Automated Coil Gun

Brian Hoehn, Josef Von Niederhausern, Kwok Ng, Ricardo Reid

University of Central Florida
Department of Electrical Engineering and Computer Science
4000 Central Florida Blvd, Orlando, FL 32817

I. INTRODUCTION

A pulsed linear induction motor commonly known as a coil gun is not considered an efficient system. Some enthusiast has achieved efficiencies of 10% but most range from one to two percent energy transfer. This project was initially motivated by a similar project found on YouTube. This was a high voltage self targeting coil gun designed by students at a University in California. In addition to previous projects some other motivation for building a coil gun was based on power systems. One of this group members is fascinated by power systems and felt this would be a challenging project. Another motivating factor was a fascination of group members with the electromagnetic field. Additionally, several members of the group are fascinated with projectile weapons and the development and research of such.

From a firearm standpoint current technology does not allow for a military use of coil guns. One of the immediate benefits is the ability of a coil gun to fire a projectile relatively silent compared to conventional firearm. One of the major negative aspects of a coil guns when used military or law enforcement is the heavy cumbersome load needed to generate the current source. The weight necessary to accommodate the current source, a capacitor bank or battery, reduces mobility driving a mounted implementation. Even if the current source could be mitigated the strength of a coil is proportional to the number of turns which tends to create a heavier unbalanced barrel assembly. This project will use a mounted coil gun to achieve the maxim velocity possible. The project's goal for mussel velocity is to achieve around one hundred feet per second which is approximately thirty one meters per second.

II. POWER SYSTEM

The power system of the coil gun plays a vital role in the operation of the automated coil gun. It supplies the power throughout its circuit and allows it to function properly. The main portion of the power subsystem is essential because it allows the gun to shoot and routes the power throughout the whole system. The main power supply utilizes a 120V AC power outlet. AC power was chosen because it is readily available. Since this is a high powered gun the need for stepping up voltage was a must. The standard 120V AC power supply's voltage is stepped up using an airplane step-up transformer. The transformer steps up the AC outlet power supply to a voltage of 480V. The voltage from the transformer goes through a voltage divider that outputs 400V which is the rating of the 5mf capacitor bank. The voltage from the transformer is rectified through a full-wave bridge rectifier that is composed of MUR860 diodes. These diodes are ultra-fast, and have a maximum DC blocking voltage of 600V. This full-wave rectifier converts the AC voltage input into DC power which is the manner at which capacitors are charged. The resistors used for the voltage divider can withstand large amounts of heat dissipation, they are rated at 50W. This was pertinent to the overall design of the project because there would be high voltages outputted across these resistors. The resistor that handles the 400V still gets relatively hot. The majority of the heat is alleviated from the resistor by hindering the large amount of current going through it. This is obtained by increased resistance in series with the circuit. The gun charges relatively fast and there is no need to have a safety because the capacitor bank does not over charge. The capacitor banks charge voltage is displayed through a digital voltmeter that is in parallel with the gun's capacitor bank. This allows the user to fire the weapon at different DC voltages. The digital voltmeter has its own 9V power supply. It requires a minimum supply of 6V. The voltage meter has a switch that is in series with its power source. This enables the voltmeter to be turned off when the voltage of the gun's supply is not need. Most of the power that is used comes from the blue LED that lights up when the voltage meter is on.

A transformer is likely the ideal choice for stepping up voltage in high voltage applications. In the coil gun its necessary in order to step up the120V AC outlet voltage. Transformers are in no way cheap and can be hard to find depending on the type of output voltage needed through the secondary. The transformer used in the coil gun circuit has the perfect output voltage of 480V AC. Stepping up voltage through DC by buck and boost convertors were also investigated. It was found that they were extremely expensive and inefficient in mid voltage applications such as the coil gun system. With that said an AC transformer had to be selected. Attached to the primary side of the transformer is a fuse holder that holds a 120V 20A fuse. The fuse is a precaution for the coil guns circuit. It protects the circuit from any shorts or electrical failures that may occur. This little addition to the coil gun is the most important safety device. It prevents an overcurrent from occurring and possibly starting a fire. The small wire in the fuse melts when an overcurrent occurs.

The gun's capacitor bank releases huge current surges through a coil that fires a projectile through a barrel. The coil or solenoid is in parallel with the capacitor bank and in series with a silicon-controlled rectifier. The silicon-controlled rectifier can conduct 10 times its current rated value of 110A. The current one in the circuit allows up to 1100A. This is perfect because the solenoid or coil experiences a peak surge current up to 1000A. The silicon-controlled rectifier is the key to allowing the current surge from the capacitor bank through the coil. The silicon-controlled rectifier or SCR for short begins conducting once a triggering voltage of 3V is applied. The 3V is applied from the emitter of a transistor that is connected to a 3V Lithium Cell battery. The lithium cell provides the gate of the SCR with the minimum current that is needed to trigger the SCR when 3V is applied. There is another SCR that is connected in series with the charge switch as well. The coil gun circuit has a charge switch, with a silicon-controlled rectifier that is in series with the full-wave bridge rectifier and a resistor. The idea behind using a SCR is the same as previously stated. When the SCR s gate is triggered the capacitor bank begins to charge.

For the coil gun the major obstacle was finding the right method of switching high currents. There were a number of choices to choose from. Any type of transistor would do for switching but the obstacle was dealing with the extremely high peak currents. The four choices for a coil gun are the power MOSFET, silicon-controlled rectifier, n-channel BJT, and an Insulated Gate Bipolar Transistor. The advantages and disadvantages of each were weighed and the appropriate switching transistor was chosen. The power metal oxide semiconductor field effect transistors and n-channel bipolar transistors had multiple issues when exposed to reverse peak voltage magnetic fields. Another issue arose when research was done because of the gun's projectile being prone to the suck-back effect with the two transistors. The two devices that showed the most promising results in all simulations were the insulated gate bipolar transistor and the silicon-controlled rectifier. Both devices were ideal since they could handle the electromagnetic fields that would be present when the gun fired its projectile. From careful research it was found that the silicon-controlled rectifier could handle the reverse electromagnetic fields. A major disadvantage for the insulated gate bipolar transistor came from it price. It is very expensive at the voltages and currents that the gun's capacitor bank releases. The silicon-controlled rectifier used in the coil gun's current state was very volatile and relatively cheap. There are various silicon-controlled rectifiers to choose from as well. The name silicon-controlled rectifier is often misunderstood. It is a major brand of thyristors that are often used.

The capacitor bank of the coil gun stores all the energy needed for the gun. The capacitors are electrolytic which are not the best capacitors but do the job. The choices for capacitors were very limited due to their cost. The total capacitance of the bank is 5mF. 5 capacitors at 1mF each are put in parallel to obtain the total capacitance. They are made parallel by a thick copper bar. The copper bar reduces the possibility of any energy loss. The coil gun's capacitor bank has low ESR and low ESL rating. ESR is the equivalent series resistance which basically is a capacitors internal resistance. Low ESR is important for a capacitors bank in a coil gun system. Low ESL is the equivalent series inductance. For the coil gun it's important that the equivalent series inductance is lower than the inductance of the solenoid. The capacitors are rated at 400V. The voltmeter in parallel with the capacitor bank monitors voltage to ensure it does not exceed 400V that could occur if a resistor is blown. The capacitors are charged using DC power that comes from the full-wave bridge rectifier. There is a manual switch that is in series with the rectifier that is a safety in case the charge of the capacitors needs to be shut off for any reason. Another safety feature for the capacitors is a wire with three light bulbs in series. They are not connected to the coil gun circuit in anyway but are used in case the capacitors cannot be discharged because of component failures. If failure was to occur the wire would be connected to the positive and negative leads of the bank. The capacitor bank is enclosed in a wooden box. On one side of the box there are switches for charging the capacitor bank and one for the switch that turns on the voltmeter. The voltmeter is mounted on the top side of the box so that it is always visible to the user or operator. In the initial design the capacitor bank was not going to have a box at all. From research it showed that there was a huge possibility that the capacitors would be hot. After continuous firing of projectiles and leaving capacitors charge from extended periods of time it was found that they do not even get a little warm. Capacitors coolers that were intended to keep the capacitors from reaching high temperatures are not needed at all.

The switches throughout the circuit of the gun needed to be able to handle high currents and voltages. The switch used for the charging of the capacitors is rated for 120V AC and 16A. Even though the voltage exceeds 120V and is DC it is still sufficient. The specifications for the switch are for general use and are for devices that are constantly plugged in. The current through the switch is relatively low therefore the switch stays cool. The switch for the voltage meter is rated for 25V DC and 5A. The current that travels through the switch is not high at all and therefore the possibility of having any problems with the switch is very unlikely.

III. FIELD GENERATION

For the coil gun to fire efficiently the best type of projectile available is used. The gun fires a steel screw bit projectile. These steel projectiles are available at all hardware stores. The steel bit projectiles have favorable characteristics that make it the most obvious choice. The saturation flux density of steel is high and the maximum permeability is within an allowable range to be affected by a magnetic field. Since a field is exerting a force on the projectile a ferromagnetic object was chosen. The dimensions of the bit naturally make it the best candidate because it alleviates the issue of the suck back effect. The length of the steel big is a quarter of its width or diameter which enables it to easily be magnetized. The dimensions help magnetizing by allowing it to stay magnetized for longer periods of time.

The barrel for the project is non-ferromagnetic. A barrel that does not conduct electricity is pertinent in the construction of the coil gun. One that conducts electricity can negatively affect the ability of the projectile to have the ability to be magnetized. Another important factor considered was energy loss. Even though a coil gun is very inefficient when it comes to power transfer, the losses were kept to a minimum. Therefore a polyvinyl chloride pipe or PVC was used. The polyvinyl chloride pipe prohibits energy loss through its low coefficient of friction that occurs when the projectile is being guided through the path. The inner diameter of the polyvinyl chloride pipe is a quarter inch or 8 mm. The outer diameter of the polyvinyl chloride pipe is 13 mm. The magnet coil wire is mounted on the upper quarter length of the barrel.

The coil mounted on the barrel consists of 16 AWG magnet wire. Despite its name magnet wire it is not magnetic at all. It is often used as an inner conductor in generators and transformers. The coil gun's magnet wire is made of copper to maximize conductivity. This wire can withstand temperatures over 100 degrees Celsius. The large 16 AWG wire was necessary because the amount of peak current surge that goes through the coil is easily over 600A. The choice was somewhat hard because all standard specification sheets for wires are for general use. In other words the specifications did not consider peak currents for short durations. With multiple calculations 16 AWG was presumed suitable for a peak current surge of 1000A for a 4 millisecond duration time. Matlab simulations helped the process of calculating these values. The table below shows standard specifications for how long it takes a certain AWG wire to melt at 1000 A.

AWG	Current (amperes)	Duration to melt (ms)	De-rated 20 %	Turns/m (bare)
14	1000	19.0	15.2	614.4
15	1000	15.0	12.0	689.8
16	1000	11.9	9.5	774.6
17	1000	9.5	7.6	869.9
18	1000	7.5	6.0	976.9

TABLE 3.1

The main goal of the project was to fire a projectile at 400V a velocity of over 31 m/s. The current state of the gun can fire a steel bit projectile well over that speed. The speed at which the steel bit projectile travels is monitored during each shot. The barrel of the gun has velocity sensors or speed traps that are mounted right after the solenoid on the outside of the barrel. The speed detection of the projectile became quite a challenge. The optical sensing is done through the infrared spectrum. The basic elements of the speed trap are a comparator and sensor. The comparator is a LM393N that is used to initiate a counter when the circuit of the speed trap is complete. The circuit is complete when the steel drill bit passes through the sensors. This creates a voltage that can be used in the calculation of the actual speed. The speed of the gun is outputted on the FPGA's board. The light emitting diode is the SE3455-003, manufactured by Honeywell and the sensor is the SD3410-002, also manufactured by Honeywell. The power for the speed sensors and diodes comes from the AC outlet. The voltage is stepped down to 5V by a step down transformer that is embedded in the plug. The power supply distributes 5V to power the comparator. Another 5V is transferred to the speed trap and 1.7V is transferred to the other sensor of the trap. The 5V transferred to the speed trap is stepped down using a voltage regulator to be able to reach exactly 1.7V. The sensor is mounted in the polyvinyl chloride pipes by little incisions made in its outer shell. They could not be mounted directly into the barrel because the potential of obstructing the projectile path.

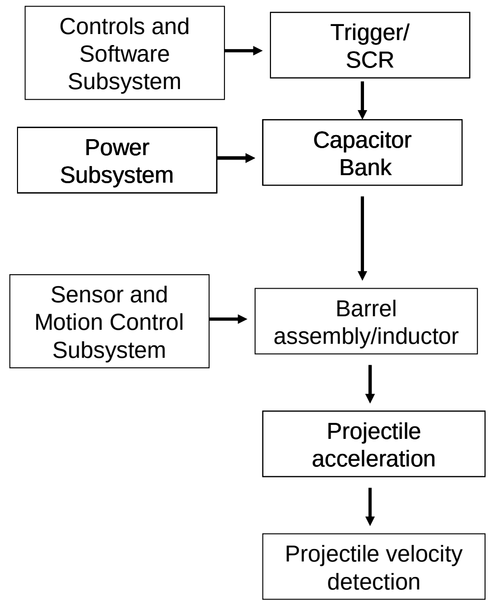

FIGURE 3.2

Field generation is a main element in the coil gun's design as illustrated in the above figure. Current is transferred through a wire to create a magnetic field. The wire is wound in a circular path with multiple layers to increase the strength of the field. With solenoids the best method for increasing voltage induced is to increase the number of turns. Another factor is increasing the cross sectional area which was not an option in the design of this coil gun. The number of layers of wire increases the field strength as well. The current is supplied to the coil from a large capacitor bank that has stored charges. When the current is released in that split second a magnetic field is created and a magnetic flux density is sent through the steel bit projectile enabling it to propel through the polyvinyl chloride pipe. The magnetic flux density is transferred to the steel bit projectile because it is ferromagnetic and ferromagnetic objects are easily magnetized. About an eighth of the projectile's length is placed into coil for a start position before firing. This perfect placement is the optimized position for maximum speed that the projectile can be shot at. This is because it receives maximum magnetic flux density if positioned just before the coil. If positioned too far from the coil the projectile at times shoots in a reverse direction. The coil gun's breech loader inhibits this dangerous incident from occurring.

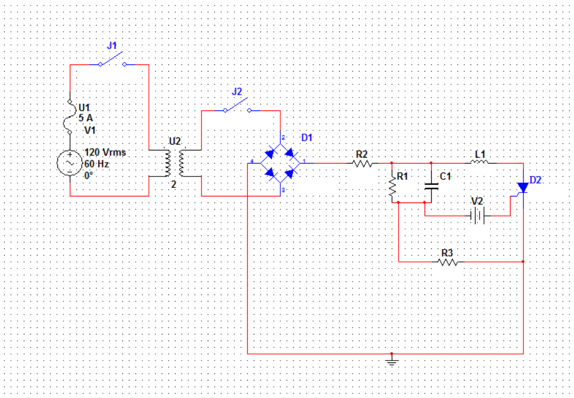

FIGURE 4.1 Brief Coil Gun Circuit

IV. CIRCUIT SCHEMATIC OVERVIEW

Above is FIGURE 4.1 which contains a brief schematic overview of the main coil gun circuit. The AC power mains outputs 120V AC into the primary windings of the 1:4 transformer. The secondary windings then outputs 480V AC. The 480V then travels into a rectifier to convert its alternating voltage into DC power. At this point in the circuit the capacitor bank can be charged because capacitors block AC voltage. The capacitor bank is charged by using a voltage divider. The voltage divider is set up so that the resistor it is in parallel with outputs the exact value of 400V.The silicon-controlled rectifier is the diode looking component that is in parallel with the capacitor bank and in series with the coil. This acts as the switch to allow current to flow from the capacitor bank to the coil. At this point in time the projectile is magnetized and a force is exerted on the projectile to push it through the polyvinyl chloride pipe.

V. MOTION CONTROL SYSTEM

The motion control system of the coil gun is constructed by the FPGA, motor control connector, two servo motors and two motion planes. The FPGA provides the control PWM signal to the servo motors, and the servo motors make the two motion plane rotate right and left or up and down. Then, the barrel of the coil gun will move to same direction of the plane move.

The most important part of the motion control which is the motor. In order to choose the proper motor for this project, the RPM and Motor Torque has been determined. For the RPM, if the motor move at the speed (v) of 3 m/s that mean the target can move 3 meters (dh) in 1 second in the horizontal direction. The distance (d) from the gun to the target is 2 meters. ∠A is the angel velocity of the require for the gun to follow the target, it can be calculate as ∠A= arctanc(dh/d)= 56.31^{o}. And the RPM can convert by ∠A/360*60=9.385 R/M. The other Once the RPM has been determined, the next step is determine the torque require for move the gun. There two difference rotating plane in this project. One plane is directly attached to the gun and it makes the gun move up and down. Another plane is at the bottom, it make the gun move left and right. The weight of the barrel is 1 lb. However, it's better to over estimating it, since it's better to use the high power motor to list the light item than use the low power motor to list the heavy item. So total weight for the barrel is estimate to 1.5 lb. Tq = r*F which is 120 in-oz. For the bottom plane, even though, total weight is a little higher than the upper plane. However, the r is much small than the upper plane, so if use the same torque motor is powerful enough to move the plane move right or less.

VI. STEP MOTOR VS SERVO MOTOR

According to the research, step motor and the servo motor are very often use for position control. Compare for both step motor and servo motor. For the step motor, it is the open loop control, but the servo motor use the close loop control that can determines accuracy and resolution.; for the step motor, it can continue rotate but the servo motor usually has the rotation limit; step motor usual is a brushless motor it has long life than the servo motor; servo motor has higher output power relative compare to the step motor. So over all, the servo motor is better choice for this project.

Nylon gear are very common in servos, they extremely smooth and is not easily to wear. Also, they are very light weight. But deal to lack in durability and strength. They haven't been use for this project. Instead the nylon gear servo, metal gear servo was use, although the weight is heavier than the nylon gear, but the side load is much greater. Also, the drawback of this kind of gear is it will be slowly wear or lost. SC-0252 is the motor use in this project, this servo motor is only require 4.0 to 6.0V to operate and the weight of the servo motor is only 49g, but the torque of the motor is up to 10.5 kg-cm, and it can run at 0.19 s/60 degree. Compare to the step motor, sanyo Denki 85004, has been consider, which weight is 600 g, 10 time of the servo motor that has use now. and the this step motor only has 55.3 OZ-in of the torque.

VII. MOTOR CONTROL

The real time control means the control system need to know when the next step should be taken and how should it operate. On FIGURE 7.1 is a control block diagram with encoder to provide the feed back to the control system. When the encoder is rotated in a position where the output of the encoder translates to a control signal to hold the motor in the initial position, then the motor will not move by itself. If the motor is rotated by external force, it will stay wherever it is left before so that the system can provide the maximum torque to the motor. For open loop control is very often use in the step motor control system since the advantage of the step motor is it can predict what next step should be. As show on FIGURE 7.2 , the feedback loop is broken. So the actual position of the rotor is unknown, however, one can construct the simulation mode to generate the encoder, so that it can predict the motor position as the close loop system did.

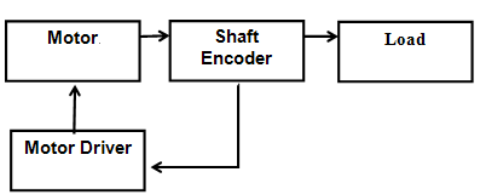

FIGURE 7.1 Close Loop Control

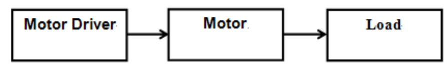

FIGURE 7.2 Open Loop Contol

Digilent PmodCON3 Servo Connector Module Board has been use for motor control. This board is not exactly a motor controller. It is only a connector board and makes the Digilent system board easily control the servo motors when the PWM signal generate by the system board. This connector board has 4 sets of the pins can connect up to 4 servo motors. Also, it has 1 terminal power supply block, which can power up 6V source which can insure sufficient power to run the servo motor at anywhere from 50 to 300 ounce/inch of the torque. There are 6 pins header for this connector board and it compatible for most of the Digilent system board as well as the BASYS FPGA Board which is use in this project. In this case, the BASYS FPGA Board will act as a motor controller to provide the control PWM signal to the motors. The PWM signal can be use to control the direction and degree of rotation. The range of the pulse signal is from 1ms to 2ms. 1ms plus signal will cause the motor to turn all the way in one direction. 2ms plus signal will cause the servo turn all the way in other direction.

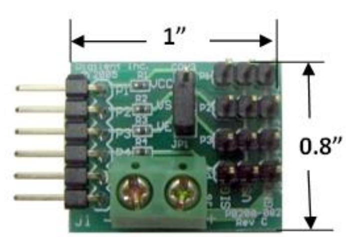

FIGURE 7.3 PmodCON3 Servo Connector Module Board

VIII. FPGA

The FPGA that the group decided to use to embed the software this project is a FPGA of the Spartan series from Xilinx. One of the advantages of using a Xilinx FPGA is the fact that IDE is free to use, thus we would only need to purchase the development board.

Within the Xilinx family the FPGA that would be chosen would be from the Spartan 3 family of FPGA. The eight family Spartan 3 can contain anywhere from 50,000 gates to five million gates, and is meant to meet cost sensitive projects.

Below is a functional block diagram, FIGURE 8.1, of a Spartan 3 FPGA:

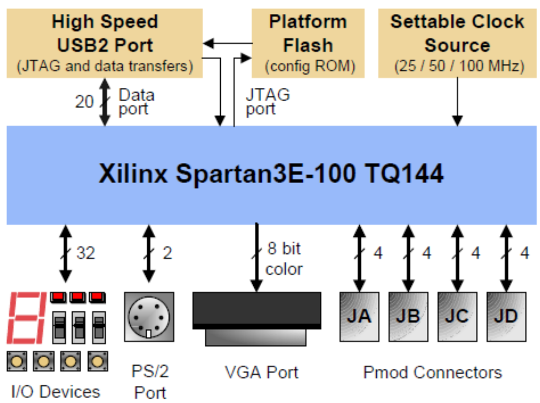

Figure 8.1 Spartan 3 FPGA, Permission from Xilinx LLC

Some of the features of the Spartan 3 board that project used directly is the seven segment display to display the mussel velocity and the I/O pin characteristics to input voltages and out voltages for different tasks. One of the tasks that will done by the FPGA using the input voltages and output voltages is the control of the servo motors this is done by sending out pulse width modulations through the output pins, which was discussed briefly in an earlier section. The second task that will be done using the FPGA is displaying the mussel velocity of the projectile using the provided seven segment display on the FPGA board.

IX. SOFTWARE

For this project all of the existing software is written in Verilog HDL. All of the Verilog code was written and implemented using the Xilinx 9.2 ISE Webpack. The main software tasks were to implement the speed trap to capture the mussel velocity and display that velocity on the seven segment display. The speed trap uses two optical sensors separated by 4 cm, that when on maintain a low voltage ~ 1.5V and as the projectile impedes the sensors view the voltage drops to zero. To calculate the velocity will count the number of clock cycles from when the first optical sensor drops to 0V up until the second optical sensor goes low. An example of the Verilog code is shown below in FIGURE 9.1:

```
always@ (posedge clk )
   if(!sensorIn)begin
      Startcount <= 1'b1;
      end
   else if(!sensorOut) begin
      Startcount <= 1'b0;
      end

always@ (posedge clk)
    if(Startcount == 1'b1)
       count = count + 1;
    else if(Startcount == 1'b0)begin
       velocity = (0.04/(count*0.00000002))*3.3;
       end
```

FIGURE 9.1 Speed Trap Code

To display the velocity using the built in seven segment display it took some manipulating of the fpga's onboard 50 MHz clock. There are seven Pins for the seven segment display and four Pins to switch between each digit, therefore theoretically you can only display one digit at a time. Though we have the ability to display four digits, only three will be shown since the ideal mussel velocity will be around one hundred feet per second making the forth digit obsolete. To get around this a counter was created to allow the display to toggle between digits for a specified amount of clock cycles. Even still none of the digits are actually displayed at the same time, though to the human eye it appears to be. Another difficulty that was run into was the fact that we were trying to display a calculated integer. To extract each digit (hundred place, ten place, one place) the integer was first divided by one hundred and then mod by one hundred, then result from the mod function was used to calculate the next digit by dividing by ten and the one digit is then calculated by taking the mod of the ten digit. The code in FIGURE 9.2 demonstrates how to extract each digit that is to be displayed from a calculated integer:

```
always @(posedge clk)
   DIG2  =  velocity/100;
   REM2 =  velocity%100;
   DIG1  =  REM2/10;
   REM1 =  REM2%10;
   DIG0  =  REM1/1;
```

FIGURE 9.2 Digit Extraction

Below is FIGURE 9.3 which includes example code of how to execute the toggle of the display:

```
always @(posedge clk)
  if(count < 15020)begin
  count = count +1;
     if(count > 5000)begin
     toggle <= 4'b1101;
     DISPOUT <= DISP0;
     end
     if(count > 10000)begin
     toggle <= 4'b1011;
     DISPOUT <= DISP1;
     end
     if(count > 15000)begin
     toggle <= 4'b0111;
     DISPOUT <= DISP2;
     count = 0;
     end
   end
```

FIGURE 9.3 Digit Output With Toggle

THE ENGINEERS

Josef Von Niederhausern, Ricardo Reid, Brian Hoehn, and Kwok Ng are all Senior Level Electrical Engineering students graduating the Fall 2010 semester. All of the engineers/students plan on continuing their education at the University of Central Florida College of Engineering and Computer Science while simultaneously entering the engineering/technology industry to start/continue their careers in their respective field of choice.

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