Robotic Football

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1. Abstract
To accelerate innovation in robotics, the Notre Dame University plans to create an intercollegiate mechatronic football league; the teams in the league compete against each other in robot football games. The first game was successfully organized and reported as a featured story by many influential media such as USA Today and NFL. The next step for Notre Dame University is to promote this league to a national level. With the sponsorship of Notre Dame University, our Senior Design group has successfully built a football-playing robot team and participated in a game between our school and IUPUI held in Notre Dame stadium.

The goal of this senior design project is to build a football-playing robot team that will be competing in the Intercollegiate Mechatronic Football game at University of Notre Dame in April, 2013. Due to time constrain and limited team size, only three different robots of a complete robotic team are built. The selected robots are the quarterback, receiver, and center. As an option of advancement, the design includes a tracking and positioning system as an autonomous ball launching mechanism from quarterback to receiver.

The robots’ design has multiple requirements that were definite in the Rules and Regulations of Collegiate Mechatronic Football and others were gathered from different prospective. One of the most important requirements specifies each player’s weight and dimensions. In fact, players must fit within a 16x16x24 inch box, and cannot weigh more than 30 pounds with an exception for the quarterback who can weigh up to 45 pounds. If these conditions are not met, the project would be a failure. In order for the project to be successful, the robots must be able to travel at a high speed, pass the ball from center to quarterback reliably, and pass the ball from quarterback to receiver reliably as well. The quantitative numbers that the team put together as goals for the project are a speed of 10 ft/sec for all robots, delivering operation from center to quarterback within 20 seconds with a success rate of 75%, success rate of 65% for complete passes, and ability of receiver to navigate through 5 cones placed 6 feet apart covering a linear distance of 30 feet in less than 10 seconds. The final requirement and constrain of the project is cost. The sponsor has given a budget of $5,000 and IEEE has given a grant of $500 for a total of $5,500.

2. Introduction
Robots have an ever-growing influence on our daily lives. Robots are a familiar example of mechatronic systems and are ideal student projects due to the necessary application of Science, Technology, Engineering, and Mathematics (STEM) knowledge in creative engineering designs. To accelerate
innovation in robotics, University of Notre Dame is creating an intercollegiate mechatronic American football league where robotic teams from the participating schools compete against each other.

Our senior design group has been selected to kick-off a new robot football team for IPFW, which will be sponsored by Notre Dame. Due to the limitation of having just six team members, only three robots (also referred to as players) will be expected to be built during this senior design project. The three players to be completed are the quarterback, receiver, and center, and they will be built using IEEE standards including those for wireless, software, and systems engineering. These three positions are the most critical part to the execution of a football game and also provide the most challenging design opportunities. The robot players have competed in the Collegiate Mechatronic Football game against IUPUI in April, 2013.

This problem statement serves as a guide for how the robots will be completed within the supplied rules of the game while maintaining an efficient schedule corresponding to the senior design program at IPFW.

A complete football robot team consists of eight players on the field. Robots can be divided into offensive and defensive type roles. The members of the IPFW team will focus on offensive players including the quarterback, center, and a receiver, while Notre Dame will provide the defensive players from previous years. Each position to be filled requires certain specialties for the player fulfilling that role. For example, the center must align itself with the quarterback and transfer the ball to begin a play, and the quarterback needs to target and throw to a receiver.

All three robots have design specifications set by both the game rules and by the team’s determined benchmarks. The common requirements for all three robots are:

**Speed**
All the robots must be capable of traveling 50 feet within 5 seconds starting from rest.

**Sensor and Light-Emitting Diode (LED) Display**
All the robots must be equipped with a digital accelerometer, supplied by Notre Dame, to sense if an upsetting event (knockdown, fall down, or tackle) has occurred and indicate robot status with a single multicolor, high intensity LED light. When the sensor detects an upsetting event, it should be able to signal the lighting system to turn RED for 2 seconds and provide a signal to the robot's microprocessor to remove power from the drive system for 2 seconds.

**Battery Recharge**
12 volt batteries must be able to be replaced within 1 minute. Special types of robots have other different requirements based on their functionalities in the game.

**Center Robot - Passing Proficiency**
The center must be capable of satisfactorily delivering a football to the quarterback. Without this function the game could not progress. Moreover, the center should fulfill a delivering operation within 20 seconds (to avoid a delay of game penalty) with a success rate of 75%.
Quarterback and Receiver – Passing Proficiency
The quarterback will be able to complete a pass 65% of the time the football is thrown. A completed pass is defined as hitting the receiver with the football before the football contacts the ground.

Receiver - Maneuverability
Receiver must be able to navigate through 5 cones placed 6 feet apart covering a linear distance of 30 feet in less than 10 seconds, starting from rest.

3. Detailed Design
From subsystems contained within the project’s three robots (the quarterback, center, and receiver), several solutions were provided. The team has picked out the most fitting solution from each subsystem to make the most efficient robots possible within our budget. The compatibility between subsystems is considered because some of the subsystems are interdependent upon each other or are affected by the function of other subsystems.

3.1 Microcontroller
The microcontroller used is the LeafLabs Maple Rev5 microcontroller board based on the STM32F103RB microprocessor. The board runs up to 72 MHz, has 39 digital input/output pins (3-12V input voltage), 16 analog inputs, native full speed USB, 3 USARTs, integrated SPI/I2C support, a power jack, and a reset button. Also, Maple has a 32 bit-processor, 128 KB of flash memory, and 20 KB of SRAM.

The board runs off of a rechargeable LiPo battery of 4.8 volts in order to meet the 3.3V operating voltage requirement. Firmware is uploaded on the board using USB interface which is supported by the Cortex-M3 or via external JTAG interface. The code is implemented using a sketch-based programming environment, which is open-source and can be downloaded from LeafLabs’ website.

Zigbee communication protocol is used for wireless communication between remote controllers and microcontroller due to its low cost and efficiency. In fact, it can communicate up to 100 feet indoors or 300 feet outdoors (with line of sight). The 2.4 GHz Xbee module from Digi, as seen in Figure 16, has been selected for this project. This module allows a very reliable and simple communication with a price tag of $21.95 apiece. Each microcontroller and remote controller uses an Xbee module.

The Xbee module is programmed using a USB to serial base unit. This unit allows for configuration of the Xbee modules via X-CTU software.

Each player operates through a customized LeafLab Maple microcontroller located on the baseplate. An Xbee module is mounted on the microcontroller using an Xbee shield, in order to communicate through Zigbee technology to the Xbee module mounted on the remote control. The Maple board runs off of a rechargeable LiPo battery of at least 3.3 V. The input/output pin configuration of each robot is synthetized below.

Receiver

*Input:*

- Accelerometer
- Remote control signal
  - Movement along x-y axis left wheel
  - Movement along x-y axis right wheel
  - Deploy Netting
  - Reset Netting

Output:

- Status LED
- Speed Controller for motor/left wheel
- Speed Controller for motor/right wheel
- Raise netting system
- Engage solenoid
- Lower netting system

Center

Input:

- Accelerometer
- Quarterback contact sensor left
- Quarterback contact sensor right
- Remote control signal
  - Movement along x-y axis left wheel
  - Movement along x-y axis right wheel
  - Hike

Output:

- Status LED
- Quarterback contact LED left
- Quarterback contact LED right
- Speed Controller for motor/left wheel
- Speed Controller for motor/right wheel

Quarterback

Input:

- Accelerometer
- Vision system
- Remote control signal
  - Movement along x axis
- Movement along y axis
- Rotation
- Pitching wheels speed slow
- Pitching wheels speed medium
- Pitching wheel speed fast
- Pass ball

Output:

- Status LED
- Speed Controller for motor/upper left wheel
- Speed Controller for motor/upper right wheel
- Speed Controller for motor/lower left wheel
- Speed Controller for motor/lower right wheel
- Speed Controller for motor/ball feeding mechanism
- Speed controller for motor/launching left wheel
- Speed controller for motor/launching right wheel
- Turn Table

3.2 Handheld Controller
The selected conceptual design for the controller is the Arbotix Commander v2.0; which can be seen in Figure 1. This controller provides all necessary functions needed for Xbee and Arduino programming. This gamepad supplies two analog sticks, two analog buttons and 8 programmable buttons; this allows for complete customization. Three will be ordered so one can be completely programmed for each robot.

![Figure 1: Arbotix Commander v2.0](image)

Figure 2 shows the controller scheme for the quarterback. Since the quarterback will be using omnidirectional wheels, the left joystick can used to maneuver the robot any direction on the X-Y axis. The right joystick can be used to rotate the robot while simultaneously moving in the X-Y axis with the left joystick. Three buttons will be designated to setting the speeds of the pitching wheels on the
quarterback, depending on how much distance is desired for the ball to travel. A slow speed will be set so the football will travel a distance between five to seven feet, a medium speed will allow the ball to travel a distance between ten to twelve feet, and a fast speed will allow the ball to travel fifteen to seventeen feet. The user will have to give judgment for which speed is desired. The right trigger will be used to activate a pass. This button was chosen so the user will be able to simultaneously rotate while they pass. The quarterback has the most complex controller design of the three, which means it has the most buttons used. There are four unused buttons and two analog buttons that can be used if more functions are needed.

![Quarterback Controller Scheme](image)

Figure 2: Quarterback Controller Scheme

The receiver and center controllers are not as complex as the quarterback controller. Since these two robots will only have two wheels, each joystick will be in control of one motor. To move the robot forward, the user will have to push both joysticks up or both joysticks down to move backwards. For a turn, one joystick will be pushed up while the other joystick remains in place or down for a sharper turn radius. The receiver controller scheme can be seen in Figure 3. The right trigger will be designated to deploy the netting before a play, while the left trigger will be used to reset the netting after a play is made.
The controller scheme for the center can be seen in Figure 4. While the center controller scheme is similar to the receiver’s, it’s two triggers will serve different purposes. The right trigger will be programmed to drop the ball into the quarterback’s cradle, while the left trigger will reset the arm after the drop is made.
3.3 Charging System
Each robot will require 7.2 V to be supplied to the accelerometer and 4.8 V to the microcontroller. All motor controllers will be powered by 12 V LiFePo4 (Lithium Iron Phosphate) batteries. The accelerometers and microcontrollers will use NiCd (Nickle Cadmium) batteries. The quarterback will require six batteries total. There will be four motor controllers in total, which will all be powered by a 20 Ah battery. Two motor controllers will used be used for the Omni-directional wheels, one motor for the pitching wheels, and one for the linear actuator. The center and receiver robots will require two additional 12 V batteries to power motor controllers. These motor controllers will power the wheels for both, the netting for the receiver, and arm for the center.

3.4 Center to Quarterback Ball Transfer
Center Design

The center, as illustrated in Figure 5 and Figure 6, has the responsibility of placing the ball accurately into the quarterback’s ball feeder. This requires precise alignment with the quarterback in the plane of the playing field with respect to both translation and orientation of either robot.

Figure 5. Solid Model Representation of Center and Quarterback Assembly
This alignment is accomplished using the trapezoidal cutout section on the rear end of the center, which mates with the complementing male end on the quarterback. The four bar linkage arm is driven by the same servo used to drive the turn table on the quarterback. This motor is capable of providing approximately 1200 oz.-in of torque, which greatly exceeds the torque requirement to lift the arm of the ball after it has been transferred to the quarterback, which is when the torque load is at its maximum. When at rest, the crank will sit against a dowel pin inserted into the servo mount and will be held in place by gravity causing the crank to tend to rotate toward the pin. When the motor is engaged, the clamp holding the ball will rotate downward, and once the custom designed gripper makes contact with the receiving ball feeder on the quarterback, the spring-loaded jaws are pried apart, and the ball slips out into place in possession of the quarterback. There is also a dowel pin on this side of the rotation of the crank to prevent the servo motor from being required to use power to hold the gripper in place as the ball falls to the quarterback.
The gripper as seen in Figure 7 is constructed from ¼ inch and ½ inch thick HDPE, and the connecting links are made from 6061 aluminum. A tension spring connects the slide to the base of the gripper and causes the jaws to close. The opposite sides of the jaws are chamfered near the contacting curve with the ball to allow the quarterback ball feeder to pry them apart when the gripper is lowered into position. On the underside of the jaw base, a plastic cylinder is positioned for the tip of the ball to fit into. This is done to ensure the orientation of the ball in the gripper is controlled.

The 1 x 0.5 x 24.2 inch bar pictured is the rocker link of the center’s arm, which holds the gripper at one end, is pivoted 15.7 inches down from the tip, and connects to the coupler link 8 inches farther. The pivot joint is obviously the area where the most stress will occur, and this warrants a bit of stress analysis to ensure it will not fail. A load of 2.75 lbs was applied to the very tip, which includes the weight of the ball, jaw, and the longer portion of the rocker arm. The pivot joints (Ø 0.25 inch) located in the middle and at one end were rigidly fixed. Using this model, a minimum safety factor of 3.6 occurs at the middle joint. Since the assumptions made for the simulation were conservative to begin with, the design was considered acceptable. It should be noted that the deflection shown in the figure is heavily exaggerated for effect. The simulated deflection was found to be approximately ¼ of a millimeter.

Quarterback Design

A representation of the “Ball Feeder” and “Ball Holder” are shown in Figure 8. The “Holder” will be made of HDPE and will be mounted on top of the ball feeder.” The holder will be driven by a 3/8” lead screw with a servo attached to it. As the servo turns clockwise, the holder will move up the feeder and will...
feed the football into the passing wheels. The servo will then turn counter-clockwise until the holder is reset on the back end of the feeder. The feeder will be made of HDPE and will be mounted on top of a turn table, which is mounted on top of the quarterback. The feeder will be mounted at a 35° angle. This angle was solved for by assuming the defender to be at a maximum height of 24 inches and a minimum distance from the line of scrimmage, which is 12 inches. The detailed calculations can be found in the Appendix. The resulting angle was 33° and this was taken as a minimum to avoid an interception; so to be on the safe side the 35° lunching angle was chosen.

![Figure 8. Solid Drawing of Ball Feeder](image)

The passing wheels will consist of two sets of two 30 shore wheels. Each wheel has a diameter of 4.875 in, with a mounting diameter of 0.5 in. The passing wheels will each be driven by a RS-540 DC motor and a 4:1 gearbox. This motor was used, because it is the same motor we are using for the drive train, so it was cost effective and would meet the requirements needed for the passing wheels. The 4:1 gearbox was chosen, because we needed a gearbox to transfer the power of the motor to the passing wheels, but we did not need as much torque as we did with the 16:1 gearbox of the drive train. The equations to determine the rotational speed of the passing wheels, based on the distance desired to throw the ball, are shown below.

\[ v_0 = \frac{x}{\cos \theta t} \] (1)
\[ y = y_0 + v_0 \sin \theta \cdot t + \frac{1}{2} (g) t^2 \]  

(2)

Where,

\( v_0 \): the initial velocity of the football.

\( x \): horizontal distance from quarterback to receiver.

\( \theta \): the launching angle of the football.

\( t \) : time.

\( y \): the height where the football will hit the receiver.

\( y_0 \): the launching height of the football.

\( g \): the force of gravity acting on the football.

Table 1 shows the initial velocity required for the football to hit the receiver in a range from 6 inches to 30 inches for three desired lengths of passes, which are 5 feet, 10 feet, and 15 feet.

<table>
<thead>
<tr>
<th>Distance from QB to Receiver (ft)</th>
<th>Min. Catch Height (ft)</th>
<th>Max. Catch Height (ft)</th>
<th>Min. ( V_0 ) (ft/s)</th>
<th>Max. ( V_0 ) (ft/s)</th>
<th>Min. RPM per passing wheel</th>
<th>Max. RPM per passing wheel</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.5</td>
<td>2.5</td>
<td>13.10</td>
<td>16.87</td>
<td>310</td>
<td>395</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>2.5</td>
<td>18.44</td>
<td>21.08</td>
<td>435</td>
<td>495</td>
</tr>
<tr>
<td>15</td>
<td>0.5</td>
<td>2.5</td>
<td>22.59</td>
<td>24.74</td>
<td>1070</td>
<td>1160</td>
</tr>
</tbody>
</table>

The results in Table 1 conclude that as long as each passing wheel is within the range of RPM’s shown for each desired passing distance a complete pass can be made.

The turntable is shown with the “Ball Feeder” and passing wheels in Figure 9. The turntable will be driven by a 360° servo. This will allow for the passing mechanism to be completely autonomous from the driving portion of the quarterback. In choosing the servo two things were the driving factors as to pick which servo. First the servo must be able to turn a full 360°. This is vital for having successful independent passing mechanism. Secondly the servo must produce a high torque to be able to turn the passing mechanism.
3.5 Netting System
One of the important aspect of a functioning receiver robot is its’ netting system to capture and secure ball thrown by quarterback. The selected conceptual design for netting system is a cross pattern netting system shown in Figure 10. The netting system will be attached to the lid of the receivers’ chassis.

5 PVC pipe poles of 0.84 in outer diameter will be attached to the lid to support the nets. 4 of these poles will be deployed at four corners of the lid and another pole will be placed in the center. PVC is selected over other pipe materials, such as brass, steel, aluminum, and copper, for its lower weight and cost. The length of these poles will be 13 in. from its joint at the lid. 4 inside nets of 13 in. height and 8.5 in. wide will be attached in between center pole and the corner pole. This will maximize the hitting area for the ball thrown by the quarterback and will allow to trap the ball inside the netting.
In order to make sure that the ball did not bounce out of the receiver after hitting the nets in the middle, a cage is designed on the perimeter of the lid of the chassis. The perimeter will be covered by 4 outside nets of 4 in. height and 12 in. wide attached in between 4 corner poles. The height of the side nets are kept low because it will also help to catch balls thrown in lower trajectory. Side nets will also allow us to complete touchdowns and secure balls during tackles.

![Receiver Netting System](image)

Figure 10: Receiver Netting System

To avoid tearing stronger net such as 150 lb rated nylon sport net with small mesh is recommended. Also to avoid bounce out of ball after hitting center nets the nets should not be attached to the poles too tight. Loose attachment will allow absorbing the force of the ball and will keep it inside.

### 3.6 Circuit Diagram

The circuit diagrams for the QB, Center, and Receiver are shown in the Figure 11, Figure 12 and Figure 13, respectively. The QB has the most complicated diagram; it has 4 drive wheels, 2 pitching wheels, and a motor to advance the football into the passing wheels. For each pair of wheels there is a Sabertooth 2x25 motor controller and for the single motor a BaneBots motor controller is used. It also
has 2 limit switches for detecting when the football advancing mechanism has reached the end of its motions. The Xbee communication used to communicate from the remote controller to the robot will be UART, which was chosen because it uses the simplest communication style that uses the fewest wires; it also appears to have more versatility when used in programming. The accelerometer will be connected to the microcontroller’s hardware interrupt. The Center’s and Receiver’s schematics are similar to the Quarterback but with fewer motors.
Figure 12. The Center Schematic

Figure 13. Receiver Schematic
The program (shown in Figure 14) flow starts by initializing ports to be inputs, outputs, PWM’s and hardware interrupts initializes the global variables, Xbee related variables. The accelerometer was going to be declared as a hardware interrupt but after learning that the delay() and msec() functions are not usable while performing an interrupt procedure, this idea was abandoned, but it may be possible to still perform a crude delay using a for loop. If the accelerometer signals the microcontroller this is known as a ‘tackle’, when a tackle happens the robot is to stop power to the motors for 10 seconds and the accelerometer will update the robot status LED. While the robot is not tackled the robot will read the data from the UART, if there is no signal being received the robot will kill power to the wheels. If the signal is good the robot will update the individual motors speeds, and will also perform that individual robot’s special functions. In the case of the omnidirectional wheels of the QB each wheel will be governed by a unique equation, which will allow the QB to travel in any direction and be able to turn about its central axis if desired. The QB remote controller will also provide the signal for the passing distance which is how fast the pitching wheels need to be spinning. The QB remoter also provides the
signal to pass the ball which activates the motor on the lead screw and will advance the ball into the pitching wheels. These will be 2 limit switches at each end of the lead screw, one will signal that the QB passing mechanism is in the 'home' position and the other switch is to signal that the ball has entered the pitching machine. Then the program repeats the whole process. The Center and Receiver both perform similar but much easier operations than the QB and will not be cover in detail here.

4. Conclusions
For the final design, the team decided to use LeafLab Maple microcontroller. The feature of having a fast clock processor, high number of input/output pins and ability to use a Real Time Operating System makes this board the best solution.

The team decided not to use the Handheld Controllers previously used by Notre Dame. These are not as easy to use and troubleshoot. On the other hand, the Arbotix Commander V2.0 offers more programmable buttons and joysticks allowing a complete customization for each player. The capability of the controller to use Zigbee communication module to communicate with microcontroller makes it a worthy match for the selected microcontroller.

In order to meet the requirement of the robots to travel at least 10 ft/sec, two 4-7/8 inch diameter wheel, attached to a RS-540 motor are used. Due to the motors having a rated torque, BaneBots P60 Gearbox of 16:1 gear ratio is used.

The locomotion of the center and receiver is similar for both, while the quarterback differs due to its functionality during the game. The drive trains of center and receiver use two driven wheels located in the center of the baseplate with 2 ball casters, one located in the front and one located in the back. On the other hand, the quarterback uses 4 omnidirectional wheels.

In order to succeed in the ball transfer mechanism from center to quarterback, the alignment is achieved using a trapezoidal cutout section on the baseplate of the center, which mates with the complementing male end on the quarterback. Passing is achieved using a rotating clamp that positions the ball into the ball feeder of the quarterback.

The ball feeder of the quarterback is mounted on a turn table at a 35° angle. 2 passing wheels, equal to the ones used for the receiver and center drivetrain, and 2 RS-540 motor are used for the ball launching mechanism. Because not as much torque is required, Banebots P60 Gearbox of 4:1 gear ratio is used.

In order to maximize our catching capabilities, cross pattern netting is implemented on the receiver.

As an extra feature of the design, the team plans to implement a simple tracking and positioning scheme using vision system technique. The camera system chosen, CMUcam4, is mounted on the quarterback and is able to maintain line of site with the receiver through a distinctly colored ball located on top of the receiver.

The total cost of the design is estimated to be about $4,230. Being below our budget, we have room for additional expenses that may be necessary during the design implementation.
5. References