University of Puerto Rico
Mayaguez Campus
Department of Electrical and Computer Engineering

Laser Tag Reloaded

Final Report

Cesar Andreu
Gabriel Cardona (Lead)
Gustavo Serrano
Mark A. Sukhram

For: Prof. Manuel Jimenez
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Abstract

Laser tag is a sport that is played by many people. It consists of at least two players or teams pitted against each other in competition. Be it to eliminate the opposing team or outscore them within the time limit. This document will outline a system that is capable of hosting a match of this sport and allowing a person to participate in the match. Simultaneously, it will record the players statistics and store them in an online database. This database can be accessed to review an individual players global statistics. It is accessed using a mobile phone application. This application can also be able to serve as a lobby system to connect players in their local areas with other laser tag players, bringing them together and allowing them to set up games in their own communities. In developing this system, many obstacles, outlined in the report, were encountered with regards to making the system cost-effective, which resulted in not meeting that goal. However a few measures to reduce the system's cost by offloading functions are noted in this report. Throughtout this document, the different software layers and hardware components in order to develop our laser tag system are presented and detailed.

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Chapter 1

Introduction

The primary motivation for this project is to bring an equivalent professional-grade laser-tag system to the lower end consumer market at an affordable price. This will help stimulate the growth and development of existing and new laser tag communities. We will match professional laser tag systems by providing statistics tracking, varying game modes, and the ability to play anywhere outdoors. We are essentially capitalizing on the existing demand for these higher end products within non-professional laser tag communities. Besides being affordable, the aim is for the system to be simple in its installation and usage, making it a system that is easy to pick up and use by any user. To become a part of our community you simply install our laser tag application on your internet enabled Android smartphone, and then you pair it with our laser tag system. Once this has been done you can join or create a lobby, or view your statistics.

Chapter 2

Theoretical Background

Economic Consideration:

There are no easily-available professional-grade laser-tag systems for the lower end consumer market at an affordable price.

Laser Consideration:

A concern for the system was to ensure that there is enough power driving the laser to ensure that the output can reach reasonably large distances. In our case, the laser can reach at least 45 feet, an adequate distance for a game of laser tag.

Battery Monitor Consideration:

In order to keep track of the remaining charge stored in our battery, we utilize an IC which employs a technique called coulomb counting or state of charge to give us an accurate estimate of the remaining charge. Our battery monitor employs a technique similar to the voltage method for determining remaining charge. The IC has a modeling scheme called ModelGauge, which is essentially an algorithm based on the discharge curves of lithium batteries, utilizing a current-sense resistor, the IC measures charge across that resistor and determines how much charge is left in the battery.

Battery Consideration:

The battery employs a protections circuit that ensures that the battery will never go below or go over certain voltage boundaries. In our case it will never go above 4.2V and never discharge below 3.2V. Although our battery is capable of discharging to 2.75, forcing the lower bound to 3.2V is a safety precaution, since constantly discharging batteries to their limits inflicts wear on the battery resulting in diminishing charge capacity over time.

GPS Consideration:

In searching for a GPS to use within our system, multiple factors were taken into consideration. These include form factor, size, cost, and accuracy. The Laser Tag Reloaded system's GPS satisfies all these needs. In particular, the GPS's accuracy of a 1.8m radius is possible mainly due to the local availablility of the Wide Area Augmentation System. Developed by the Federal Aviation Administration (FAA), this free system consists of a series of ground-based stations that can be used in conjunction with a GPS in order to reduce error when receiving one's location. This is achieved by differential correction.[2]

Part I

Hardware Description

Chapter 3

Top-down System Explanation

At its highest level, the Laser Tag Reloaded system consists of a gun, connected directly to a vest and wirelessly to a phone, which connects to a remote server. The vests will contain two infrared sensors which communicate to the system within the gun when it has been hit. The connection between the vests and the gun consists of a handset coil cord, which reduces noise due to cable length and offers ease of mobility for the user to move the gun while in a match.

The gun contains the remaining components, including the microcontroller, the infrared laser and the bluetooth modem. The MapleMini board, which has an ARM Cortex-M3 microcontroller, is connected to, and controls, the other components in the system. In addition to controlling the components, power from the battery is routed through this board to the other system components using its internal voltage regulator. The gun's GPS, a Fastrax UP501, tracks the user's position when he is hit during a match. In order to communicate shots and hits to the user, a speaker in the system plays individualized sounds for relevant events. Regarding the battery, the system includes a coulomb counting fuel gauge and a battery charger. The fuel gauge, in combination with a LED array and a button, indicates to the user how much charge is available on their units. A WRL-10269 Bluetooth Module establishes communication between the gun and a user's phone, allowing them to participate in matches and transmit match-related information as the game progresses. The phone, which can be any android phone running version on version 4.0 or higher, will connect users to lobbies, where matches can be hosted between individual players.

Chapter 4

Block Diagram

4.1 Diagram

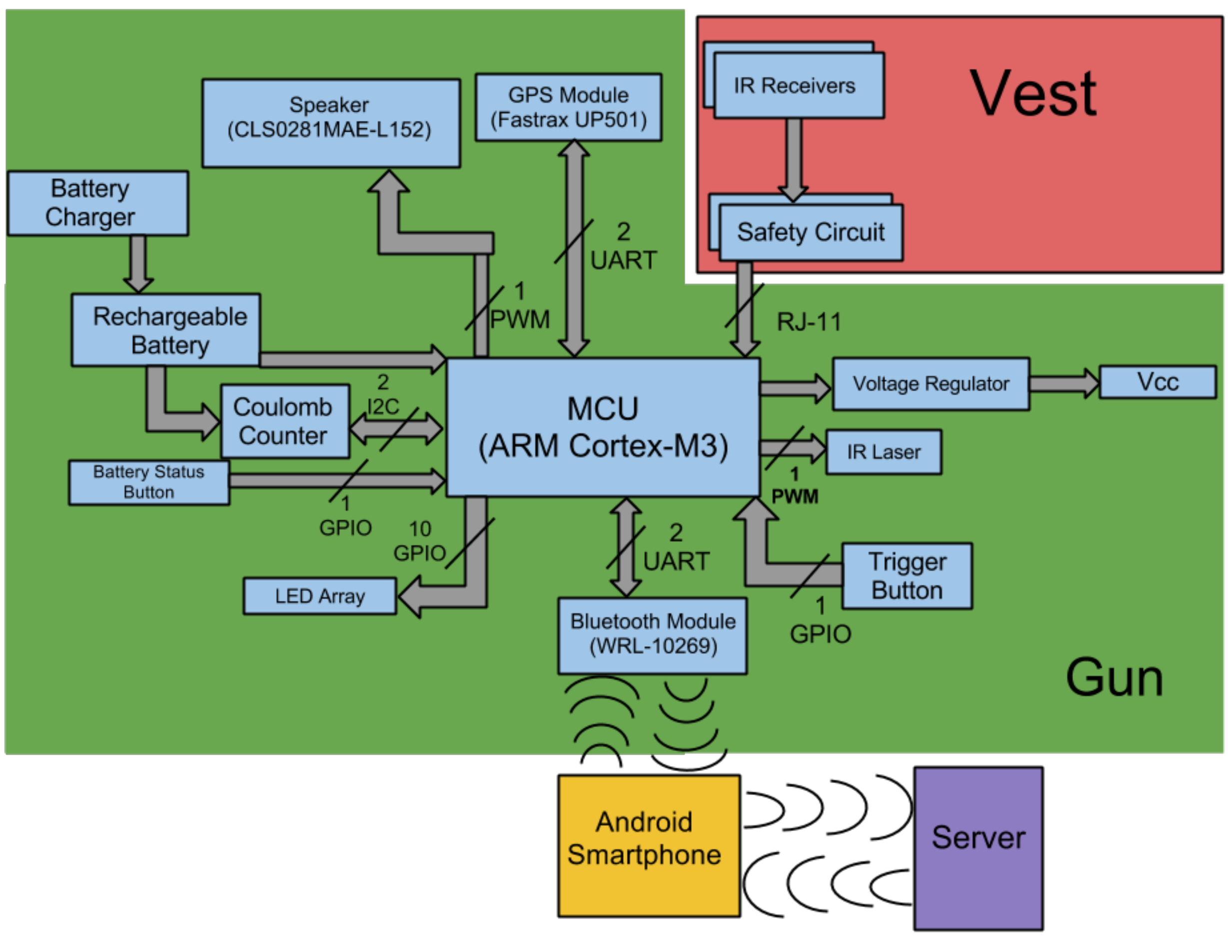

Figure 4.1: The system's block diagram.

4.2 Components Explanation

- Laser Tag Gun
  - 1 MCU (Maple Mini (ARM Cortex-M3)) - Used to process game logic as well as any input and output to and from our system. It also includes the voltage regulators which route power to the entire laser tag system from the battery.
  - 1 GPS (Fastrax UP501) - Used to determine a player's position within 1.8m when hit during a match.
  - 1 Bluetooth (WRL 10269) - Used for communication between the laser tag gun and the user's mobile phone.
  - 1 Speaker (CLS0281MAE-L152) - Used to provide the user with audio feedback in the event of being shot, shooting and more.
  - 1 Coulomb Counter (Sparkfun LiPo Fuel Gauge) - Used to accurately determine the system's battery's state.
  - 1 Battery Charger (Sparkfun MicroUSB LiPo Charger) - Used to charge a LiPo battery at a rate of 500mA per hour, allowing a user to charge his laser tag unit after a match.
  - 1 10-LED Array - Used to indicate the battery's state when the battery state button is pressed.
  - 1 Rechargeable Battery - A 3.7 V/1A rechargeable 2000mAh battery used to power the laser tag gun and vest.
- Laser Tag Vest
  - 2 Infrared Receivers - Used to receive infrared data sent from other players' guns.

Chapter 5

Power Analysis

5.1 Analysis

Bluetooth Module

Bluetooth		MCU
$V_{OH} = 3.1V$	$>$	$V_{IH} = 2V$
$V_{OL} = 0.2V$	$<$	$V_{IL} = 1.3V$
$V_{IH} = 2.31V$	$<$	$V_{OH} = 2.4V$
$V_{IL} = 0.8V$	$>$	$V_{OL} = 0.2V$
$I = 5uA$	$<$	$I = 25mA$

The Bluetooth module is voltage compatible with the MCU. The current requirements from the Bluetooth are negligible.
Power:
V_{DD} = 3.3 V
I_{MAX} = 45 mA

Infrared Receiver

IR Receiver		MCU
$V_{OH} = 3V$	$>$	$V_{IH} = 2V$
$V_{OL} = 0.1V$	$<$	$V_{IL} = 1.3V$
$I = 5mA$	$<$	$I = 25mA$

The IR Receiver is voltage compatible with the MCU. The current requirements from the IR Receiver do not overburden the MCU.
Power:
V_s = 3.3 V
I_s = 0.35 mA

Infrared Laser

IR Laser		MCU
$V_{IH} = 1.6V$	$<$	$V_{OH} = 2.4V$
$V_{IL} = 1.4V$	$>$	$V_{OL} = 0.2V$
$I = 20mA$	$<$	$I = 25mA$

The IR Laser is voltage compatible with the MCU. The current requirements from the IR Laser are compatible.
Power:
$V_{DD} = 3.3$ V
$I_{MAX} = 20$ mA

Battery Monitor (Coulomb Counter)

Battery Monitor		MCU
$V_{IH} = 1.4V$	$<$	$V_{OH} = 2.4V$
$V_{IL} = 0.5V$	$>$	$V_{OL} = 0.2V$
$V_{OL} = 0.4V$	$<$	$V_{IL} = 1.3V$

The Battery Monitor is voltage compatible with the MCU. The current requirements from the Monitor do not overburden the MCU.
Power:
$V_s = 3.3$ V
$I_{active} = 50$ uA

LED Array

LED Array		MCU
$V_{IH} = 2V$	$<$	$V_{OH} = 2.4V$
$V_{IL} = 2V$	$>$	$V_{OL} = 0.2V$
$I = 20mA$	$<$	$I = 25mA$

The IR Array is voltage compatible with the MCU. The current requirements from the IR Array are compatible. I_{MAX} calculations are taking into consideration that each LED in the array is connected in series with a 330 Ohm resistance in order to reduce current load to the MCU. Power:
$V_{DD} = 3.3$ V
$I_{MAX} = 0.05$ mA * 10 LEDs = 0.5 mA

GPS Module

GPS		MCU
$V_{OH} = 2.4V$	$>$	$V_{IH} = 2V$
$V_{OL} = 0.4V$	$<$	$V_{IL} = 1.3V$
$V_{IH} = 2V$	$<$	$V_{OH} = 2.4V$
$V_{IL} = 0.8V$	$>$	$V_{OL} = 0.2V$
$I = 2mA$	$<$	$I = 25mA$

The GPS module is voltage compatible with the MCU. The current requirements from the GPS are compatible.
Power:
$V_s = 3.3$ V
$I_{MAX} = 25$ mA

MapleMini

Currents:

I_n = 3 mA

Bluetooth IO Current

I_{BT} = 45 mA

Infrared Receiver Current

I_{IRR} = 2 x 0.35 mA = 0.7 mA

Battery Monitor Current

I_{BM} = 0.5 uA

IR Laser Current

I_{IR} = 20 mA

LED Array Current

I_{LA} = 0.05 mA * 10 LEDs = 0.5 mA

GPS Current

I_{GPS} = 20 mA

$I_{Total} = I_n + I_{BT} + I_{IRR} + I_{BM} + I_{IR} + I_{LA} + I_{GPS}$ = 3 mA + 45 mA + 0.7 mA + 0.5 uA + 20 mA + 0.5 mA + 20 mA = 89.2 mA

Power Consumption:

P = I_{Total} * 3.3 V = 294.36 mW

Package Temperature

T_{jMAX} = 150 C

$T_j = T_A + \Theta_{jA}$ x P_{DISS}, Θ_{jA} = 55 C/W

=27+55 x 0.29436

=43.19 C < 150 C OK

5.2 Power Supply/Battery Calculations

Battery Life and LDO Efficiency Calculations:

Eff_{LDO} = (V_R*I_R) / (V_{NR} * (I_R+I_{GND})) * 100%

Eff_{LDO} = (3.3 V * 66.2 mA)/(3.7 V * (66.2 mA + 40 uA)) * 100% = 89.14%

I_{GND} = 40 uA

$I_{NR} = I_R + I_{GND}$

t_{BAT} = (Qbat / I_{NR}) * (Eff% / 100) = (1400 mA / (66.2 mA + 40 uA)) * (89.14 / 100) = 18.84 hrs

I_R = 45 mA + 0.35 mA + 0.35 mA + 0.50 uA + 20 mA + 0.5mA = 66.2 mA

Chapter 6

Port Loading & Driver Analysis

- Considerations
  - The only devices that surpass the 25mA driving current are the GPS and bluetooth. The GPS's V_{DD} pin is connected to V_{DD} via a BJT controlled by PA8. The bluetooth's V_{DD} pin is directly connected to V_{DD}.
- $I_A = PA2$(BlueTooth USART)$+PA3$(BlueTooth USART)$+PA4$(LED Pin)$+$ $PA5$(LED Pin)$+PA6$(LED Pin)$+PA7$(LED Pin)$+PA8$(GPS Power)$+$ $PA9$(GPS USART)$+PA10$(GPS USART)$+PA13$(Trigger Button)$+$ $PA15$(IR Receiver)$= 5uA + 5uA + 0.05mA + 0.05mA + 0.05mA + 0.05mA + 2mA + 0.05mA + 0.05mA + 3.3mA + 5mA = 10.56mA < 25mA$ (Maximum Port Current)
- $I_B = PB0$(Speaker)$+PB2$(LED Pin)$+PB3$(LED Pin)$+PB5$(IR Receiver)$+$ $PB6$(Battery Gauge)$+PB7$(Battery Gauge)$+PB10$(LED Pin)$+PB11$(LED Pin)$=$ $2mA+0.05mA+0.05mA+5mA+0.2uA+0.2uA+0.05mA+0.50uA+0.50uA+0.05mA = 7.2514mA < 25mA$ (Maximum Port Current)
- $I_C = PC13$(LED Bar Button)$+PC14$(IR Laser)$+PC15$(LED Pin)$= 2mA + 3.3mA + 0.05mA = 5.35mA < 25mA$ (Maximum Port Current)

Chapter 7

Base Times and Timing Analysis

LED Array

- ON time: 5 s
- Frequency = 72 MHz
- Time/Instruction = 13.8 ns
- Set PS = 10986
- Set TC = 32769

Invulnerability:

- ON time: 5 s
- Frequency = 72 MHz
- Time/Instruction = 13.8 ns
- Set PS = 10986
- Set TC = 32769

Speaker:

- ON time: Varies*
- Frequency = 72 MHz
- Time/Instruction = 13.8 ns
- Set PS = 4
- Set TC = 30600
- *Calculations done with the worst case of 1700 microseconds.

Point-to-Point:

Bluetooth Module:

- Baud Rate: 115200bps
- MCU Frequency to be used: 72MHz
- Maximum Error = 0.06%

GPS Module:

- Baud Rate: 9600
- MCU Frequency to be used: 72MHz
- Maximum Error = 0.01%

Chapter 8

MCU Memory Usage

When we compile our C code one of the outputs we receive a .sizes file which depicts the memory consumption. From this file we find that the final binary has a size of 49,092 bytes.

We are also shown that the binary is split into three parts:

- .text - 36,140 bytes
- .data - 11,448 bytes
- .bss - 1,504 bytes

The .data section contains all the variables which have explicitly initialized values, while the .bss section contains all the uninitialized variables. The variables in the .bss section are initialized to zero when the MCU initializes. [5] The .text section contains all the instructions which the MCU runs.

The storage library (storage.c) utilizes the most memory, using up 9,220 bytes. This library is capable of storing data for up to 256 hits at any given moments. Each hit entry has a size of 36 bytes, which accounts for most of the used memory in that library.

Chapter 9

Hardware Reliability & Professional Component

- Verification is done to check that all soldering joints are solid and no short circuits are occurring. This protects the circuit from damage and also prevents undesired system behavior such as false interrupt triggers, voltage overloads, current surges, etc.

- The battery has a protection circuit limiting the amount of voltage it can charge up to (approximately 4.2V) and also limits how far the battery can discharge (3.2V). Without this circuit the battery discharges to approximately 2.75V; the advantage of having this protection circuit is that you extend the batterys usable life, since one of the major causes of battery degradation and wear is constantly discharging it to its limit.[4] The incorporation of this protection circuit does not allow the user to drain the battery to this threshold, minimizing the wear on battery, hence extending is usable life.

- We utilized a single layer PCB to make the circuitry cleaner and much safer to handle.

- We utilize a RJ11 cable (telephone handheld cable); this cable significantly reduces noise when transmitting data between the laser tag gun and the vest. Another advantage of using the RJ11 cable is that we are able to utilize the RJ11 connector (phone head) and the female connection (phone jack); this is useful because the cables through which the data is being transmitted are delicate, and soldering extensions to them or soldering directly on to the PCB is not an option since it will not guarantee reliability.

- The microcontroller purchased for this project is a STM32F103RCBT6 (which is modeled around the ARM Cortex M3), it has been included in a board (Maple Mini) that has integrated LDOs which are capable of dropping voltages as high as 16V to the standard 3.3V logic level that all components in this project utilize.

- Simple RC debouncing circuits were implemented at each button to minimize the bouncing effects switches innately exhibit and ensure the reliability of the interrupts produced by those switches.

Chapter 10

Level of Completion

Component Name	% Completion	Comments
Infrared Emitter	100%	
Infrared Receiver	100%	
Bluetooth	100%	
GPS	100%	
Fuel Gauge	100%	
Speaker	100%	

Part II

Software Description

Chapter 11

System Flowcharts - Operation Explanation

At a high level, our system's operation can be shown as the following two flowcharts. In addition, flowcharts demonstrating the other components and layers of our system's software can be found in the Appendix.

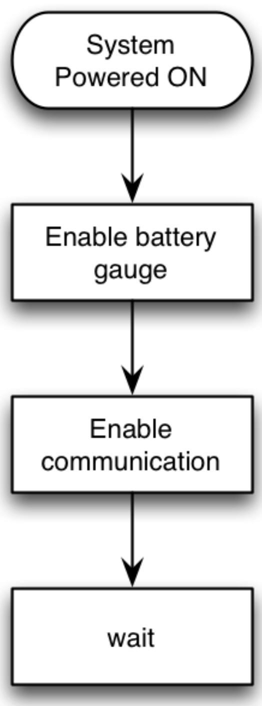

Figure 11.1: System Initialization.

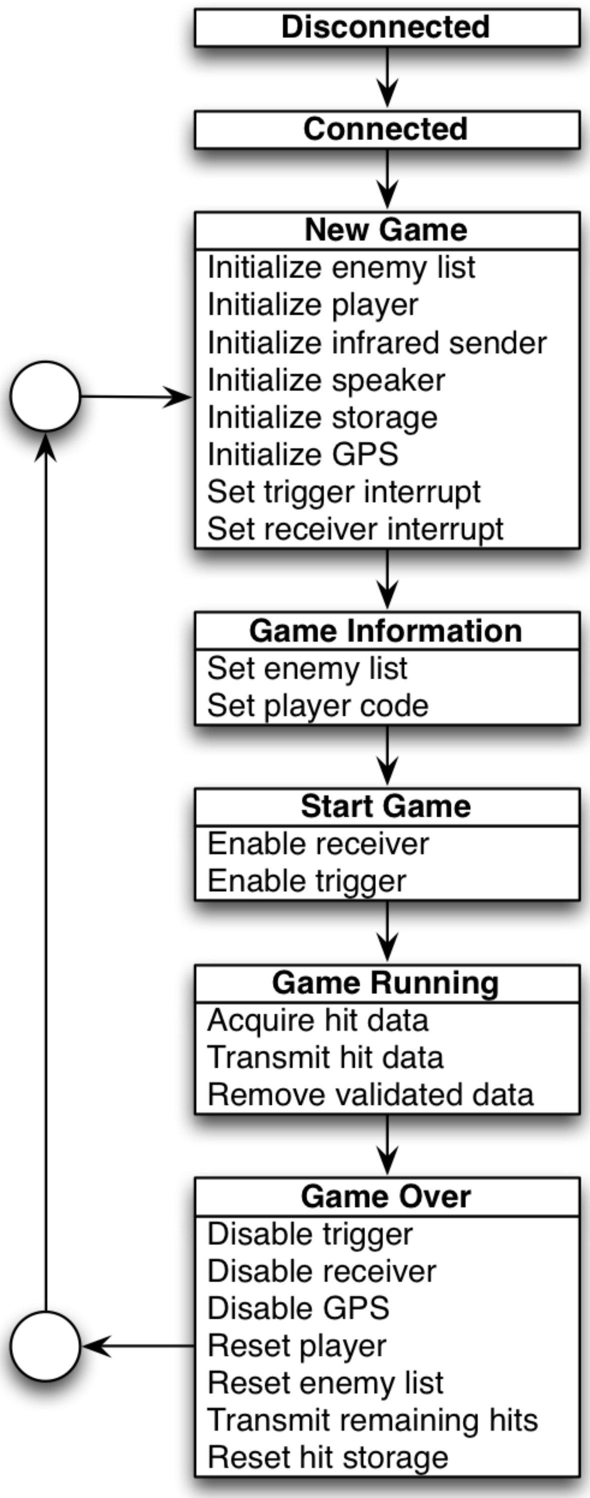

Figure 11.2: The system's main operation.

Chapter 12

Host/Multi-unit Software Organization

Every system is divided into two main components: the gun and vest are one component, and the phone is the other component. The phone controls the gun; it is responsible for changing the gun's state and processing the hit data. The gun sends all the hit information to the phone through bluetooth and stores it. When the phone messages the gun saying that the hit data has been processed it is deleted from the gun. The vest sends the received enemy ID to the gun upon being shot.

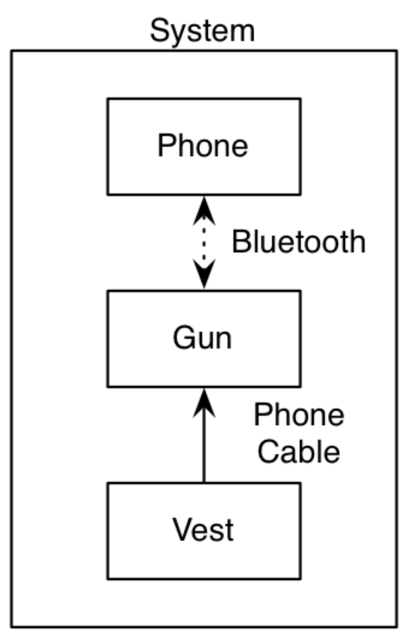

Figure 12.1: Host-Device Interaction Diagram.

Each system requires a phone, a gun, and a vest; with each set of these three components representing a player. Every player interacts with other systems and the server. The server is responsible for coordinating the game between all the players. A player interacts with opponents by shooting at the enemy's vest with their gun. Figure 12.2 depicts the interactions in systems, between systems, and the interactions with the server.

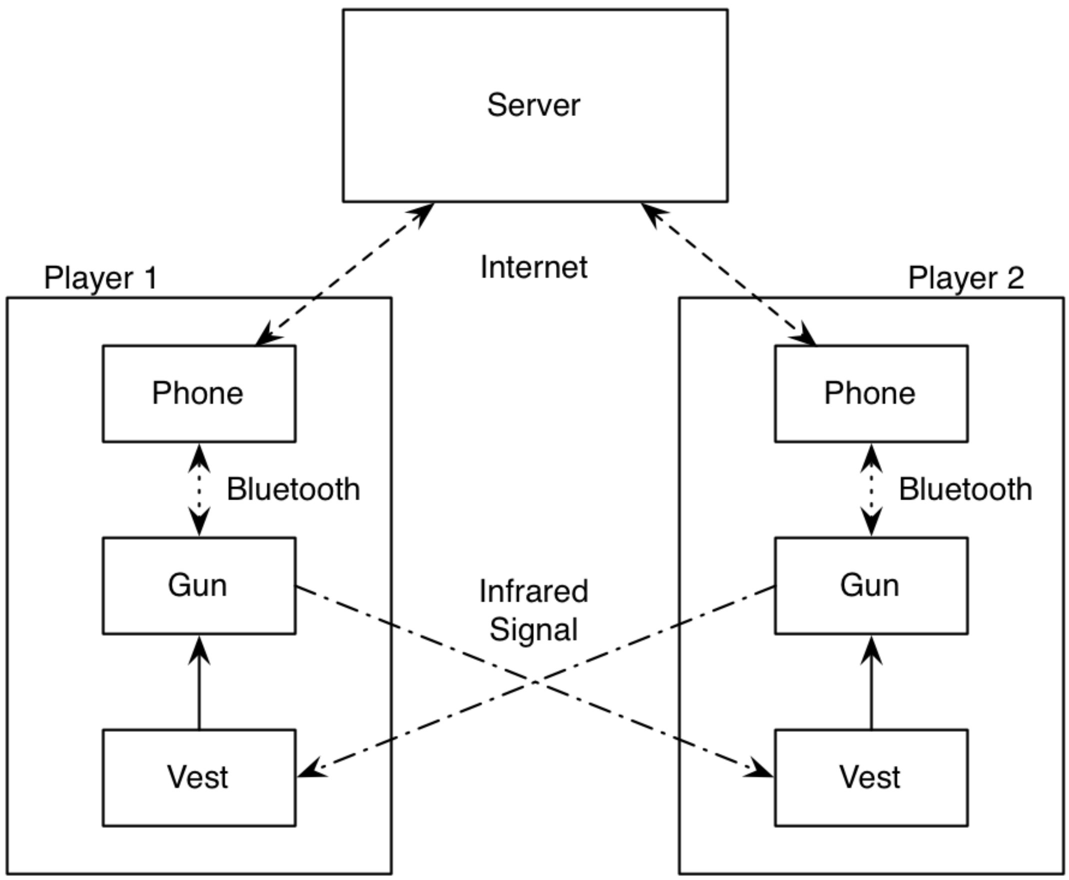

Figure 12.2: Multi-Device Interaction Diagram.

Chapter 13

Software Reliability: Professional Considerations

The system is capable of functioning even if some hardware components fail. The essential components are: bluetooth, infrared laser, infrared receivers, and trigger button. These components are essential for the system to function, if any of them fail the system will not be usable. However, certain other components can fail without harming system operations. If the GPS fails or if it does not have valid data it will simply transmit "GPS_DATA_NOT_VALID_SORRY". If the speaker fails then the user will not receive auditory feedback for events, but the system will still function. Due to the way i2c is implemented, if the battery monitor is broken/removed, and the battery monitor button is pressed then it will enter a loop where it keeps waiting forever for a response. Almost all variables are created statically as a safety measure to reduce the risk of memory overflow. The hit data is stored in a data structure that behaves similarly to a fixed size circular linked list. In the event that the gun were to receive the maximum number of hits that can be stored and none were processed, then the gun would begin to overwrite the oldest data. With this, we can be assured that there will be no overflows.

Chapter 14

Level of Completion (Target & Host)

Task	% Completion	Comments
Infrared Communication	100%	
Bluetooth Communication	100%	
Acquiring GPS Coordinates	100%	
Lobby Creation	100%	
Phone-to-Server Integration	45%	

Part III

Closing Section

Chapter 15

Conclusions

In the process of designing and developing an affordable laser tag system, there have been compromises and changes throughout the development process. However, the goal of developing and building a functional laser tag system with an online lobby has been achieved. Due to the costs of the GPS module, microcontroller board, and bluetooth module, we were unable to meet the goal of making our system affordable in comparison to professional laser tag systems. Considering that our system differentiates itself from other systems in the GPS and bluetooth offerings, for which no similar products were found, we understand that the increased system cost comes with an increased value for our system due to its unique nature. To alleviate this, removing the GPS and offloading that functionality to a user's phone would be a possible way to reduce power consumption as well as a large portion of the system's cost. Additionally, using a microcontroller without a board and using a separate voltage regulator would reduce the cost incurred by using the MapleMini.

In making changes to our laser tag system, an unintended benefit was discovered in replacing the infrared LEDs with an infrared laser. The laser offers lower power consumption, improved accuracy, and a long range for each shot. This improved the initial power estimates as well as the system's battery life. The longer range also supports the system's focus on outdoor use, allowing for larger fields of play than expected with the infrared LEDs.

In undergoing the entire process from developing the idea to the actual prototype, we learned about and applied many lessons learned regarding microprocesor interfacing. Developing our prototype required understanding UART and I2C communication, timers and interrupts. Additionally, we developed the ability to read and understand multiple datasheets, develop software in C, and think out of the box. A key example of this is the use of a phone's handset cord to function as a long-distance GPIO cable, which helped both reduce the noise that results from using a standard cable as well as provide the user with a more comfortable experience when using our prototype.

Chapter 16

Future Work

- Reduce system costs by using a cheaper board.
- Develop secondary firing modes (Shotgun, Semi-automatic, etc)
- Add additional game modes (Team Deathmatch, Capture the Target, etc).
- Reduce system power consumption and implement sleep modes for GPS and Bluetooth.
- Improve gun enclosure for sleeker appearance.
- Add community functionalities to the phone application.

Bibliography

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[3] Manuel Jimenez, Rogelio Palomera, and Isidoro Couvertier. *Embedded Systems: Theory and Applications Using the MSP430*. n/a, 2013.

[4] Celina Mikolajczak, Michael Kahn, Kevin White, and Richard Thomas Long. Lithium-Ion Batteries Hazard and Use Assessment. Technical report, Fire Protection Research Foundation, July 2011. http://www.nfpa.org/assets/files/pdf/research/rflithiumionbatterieshazard.pdf.

[5] Kumar B. Vijay. Embedded Programming with the GNU Toolchain - C Startup, September 2011. http://www.bravegnu.org/gnu-eprog/c-startup.html.

Appendix A

Users Guide: Installation, Setup, & Operation

A.1 Installation Guide:

The Laser Tag Reloaded system requires no installation.

A.2 Setup Guide:

To set up your Laser Tag Reloaded system,

1. Just plug one end of the coiled cord into the gun's jack, and the other to the vest's jack,
2. Download the phone app,
3. Activate your phone's internet and bluetooth,
4. Turn on the gun,
5. Pair the phone and gun using the bluetooth.

Now, your system is set up and ready to jump into a game!

A.3 Operation Guide:

To operate the system,

1. Select your paired gun from the list of devices. (See Figure A.1)
2. Choose a nickname that suits you. (See Figure A.2)
3. Once logged in, in the main menu, select to join or create a game. (See Figure A.3)
4. If you choose to create a game then input a room name, select the game type, and the limit. (See Figure A.4)
5. Once you've created or joined a game, either start the game or wait for the host to start the game.

6. Play the game until the kill or time limit has been reached.

7. Have fun!

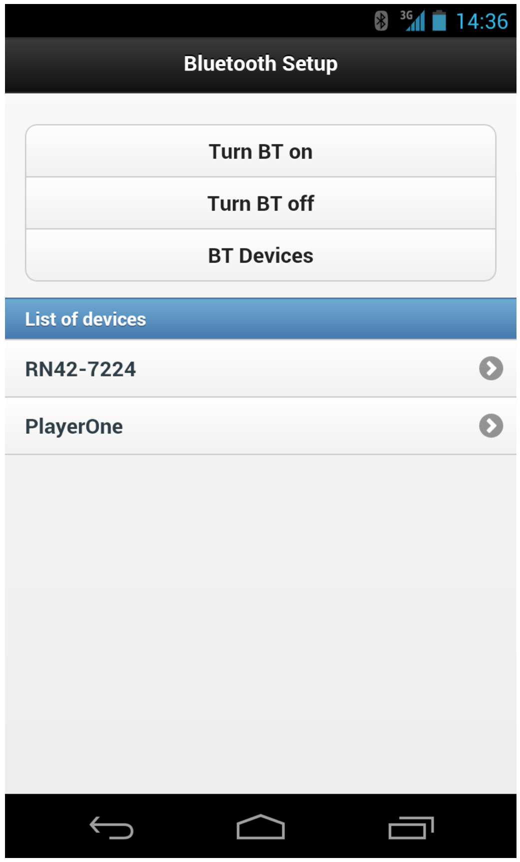

Figure A.1: The bluetooth device select screen.

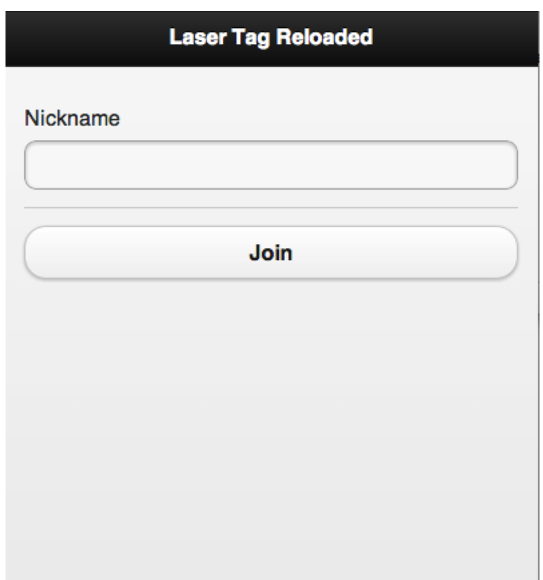

Figure A.2: The username select screen.

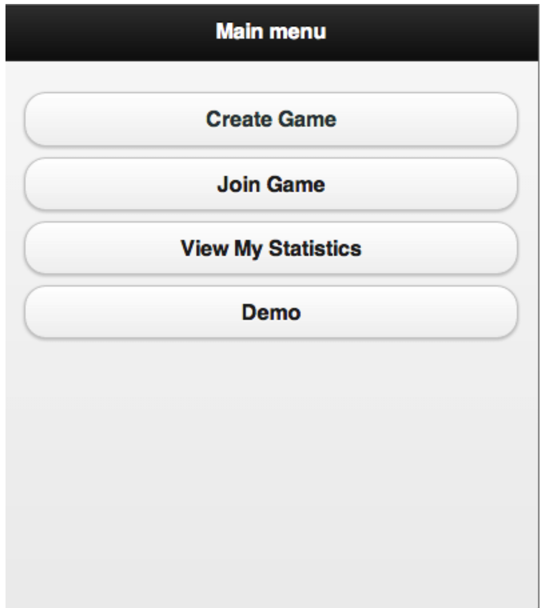

Figure A.3: The game's main menu.

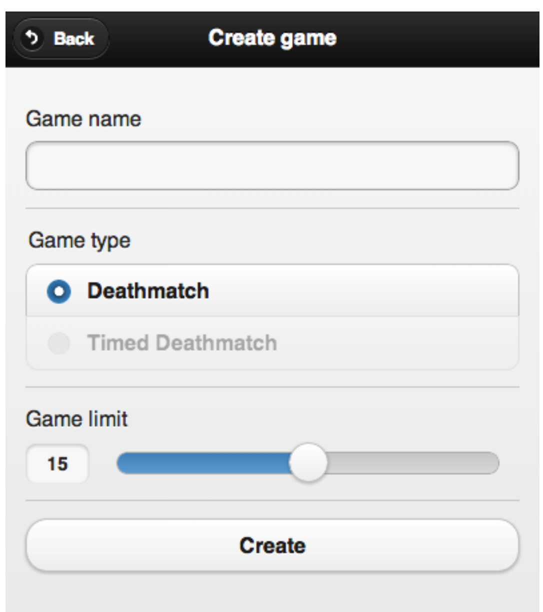

Figure A.4: The game creation menu.

Appendix B

System Specs

- Clock Speed: 72 MHz
- Memory: 20 KB
- Power Consumption: 360.36 mW
- Current Usage: 66.2 mA
- Battery Life: 18.84 hours
- GPS Error Margin: 1.8 meters
- Recommended Bluetooth Range: 3 meters
- Infrared Frequency: 56 KHz
- Android 4.0 Required

Appendix C

Schematics

C.1 PCB

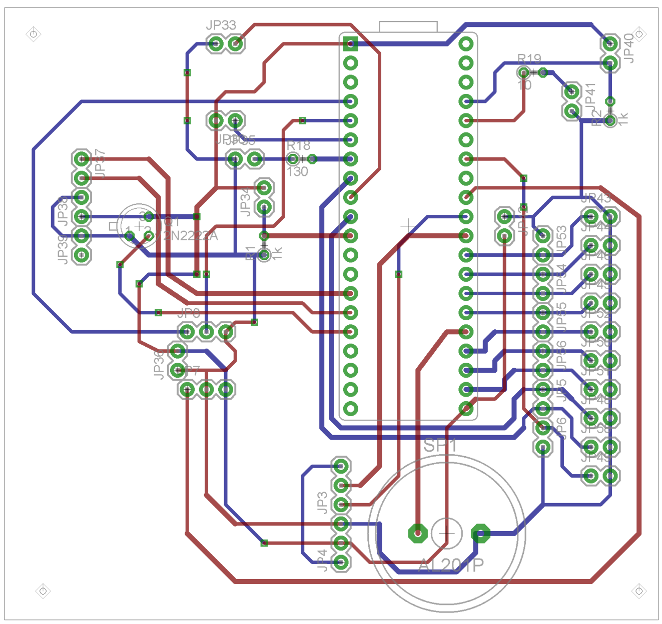

Figure C.1: The system's PCB design.

C.2 Schematic

(See next page)

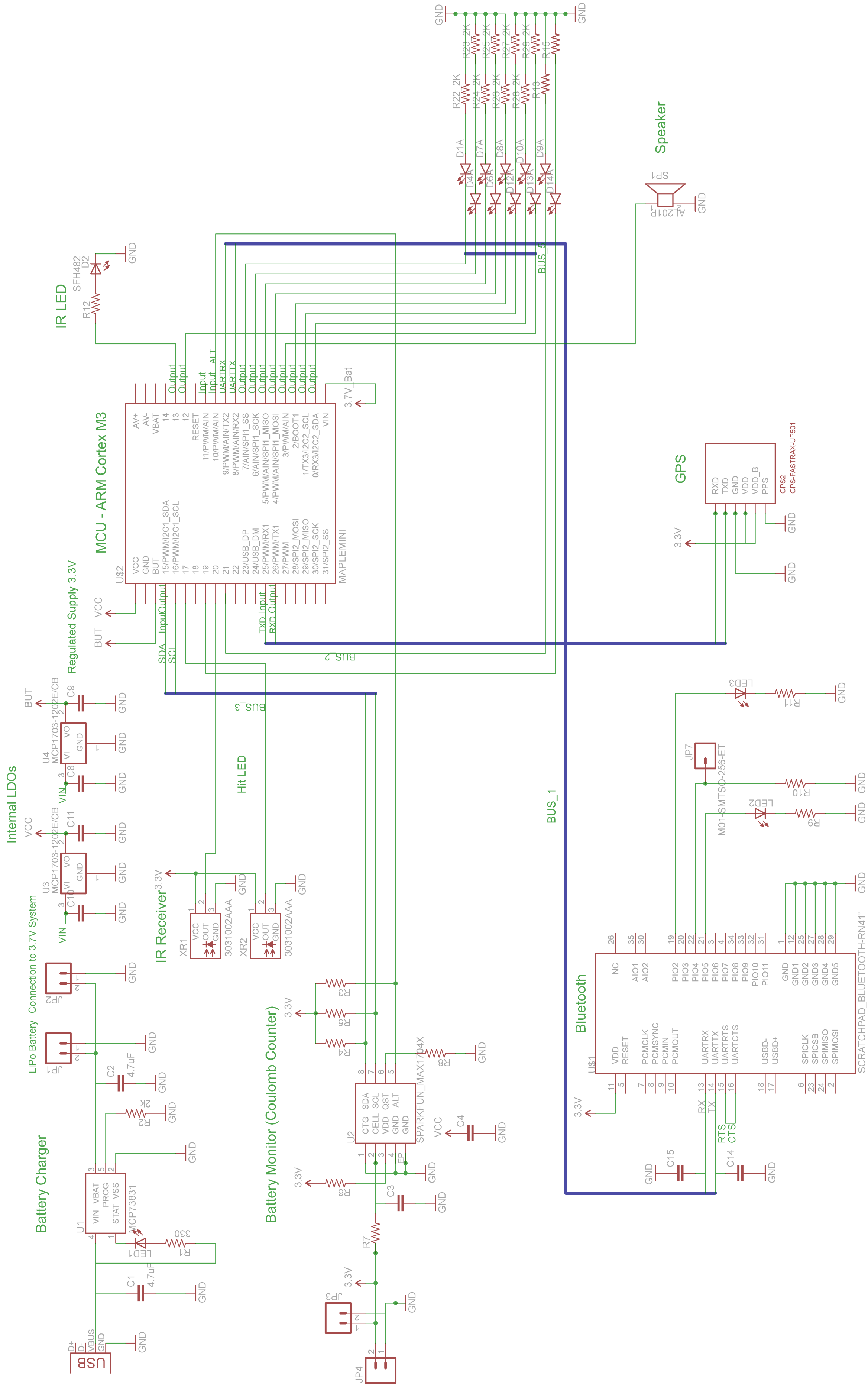

Figure C.2: The system's final schematic.

Appendix D

Component Layout

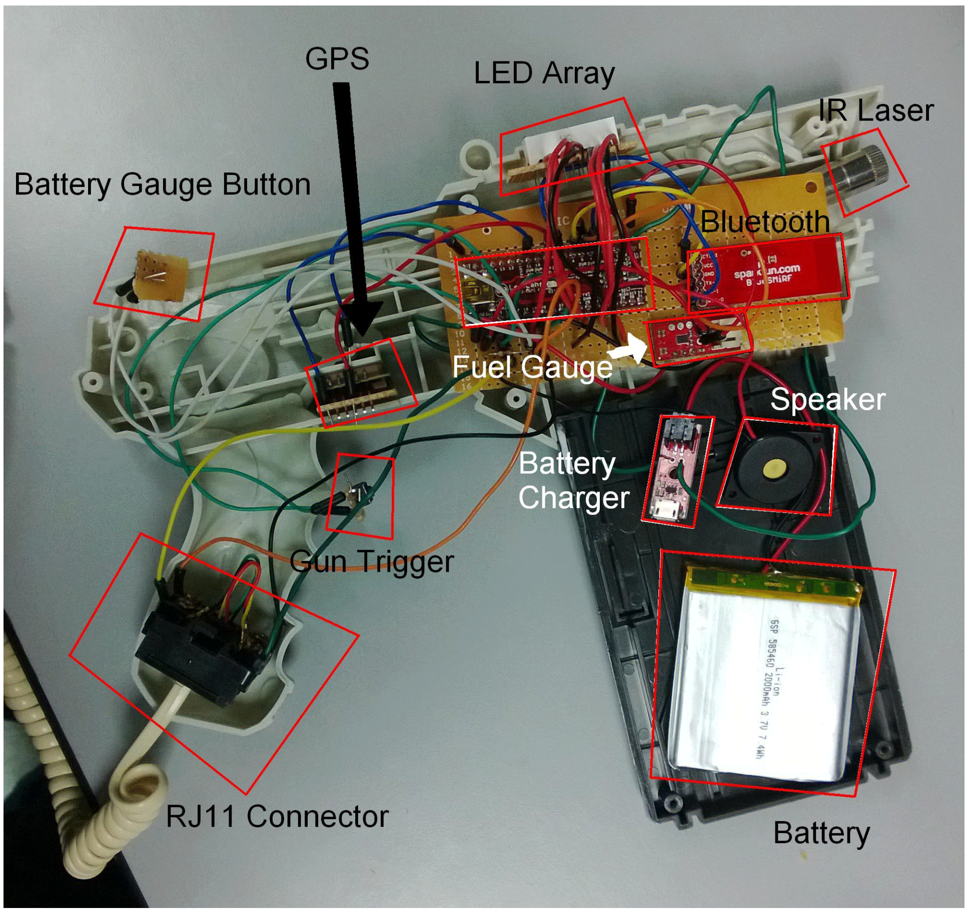

Figure D.1: The gun's component layout.

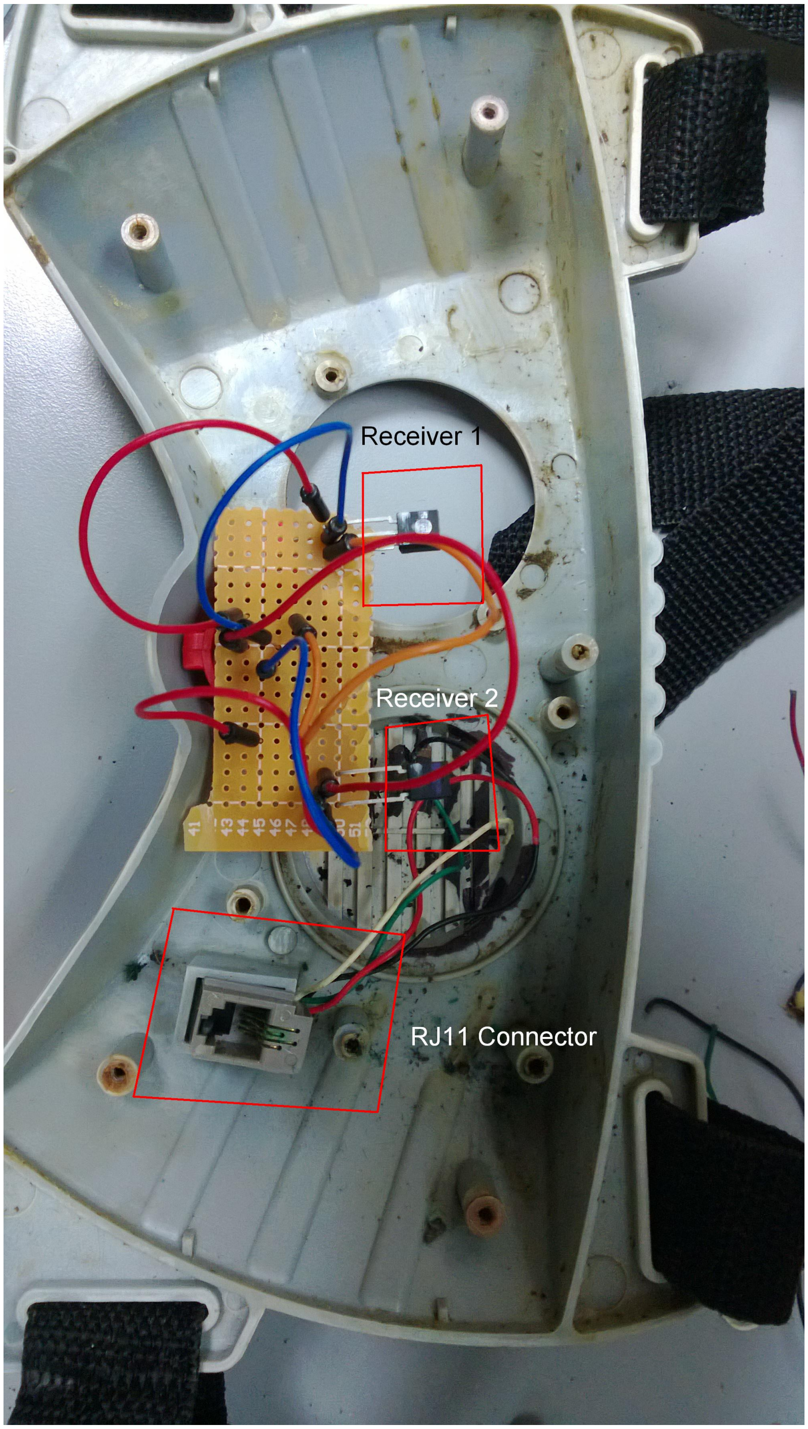

Figure D.2: The vest's component layout.

Appendix E

Cost Analysis

E.1 Bill of Materials

Device	Value	Description	Qty	Cost p/Unit	Total Cost	Distributor
Blue SMiRF Silver	WRL-10269	Class 2 Bluetooth Radio Modem	2	39.95	$79.90	Sparkfun
Fastrax UP501	UP501	GPS Receiver Module w/embedded antenna	2	$31.35	$62.70	Mouser
Female Headers	PRT-00115	Single row of 40-hole female headers	2	$1.50	$3.00	Sparkfun
LiPo Fuel Gauge	TOL-10617	Fuel gauge system for single-cell LiPo batteries	2	$9.95	$19.90	Sparkfun
Speaker	N/A	Speaker	2	$1.76	$3.52	Mouser
LiPo Charger Basic - MicroUSB	PRT-10401	LiPo Charger Basic - MicroUSB	2	$9.95	$19.90	Sparkfun
IR Receiver Diode	782-TSOP4856	IR Receiver	4	$0.95	$3.80	Mouser
Sub-Mini PC Mount Pushbutton	SLHHAK409A	NO-Pushbutton	8	$0.25	$2.00	AllElectronics
IR Laser	LB-01227MD	IR Laser	2	$10.00	$20.00	Ebay
10-Segment LED Bar Graph - Red	COM-09935	10 Red LEDs housed together	2	$1.95	$3.90	Sparkfun
Resistor Network - 330 Ohms	COM-10855	5 330 Ohm resistors w/common GND	2	$0.50	$1.00	Sparkfun
MapleMini	DEV-11280	MapleMini	2	$35.00	$70.00	Sparkfun
Jumpers	N/A	Male and Female Wiring	4 Paks	$5	$20	TIAO
Transistors	2222NA	BJT	8	$0.95	$7.60	Mouser
Resistors	N/A	N/A	4 Paks	$4	$16	TIAO

Device	Value	Description	Qty	Cost p/Unit	Total Cost	Distributor
Capacitors	N/A	Polarized for filtering Purposes	2 Pak	$4.49	$8.98	TIAO
2 Connectors	N/A	Micro JST Connectors	1	$5.99	$5.99	Ebay
IR Receiver Vest	N/A	Toymax Laser Challenge	2	N/A	N/A	N/A
Gun Enclosure	N/A	Quickfire 6	2	$12.30	$24.60	Toys R Us

Total: $372.79 ($186.40 p/Gun+Vest)

E.2 Labor

Name	Rate (per Hour)	Hours	Total
Cesar Andreu	$30	240	$7,200.00
Gabriel Cardona	$30	240	$7,200.00
Gustavo Serrano	$30	240	$7,200.00
Mark Sukhram	$30	240	$7,200.00

Labor Total: $28,800

E.3 Infrastructure & R&D

E.3.1 Infrastructure

Our infrastructure costs are $0 as the prototypes were produced using the university's laboratories and equipment.

E.3.2 R&D

Device	Value	Description	Qty	Cost p/Unit	Total Cost	Distributor
AVR Programmer	N/A	AVR Programmer	1	$14.95	$14.95	Sparkfun
AVR Programming Adapter	N/A	AVR Programming Adapter	2	$1.90	$0.95	Sparkfun
LEDs	N/A	Blue and Red LEDs	4	$2.00	$0.50	Sparkfun
Shift Register Breakout	N/A	Shift Register Breakout	2	$5.90	$2.95	Sparkfun
Lens	N/A	40mm Lenses	2	$20.80	$10.40	Laser Tag Parts
Infrared LED	N/A	Infrared LED	2	$1.10	$0.55	Mouser
PVC	N/A	PVC Pipes and Couplings	1	$11.05	$11.05	Home Depot
Saw	N/A	Buck Bros Saw	1	$8.36	$8.36	Home Depot

Total: $66.06

E.4 Total Cost

The total cost for the laser tag prototype is $29,173 ($14,586.90 per unit).
Assuming a sales volume of 1 million units:
$C_T = NRE + RP * V = (\$28,800 + \$66.06) + 186.40 * 1,000,000 = \$186,928,866.06$
$U_C = C_T / V = \$186,928,866.06/1,000,000 = \$186.93$

Appendix F

Work Distribution Table

Task Assignments	Mark	Gabriel	Cesar	Gustavo
Report 1			✓	
Report 2		✓		
Report 3	✓			
Report 4				✓
Report 5	✓			
Final Report		✓		
Email and Meeting Summaries				✓
IR Laser Calibration and Design				✓
IR Laser Effective Range Testing				✓
IR Receiver Design and Calibration	✓			
IR Data Transmission Range Testing				✓
Sound System Design and Testing		✓		
Gun and Jacket Design/Implementation	✓			
SmartPhone App Coding and Testing			✓	
Bluetooth Testing and Design			✓	
SmartPhone App/Bluetooth Interfacing			✓	
Server/Database Design and Implementation			✓	
Battery Monitor and Charger Software	✓			
Battery LED Meter Design and Software	✓			
Infrared LED and PWM Software				✓
GPS Software and Implementation		✓		

Figure F.1: The work distribution table.

Appendix G

Flowcharts

The following flowcharts detail our system's software from the gun, to the phone, to the server.

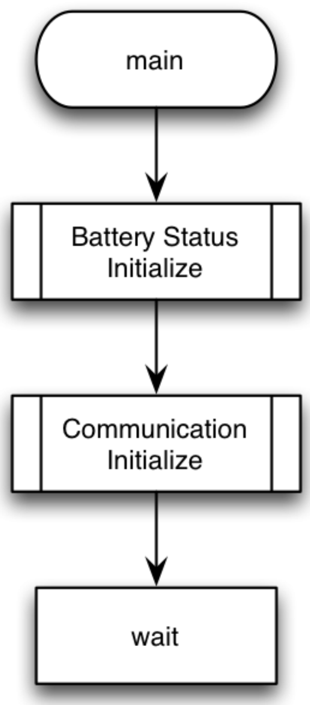

Figure G.1: The system's main operation.

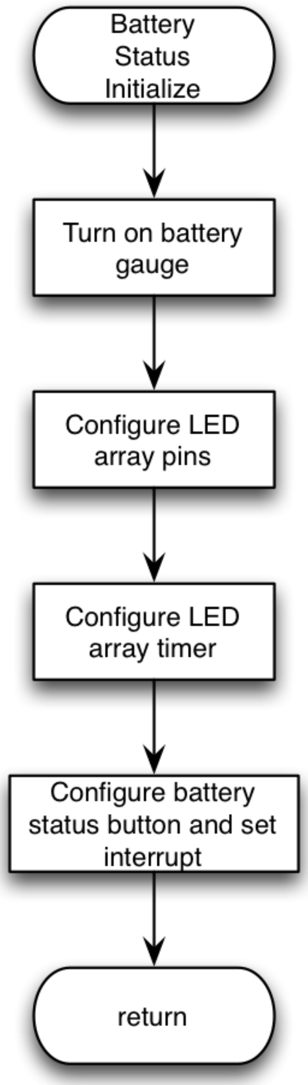

Figure G.2: The battery monitor's operation.

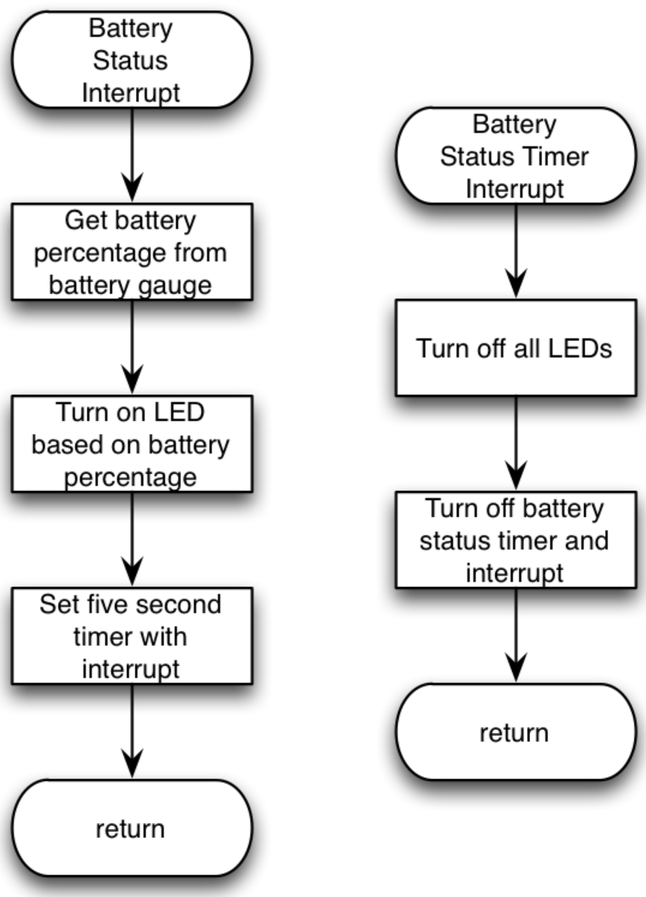

Figure G.3: The battery monitor interrupt logic.

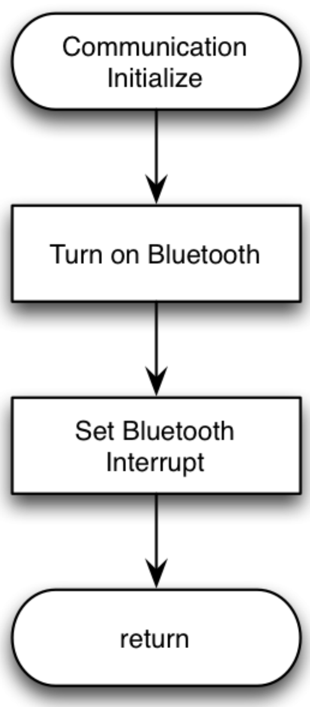

Figure G.4: The initialization of the system's communication peripherals.

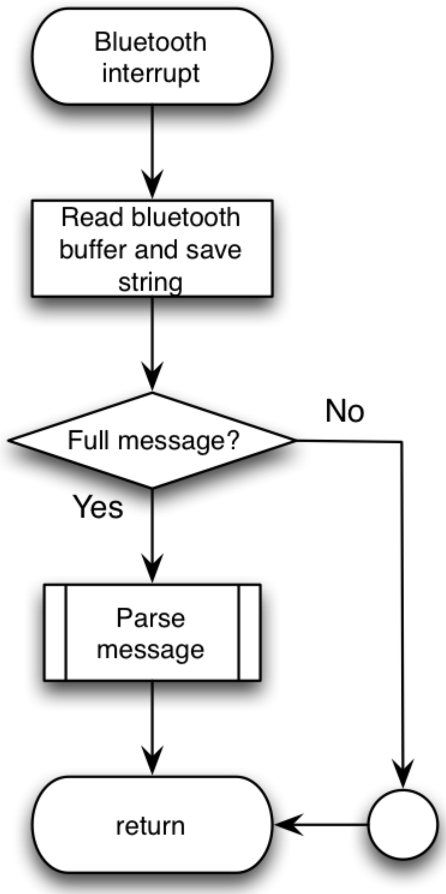

Figure G.5: The bluetooth interrupt logic.

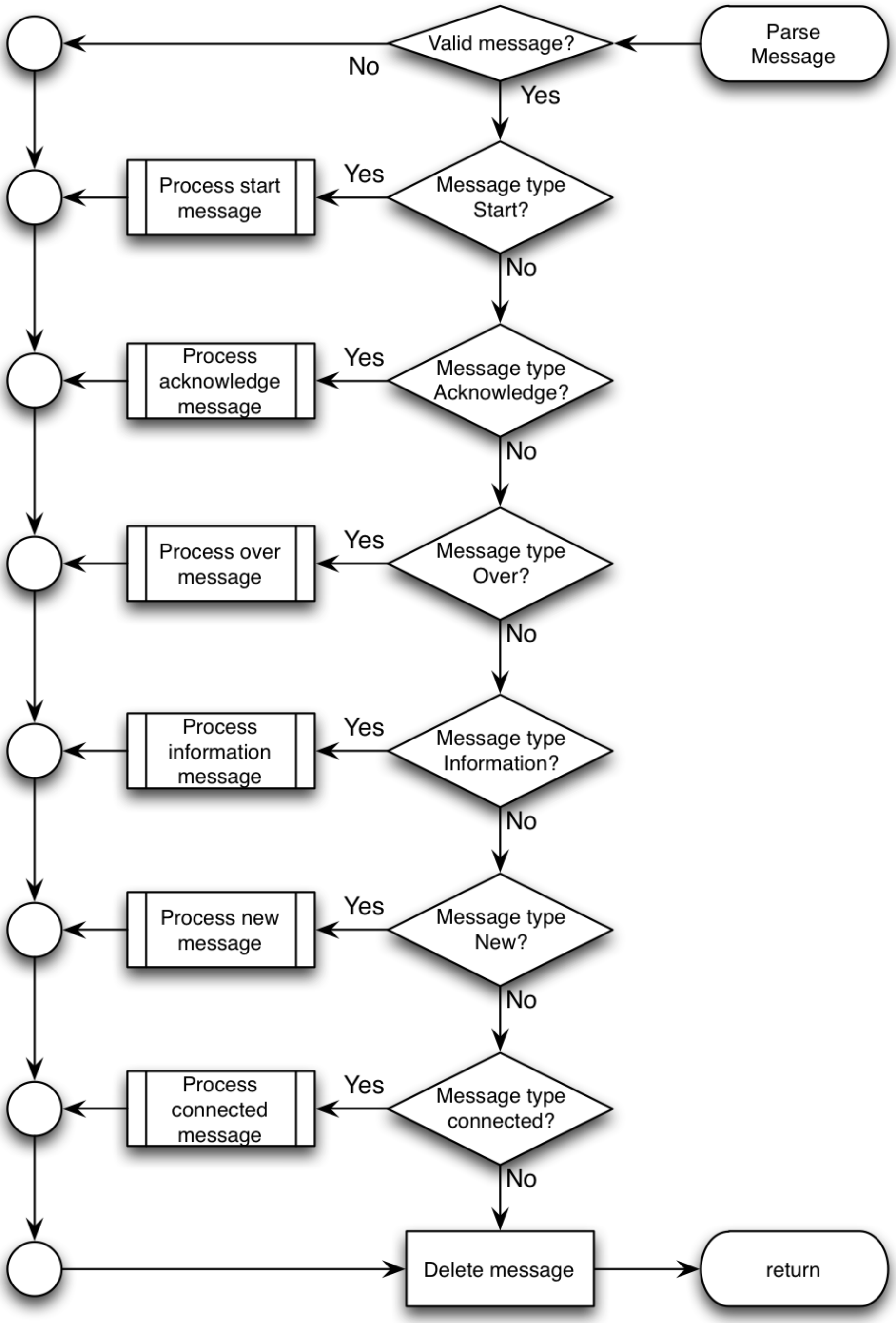

Figure G.6: The message parsing logic.

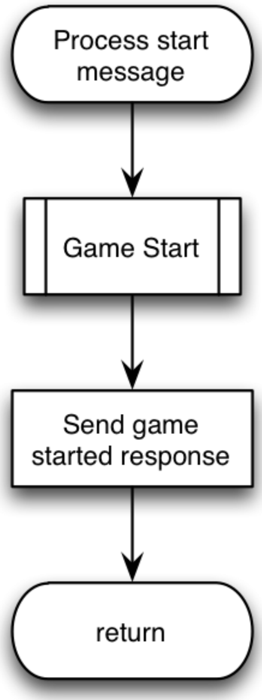

Figure G.7: The start message processing logic.

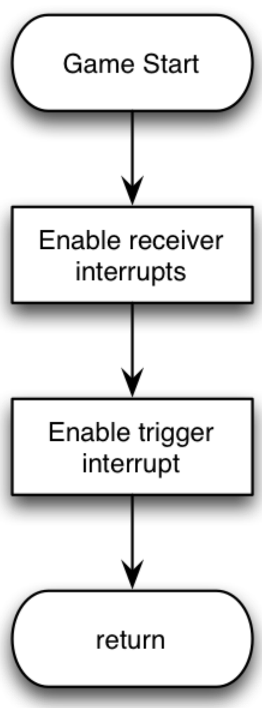

Figure G.8: The game start logic.

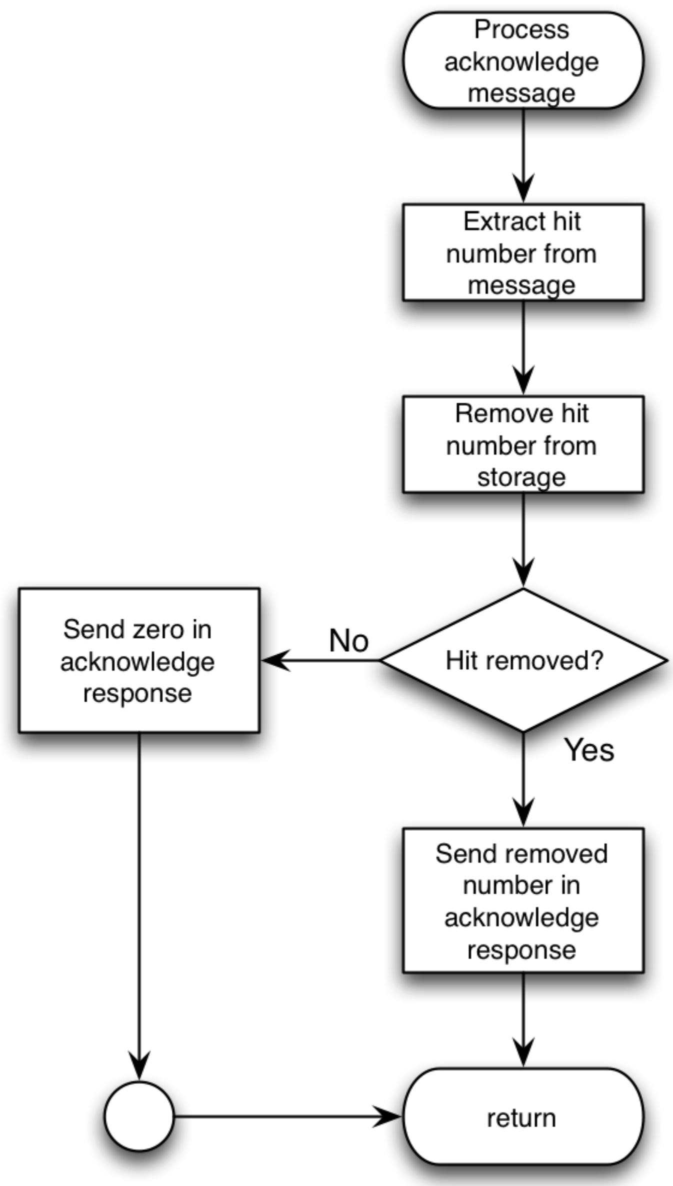

Figure G.9: The acknowledge message processing logic.

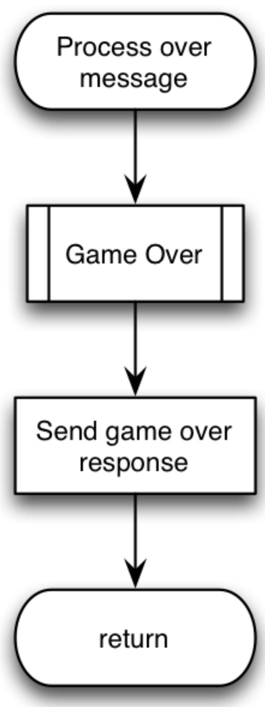

Figure G.10: The game over message processing logic.

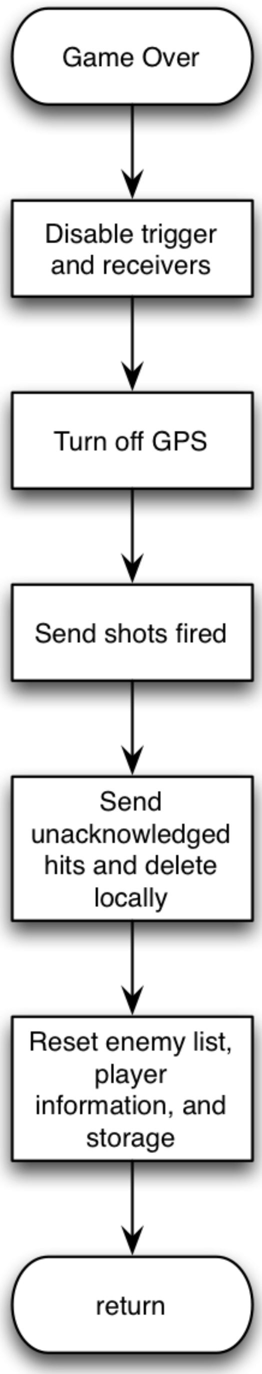

Figure G.11: The system's game over operation.

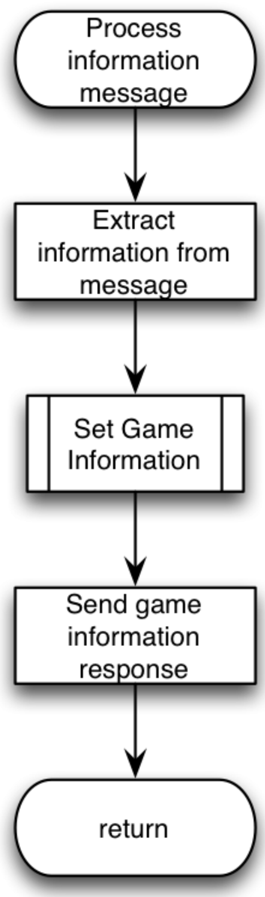

Figure G.12: The information message processing logic.

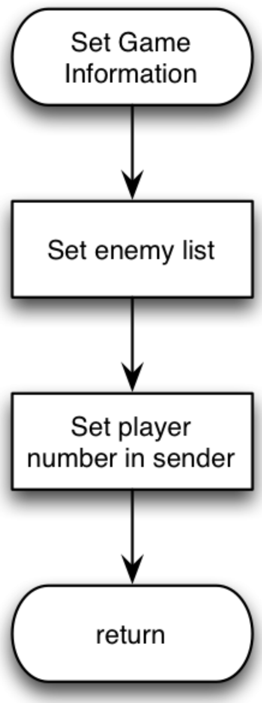

Figure G.13: The system's set game information operation.

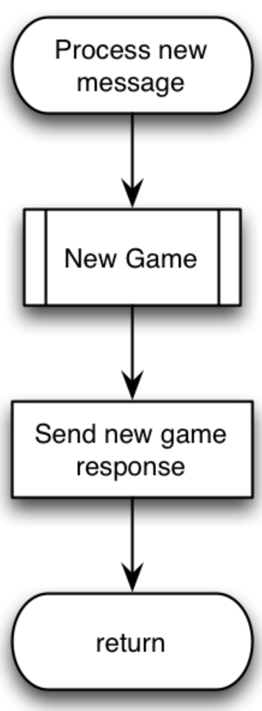

Figure G.14: The new game message processing logic.

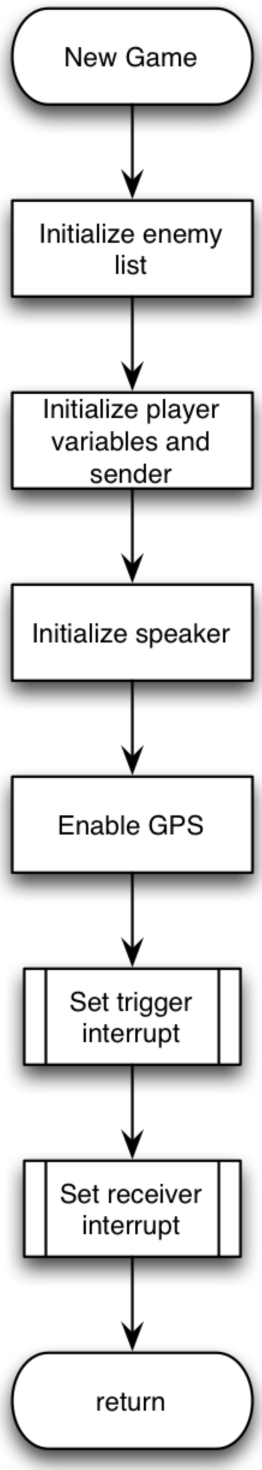

Figure G.15: The system's new game operation.

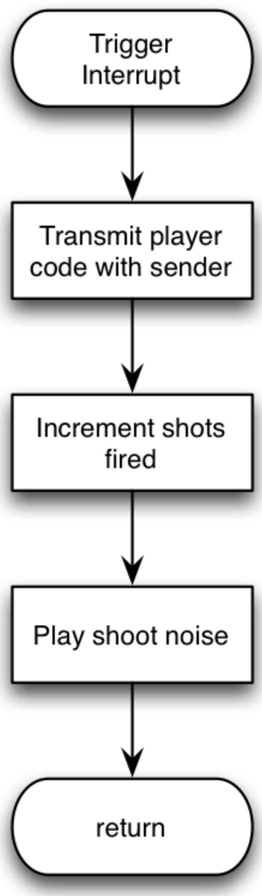

Figure G.16: The trigger interrupt logic.

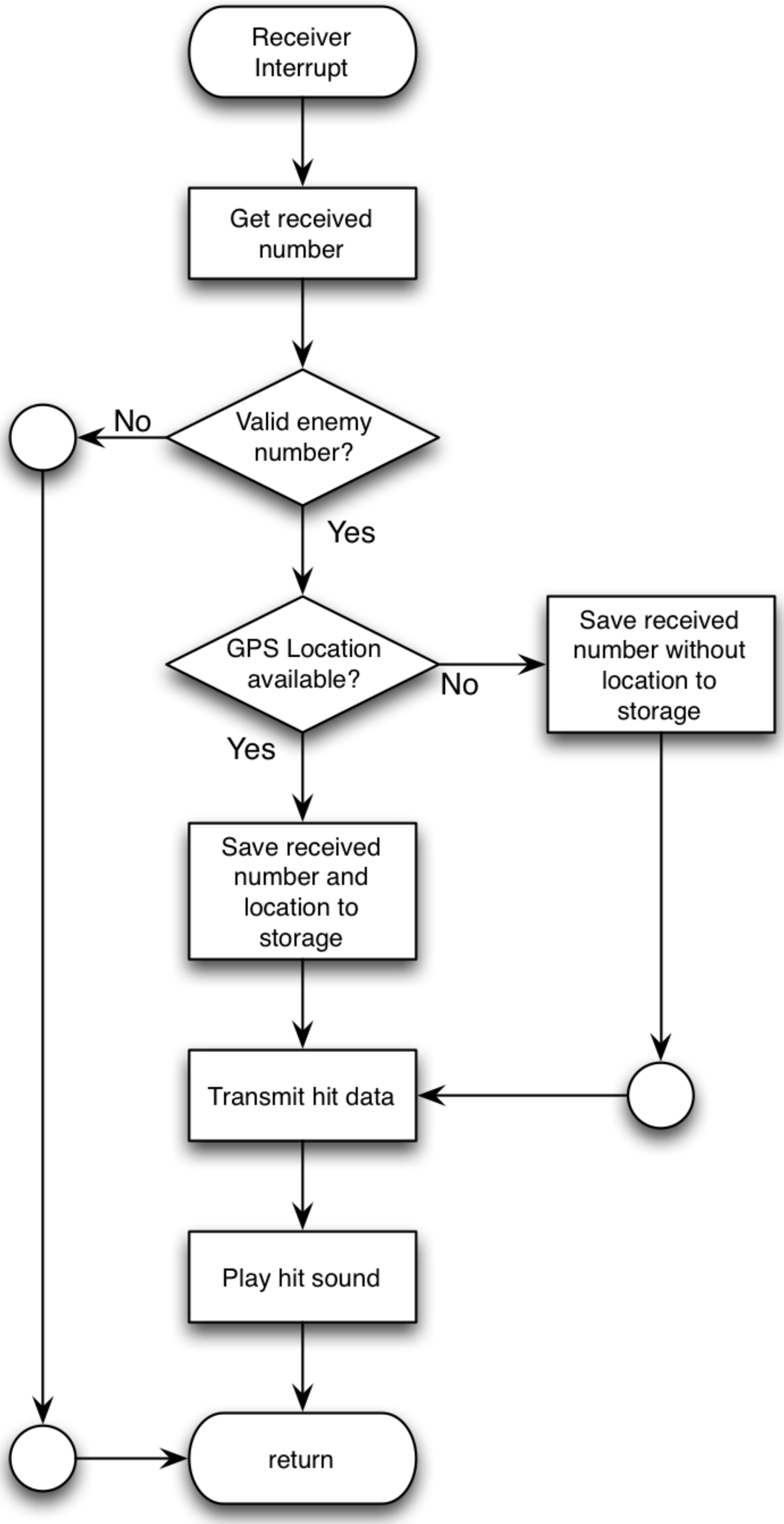

Figure G.17: The receiver interrupt logic.

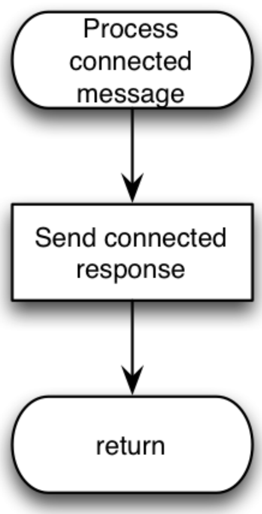

Figure G.18: The connected message processing logic.

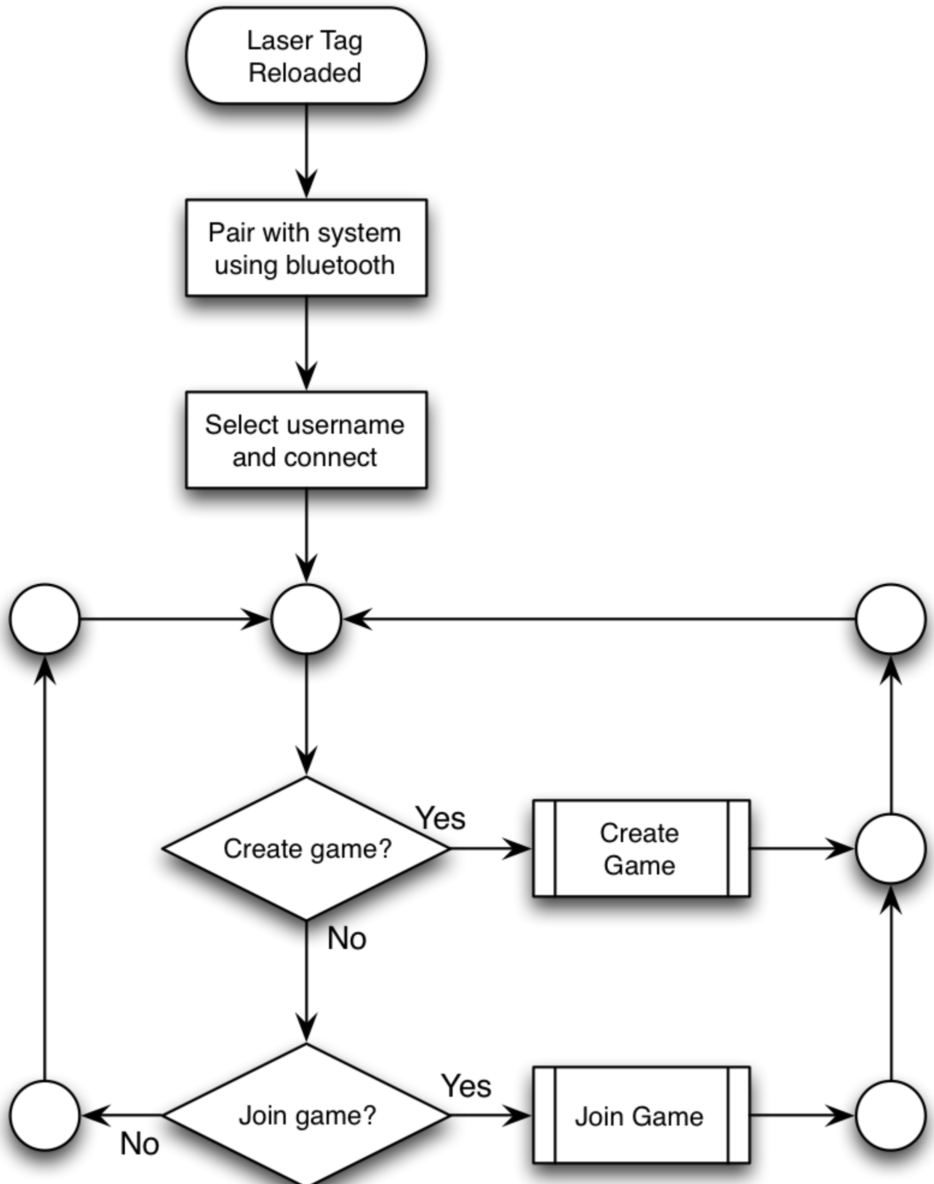

Figure G.19: The phone's high-level operation.

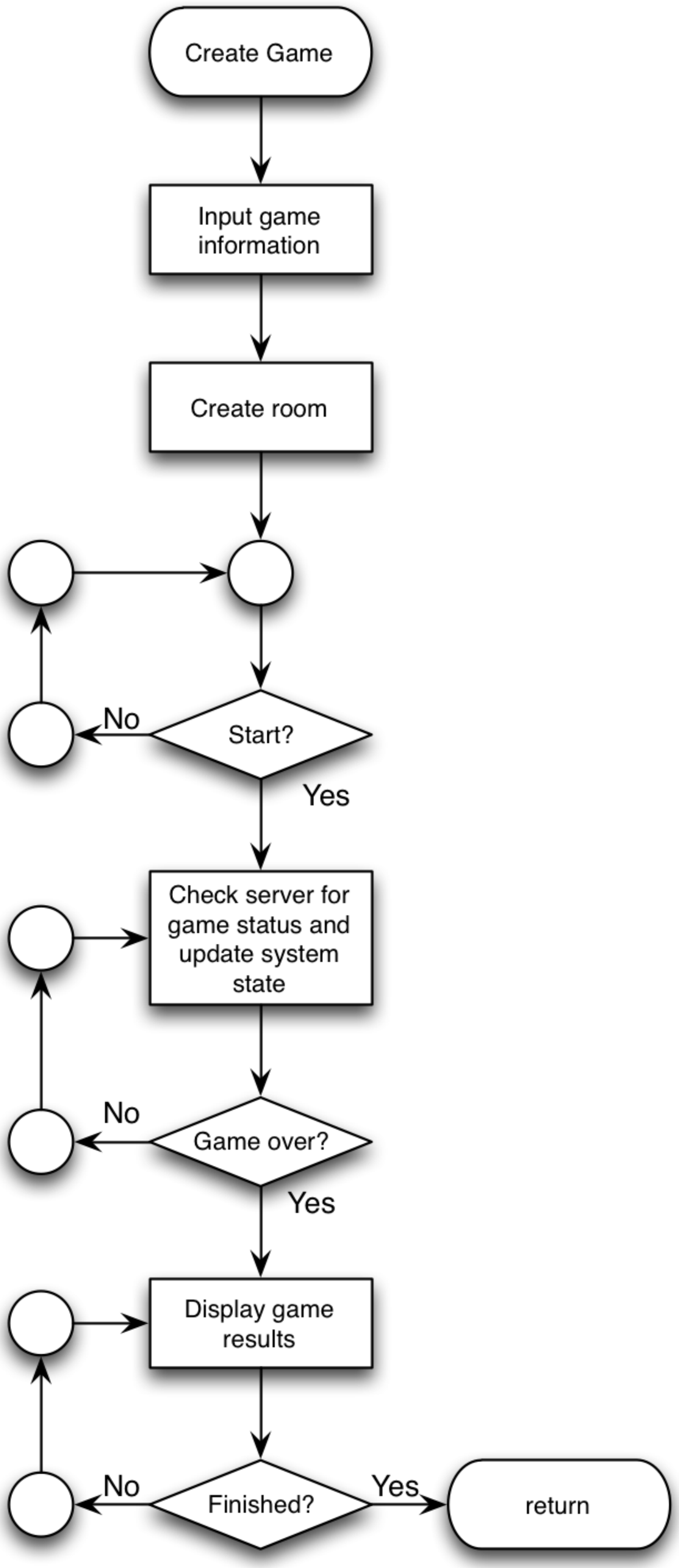

Figure G.20: The phone's create game operation.

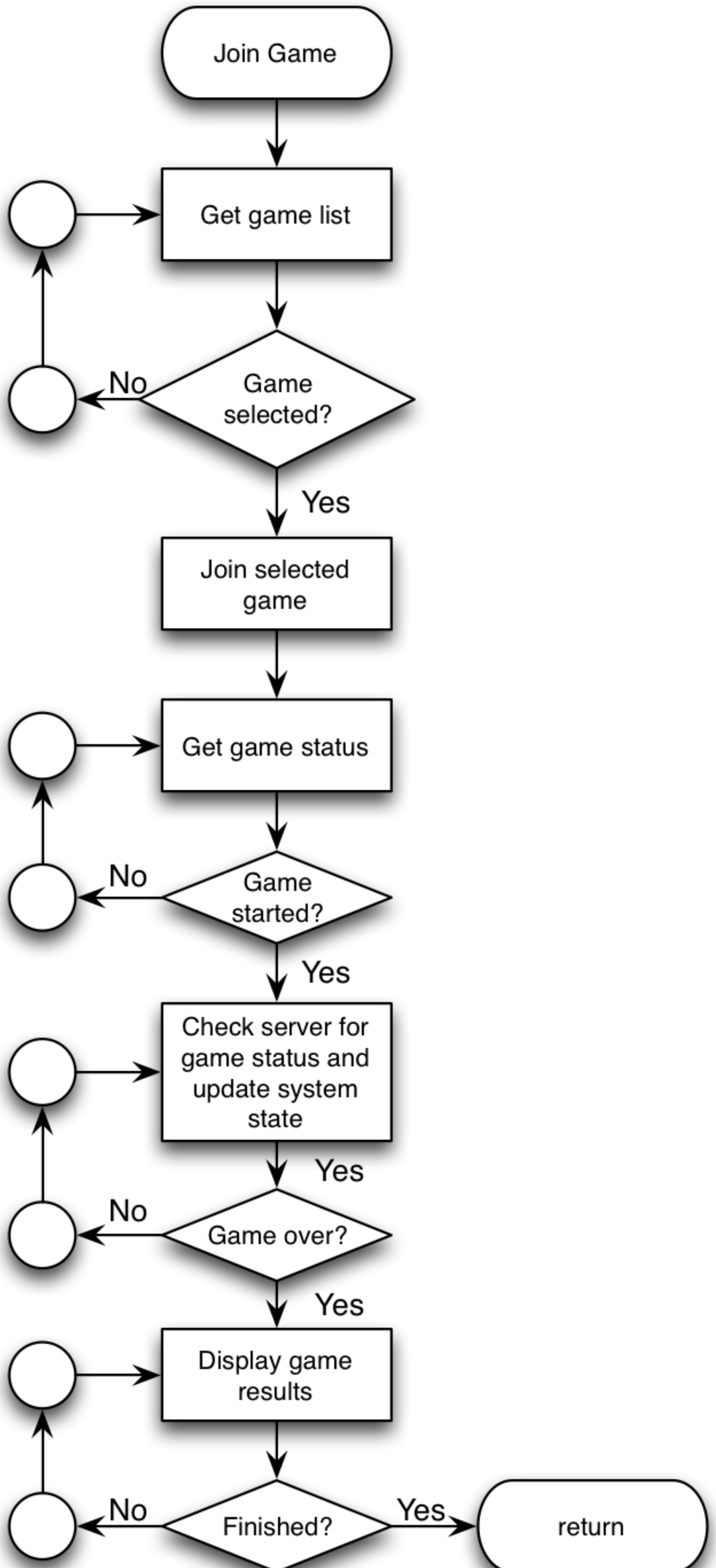

Figure G.21: The phone's join game operation.

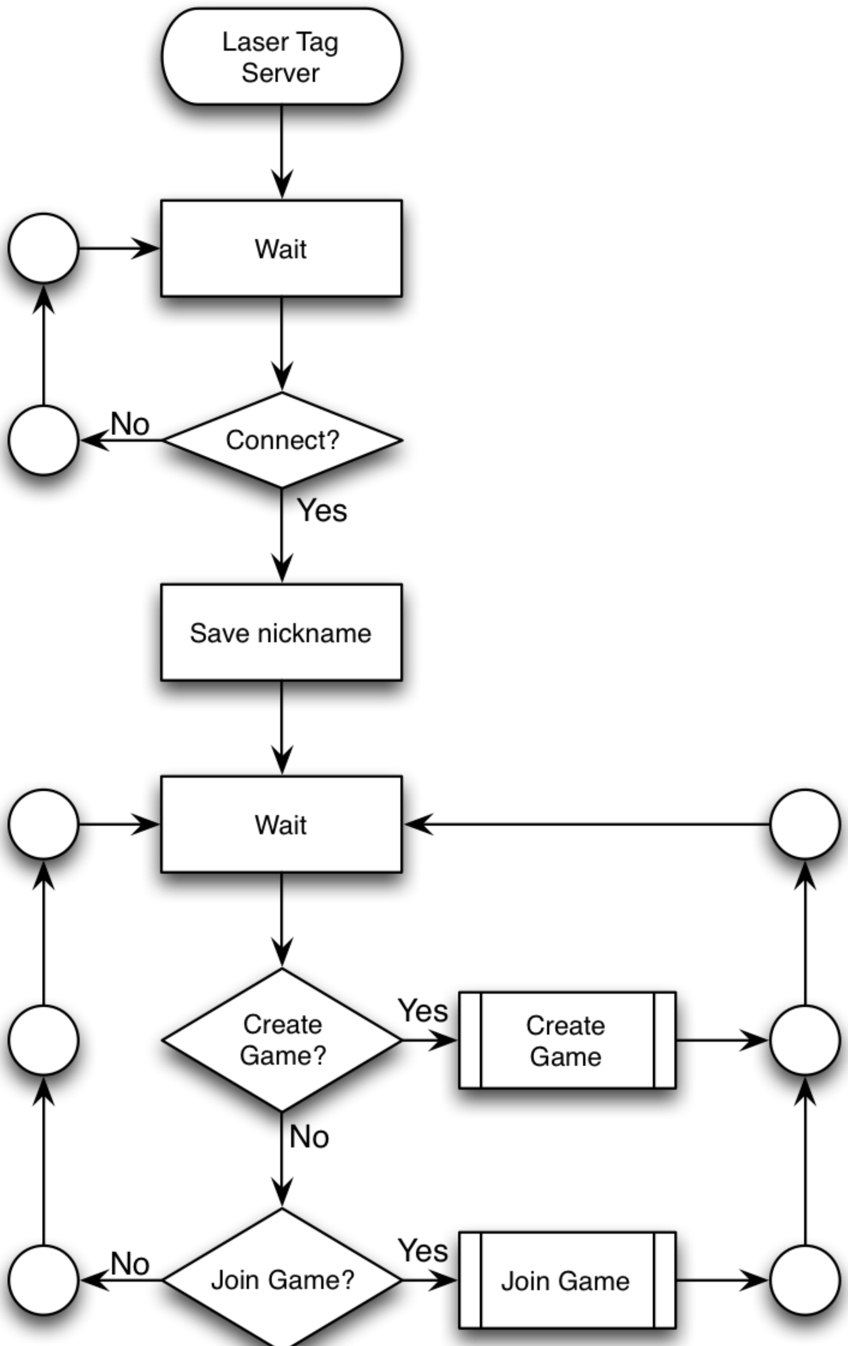

Figure G.22: The server's main operation.

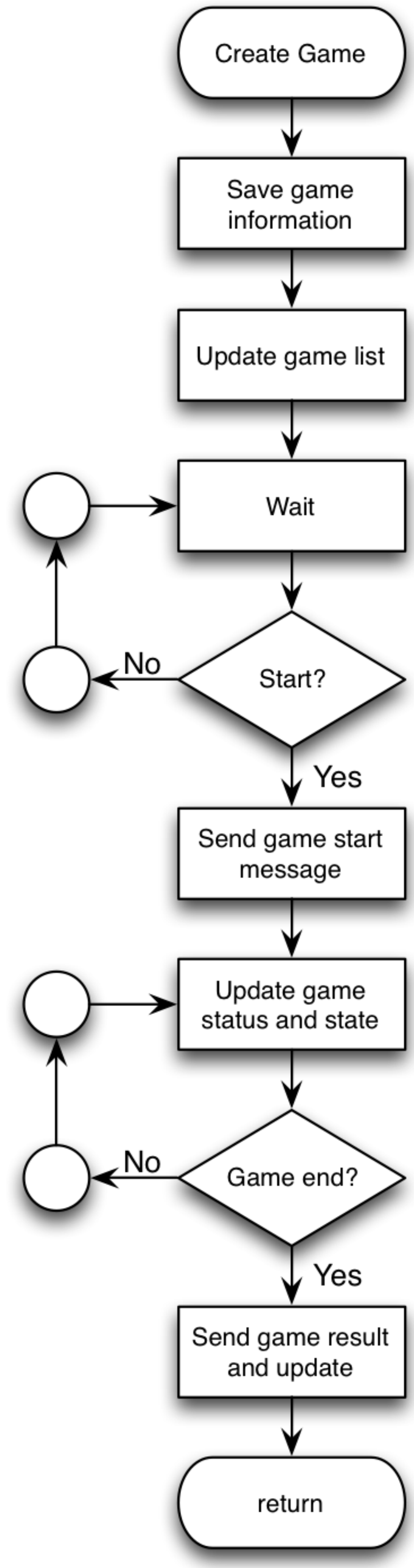

Figure G.23: The server's create room operation.

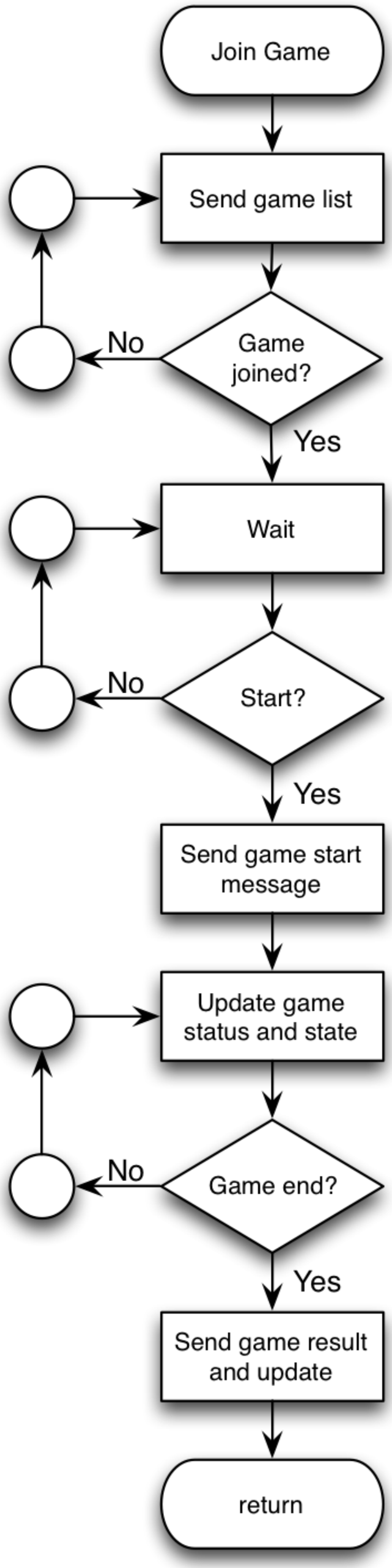

Figure G.24: The server's join game operation.