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Community College Approach To System Engineering Concepts

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Abstract

Systems engineering at the community college level is an often overlooked concept. Educators realize its' importance, but the curriculum is already packed with other essential topics. Most complex engineering projects today all have a heavy focus on system engineering elements for their successful completion. These projects include Spacecraft design, military weapon systems design, aircraft, missiles, etc. and even communication systems design, both wired and wireless. In fact one of the earliest mentions of the importance of systems engineering concepts was at Bell Laboratories in 1940 .

This paper will highlight three different aspects of our approach to systems engineering concepts at Queensborough Community College. Our first application of system engineering is a communication system project in our Computer and Electrical Devices Applications course. This project introduces the building blocks of a fiber optic communication system including a transmitter, receiver and an amplifier. The stages are built by independent teams and then integrated to operate as a functional system.

Robotics is our second system application. Students integrate software programming and hardware design to produce a functional robot. Software teams develop and debug programs, which run on the robot's microcontroller. Hardware teams build and test the hardware independently to insure proper functionality. The teams synthesize their designs to satisfy the system design challenge.

Our third example focuses on meeting required system level specifications for a two stage amplifier with power supply. The students are given the specifications for the supply voltage, amplifier gain, input, and output impedance. The design project is divided amongst the teams, who then combine and test the overall system.

Introduction

Systems engineering at the community college level is an often overlooked concept. Even though educator may appreciate the importance of system engineering concepts, it is somewhat difficult to include this material in an already packed curriculum. An engineering education should include system engineering concepts because most complex engineering projects today focus heavily on system engineering elements for their successful completion. These projects include the design of space crafts, military weapon systems and both wired and wireless communication systems. One of the earliest mentions of the importance of systems engineering concepts was at AT&T Bell

Laboratories in 1940 [1]. The National Council on Systems Engineering (NCOSE) was formed in 1990 to advocate and further the area of System Engineering. Increasing contributions from the community outside the US predicated a name change to the International Council on Systems Engineering (INCOSE). System engineering is defined by INCOSE as: ". . . an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem [2]: NASA defines systems engineering as: "an interdisciplinary approach encompassing the entire technical effort to evolve and verify an integrated and lifecycle balanced set of system people, product, and process solutions that satisfy customer needs. Systems engineering encompasses (a) the technical efforts related to the development, manufacturing, verification, deployment, operations, support, disposal of, and user training for, system products and processes; (b) the definition and management of the system configuration; (c) the translation of the system definition into work breakdown structures; and (d) development of information for management decision making." [3]

Community colleges are a rapidly growing part of the US higher education system and will become increasingly important in retraining the American workforce for the 21st Century. President Obama proclaimed that community colleges are vital to America's future competitiveness, and he envisions an additional 5 million graduates from these education institutions by 2020. [4] This paper will concentrate on highlight the different aspects of our approach to introducing systems engineering concepts to the students at Queensborough Community College. In our Computer and Electrical Device Applications course, we introduce a fiber optic communication system consisting of a transmitter, receiver and a gain stage amplifier. The stages are built separately and the students then integrate them and try to get the system to operate from a system point of view. In our software and hardware design classes the concepts of robotics are introduced. The software class focuses on programming fundamentals and the project lab class focuses on hardware concepts. The Robotics Club builds on the fundamentals of the aforementioned classes and integrates the electronic, mechanical, and programming concepts involved in the analysis, design, and construction of robotic systems and focuses on systems integration of these systems. Finally in our electronics program the circuit analysis course focuses on electronic devices including diodes, bipolar junction transistors, and field-effect transistors, along with circuits such as amplifiers and power supplies.

As in all of the electronic circuits courses, the students practice using their theoretical skills to analyze electronic circuits and they apply their hands on skills when building the circuits in the laboratory. A system level analysis project is assigned in the middle of the semester, which provides the opportunity for the students to apply what they have learned to a real world engineering project. In this project, the students analyze an electronic system such as a multistage amplifier with a DC power supply. The students analyze the individual circuits and then integrate their results to obtain the system level parameters. The system is simulated using circuit simulation software and the students can use their results to write a detailed project report, which includes block diagrams, detailed schematics, and an analysis of the system including the application of all pertinent equations. The students can also discuss the limitations of the design and they can make suggestions for improvements.

Fiber Optics Communication System

The Computer and Electrical Device Applications course places an emphasis on technology topics in computer engineering. The class discusses electronics applications in BJT switching and amplification, and the student perform related experiments. The course also introduces Programmable Logic Devices [PLD], by using Very-high-speed integrated circuit Hardware Description Language [VHDL] to program a field-programmable gate array [FPGA].

The course also includes system engineering activities. It is this area of the course that we will concentrate on in this paper. The project of interest is one where the students build a simple fiber optic communication system in discrete stages and then integrate them to make a complete system. The challenges in this experiment are designed to mimic the constraints a student would face in "real world" engineering design problems. These challenges include

- Time constraints
- System complexity
- Working with multiple teams
- Being judged on the work of the team and NOT the individual team member performance.

Let us now look at the individual challenges mentioned above.

Time constraints

This laboratory experiment that has to be completed in the three hours allocated. The groups work simultaneously to complete their own sub systems in a single three hour lab session at QCC. Typically student who pace themselves and accept the challenge are able to work efficiently and complete the assignment within the time constraints. However, easily distracted students do meet the time constraints.

System Complexity

One of the challenges of this laboratory exercise is to experience what it is like to function as a team to build a complex system. The individual stages consist of circuits that are all breadboard wireable. These circuits contain components such as Operational Amplifiers [Op Amps], BJTs, and photo diode transmitter and photo diode receiver pairs. The entire system could be built sequentially by one team of students. However, the work is divided amongst three teams who work simultaneously. This divide and conquer method is a common practice for larger engineering projects. The work is divided into smaller manageable portions to shorten the project development time. The team will then combine their work at the end of the experiment to build a larger system. The functionality of the larger system will depend on the success of each individual team's ability to deliver quality work and function as a member of a team. As shown in the diagram above, the total system is divided into three sections and each section has a team working to deliver a functional block.

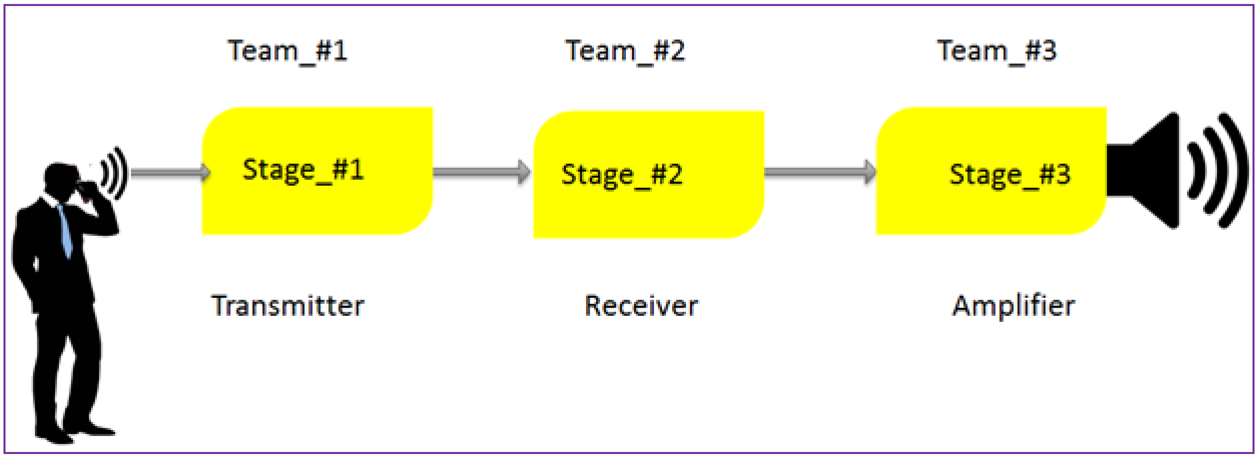

Figure 1. Fiber Optic Communication System

Working with multiple teams

The system is made up of three stages and is divided amongst the three teams as shown in Figure 1. The success of the system depends on the success of the individual teams. To emphasize this, the teams must combine their individual efforts to obtain an operational system. Each team must build, test and troubleshoot their individual stages. The stages are then combined to build a larger system. This entire system is integrated and tested at a higher level.

Being judged on the work of the team and NOT the individual team member performance

The grade for the lab will be evaluated on total overall team performance and not on individual contribution.

Power Supply and Amplifier System

This section highlights the synthesis of a power supply and cascaded amplifiers stages. The goal of the amplifier design is to obtain a voltage amplifier with the following characteristics:

- Relatively high voltage gain magnitude
- Relatively high input impedance
- Relatively low output impedance

The individual stages are synthesized into the following amplifier system:

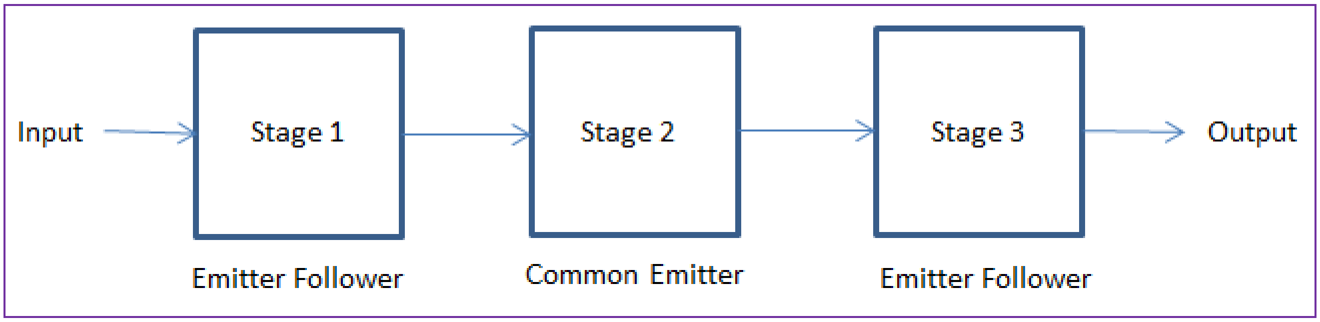

Figure 2. Amplifier System

The amplifier system typically consists of multiple stages, including common-emitter with voltage-divider bias and emitter-follower with emitter-stabilized bias configurations. The students learn that it is necessary to take a systems approach to the amplifier design in order to meet the given specifications of voltage gain, input impedance, and output impedance. The common-emitter stage provides relatively high voltage and current gains. The emitter-follower stages provide high input impedance and low output impedance, with a voltage gain that is typically slightly less than one. Stage one is an emitter-follower with gain $\mathbf{A_{V1}}$ and relatively high input impedance $\mathbf{Z_{IN1}}$. Stage two is a common-emitter amplifier with relatively high voltage gain $\mathbf{A_{V2}}$. Stage three is an emitter-follower with gain $\mathbf{A_{V3}}$ and relatively low output impedance $\mathbf{Z_{OUT}}$.

The overall voltage gain is:

$$A_{V\,SYSTEM} = A_{v1} \times A_{v2} \times A_{v3} \qquad (1)$$

This equation assumes that the loading of each stage on the previous stage is taken into account.

The system input impedance is:

$$Z_{IN\,SYSTEM} \approx Z_{IN1} \qquad (1)$$

The system output impedance is:

$$Z_{OUT\,SYSTEM} \approx Z_{OUT} \qquad (2)$$

The system output impedance $Z_{OUT\,SYSTEM}$ takes into account the effect of stage 2 on the output impedance of stage 3.

We discuss the fact that typically it would not be possible to design a single stage amplifier with all of the desired characteristics. A block diagram approach is used to provide a synopsis of the amplifier system, and then the amplifier circuitry is analyzed in detail to find the overall voltage gain, input impedance and output impedance based on each stage and the interaction between stages. The students learn very important system concepts such as the loading effect of each stage on the previous stage. Furthermore, the students learn that the overall voltage gain is the product of the individual voltage gains of the stages, taking loading into account. The amplifier and power supply designs are synthesized into a complete system, which meets the design criteria.

The Students in the Electronics and Computer Engineering Technology (ECET) degree program take a course in Electrical Circuit Analysis I (DC) in their first semester. In the second semester the students take the Sinusoidal (AC) and Transient Circuit Analysis course and the Electronics I course. The Electronics I course utilizes the concepts from the DC and AC circuits courses in the analysis of systems containing electronic devices such as diodes and transistors, along with resistors, inductors, capacitors, and sources. Each of the courses presents a different challenge to the students. The DC circuits course is challenging because it is the first electrical circuits course which the students take, while the AC circuit's course uses complex number mathematics. The electronics course provides a unique challenge because diodes and transistors are non-linear components and transistors are three terminal devices, which include a controlled source in the device model. Therefore, it is necessary to determine the region of operation of a diode or transistor and use the pertinent approximations in the circuit analysis. Such an approximate analysis requires physical reasoning, which is obtained with practice and experience. This represents a departure from the analysis of DC and AC circuits containing linear devices only, where the students use KVL, KCL, and Ohm's Law (or complex impedances and phasor voltages and currents) to write linear equations, which are then solved algebraically.

We discuss Bipolar Junction Transistor (BJT) amplifier designs including both the common-emitter and emitter-follower configurations with fixed-bias, emitter-stabilized bias, voltage-divider bias, and collector-feedback bias. Amplifiers based on Field-Effect Transistors are also discussed in the electronics course. The BJT amplifiers typically use voltage-divider bias for the common-emitter amplifier stage and emitter-stabilized bias for the emitter-follower stage because they provide good biasing stability and allow the Quiescent Operating Point to be centered on the load line for each stage. The students observe the large possible variation of Beta indicated on the transistor data sheet. Therefore, the biasing circuit must be designed such that it is relatively independent of Beta. The students use the superposition theorem to analyze the circuit by first analyzing the DC biasing circuit and then analyzing the AC equivalent circuit. The capacitors are open circuits to DC and approximate short circuits to AC. The students are using the concepts from the DC circuit's course, AC circuit's course, and the electronics course to analyze the amplifier.

The students gain a deeper understanding of system engineering problems by using component models and approximations, which hold in the normal active region of transistor operation. They also learn that all approximations are only valid over a particular range of operating conditions. The design of the amplifier involves the selection of the quiescent operating point, which is set by the DC biasing circuit. A discussion of suitable operating points is included in terms of the load line, which graphically shows the location of saturation, cutoff, and the quiescent operating point. We discuss the fact that the optimum location of the quiescent operating point is at the center of the load line, in order to obtain the maximum *possible* symmetrical peak-peak unclipped output signal. The students plot the load line and find the voltage gain and input and output impedances of the amplifier. The input voltage is specified at two different levels such that the output is undistorted at the lower level and the output exhibits clipping distortion at the higher level. The condition for clipping of the output waveform is determined from the load line. In addition to the detailed analysis of the amplifier circuit schematic, the two-port representation of an amplifier system and the individual stages is discussed. The students learn that the input circuit of the amplifier can be represented by the input impedance and the output circuit of the amplifier can be represented by a Thevenin equivalent circuit. The Thevenin equivalent of the output circuit consists of a Thevenin voltage-controlled voltage source, which is obtained from the open circuit or no- load output voltage, in series with the Thevenin output impedance of the amplifier. The students observe that a voltage divider is formed between the source impedance and amplifier input impedance, and another voltage divider is formed between the amplifier output impedance and load impedance. The two-port model can then be used to represent each stage of a cascaded amplifier system, which can be analyzed using a systems approach.

We expand our discussion in the electronics course beyond the amplifier to include the analysis of a linear DC power supply consisting of a transformer, full-wave bridge rectifier, capacitor filter, and voltage regulator circuit, as shown in the block diagram directly below.

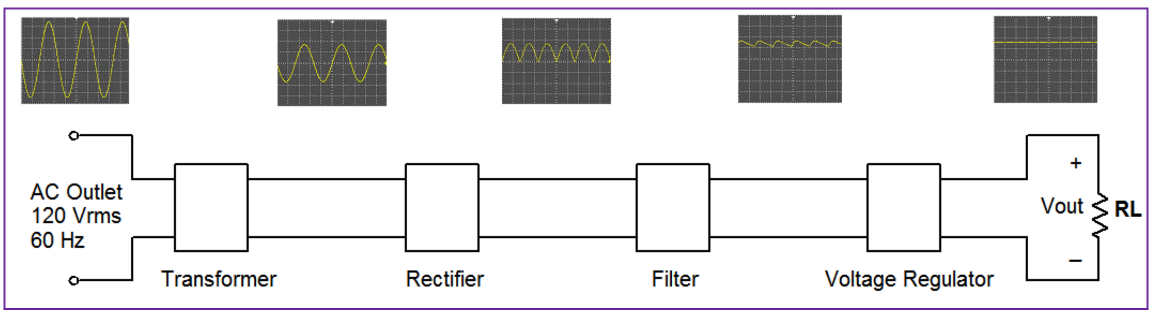

Figure 3. DC Power Supply Block Diagram

The voltage regulator contains a series pass transistor, zener diode, and resistors. The power supply circuit is analyzed in stages beginning with only a transformer and rectifier and culminating in the analysis of the entire circuit. A block diagram is used to represent the function of each stage and then the power supply circuitry is analyzed in detail. The DC component and approximate AC ripple voltage component are calculated at the output of the filter stage and then at the output of the regulator stage. The students discover that the approximations we use are valid only in the low ripple case. Such approximations can often be used in the design of a power supply because low ripple is the design goal and the actual design will perform better than the predictions obtained by approximations in this particular case. The students solve problems where they calculate the required capacitance value of the filter capacitor to obtain a sufficiently small ripple voltage for a given power supply design. A laboratory experiment is performed where the students analyze and construct an entire DC power supply. The DC power supply used in the lab experiment is designed such that the magnitude of the AC ripple voltage across the filter capacitor is high enough to see on the oscilloscope, but low enough to insure that the calculation of the ripple voltage represents a decent approximation of the measured ripple voltage component.

The students solve analysis and design problems related to amplifiers and power supplies on homework assignments. The design problems consist of power supply and amplifier circuits where the desired currents and voltages are provided and the students have to calculate the required circuit resistance and/or capacitance values and the required power supply voltage for an amplifier in some cases. Most of the students are able to complete all of the analysis problems perfectly. However, the design problems present a much greater challenge, which the more ambitious students meet. However, students are allowed to work together on homework assignments as long as each student submits his or her own work, and this helps to build learning communities where students help each other. In addition, the faculty members provide extensive tutoring in their offices and the assignment of highly challenging problems is a great way to get students to come to the office for additional help.

The students build amplifier and power supply circuits in the laboratory, which they also analyze theoretically. The measured results are compared to the theoretical results using percent difference calculations and the students are asked to explain the sources of discrepancies in their laboratory reports. For example, the students should consider the percent tolerance of the resistors used in the experiment. Additional sources of error include the following: 1) Differences between the actual diode voltage drop and the approximate value of 0.7 V (for a forward biased Silicon junction), which is often used in calculations. 2) Variations in the Beta (β) of a transistor. 3) Actual capacitive reactance (X_C) of a capacitor as opposed to approximating coupling and bypass capacitors as short circuits to AC in the AC analysis of an amplifier (students are taught how to calculate and use the complex impedance of a capacitor in circuit analysis in the AC circuits course). The students learn that real world systems should be designed such that they are desensitized to the sources of error mentioned above. The students investigate the non-linearity of the amplifier circuits in the laboratory by observing that the output waveform of an amplifier, with a sinusoidal input, is not "perfectly" sinusoidal (even before clipping occurs). The positive and negative alternations of the output waveform have different peak values and time durations, which the students observe on the oscilloscope (at input voltages which are higher than those required for small signal operation). Moreover, the students are asked to increase the input voltage to the point where output clipping distortion occurs and the amplifier operation is now grossly non-linear. A system level approach is taken in the analysis where, for example, such behavior is compared to home stereo equipment in the case of clipping distortion. The operation of an amplifier circuit is also simulated using circuit simulation software and the results are compared to the measured and calculated values. Therefore, the students obtain real world experience in the systems design process. They also observe the importance of the final system design step, which includes breadboarding, and taking measurements. The final design step will often indicate that the design may need to be modified to function properly. For example, power supply bypass capacitors may be needed for the breadboarded circuit design to function properly, which would not typically be discovered in a simulation.

The amplifier analysis is performed using an ideal model for the DC voltage source in order to simplify the schematic. After performing the complete amplifier analysis, the overall amplifier and power supply system is represented by a block diagram. The complete schematic of the amplifier and power supply system is then drawn showing the circuitry of the actual amplifier and power supply sections in detail. This system is a synthesis of the amplifier and power supply subsystems, along with many of the concepts presented in the DC circuit course, AC circuit course and the electronics course.

Robotic Systems

A Robotic system is our third example of our approach to teaching systems concepts. Our goals are to design Robotic Systems which utilize the following ideas:

- Hardware modules
- Software concepts
- System Integration of hardware and software

We will now examine each component mention above.

Hardware modules

In the hardware project laboratory, we examine the hardware modules that are common to all robots. These include contact and infrared sensors, closed loop control systems using a microprocessor, servo motors and H-Bridge motor interfaces in robotics applications.

Students are required to complete a project laboratory in which they build a programmable robot. The Project class is a requirement for students completing the Computer Engineering Technology degree program (A.A.S). The approach to the hardware project laboratory class at QCC focuses on digital and analog electronic circuit theory, and some mechanical concepts. The learning objectives are for students to understand electronics as related to applications in robotics. Students also obtain practical experience in troubleshooting electronic circuits and motor controllers, using effective instrumentation and measurement techniques. The students should have prior knowledge of digital systems, including memory, memory interfacing and I/O systems. The students also need to know the basic theory and operation of electronic devices including semiconductor switching diodes, zener diodes, and transistors. The students use the schematic and block diagram to troubleshoot the digital and analog electronic systems of the robot in order to solve any functional problems as shown in the Figure below.

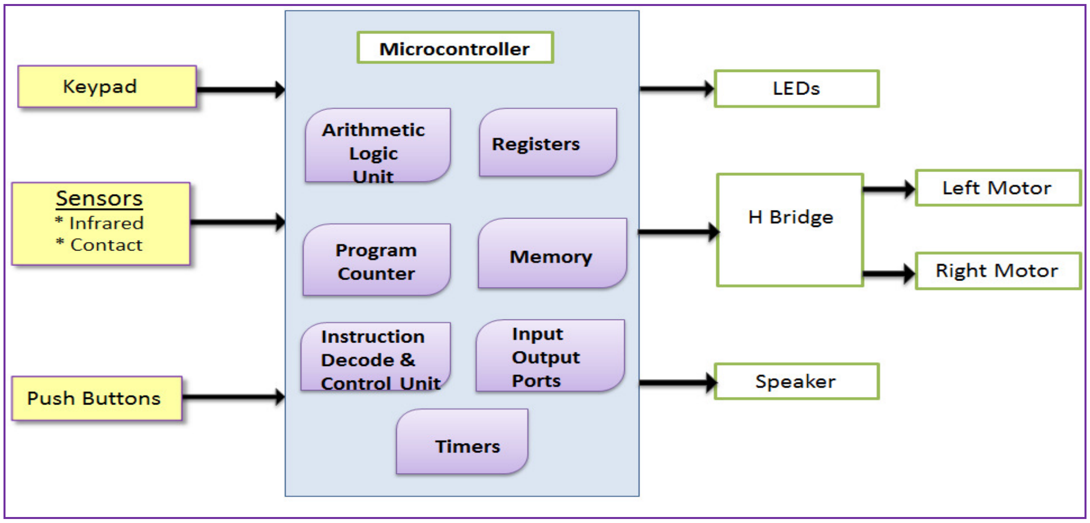

Figure 4 Typical Robotic System Block Diagram

The unique feature of the robot used in the project lab class is that it consists of discrete subsystems, which include power supplies, clock oscillators, memory, digital logic circuits, transistor drivers, and motors. The students build and test each of these subsystems in a sequential manner, and then integrate them into a functional robot. The students build a programmable robot from components in stages, which are then integrated into an autonomous system. The components are soldered to a printed circuit board, which is then mounted to a mechanical chassis assembly that consists of motors and gears. The motors and gears used in the mechanical assembly of the robot provide the steering function. The robot is then programmed by a keypad to follow the designated instructions.

To program this robot, instructions are fed through a keypad that connects directly to the memory load sequence circuit, which increments each command into memory. The instructions for the robot are programmed into memory in desired order such that the robot can navigate through its' environment. The robot exits the programmable mode and enters the execute mode upon removal of the keypad. The instructions are read from memory in the order in which they were programmed and are repeatedly executed in a continuous loop. This method is fully utilized in a robot that has to perform monotonous tasks such as those on a manufacturing assembly line. Students gain a great deal of exposure to Analog, Digital and Mechanical theory by building this robot. They have the opportunity to observe how all of these systems work individually and together as a whole.

Software concepts

The software class focuses on programming application as it relates to robotics. The programming class builds on the aforementioned hardware concepts to introduce topics in robotic control from a software point of view. The programming class uses Visual Basic to reinforce programming concepts. Once the students have mastered these topics, they begin to use their knowledge of robotics hardware and software to solve a challenge.

Students learn how to control the servo motors by using pulse width modulation at the appropriate microcontroller output. Students write the interrupt service routines that will process any interrupts generated. The students apply programming concepts such as looping, decision making, processing and I/O operations to autonomous robotics applications.

System Integration of hardware and software

After the hardware and software fundamentals are established, the students are given a design challenge. The challenge is to build an autonomous robot that will exhibit random wandering with object detection and avoidance behavior. We divide this challenge into several manageable tasks, which are implemented by various student teams. These tasks include object detection, motor control, obstacle avoidance, and displaying status information

- **Task one: Object Detection**

Object detection can be handled in one of two methods. The students can use a sensor which is designed to open or close a switch upon contact with an object. The change in the state of the switch generates an interrupt which is serviced by the microcontroller. An alternate method is to use an infrared sensor to detect a reflected light beam of an object ahead. The preferred method is the non-contact technique which uses infrared sensors. After the robot has detected its' proximity to an approaching object, it uses that information to avoid contact. The robot uses two sensors to detect whether the obstacle is on the left or right side. The robot uses this knowledge to pivot or turn in order to navigate around the object.

- **Task two: Motor Control**

When necessary, the software is used to alter the direction of the robots movement by controlling the pulse and duration of either the left or right servo motors. The challenge comes from the student generating the code needed to turn the robot by +90, 180, or -90 degrees.

- **Task three: Combining the effort of the other teams**

The primary task here is to synthesize the work done by the other two teams. The end result is to obtain an autonomous robot that will execute random wandering with obstruction avoidance behavior. The microcontroller program must monitor the sensors, process information by executing computation and decision making statements, and then update outputs. Monitoring the sensors and updating the outputs requires the consideration of real time constraints, which are unique to embedded systems programming and robotics. The flow chart below demonstrates the algorithm need to accomplish our task

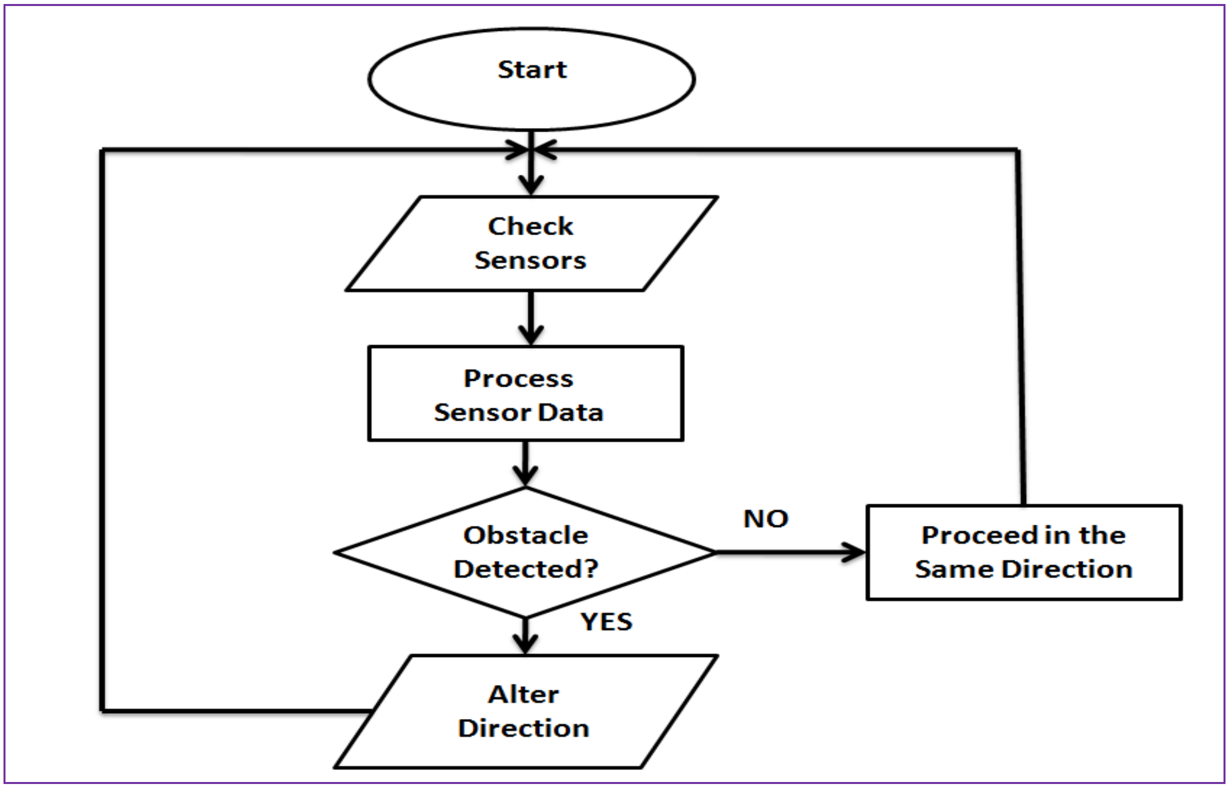

Figure 5. Design Flow Chart

Conclusion

System engineering concepts are divided among various courses in our curriculum at Queensborough Community College, even though we do not have a dedicated system engineering program. It is an important, but sometimes overlook concept. For the success of any real world engineering product, hardware and software developers must work in groups for efficacious product design and implementation. The characteristics of a system engineering approach are highlighted below. Teams work in parallel to shorten the development cycle. Complex projects are broken down into simpler and more manageable modules. The overall success of the project depends on each team delivering a quality subsystem. These subsystems are then synthesized into a larger system. The concept of team recognition and not just the contributions of the individual members is appreciated.

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