followed by interfacing to the microcontroller ports. Finally, students developed a program that implements a PI controller using the PWM capability built in HCS12 microcontroller. At the end of the module, students were informed of the availability of off-the-shelf ready made DC motor driver circuits based on similar principle as this one.

MODULE 9: Microprocessor Control of a Stepper Motor:

1. **Objectives:** This module focused on teaching speed and displacement control of stepper motors and illustrate applications where accuracy in both speed and displacement are important. The module objectives were not to show students the principles of open loop stepper motor control.
2. **Approach:** In addition to the microcontroller evaluation board, students were provided with one 24Y2 Anaheim Automation stepper motors, which can be configured to run in either unipolar or bipolar mode. Additionally, students had an assortment of logical gates, and switching power transistors. They were required to carefully study the motor specifications and build an appropriate drivers for each mode of the motor. After completing the driver circuit and interfacing to the microcontroller, students were required to write the open loop control program to implement the motor displacement by counting the the number of steps. The resulting system was tuned by increasing the driver voltage until the motor was found to un smoothly. The module was finalized by changing the pulse frequency and number of pulses in the control

software to achieve different motor speeds and displacements. Just like the case for the previous module, students were also informed of the availability of off-the-shelf steppe motor control drivers.

MODULE 10: Microprocessor Control of a Pneumatic Cylinder:

1. **Objectives:** At this point, this session was probably the shortest and the simplest of all modules in this program. Its objective was only to illustrate to students that pneumatic and hydraulic actuators can be controlled by using a microcontroller interfaced with with solenoid valves. Due to the nature of the solenoid valves used in this class, the module focussed only on the FORWARD-BACKWARD actuation motions of these actuators.
2. **Approach:** Students were supplied with Clippard double acting pneumatic cylinders along with 3-way Maximatic solenoid valves and a number of logic gates, dip-switches, LEDs and power transistors as necessary. First, students were given an opportunity to play with and examine how the double acting cylinder and the 3-way solenoid valves work. Then they were guided in the process of building a control system that extends and retracts the cylinder as a response from input signals to a microcontroller using a microcontroller. Finally, students were asked to build a control system that achieves that goal above by using the provided components.

In general, each of these modules was made of interactive sessions that mix both theory and applications. Although there are cases when destruction of the components was deliberate permitted as way of teaching students, the instructor was always monitoring student activities and providing close guidance to avoid unintended equipment damage; additionally, the instructor also provided theoretical explanations of most observations as needed during the session. Unfortunately, there were certain theoretical facts that could not be directly be seen using these modules only; in that case, the instructor would conclude the session by discussing those unobserved theoretical facts.

At the end of the program, students were asked to complete a term project of developing a microcontroller based mechatronic system for performing a particular task. Some of these project tasks included a control system for the four-storey elevator, a dispenser system for a vending machine, centralized urban traffic control system, and a differentially steered two motor robot drive.

3 Student Response and Program Improvements

Program evaluation results by students have so far been positive. During the first year, the course received an ‘A’ rating from all five students who participated; however, during the second year, when there were six students, one student was not happy with the microcontroller programming tasks. One obvious reason that seemed to frustrate this student was the requirement to plan and write a fresh program for each module and each task. It is possible that assembly language programming may have overwhelmed him especially since most of our students do not have solid foundations in computer programming languages such as C, C++ and VBASIC. This lack of programming background and the tightness of the program makes assembly language programming the best approach in this course. As a way of improving the course, the microcontoller programming module will be simplified further and given more coverage time to enable student grasp the necessary skills. Additionally, students will be asked to keep all of their programs for future reuse to avoid frustrations that can arise out of having to rewrite same programs over and over again. Other than the single students who was unhappy with assembly language programming, most of the students were happy with the course.

On the grading system that awarded more to those who learn and finish the module fast, student's were almost equally divided on their support for and against this system. About half of them dislike this approach while another half liked it. It is thought that slow students, who seem to have been affected by this system did not like it while the fast students who benefited from it, liked it. There is no plan to significantly change this approach, however, the gap between fast learners and slow learners will be reduced; i.e the speed component of grading will be small although it will remain there.

4 Summary and Conclusions

Mechatronics is a multidisciplinary design philosophy that draws knowledge from mechanical engineering, electronics, computer science, and control systems. Mechanical engineering programs often find it difficult to comprehensively cover all principles of mechatronics because of its wide coverage spectrum and limitations in instruction time. This paper has presented the approach taken by North Dakota State University to teach this course using problem-based learning approach. Although only few students participated in this project, the results were generally very encouraging. All topics intended for the course were actually covered, and students responded positively to the approach. The only limitation observed from this approach was that there were certain theoretical details that could not be learned using this approach because they were not easily visible. This approach can be improved further by making sure that all theoretical details that may not be visible through practical session are identified and discussed before the students start working on the module activities instead of discussing them after the module.

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