**RoboWars Final Report**

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# Introduction (Alex Craig)

This report is intended as a final report of progress by the RoboWars SYSC 4907 engineering project team. The RoboWars project aims to further develop solutions in the area of remote robotics control systems. Control systems for remote robotics available today often require custom, specialized hardware to interface with the robotics, and may provide only rudimentary control functionality. By exploiting widely available consumer hardware and open source software, the RoboWars project aims to create a feature rich robotics control system that can be easily adapted to any Bluetooth capable robotics system.

Developing a robotics control system on a widely available mobile platform provides developers with greater accessibility and reduced development time. Using smartphones to remotely control devices, robotic or not, eliminates the need for extra time and development resources to be spent on designing and building a specialised hardware platform to run the control software on. With smartphones already in widespread use by the public it is simple and intuitive for a user to download, install, and immediately use the application to remotely control their device. This provides developers with a well established and easily accessible customer base.

In addition to avoiding hardware development costs, smartphones provide a powerful platform which can support a wide range of features to enhance the usability of the controlled robotics. Smartphones are typically equipped with high resolution touch screens, Wi-Fi and Bluetooth communication capabilities, accelerometers, and dedicated graphics processors. These capabilities allow a robotics system to support enhanced features that may not be available with simpler dedicated hardware, such as live video streaming, three dimensional graphical rendering, tilt or touch screen based movement control, and high bandwidth data exchange to support advanced robot behaviour.

The RoboWars project has two primary objectives:

* The first project objective is to develop a robotics control system which is both intuitive to use and is implemented on a mobile platform that is widely available and used by the public. Specifically, the project targets mobile smartphones running the Android operating system as the client platform.
* The second project objective is to experiment with the combination of live video and virtually generated, overlaid imagery to enhance the ease of use and feature set of a robotics control system. This technology is commonly referred to as augmented reality.

To combine these objectives, the project aims to create a solution which allows two remotely controlled LEGO Mindstorm NXT 2.0 robots to share and interact with a simple virtual world which will be rendered in three dimensions and overlaid on a live video feed to be displayed to the remote operators. Users can connect to the system from smartphones anywhere where an internet connection is available, and use the robots to play simple virtual games supported by augmented reality overlays.

The following components of the proposed solution have been successfully implemented:

* Centralized server software which manages connections, propagates commands and messages, and records client state from Android clients (via standard IP) and Mindstorm NXT 2.0 robotics kits (via Bluetooth).
* Mindstorm NXT 2.0 Intelligent Brick software which supports duplex Bluetooth communication, remote execution of commands received from the central server, dead reckoning position tracking and error correction, and real time position and heading data transmission to the central server.
* Server side virtual world implementation which is capable of asynchronously updating robot positions, filtering client commands based on validity against the current game state, and generating outgoing robot commands to ensure physical robot movement does not violate the virtual game state.
* Real time video streaming from a USB webcam connected to the central server to Android clients using a custom UDP protocol.
* Android client software which supports OpenGL rendering of an incoming real time video stream, as well as rudimentary three dimensional graphics rendering (simple textured polygons).

The remainder of this report will detail the development methodology of the RoboWars project, and the technical specifications of the implemented solution. First, the requirements for the project will be discussed, as well as the engineering principles and development practices used to implement the proposed solution. Next, the technical details of the implementation will be discussed, followed by a discussion of the testing methodology employed and results obtained. Finally conclusions and recommendations for alternative implementations and further work will be presented.

# The Engineering Project (Steve Legere)

Doing this last...

# Background and Terminology

## Android (Steve Legere)

Android is a set of software which includes a mobile Operating System (OS), middleware, and required applications. Android is open source software (OSS), meaning the source code is freely available to the general public to use and modify so long as the licensing restrictions are adhered to.

### Operating System

The Android architecture is layered in four key categories: applications, framework, libraries, and kernel. An additional fifth layer, the runtime layer, contains core libraries essential in any application or program, as well as the Dalvic Virtual Machine (DVM). [sl1]

The Android core libraries allow the Java programming language to be seamlessly implemented and used on Android mobile devices alongside the DVM. DVM is a non-licensed implementation of the Java VM which was built for mobile devices; it is small, efficient and optimized for mobile devices such as the HTC Desire. [sl1]

The libraries included in the Android software development kit (SDK) are:

* Libc: Standard C library;
* SSL: Secure Socket Layer;
* SGL: Custom engine library for 2D images;
* OpenGL/ES: An engine library for 3D images;
* Media: Library which deals with all multimedia intents;
* SQLite: Deals with SQL databases, used for data storage;
* WebKit: Library for web-based applications, such as browsers;
* FreeType: Deals with images and vectors; and
* Surface Manager: Provides surface holders for various applications. [sl2]

Of the nine listed libraries, two were used extensively (OpenGL/ES and Surface Manager) and will be discussed in further detail in sections 8.1 and 8.2.

### Emulator

Android applications can be run either on the physical device or on the Android Emulator, which is shipped with the Android SDK. The main benefits of utilizing the Android Emulator are twofold:

* Integrates very well with the Eclipse Integrated Development Environment (IDE); and
* Eliminates a fair amount of “real-world” testing, as the application programming interface (API) is nearly identical to a physical mobile device.

Of course, there are some functionalities which even the Android Emulator does not implement, such as the built-in gyroscope of more modern mobile devices. This particular issue is covered in section 3.1.3 below.

### Additional Libraries

In order to properly test the tilt functionality of the Android mobile device without access to such hardware, an open source project by OpenIntents was utilized. As mentioned in section 3.1.2, the Android Emulator does not implement or support the gyroscope functionality which the RoboWars project has taken advantage of. Fortunately, OpenIntents has already solves this problem by implementing their own open source project – Sensor Simulator – which directly addresses this issue.

The Sensor Simulator project allows the designer to “simulate sensor data with the mouse in real time. It currently supports accelerometer, compass, orientation, and temperature sensors, where the behavior can be customized through various settings.” [sl3] As the API for this particular library is nearly identical to the API of the actual Sensor Event Listener class, modifying source code to use this library in place of its hardware counterpart is extremely easy and involves modifying only a couple of lines of code. [sl3]

## Lego Mindstorm NXT 2.0 (Michael Wright)

### Robotic Requirements

The robots required for Robowars were required to have 4 characteristics which were identified as crucial to the implementation of the project. These characteristics are: zero radius turning, to enable the playing of the “light-cycles” game mode. The second characteristic required independent wheel/motor control to avoid having to build a complex steering system. The third requirement dealt with a wireless communication ability which provided the means to have controls being provided from either a server or mobile device, as well as allowing the robot to communicate back to the server. Finally the last requirement involved robot side position tracking. Robot side tracking was deemed the most crucial of the requirements as should a packet be dropped coming from the robot to the server the model can still remain consistent. Had the server done the position tracking, and a packet had been dropped there could have been a model inconsistency which would render all usage pointless.

### Mindstorm NXT 2.0 Capabilities

The NXT 2.0 Mindstorm kits are the 3rd generation of LEGO Mindstorms. The kit consists of three main types of devices: servo motors, input peripherals, and the NXT brick. These devices, when working together alongside the LEGO bricks offers an almost limitless number of design possibilities. The NXT brick is a 48MHz microprocessor with 64KB of SRAM. It allows up to 3 servo motors and 4 input peripherals. The brick can be connected through a wired USB 2.0 connection or wirelessly over a Bluetooth 2.1. It also has an LCD screen and a speaker capable of 8Hz playback. The servo motors are motors controlled using on board tachometers. They provide up to 180RPM with 15N•cm torque[m1]. The peripherals included in the kit are: two touch sensors, a colour sensor, and an ultrasonic sensor. The sensor used in our design is the LEGO colour sensor. This sensor consists of three devices: a white flood light, an infrared colour reader and a RGB LED bank for colour output and reading. This sensor can read values in full 8bit RGB colour while countering for light saturation, and brightness to return the correct 0-255 RGB value as well, LEGO provides 6 pre-programmed colours: white, black, yellow, green, blue and red [m2].

### RoboWars Robot Design

RoboWars has built its own custom robots for this project. In our design we have used 2 servo motors to provide both drive and steering, balanced over a central steering column. These two servo motors can provide zero radius turning by having them spin in opposite directions. To ensure the robots are able to function as liberally as possible the design has added a gearing system with a 3.38:1 gear ratio. The robots communicate to the server over a custom built messaging protocol over a Bluetooth connection. The robots also have a front mounted colour sensor used to provide readings from the map to provide error corrections.

# Requirements (Alex Craig)

The RoboWars project was an original idea proposed by the project team, and as such no external client existed to participate in requirements elicitation. To ensure that the project scope and requirements were clearly defined requirement elicitation was performed within the project group, and the requirements were documented through the collection of use cases shown in Table 4.1. A complete use case specification was produced, which has been included as Appendix A. This document provides a detailed description of the actors which interact with the system, as well as a formal specification for each use case. In addition, use case realizations (in the form of sequence diagrams) were also produced for selected use cases to aid in early design work. These sequence diagrams are included as Appendix B.

Table .: RoboWars Use Case Names and Descriptions

|  |  |
| --- | --- |
| **Name** | **Description** |
| **Configure wired camera** | The server administrator selects the camera to use from a list of detected cameras, and configures the position, facing, and field of view of the selected camera. |
| **Display local video feed** | A live video feed of the “arena’ containing the remote robots is read from the attached camera and displayed through the server administration GUI. |
| **Reset robot positions** | The server administrator forces a reset of the robot positions in the system’s internal state. This should be performed if the system’s positioning information for a robot becomes out of sync with the robot’s actual position for any reason. |
| **Display simplified game state** | The server administrator triggers the display of a simple 2D rendering of the current game state which is visible in the server administration GUI. |
| **Register robot for remote control** | A remote robot connects and registers with the system. |
| **Unregister robot for remote control** | A remote robot unregisters from remote control and disconnects from the system. |
| **Update robot position** | A robot asynchronously updates the system to reflect its current position. |
| **Join waiting lobby** | A mobile client initializes a connection to the server. |
| **Send chat message** | A mobile user sends a chat message to be displayed to all other connected mobile users. |
| **Opt-out of robot control** | A mobile user who wishes to view rather than control the remote robots may choose to opt-out of robot control and become a pure spectator. |
| **Select game type** | A player selects the type of game to play prior to starting a new game. |
| **Pair play to robot for remote control** | A specific player is paired to a specific robot for the duration of a single game. Any commands from the player will control only the robot paired to the specific player. |
| **Launch game** | A player in the lobby initiates a game. The lobby is replaced with an augmented video feed, and players are paired to robots for remote control. Virtual gameplay begins. |
| **Display augmented video** | The live video feed of the camera overlooking the robot arena is combined with the internal game state representation to produce virtual elements overlaid on the live video feed. |
| **Move robot** | A mobile player issues a command for a robot to move, which is passed to the robot by the system. |
| **Fire virtual projectile** | A mobile player issues a command to fire a virtual projectile, which is created and simulated in the system. |
| **End game** | A game in progress is ended and all connected mobile users are returned to the game lobby. Any paired robots are freed and considered unpaired. |

# Overall System Architecture (Alex Craig)

The RoboWars system is designed as a centralized system, in which both robot and Android clients connect to a central server which manages the system state and propagates information between clients as required. The RoboWars system is distributed over three types of nodes:

**Central Server:** This node represents standard consumer desktop hardware, with the minor addition of a Bluetooth dongle to support communication with the Mindstorm NXT 2.0 robotics kits. A Model-View-Controller architecture is used to separate the main server application into three subsystems which are all deployed on this node. The controller subsystem is responsible for managing robot and Android client connections, broadcasting the real time video stream, managing the server lobby (which entails broadcasting chat messages, and launching / terminating model instances), propagating robot position changes to the model, and continually triggering physics updates to provide real time physics in the virtual world. The model component is dynamically constructed whenever a new game is initialized, and is responsible for storing the current game state (including virtual simulated entities), broadcasting state changes to the other subsystems, and filtering all client commands to ensure that virtual game state will not be violated by physical robot movement. The view component observes both the model and controller components, and provides an admin interface through which the server and camera settings are configured, the chat lobby is monitored, and the current game and client connection state is displayed.

**Robot:** The robot node represents a Mindstorm NXT 2.0 Intelligent Brick. Up to two connected robot nodes have been tested, although the implementation is designed to support an arbitrary number of robots. The robot client is implemented as a single subsystem which is responsible for local position tracking and remote execution of commands from the central server. Although the RoboWars implementation is designed with a custom Mindstorm NXT 2.0 client in mind, any Bluetooth capable robotics kit could be adapted to this purpose.

**Android:** The Android node represents any Android 2.2 smartphone. Up to two connected Android nodes have been tested, although the implementation is designed to support an arbitrary number of Android clients (including spectators who do not directly control a robot). The Android client is implemented as two subsystems: the Android client, and the game model (which is shared with the server implementation). The Android client subsystem is responsible for transmitting chat and control messages to the server, receiving and rendering the real time video stream, rendering OpenGL graphics, passing orientation and touch screen input to the central server, and receiving game state updates to be integrated into the model. The model subsystem is continually updated to match the current server state, and is used to determine the positions of entities for use with OpenGL rendering.

A deployment diagram demonstrating the distribution of subsystems among nodes is shown in Figure 5.1.

Figure .: A deployment diagram of the complete RoboWars system. Note that multiple instances of the Robot and Android nodes can be serviced by a single Central Server node.



# Server Implementation

The central server is the most complex node in the RoboWars system, and manages all communication flows between the Android clients and robots. See Appendix D for class diagrams of the server implementation.

## Controller - User and Robot State Management and Data Propagation (Alex Craig)

The central component of the controller with respect to user and robot state management is an instance of the ServerLobby class. ServerLobby is a passive class that is not concerned with any real time aspects of gameplay, but rather manages lists of references to instances of UserProxy and RobotProxy (each of which represents a connected client), and controls the launching and termination of real time gameplay. The ServerLobby uses an event model to allow any class which implements the ServerLobbyListener interface to receive events whenever a player or robot joins or leaves the server, whenever a chat message is received, or whenever a game is launched or terminated. In the current implementation, this functionality is used primarily to allow the view subsystem to display lists of connected clients and the server chat lobby.

To manage incoming Android client connections, the controller uses an instance of TcpServer, an active class which runs a separate thread to continually accept incoming TCP connections on a specified IP address and port. Whenever a new connection is received, the reference to the client’s socket is used to construct a UserProxy instance. Each UserProxy is an active object which runs a dedicated thread to continually read new messages from the client’s socket. Once a UserProxy is generated, a handshake procedure is carried out to ensure the version of the RoboWars client is compatible with the server. The client must also provide a unique username, and the client will be required to select a new username if the username is already in use. Once the handshake procedure is complete, the user is registered with the server’s main lobby. Users can interact with the server lobby by sending chat messages, changing the game mode, changing their own ready or spectator status, and initiating game launches. In addition, once the handshake is complete all further communication is achieved by sending serialized event classes rather than raw strings, and the UserProxy registers as a listener on the ServerLobby. In this manner, instances of UserProxy listen on the main ServerLobby instance, and propagate events to their respective clients. This could have been implemented without an event model (as the ServerLobby stores references to all connected instances of UserProxy and could call functions directly), but it was decided that an event model was preferable as an event model was already desired to avoid coupling with the view subsystem, and it is preferable if a standard communication path is used for both the view subsystem and instances of UserProxy.

Robot connections are handled similarly to Android clients, but rather than awaiting incoming connections, the server actively attempts to discover compatible Mindstorm NXT 2.0 clients within Bluetooth range. This is accomplished using the PC libraries of LeJOS (“Java for LEGO Minstorms”) [ac1]. The functionalities of LeJOS in general will be discussed further in Section 7 (“Robot Client Implementation”). LeJOS provides a simple interface to enable either Bluetooth or USB communication with Mindstorm NXT 2.0s running LeJOS firmware. First, an NXTComm object must be generated by supplying a static method of the NXTCommFactory class with a constant specifying whether USB or Bluetooth communication is desired. In the case of Bluetooth communication, the NXTCommFactory will automatically select a compatible underlying implementation from one of several supported libraries based on the underlying operating system. RoboWars has been implemented and tested exclusively on Windows, and in this case LeJOS will select Bluecove [ac2] as its underlying Bluetooth implementation. Bluecove is an open source library implementation of the standard Java Bluetooth API specified in JSR-82. However, the details of the underlying implementation are largely unimportant for the purposes of RoboWars, as LeJOS provides methods to write and read from Bluetooth using the standard Java input/output stream API once a connection has been established. It is worth noting that the Bluetooth discovery process blocks for a significant duration (approximately 5 seconds for each detected Bluetooth device), and the BluetoothServer class is implemented such that robot redetection always runs in a separate thread from the caller. Once a connection is established, a RobotProxy instance is created and registered with the ServerLobby. RobotProxy is similar to UserProxy in that it is an active class that continually reads the Bluetooth input stream to receive position updates from its associated robot. When a game is in progress this position information will be propagated into the game model, and robot commands will be propagated through the RobotProxy to its associated robot.

Once both instances of UserProxy and RobotProxy are registered with ServerLobby, a game can be launched. Game launch requests must be issued by an Android client, and a UserProxy propagates the request to the ServerLobby. The ServerLobby will ensure that enough (non-spectator) players and robots are registered for the selected game type, and will generate a new GameController instance to represent the new real time game. The GameController is an active class which generates an encapsulated instance of the game model, and runs a thread to continuously update the model’s physics implementation. Users are selected for pairing with robots by the ServerLobby (based on which users have been paired most recently), and the ServerLobby generates an instance of ControlPair for each pairing. ControlPair class is a passive class used primarily for data encapsulation which stores a reference to a single UserProxy and RobotProxy. Instances of ControlPair are registered with the GameController, and once all control pairs have been registered with the GameController additional players are added as spectators. When this is complete, the game is launched. This generates a ServerLobbyEvent which signals to clients that a game has begun and OpenGL rendering should be displayed.

Once game play has been initialized, instances of UserProxy send tilt vectors and button input to the GameController where the data is used to generate instances of RobotCommand based on the control scheme specified by game mode in use. These commands are validated against the game model to ensure that game state will not be violated, and are then serialized and written to the user’s paired robot through the RobotProxy reference contained in the instance of ControlPair. Whenever the model’s game state changes, the GameModel generates GameEvent objects which are captured by the listening GameController, and passed to all connected instances of UserProxy.

## Controller – Real Time Video Streaming (Alex Craig)

### Alternative Solution – RTP/RTSP Streaming

Ideally, the real time video streaming in the RoboWars should use an established and well defined protocol. The first attempts to implement video streaming in RoboWars made use of the Real Time Transport Protocol (RTP) for data transmission, and Real Time Streaming Protocol (RTSP) for control signals. This functionality is well supported by the standard Android library, which provides a MediaPlayer class specifically designed to receive and display and RTP/RTSP stream [ac3]. To test this functionality, the Android client for RoboWars was modified to make use of the MediaPlayer class to accept and display an RTP/RTSP video stream.

The server side generation of the RTP data stream was partially implemented using the “Freedom for Media in Java” (FMJ) project [ac4], which provides an open source implementation of the standard Java Media Framework API [ac5] for capturing, playing, and streaming media. JMF provided the means to easily generate an RTP data stream, but further investigation determined that alternate means would need to be used to implement an RTSP server to generate the required control signals expected by the Android MediaPlayer. Rather than continue with server implementation, the open source VideoLAN (VLC) project [ac9] was used to generate RTP/RTSP streams purely to test the Android client implementation.

Through this testing, it was determined that the capabilities of the Android MediaPlayer implementation were insufficient for the needs of the RoboWars project. Although the video stream could be reliably displayed, an unacceptable delay of approximately 10 seconds occurred between the transmission and rendering of the video stream. Further testing determined that the cause of this delay was the buffering behaviour of the MediaPlayer implementation. The MediaPlayer class is intended to be used for the streaming of relatively static media (ex. YouTube videos) rather than real time streams with low delay requirements. The implementation of MediaPlayer buffers video based on a fixed length of video, rather than data size, and does not provide any external API to modify this behaviour. Regardless of the resolution, encoding, or bit rate of the video stream generated by VLC the ten second delay on the client side remained constant. Further investigation of the Android source code revealed that this buffering functionality is implemented at the level of phone firmware. Modifications to the Android firmware would require that all users of RoboWars install custom firmware on their phones, and would limit RoboWars clients to phones that have had firmware specifically modified for RoboWars. This would have significantly reduced the generality and potential market for RoboWars, and as such further modifications were not attempted at the firmware level.

### Implemented Solution – Custom UDP Protocol

In order to provide real time video streaming with an acceptably low delay a custom protocol for data transmission was required. The use of the FMJ project to interface with the webcam was discarded (as the RTP stream generation was no longer required), and replaced with the simpler LTI-Civil library [ac6] (which is also used internally within FMJ). LTI-Civil is an open source library which provides a simple API for capturing images from video devices entirely independently of the JMF API.

Video streaming is implemented through two classes in the controller subsystem: CameraController and MediaStreamer. The CameraController class is responsible for storing the position, heading, and field of view of a specific camera, as well as opening and making available the instance of CaptureStream interface which is used to read images from the camera. The MediaStreamer class is responsible for discovering available cameras, maintaining a valid list of instances of CameraController, and maintaining a list of users that video packets should be served to. The MediaStreamer also provides methods to select an active camera from the list of CameraControllers, and methods to start and stop the active capture stream. The MediaServer is registered as a listener on the main ServerLobby instance, and automatically adds and removes users to its list of clients to serve whenever a user joins or leaves the main lobby. In addition, the MediaStreamer also receives game launch and termination events from the main ServerLobby, and the video stream is launched or terminating along with real time gameplay. Camera position information is attached to game launch events before they are transmitted to clients, ensuring that the position of the camera is known for OpenGL rendering purposes.

To serve video the MediaStreamer must receive a valid instance of CaptureStream from the active CameraController. At this point, the observer pattern is used to read frames from the webcam. MediaStreamer implements the CaptureObserver interface, which allows it to register as a listener on the active CaptureStream instance. Once the stream has been launched, the onNewImage() function of MediaStreamer will be called by LTI-Civil at a fixed rate (determined before the CaptureStream is launched).

Video is transmitted to clients as a series of individual frames encoded as JPEGs. The onNewImage() function of MediaStreamer receives frames from the webcam in an unspecified format internal to LTI-Civil which is converted into an instance of BufferedImage from the Java standard library using a static method of the AWTImageConverter class (provided by LTI-Civil). Once the frame is in BufferedImage format, a static method of the ImageIO class (from the Java standard library) is used to encode the frame as a JPEG and write the result to a byte array. This byte array is split into segments of a configurable size (set via a static constant in MediaStreamer), and each segment is packaged into a separate UDP DatagramPacket. Each packet carries three fields in addition to the video data payload:

* **Frame number**: Specifies which frame this packet belongs to. In the current implementation this field alternates between 1 and 0, as it is unlikely that an individual segment will arrive more than a full frame out of sequence (and carrying the next segment number expected by the client). Even if this does occur the frame will be discarded as corrupt when decoding is attempted on the client side, and a single dropped frame is unlikely to be noticed by the user.
* **Segment number**: Specifies which segment of the current frame this packet carries. This field starts at 0 for the first segment of each new frame, and is incremented by 1 for each packet sent.
* **Last segment**: A Boolean field which is set to true only on the last packet of a given frame.

These generated packets are transmitted to all connected clients through UDP unicast on a specified port (the main server TCP port incremented by 1). UDP multicast would be preferable for this application as it reduces the overall bandwidth requirements (as packets are duplicated as required at the network level rather than at the server), and this method was originally implemented. However, the HTC Desire smartphones utilized by the project for testing were determined to be incapable of receiving multicast or broadcast packets, and as such the usage of UDP multicast could not be properly verified. This shortcoming is not officially documented, but is well corroborated by other developer reports [ac7]. Although UDP unicast is less bandwidth efficient, its usage allowed for the project to test video streaming functionality and perform demos with the available hardware.

The Android video client only supports the decoding of incoming video frames, and does not exchange any further information with the server (over UDP). A byte buffer is generated, and the video data from each incoming packet is appended to the buffer whenever a packet is received that matches the next expected frame and sequence number. When a packet with the “last segment” field is received, the buffer is decoded into the standard Android image format using the BitmapFactory class provided by the Android standard library. This bitmap is then passed to the OpenGL renderer to be loaded as a texture. The client’s buffer is cleared and the expected incoming frame and sequence numbers are reset whenever a new packet is received with a segment number of 0 (indicates the first segment of a new frame).

## View – Administration Panel and Camera Configuration (Alex Craig)

The administration panel uses standard Swing libraries to provide a GUI for the administrator to configure the server. The main frame of the administration panel is implemented in the AdminView class, which subclasses JFrame. The AdminView class implements ServerLobbyListener and listens for events from the main ServerLobby instance to update the connected user/robot lists and the main chat panel. The AdminView also contains a reference to the BluetoothServer instance, which is used to manually trigger robot redetection. This was originally implemented as a periodic function that did not require administrator interaction, but the period redetections were found to interfere with communication with robots during gameplay. The AdminView also generates an instance of CameraSelectionView which contains a reference to the MediaStreamer instance, and allows the administrator to configure the camera settings for the server.

## View – 2D Display (Alex Dinardo)

The 2D display (contained within the class Admin2DDisplay) is meant to provide a simple 2D visual representation of the current state of the game and virtual world. It is a JFrame with just a Canvas as part of its content pane. GameEntities are drawn on the screen using the same coordinate system as the model; only it is always scaled to 500 pixels squared no matter the size of the actual game arena.

Java graphics allow for easy drawing of polygons with vertices as inputs, which works well with the model as GameEntities already represent their shape as an array or vertices.

The 2D display class implements GameListener, so every time the game state changes in any way, the canvas is redrawn and displayed, showing any change in position of any GameEntity.

## Model - Virtual World Model Implementation (Alex Dinardo)

### Architecture

The server model is the backend of the server. There are two basic classes that handle all basic functionality of the modeled virtual world. All data concerning the virtual representation of the robot and the associated virtual entities are stored within an abstract class called GameEntity. Its main purposes are to store the entity’s x and y location as well as its heading, as measured from the positive x-axis, exactly the same way position is stored on the robot client. It also stores the 2d polygonal shape of the entity, represented as an ArrayList of x and y coordinates relative to the central position of the entity. The shape of the entity not only serves as something to draw with on the 2D display, but more importantly it serves as the bounding area of the entity for which the collision detection system is concerned with. The large majority of its methods deal with collision detection, the mechanics of which is explained later in the section.

Position tracking and related functionality are common between different types of entities, but as for specific behaviours and entity states, subclassing is required. Currently, there are three types of GameEntities: GameRobot, Projectile, and Obstacle, each one with its own special fields and methods that dictate its behaviour in the virtual world.

All game logic and game state checking are performed by the abstract class Game Model. It is the top level class of the model and it is the only one the Controller has access to. The architecture is such that abstract superclass contains all the base methods that its subclasses as well as the controller will need to access, while the subclasses that are actually instantiated represent the game type that was selected, and as such, implement the specific behaviour and fields required of that game type. There are currently three game modes (and subclasses of GameModel by the same name): Tank Simulation, Light Cycles, and FreeTest.

### Use of Java Event Model

It is necessary for the higher levels of the system to know when certain events happen within the model, for example when a robot fires a projectile, a collision is detected, or when the game is terminated. Thus, much like how the ServerLobby utilises event passing to manage robot or client connections and chat messages, the event model is used here to let the controller know when critical events happen in the currently running game.

Specifically, classes that need to listen to the GameModel implement an interface called GameListener. Two classes currently need to listen to the GameModel: GameController and the Admin2DGameView.

One final application of note is how the method of event passing is used with the android client. Since the client is meant to have a local copy of the model content, the controller must have a way to pass the server model to the client every time the game state is changed. Using the event model, a reference to GameModel is always passed with every event that is generated. Thus, passing every event along the network provides the client with an updated GameModel every time it is changed.

### GameEntities and 2D Collision Detection

Every virtual world object, or GameEntity, has x, y and heading values to denote its position on the map. These values are conglomerated into a class called Posture. Additionally, an array of x and y values denote the vertices of the polygon shape relative to the map origin (they are supplied to the constructor relative to the Posture for easy visualisation of the shape, and then are compensated for the map origin). This polygon shape is used as the bounding area for collision detection.

How detection works is first the x and y differences between values of different vertices on both polygons, effectively giving the line segment vectors of the polygon’s “edges”. Then for each edge on both polygons, project both polygons on the perpendicular axis of that edge. If at any point during this loop that the projections on a given axis don’t overlap, then the two polygons are not colliding. Only if the loop finishes and all projections overlap, is there a collision.

Compensating for rotation about the Posture is another challenge. Since the vertices are stored relative to the origin, temporarily relocating the Posture to the origin is needed. Then the x and y coordinates of the Posture are changed into polar coordinates r and θ to easily rotate the vertices about the origin. Each θ value is incremented by the amount needed, and then each vertex is changed back to rectangular coordinates and moved back to the original position of the Posture. Thus, the shape appears to have rotated by the degree value supplied.

### GameRobot and Server Side RobotCommands

GameRobot has special functionality in the model. In addition to behaving as any other GameEntity, it also has the added function of storing a RobotCommand, which the GameController would access to see if it would have any priority over RobotCommands issued by the client.

Sometimes the model generated RobotCommands override the ones form the client, such as when the robot collides with a virtual Obstacle. The GameModel would set the STOP RobotCommand in the GameRobot that collided with the wall. In this case, if the client wishes to move the robot forward, the model would not allow it because it is made so that the robot would not be allowed to pass through walls.

Other times it is the client generated RobotCommands that should override the ones form the model. An example of this is in the LightCycles game mode, where the default action of the robots would be the MOVE\_CONTINUOUS command. When no other command from the client is present, the robot would execute the model generated command. When the client sends a left or right turn signal, then in that case the client generated command would override the model command.

### Android Incompatibility with Lejos Pose

It used to be that GameEntities used the Lejos class Pose to store x, y, and heading. It was believed that using the same position tracking data structure between the robot, server and client would reduce the need for adapters between modules. However, it was found that Pose makes a reference to the Java AWT class Point2D, and that Android does not in any way support or recognise the Java graphics library, which causes fatal exceptions to arise. This problem was detected very late in the final stages of module integration, so a quick, but feasible solution was needed.

The Pose class was already tightly integrated in all aspects of the system, but all that was needed was to get rid of the java.awt.Point2D reference. So class Pose was copied over into a new custom class called Posture, and the Point2D reference was replaced with a much simpler custom class called Vector. Other than a few minor changes to make Posture compatible with the system all that was needed was a few line changes to change the Pose objects incoming from the robot into new Posture objects for the server and Android client to understand.

## Logging (Alex Craig)

RoboWars makes extensive use of the Apache Log4j open source logging library [ac8] in order to aid with debugging and performance testing. This carries a number of advantages over console logging, including:

* All logging statements are tagged with the thread identifier of the thread which initiating the logging, the class name of the class which initiated the logging, and the current system time (in milliseconds). This data is very useful to have in a standardized format when debugging and acquiring performance metrics.
* Up to 6 independent levels of logging are supported (TRACE, DEBUG, INFO, WARN, ERROR and FATAL), each of which can be configured separately.
* Logging configurations are modified through a configuration file which is read at runtime. Logs can be directed to console or file, and these settings can be set independently for each logging level (by default, RoboWars logs DEBUG messages to file, and INFO and ERROR messages to both console and file). Suppressing log output can be done through runtime configuration, rather than modification of source code.

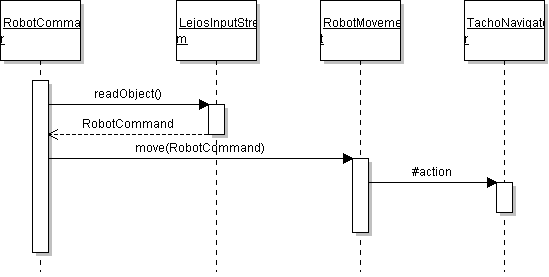
# Robot Client Implementation (Mike Wright)

## Client Implementation

The robot client is a rather simple structure. It consists of many classes running independently. They are as follows:

* RobotMain: The main class which is used to initialize the RobotCommandController and the listener for key Interupts.
* RobotCommandController: Robot Command Controller acts as the main thread. It has the main representations of RobotMovement and ColorSensor, further more it contains the thread which will periodically return the position of the robot. RobotCommandController’s main purpose is to receive incoming objects and call the corresponding functions in RobotMovement or ColorSensor see figure 6.1.
* ColorSensor: The class used to generate and posess the RobotMap used to correct the errors through movement. In this class is where the error correction color reads are done and handled
* RobotMovement: This is the thread safe access point for the RobotCommandController to access the navigator classes , it simply forwards the commands onto the navigator through calling the correct methods in a safe manner.
* PositionTracker: This class simply returns the robot’s pose on a periodic interval through the LejosOutputStream and then returns to sleep.

Figure .: How commands are received.



## LeJOS and Modifications

### LeJOS

Lejos is an open source firmware to provide a JVM which can be embedded on microcontrollers, thus allowing the microcontrollers to be programmed in Java. Originally started in 1999 providing the firmware for devices which were sent to the international space station in 2001 Lejos has continued to grow. Since 2006 Lejos has be focused to the LEGO RCX and LEGO NXT bricks as its primary target microcontrollers. Lejos features a large API as well as a vibrant community which is still active on a daily basis. Furthermore it features a large number of tutorials and reference materials to allow easy development. Although this seems ideal there were many occasions where there were inconsistencies which required major modification, which will be expanded upon in the following sections

### Bluetooth Communications and I/O Modifications

Lejos provides by default an effective handshake system as well as a means with which to provide input and output through subclasses of the Java input and output streams. Lejos also boasts the ability to provide Object passing over these input and output streams. Unfortunately these boasts are unfounded; although a potential system was started it was never fully implemented. Thus a new system was required to be implemented to allow object passing. From this new implementation LejosInputStream and LejosOutputStream were born as well a new message protocol scheme was implemented.

#### LejosInputStream

LejosInputStream is used to receive and decode packets sent over the server to the robot. It receives a byte stream over Bluetooth (or any other inputstream), which it records into a byte array. This array is then converted into a plain text string. The plain text string is then decoded and new objects are created and returned. This input stream though is unable to decode all objects only those which are used in RoboWars (RobotCommand, RobotMap, Vector <Color>, and Pose).

#### LejosOutputStream

LejosOutputStream is used to decode and transfer objects to and from the robot. All objects which can be sent and decoded successfully over the two streams have a function which returns a designated output string in the correct message format. This string is then converted into byte representations of the text. From there the newly formed Byte[] is transferred a byte at a time using the standard OutputStream.write(Byte b) function in java.

#### RoboWars Message Protocol

In RoboWars we have implemented a message protocol to allow the transferring of particular objects over LejosInput/OutputStream. At the moment 4 objects can be sent over the protocol: RobotCommand, RobotMap, Vector<Int>, and Pose. They turned into transferable objects by calling the corresponding toOutputStream function. The message protocol for each object is as follows:

* RobotCommand: [<type>|<speed>|<turnbearing>|<special flags>|<pose>]
* RobotMap: [[MapPoint0],[<x>|<y>|<color>],….,[MapPointN]]
* Vector<int>:[<r-value>|<g-value>|<b-value>|<saturation>]
* Pose: [<x-cooridinate>|<y-coordinate>|<heading>]

### Navigation and Piloting Modification

Lejos by default provides a system to track position and heading of the robot in multiple ways. The main two tools used are the HiTechnic sensor compass paired the lejos CompassNavigator class or using the onboard tachometers in each servo motor coupled with the lejos Tachonavigator class. Due to the hardware available to the project we were required to use the tachometers embedded in the servo motors to our positioning. These navigators were used to provide high level position tracking as well as act as the access point to the Pilot class which actually operates the motors. As the project progressed there became a series of issues and challenges that needed to be overcome and corrected. They are identified and explained in this section.

#### Blocking on a steer() Call

In order to implement the rolling turns that are provided to the robot from the server as a representation of the movements done by the telephone we were required to use the steer function provided by lejos. The steer function was designed to have the servo motors rotate with varying degrees of power dependant on a provided ratio. This ratio was from [-200,200] with 0 being drive directly forward, and ±200 being a zero radius turn in either direction. There was a crucial error though in the TachoPilot implementation of steer. The Pilot and all threads would block whenever a non-zero value was provided to steer. This was caused by the default TachoPilot was doing comparisons between the provided float values and hard coded integer values on its branching decisions. This issue resulted in the code driving itself into an infinite loop as it tried to calculate the actual turn ratios this issue was overcome by modifying the hard coded values to reflect the true types of inputs provided. Thus the RoboWarsTachoPilot was born. By correcting this issue the robot was now free to operate in an 180o field as required for the LightCycles game mode.

#### 360 Degree Controls and Tracking

One of the two game modes that are implemented for the project it TankSim. TankSim is a simulation as if the robots acted as tanks thus the robots needed to be able to go forwards backwards and any way in between. Unfortunately the code provided in the PilotClass used to drive the motors was only capable to drive the robot in a 1800 range thus not allowing the ability to travel backwards. To overcome this issue a new steer function was implemented which was able to account for the throttle provided by the user. Should the throttle be a value less than zero the parity bits for both servo motors were flipped causing them to rotate in the opposite direction. This allowed for 360o motion and actions to be performed by the robot. There was an unintended consequence of this change though. The position tracking system was not designed to operate in a 3600 environment, it considered everything forwards. Thus resulting in a complete failure of the tracking, caused by two main components:

* The robot no longer knew what way was up: As it had no frame of reference for which way was forwards (usually provided by the parity bit) the robot would always assume that it was travelling forwards. To overcome this UpdatePosition function in SimpleNavigator had to be rewritten to account for the parity of the motors in reference to their original state.
* On a context switch from forwards to backwards the position information would become non-sensical: This issue was caused by other functions that would call UpdatePosition before the change in parity could be taken into account. Thus causing the robots to believe it had turned very far angles (>4000) even though the robot would only track from ±1800, furthermore the robot would lose track of where it was causing the (X,Y) co-ordinate to be meaningless. To overcome this whenever a context switch occurs the pilot is reset and then told where it is. Thus it believes that it started at that point and has travelled no distance at all.

## Position Tracking and Error Correction

### Position Tracking

RoboWars robots use dead reckoning to figure out its location. Dead reckoning uses a starting location and a displacement for the robots to be able to figure out where they are. This is performed by the Navigator classes provided by Lejos, they are used to update the Pose representation of the robot (x co-ordinate, y co-ordinate, and heading). The default system also does not take into account for the geared wheels so the displacement functions in SimpleNavigator had to be rewritten to overcome this difference. The displacements are based off of degree turns of the internal tachometers for each servo motor, and are then converted into units provided by the user, based off the provided dimensions of the robot’s wheel diameter. In our project the units are all based in cm.

### Error Correction and the Grid

As the robots move about the world errors are introduced into the position tracking. Although we have tried to make this as small as possible it is impossible to remove all errors. At the moment there is a drift of ±2mm in either direction as well as a shift of ±2o on the heading per 30cm travelled. Although this is small it is still an issue that needs to be overcome. Despite our grandest efforts there is no way to conclusively correct the heading error if our tracking system is based off of tachometer rotation due to wheel slippage.

#### The Grid

To correct this, a complex system was created to track the robots with in a world. This system is known as the grid. The Grid is a grid of dots with 1.5cm diameter in varying colors placed on the game mat. This is a real world representation of an onboard RobotMap that the robot generates based upon inputs provided by the server or as the default setting. When a robot using its colour sensor drives over a dot and detects its colour the robot will determine where the nearest dot of that colour in the correct direction is and adjust its position accordingly. This “Snapping” action snaps to the location of the center of the robot not the sensor, so this generated value is generated by the Robot using basic trigonometry.

#### Future Suggestions

Due to technology available at the time, we have not been able to create a perfect tracking system. Yet alternatives to our design have been devised should there be a chance to improve upon it. These suggestions are as follows:

* Heading Correction: At the time we started there was not the budget to get the HiTechnic Compass sensor. In any future designs the robots should be equipped with such a sensor the heading error becomes 0. This will help in both the position tracking but also the snapping action done by the colour sensors as they use the heading during trigonometry.
* Digital Correction: When we began certain technologies were not released yet. The main important one would be the Microsoft Kinect. The Kinect projects an RGB grid. If we were able to project a similar grid on the game mat we would be able to get perfect position tracking using similar methods as are currently implemented[mw3].
* Gradient Colour Scheme: Due to the means available to us we are unable to implement this idea in its fullest. By making the grid into a colour gradient we would be able to get the correct position based off the RGB value read by the sensor. Because of the sensitivity we would be able to get an absolute position but will still be unable to correct the heading error.

# Android Client Implementation (Steve Legere)

## Android Libraries and Application Layout

### Android Libraries

As mentioned previously, the two main libraries utilized in this project (on the client side) are the OpenGL/ES library and the Surface Manager library.

#### Surface Manager

Android’s surface manager is quite elegant in that it does not draw directly to the screen buffer, but rather forms the entire screen layout before drawing anything at all. In doing so, the developer has much more flexibility in terms of implementing graphical/visual effects such as transparent windows and transitions.

There are many built-in view layouts, such as a RelativeLayout, LinearLayout, and TableLayout, all of which were utilized in the RoboWars project. All of the layouts support all of the built-in widgets, and are very easy to understand, implement and use.

#### OpenGL/ES

The OpenGL/ES library shipped with Android is extremely useful, versatile and relatively well-documented. Although support specifically for OpenGL/ES is slightly more difficult to find than other Android documentation, OpenGL/ES conforms to the OpenGL 1.5 standard, which is very well documented and widely used. Section 8.2 discusses further detail about OpenGL/ES.

### Application Layout

The layout of the RoboWars Android application is relatively simple. The majority of the view components and characteristics are stored in an XML file; this approach keeps the source code clean and simple, and at the same time improves reusability. The remainder of the classes are generally models, for storing data, and controllers, for handling user input. Below is a list of classes and a brief overview of their functionality and purpose:

***Views***

* RoboWars.java: This is the main application class that is loaded and executed when the Android application is run. Its purpose is to identify the view (in this case, the file main.xml), handle tilt functions, and to make calls to OpenGL methods to render 3D objects on to the screen. It also inheritably handles basic user-device interaction, such as touch screen events, button presses, and so on.
* ImageStreamView.java: A relatively simple class which is used for displaying a bitmap image (sent from the MediaClient) updated in real time. Essentially the surface holder for live video feed.

***Controllers***

* TcpClient.java: An active class which handles incoming information from the application server, as well as sending out updates of the current models. All critical information is sent via serialized objects over the input/output stream; non-critical information, such as chat messages, are sent as UTF-encoded Strings.
* MediaClient.java: The MediaClient is responsible for handling incoming UDP packets regarding the live video stream. Its sole purpose is to handle these packets and to reconstruct the video feed.

***Models***

* LobbyModel.java: Keeps track of all users and robots in the lobby, as well as all chat and game events, which are displayed in the chat interface.
* ClientGameModel.java: Keeps track of all game entities and the state of the current game. This includes players, various obstacles, projectiles, as well as locations, life, ammunition, etc.

***Passive***

* Player.java: Used to store in-game player information, such as their name. Used by the ClientGameModel.
* User.java: Used to store out-of-game player information, such as name, ping, flags, etc. Used by LobbyModel.

***OpenGL***

* OpenGLRenderer.java: A custom OpenGL renderer class which takes a particular Mesh (see below) and renders it on to the OpenGL view (set up in RoboWars.java).
* Group.java: A simple storage and access class to manage a group of Mesh objects (see below).
* Mesh.java: A super class which can be implemented to form any type of 3D polygon. Used to map vertices, textures, and indices, and defines how to draw the object. Also controls the position and the rotation of the object.
* Cube.java, Plane.java: Polygon classes which have extended the functionalities of

## OpenGL Rendering

OpenGL/ES is a cross-platform API that renders both 2D and 3D graphics on embedded systems. Theoretically, any OpenGL program created under the OpenGL 1.5 standard (or earlier) should work in OpenGL/ES, therefore there exists plenty of documentation for OpenGL/ES that is relevant to mobile developers. [sl4]

Rendering 3D objects in OpenGL is relatively straight-forward, yet takes some time to learn and adjust to. An OpenGL drawing starts as a set of vertices, which define the corners of the polygon. Next, a set of index triplets are supplied; these define the order in which to connect the vertices. When texturing is enabled, another set of indices must be supplied, these ones relative to the polygon and not an absolute coordinate system. Once the shape of the polygon is defined, it must be placed and rotated. It is easier to think of the OpenGL surface as moving and not the actual polygons; placing a polygon at (0,0,0) will place it exactly where the previous polygon was placed. Further, once one polygon has been rotated and placed, all subsequent polygons will retain the same rotation. This is due to the fact that the polygons are not being rotated at all, but the OpenGL surface is.

## Development Issues and Solutions

### Android Emulator

Two prominent issues with the Android Emulator came up, both during implementation and during testing. The first, and most easily handled, was the fact that the Android Emulator has no built-in gyroscope emulator or stub. As the RoboWars mobile application depends on the tilt controls for steering during a session, either the application needed to be tested on a physical mobile phone, or an alternative software solution was needed. After some research, an open source library, named SensorSimulator, was found and used. Not only was this library very well documented, it also turned out to be very easy to implement into any existing project. Assuming source code already exists in the project which uses the hardware gyroscope, only a couple of lines of code require modification in order to switch between the SensorSimulator and the actual hardware gyroscope. The application, as seen in Appendix X, allows the user to control the tilt of the phone along all three axes through a software interface. The application communicates with the RoboWars project through a TCP connection, so information transfer was not an issue, as it was already fully implemented and working.

The second, and more prominent issue regarding the Android Emulator, is the way it handles the OpenGL interface. Unfortunately, the emulator only draws the very first frame of an OpenGL scene, which means that none of the rendering or moving of objects can be tested over the Android Emulator. Unfortunately a solution was never found for this problem; the remainder of OpenGL testing was done through actual Android hardware as opposed to the emulator.

# Testing

## Robot Client Testing (Michael Wright)

As continuing with the projects modularity the client can be identified into two sections, the I/O streams that are connecting the robot to the server and the code to run the robots. Both systems have been given the means to be tested the testing is as follows:

* IOTest.java: This script runs a simulation to check that the LejosIn/OutStreams are able to successfully encode and decode every type of object that is used in communication for RoboWars matches.
* TestColourSensor.java: This script is used to check if the Colour sensor is still working properly. ColorSensor in RoboWars can be run in test mode where it returns the read and these reads are output on a server screen. Unfortunately this output must be approved by a human oracle.
* KeyController.java: This script is used to check that the robot is moving correctly. It acts as an interface to run all commands used by RoboWars over Bluetooth. The movements must be verified by a human oracle as there is no way to assert that the correct movement occurred programmatically.

## Android Client Testing (Steve Legere)

The Android client was tested mainly through the use of the Android Emulator software, and later via physical mobile devices. During the first half of the project, in testing various elements of the design of the Android application such as scrollbar functionality, button presses, and basic user interaction, it was crucial to take advantage of the Android Emulator; this allowed for quick, easy and efficient testing of the application’s interface without any prior knowledge or experience in Android application development. <expand further>.

## Server Side Testing (Alex Dinardo)

There are two types of testing as far as the server is concerned. One involves testing the internal mechanics and ensuring no bugs are present there, the other type relies on integrating the disparate modules of the system together and ensuring that all signals passed between them are compatible with each other.

### Unit Testing (Alex Dinardo)

Unit testing takes on several different forms in the server. For the controller, that aspect is covered by extensive unit testing on the server lobby functions. Those functions include: checking that chat message event was received properly, proper registration of robots and clients, proper game set up and termination, and so on.

Classic unit testing can only go so far however. In the case of the collision detection model, in order to have exhaustive testing of the algorithm one would need to have as test input every possible combination of entity shape, number and order of vertices, permutated by all possible positions and rotations of the two entities in question.

A much more feasible, if not as precise way of testing is to instantiate and run the model independently of the controller (create a stub of the controller to simulate the signals the model needs) and to manually control the virtual entities at the keyboard to test the basic cases of collision detection.

The reasoning behind this method of testing is that the collision detection does not have to be perfect. Spending the time to design an extremely precise test framework is too expensive because all that is required is that collision to be detected when two polygons look somewhat too close together. If it is plausible that two polygons should collide to the naked eye, and it is indeed colliding according to the test, then the test is a success.

### Integration Testing (Alex Dinardo)

Integration testing is putting the whole system together for full system testing and working out the faults that arise between modules. At this point, all internal functionalities are working correctly.

This type of testing was found to be most useful with revealing flaws not with the system itself, but rather the problems to do with the referenced libraries. For example, only when the whole system was put together did the problem with Android not accepting java.awt arise. As well as the problem with the steer function in Lejos.

# Conclusion (Mike Wright)

Through rigorous work we have completed the project based upon the original specs and recommendations. We believe that we have successfully implemented a system that provides an intuitive means to control robots using a general purpose mobile device. We have been able to achieve these goals through implementing centralized server software which manages connections, propagates commands and messages, and records client state from Android clients (via standard IP) and Mindstorm NXT 2.0 robotics kits (via Bluetooth). Furthermore Mindstorm NXT 2.0 robots were configured to support duplex Bluetooth communication, remote execution of commands received from the central server, dead reckoning position tracking and error correction, and real time position and heading data transmission to the central server. A Server side virtual world implementation which is capable of asynchronously updating robot positions, filtering client commands based on validity against the current game state, and generating outgoing robot commands to ensure physical robot movement does not violate the virtual game state. To enable long distance robotic control real time video streaming from a USB webcam connected to the central server to Android clients using a custom UDP protocol was successfully implemented. Finally android client software which supports OpenGL rendering of an incoming real time video stream, as well as rudimentary three dimensional graphics rendering (simple textured polygons) was created to support our mobile goals. While implementing these features we were able to overcome many challenges. These challenges were made easier through our rigorous design phase as well as the modularity of our system. Furthermore we were able to validate our results through rigorous testing criteria with the goal of having both 100% code and functionality coverage. Through completing this project we have been able to evaluate situations where the current system could be improved but due to time, budget or scope constraints we were unable to implement these lofty goals. These include the recommendations for improvements in the position tracking of the robots, <Improvements to steve’s section>, and <improvement to dinardo’s section>. Should these steps be implemented we feel there would be a much more effective system.

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# Appendix A – Schedule Gantt Chart

# Appendix B – Use Cases

# Appendix C – Use Case Realizations (Sequence Diagrams)

# Appendix D – Class Diagrams