

Design of an embedded data acquisition and display system using a
modular approach



Beau Trepp

Electrical, Electronic and Computer Engineering

University Of Western Australia

A thesis submitted for the degree of

Bachelor of Computer Science/ Bachelor of Electronic Engineering

2011 November

Abstract

The topic of electric vehicles is becoming increasingly popular due to rising fuel costs and growing concern over emissions. Despite this attention, most electric vehicles have little or no telemetry systems, making many aspects of their operation and efficiency a mystery.

The aim of this project was to develop an extend-able system in order to capture various data-points that can be available in a vehicle, as well as an interface to display this data inside the car. The design developed differs from traditional embedded systems by being completely modular. It uses existing network protocols to allow the system to be distributed between various smaller embedded components. This will enable it to be easily extended, should the need for more data-points arise, and allows the use of many smaller systems to be implemented incrementally, rather than one expensive monolithic design.

In order to help facilitate robustness and code re-use, a windowing toolkit was also developed. This provides a common platform for user interaction, and defines pre-built components in order to speed up the design and implementations of the user interface.

By exposing and recording more data, deeper analysis can be done on the efficiency of the car, and help justify different technological improvements to the vehicle. The higher granularity of data acquired can also be used to analyze the economy of the vehicle in different conditions.

Acknowledgements

During work on this project, I received help from many people whom I would like to thank.

The members of the gumstix and ZeroMQ mailing lists who helped me with issues regarding compilation of both code-bases.

Ian Hooper who helped with work on the vehicle, and provided knowledge into the construction of the vehicle.

Jonathan Oakley who showed helped me with understanding the safety issues regarding driving the car, and for showing me the routes used to performance test it.

The maintainers of the open icon library, for the images used in the project.

To my supervisor Prof Thomas Brunl for the opportunity to work on the project and vehicle and for guidance during the project.

Kevin Vinsen, for looking after the REV project while Thomas was on sabbatical.

Finally I would like to thank all the members of the REV Team, for providing assistance and support throughout the project.

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Glossary

| | | | |
|---------------|--|--------------|--|
| ACK | Network Acknowledgment | Linux | Open source operating system developed by Linus Torvalds |
| ACSII | American Standard Code for Information Interchange | LSB | Least significant byte/bit |
| ARM | Microprocessor manufactured by Arm holdings | MSB | Most significant byte/bit |
| BMS | Battery Management System | NACK | Negative Network Acknowledgment |
| C | Low level programming language | OOP | Object Orientated Programming |
| C++ | Extension of C that supports OOP | PC | Personal computer |
| CPU | Central Processing Unit | PNG | Portable Network Graphic |
| CSV | Comma Separated Value | PPM | Portable Pixel Map |
| FPGA | Field programmable gate array | Qt | Windowing toolkit developed by Nokia |
| GPS | Global Positioning System | RGB | Red Green Blue |
| ICE | Internal combustion engine | RGBA | Red Green Blue Alpha |
| IMU | Inertial Measurement Unit | RPM | Revolutions per minute |
| IP | Internet Protocol | RS232 | Standard for serial communication |
| IPC | Inter Process Communication | TBS | Manufacturer of industrial electronics devices |
| Kernel | Central component of operating system | TCP | Transmission Control Protocol |
| | | TTY | Text terminal |
| | | UI | User Interface |
| | | UML | Unified Modeling Language |
| | | USB | Univeral Serial Bus |
| | | ZMQ | Zero MQ |

GLOSSARY

1

Introduction

1.1 The REV Group

The Renewable Energy Vehicle project aims to explore the use of electric engines in vehicles in place of the traditional internal combustion engine. This can provide many benefits; including helping remove societies dependency on oil and reducing emissions from personal transportation. The Hyundai Getz is designed to be a substitute for economical cars. This car is designed to fit into the daily driver market. This market needs smaller cars, with short range but cheap running costs, as well as being enjoyable to drive.

1.1.1 Motivations

Many factors motivate research into electric based vehicles. The two most prominent are the emissions of traditional vehicles and the continuing rise in cost of fuels.

1.1.1.1 Pollution

Electric vehicles are advantageous over traditional ICE vehicles as they operate with zero emissions while operating . These vehicles have no exhaust, so therefore have no emissions. While this does not make them completely pollutant free, it does help limit and control the emissions being produced by the act of transport. It is important to remember when discussing electric vehicles that the components must be manufactured using industrial processes and the act of generation electricity. This does not making

1. INTRODUCTION

them truly carbon neutral, but helps limit the sources of pollution. It is much more easier to manage the pollution produced from one power plant, than that from thousands upon millions of vehicles.

1.1.1.2 Rising Fuel Prices

Public concern over rising fuel prices has also sparked interested in electric vehicles. As the vehicles do not consume traditional fuels directly, and use a cheaper source of power, they become attractive to those trying to save money. This has created consumer demand for this mode of transport, triggering research into the efficiency and effectiveness of said vehicles.

1.2 Hardware used

1.2.1 Vehicle used in this project

The vehicle that this project will be developed for is a 2008 Hyundai Getz. This vehicle contains a 39kW electric motor (1). To power these motors, batteries have been installed resulting in a providing a total of 13kWh of power. These batteries are protected by the use of an EV Power Battery Balancing System (2). This system balances the charge contained in each cell, and prevents the individuals cells from under or over charging.

1.2.2 Embedded Controller

An Eye-bot M6 embedded controller is the platform that all software developed in this project will run on. This controller contains a Gumstix board with a 400Mhz PXA255 processor that uses the ARMv5TE instruction set (3). This runs a version of busy-box linux and has also had libraries developed by the University of Western Australia to access a Xilinx FPGA and a Samsung LTE430WQF0 touchscreen (4). This hardware is no longer supported by the manufacturer, and as of writing the kernel is a few years old (5). This hardware is currently installed in the vehicle.

1.2.3 Battery Monitor

The battery monitor is currently installed in the car also. It is a commercial product manufactured by TBS electronics (6). This device is able to read the voltage charge and current of the battery cells installed in the vehicle. It will interface with the embedded controller via a RS232 serial link. It transmits all the information automatically over the link every one second (7).

1.2.4 GPS

GPS works via the concept of resection. This is a mathematical concept that can determine the an objects current location relative to 3 or more other locations (8). There are many satellites in the sky which transmit signals received by a GPS unit. By calculating the intersection of 3 or more spheres, each centered at a different satellite, the unit is able to calculate its current position on the earth. Once positional data has been obtained this can be compared against other values such as time, in order to calculate distance. This information can also be interpreted to calculate the distance the vehicle has traveled over arbitrary intervals.

1.3 Technological concepts

1.3.1 Threading and Process

Having a program complete multiple tasks at once is a must for modern day systems. This is usually achieved through two methods. The first method is threading, in which a single program will have multiple "threads" accessing the same memory. The other technique is daemons, or individual processes, in which each concurrent aspect of the system will be handled by a separate program.

1.3.2 Messaging

Communication between devices can often be abstracted to the use of messages. There are two ways of dealing with messages, the two methods are called broker and broker-less (9) . In this project a broker-less model will be used.

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1.3.2.1 Brokerless

The broker less method allows each component to connect directly to any other component. There is no centralized "broker" to send messages to. This provides extra resilience as there is no single point of failure. A open source implementation that supports the broker-less method is called ZeroMQ (10). It has many different internal models and supports communication over TCP/IP.

2

Aims of the project

2.1 Final Aim

The Ultimate goal of the project is to developed a distributed system for use in an automotive environment. This will culminate into a completed system, provided data logging functionality and a user interface to view the live data.

2.2 Goals

The goals this project aimed to achieve were set out as follows.

1. Investigate the use messaging protocols inside a minimal embedded systems
2. Develop GPS capability
3. Develop Battery monitor capabilty
4. Integrate this data into a user display
5. Log this data to be reviewed later

During development, the author also kept the following goals in-line, to make the system easier to develop for. This was done to give the software a better chance of being developed further by future projects on this topic.

1. Allow the system to be easily extend-able
2. Attempt to minimize future exposure to concurrency

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3. Use simpler individual designs, to make it easier for engineers (as opposed to programmers) to modify
4. Develop standards for inter-module communication
5. Develop common UI elements to facilitate ease-of-layout and interface design.
6. Develop the system in such a way that it is portable to other devices. The hardware used is slightly older, and the system will be developed in a way that it can be ported across to new hardware.

3

Literature Review

This section discusses similar work that has previously been undertaken. The vehicle that is the basis for this project has been worked on for the past few years. Many solutions to the various problems have been developed. This section will examine the strengths and weaknesses of each project, so the strengths can be applied to the new design.

3.1 Getz Graphical User Interface

In 2009 a student named Jurek Malarecki performed work on the Getz (11). This is documented in a report called *'Getz Graphical User Interface*. The objective of the project was display information that had been partially completed in previous work.

Malarecki opted to store all the user data in one structure. This contained all the variables in one element. This would have allowed for all the variables to be easily accessible, but has many obvious dis-advantages. There is very little separation between the functionality of different components, they all occupy a similar space in memory. This makes it very easy for the data to be changed by any aspects of the program, either accidentally or maliciously. This also presents the problem of synchronization. If locking is used on the whole structure, it prevents the other variables from being updated when an unrelated variable is updated.

Malarecki implemented basic map functionality using a tiling technique. This splits a map up into different smaller "tiles" which can be loaded individually. Malarecki converted the images to PPM format, which is supported by the Eyebot, but is a very

3. LITERATURE REVIEW

rare file-format today. This can cause problems as conversions will always need to be conducted to get PPM format files. This becomes an extra step in obtaining map files. Malarecki also used lookup tables in order to determine which image to display in order to determine which image to display. This involves scanning a text file for co-ordinates that correspond to the current position. This technique would have problems as the time taken to find a image will increase as the total number of images is increased. This gives the method an $O(n)$ complexity at best. This is problematic as if the world was stored in the map data, it would take very long to load any image.

External storage was utilized to overcome the small storage capabilities of the Eye-bot. This enabled virtually unlimited storage possibilities to be used. This idea allows much a larger scope of maps to be stored and displayed, and also greatly increased the logging duration possible with the system.

The use of tiles and external memory is the strong points of Malarecki's design. Other aspects of the program, while functional, were not optimized to their full extent. This would result in instability due to bugs, and a larger than needed time to load map data.

3.2 Renewable Energy Vehicle Instrumentation: Graphical User Interface and Black Box

In 2009 Daksh Varma completed a project entitled '*Renewable Energy Vehicle Instrumentation: Graphical User Interface and Black Box*' (12). This project developed systems for the Hyundai Getz featured in this project, and another vehicle, a Lotus Elise. This project focused on developing user interfaces and logging functionality for both vehicles.

The system for the Getz was implemented on the current hardware installed in the vehicle. Varma implemented everything using C, rather than experimenting with more complicated languages. This code was very much tied to the current hardware configuration of the car, and is not functional with the unknown hardware changes that have occurred to the car since 2009. This highlights an interesting point, even though Varma had created a functional system, changes that happened after his system was deployed had large negative effects. Changes that were not under Varma's control,

3.2 Renewable Energy Vehicle Instrumentation: Graphical User Interface and Black Box

caused the system to crash and hang. This decreased the acceptance and view of the system.

Varma used the FPGA present on the board to interface with the digital outputs available. This implementation would produce the fastest speed, but has some problems. Due to differences in the hardware revisions of the eyebot, several eyebots require different drivers for the FPGA. This means any code developed would require the correct drivers, which can be difficult to maintain. It also greatly ties the program to the eyebot platform, which limits future expansion to other machines.

For threading Varma used the timers that were implemented in the RobiOS libraries. These would cause functions to be called at periodic intervals. Varma discussed the use of locks in order to protect shared variables. This of course did make the system complicated. Locking variables in thread's, if not implemented correctly, has a chance of causing deadlocks. This can cause the program to never respond to user input. The use of timers also restricts the ability of implementing the code on platforms that do not run RobiOS.

When developing code for the Lotus, Varma separated front-end and back-end functionality. This separation was a good idea, as it helped provide robustness. The use of two programming languages allowed Varma to leverage the strengths of each individually.

When implementing the maps functionality in the Lotus, Varma created the whole of Perth as one giant image. This would make the code simpler to maintain, as there is no complicated image swapping that needs to be performed. However this greatly limits the usability of the map system developed. The giant map image would need to be replaced manually for driving the car in different locations. It would also consume more ram than is necessary, as the whole image is always in memory. The map system develop also has no support for zoom, leaving the display stuck at the one size.

Varma's system was functional and performed its tasks well. It suffers from a very rigid design, that is not very expandable. While a good technique of separating the user interface and the backend functionality was implemented for one vehicle, it was not done for the other. There is no indication why this was the case. Varma's system implemented functionality not seen on other cars, and improved the experience for the driver.

3. LITERATURE REVIEW

3.3 Development of a User Interface for Electric Cars

In 2010 Thomas Walter undertook a project names '*Development of a User Interface for Electric Cars*'. This project was concerned with developing a user interface for the Lotus Elise.

Walter implemented the interface by using a windowing toolkit named Qt. This toolkit is available for all major platforms, such as the windows operating system the project was developed on. Qt provides a large array of elements that the designer can use to lay-out the interface. The use of this framework would make development easier, and the final product more stable.

Like Varma in 2009, Walter continued the ideal of separating the user interface from the back-end of the program. This helped diagnose problems with the system, and provided increased flexibility in development.

Walter heavily relied on the use of an Object Orientated language in order to implement his system. This abstraction made it easier to identify what each classes functionality was, and makes the overall system design easier to understand. This also tied in well with the use of Qt for the user interface, as Qt is written in an Object Orientated Language.

Network logging was an interesting feature added in Walters project. This logger enable the system to log data via an Internet enabled server. This logger functionality takes into account the unreliable nature of the connection used, and stores unsent messages in a queue if communication is lost.

Walter provides a solution to the problems with the map system used in Varma's project. Rather than storing the map in one giant file, Walter uses a technique called tiling. This technique breaks the map up into many smaller images. By knowing the current location, the relevant images can be loaded and displayed. This reduces memory consumption, as only the active tiles are displayed, and allows the system to expand to other locations.

Walter's design utilized abstractions and data structures in order to provide a more expandable system. This enabled the system to adapt to changes in location, and problems with the network. These two features are highly desirable, and would be welcome additions to the system installed in the Getz.

4

System Design

4.1 Distributed Design

The system design developed is a distributed system. This means all that all the components of the system are isolated from each other. They are able to run independently, and can developed separately. In order to share data between different components of the system, a protocol is developed using the ZeroMQ messaging framework to transmit the data between components. This also helps separate the user interface from the design, which benefits the development of both sections (13).

4.1.1 Isolation

The main motivation for developing the complete system as a distributed system is isolation. Each component is isolated from the code in other components. This isolation property brings numerous advantages to the system design.

The first advantage is that each component of the system can be developed independently. As the code for each component is separate, the component can be developed at different rates, even completely different developers. This can be used to speed up the development, and debugging process, as individuals do not need to worry about conflicts created due to changes they may make.

Another advantage of the isolation property is robustness. As each system component is run, it consumes it's own space of the operating systems memory. This space is protected from interference by the operating system. No other running process will

4. SYSTEM DESIGN

be able to manipulate its contents. This protects the process as errors in other components cannot affect this process. If any process were to hang, or exhibit unexpected behavior, its effects will be isolated to the process that caused it. This provides stability in the final system, as an error in one component will still allow all the other components to function correctly.

4.1.2 Distribution of Components

Another advantageous property of the distributed system is that each component can run on isolated hardware. The entire system can be spread among many devices, or just the one. This property allows for increased flexibility in the allocation of resources. If the current hardware is unable to support all the components at the same time, extra hardware can be purchased to take some of the load. Due to the design, the displaced components will not need to be re-compiled or modified in order to run on the new hardware. The displaced components will only need to be installed and configured to communicate with the existing hardware.

By allowing flexibility in the layout of hardware, the system can be simply expanded in future. Hardware requirements can be much more flexible, allowing older slower hardware to be supplemented by newer components, rather than replaced entirely. This will save costs in development of the system.

This property also has advantages for debugging the system. Components can be run on other devices, such as the machines used to develop them. These machines can also use the network protocol to communicate to the existing system. This allows utilities to simulate the functionality of components, see Appendix E, which greatly simplifies the task of debugging the system.

4.1.3 Simpler Component Architecture

As the system uses individual processes for each component, development does not require extensive knowledge of threading. Threading and synchronization is complicated. It is hard to analyze and debug multi-threaded programs, as any variable may be changing at any time. This architecture removes threads, as concurrency is provided by running multiple components in isolated processes. This greatly simplifies the design and debugging of each individual component, which results in a more stable and faster developed system.

4.2 Network Protocol

As each component cannot access the memory of any other component, a protocol was developed to facilitate communication between different components. This protocol is transmitted using the ZeroMQ layer, which exists on top of the standard TCP/IP network layer. This library was used as it has been developed by a larger group of developers than this single project, and as such will implement more functionality and have more robustness than could have been developed in the time-frame for this project.

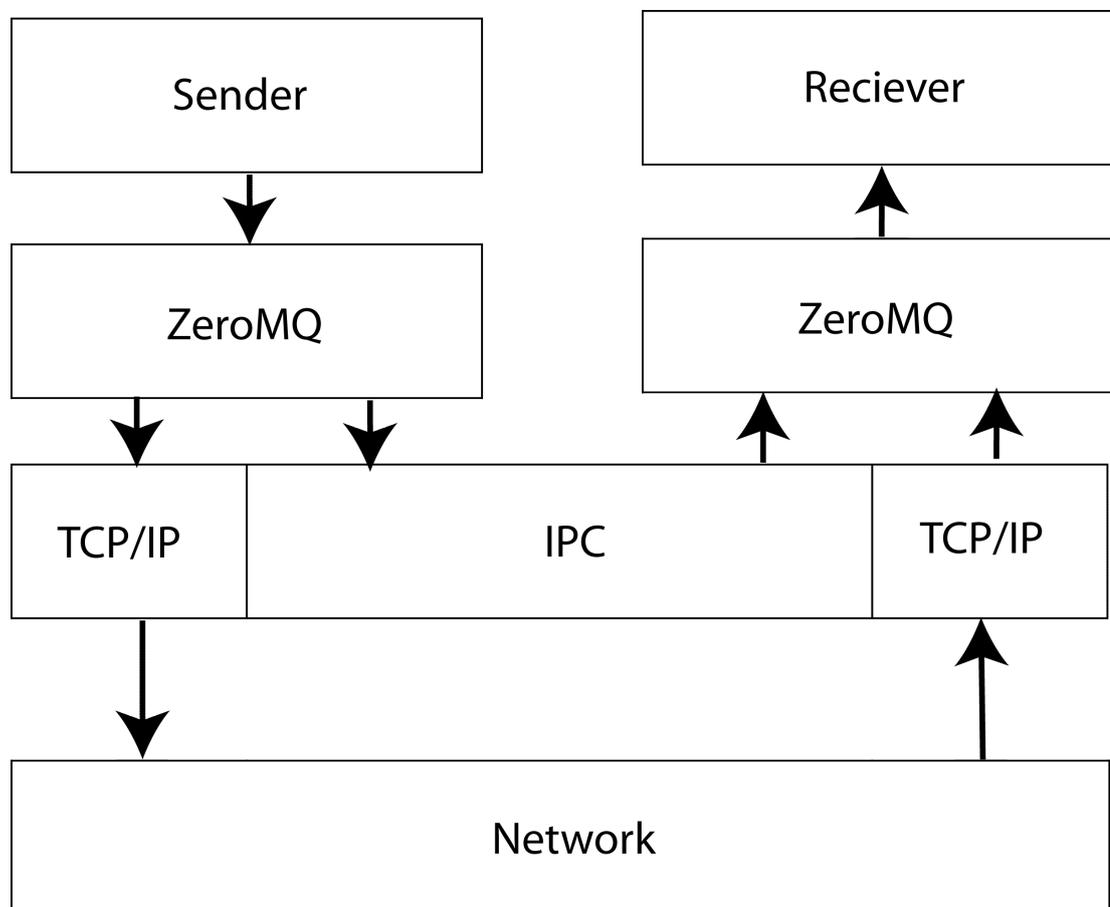


Figure 4.1: ZeroMQ layer in network topology -

Figure 4.1 shows the ZeroMQ layer with respect to the application and network layers. It illustrates how ZeroMQ exists between the applications and the TCP/IP layer. ZeroMQ can also be used to communicate without using the network, however both applications must be running on the same device. This gives performance increases, as

4. SYSTEM DESIGN

it does not transmit the messages onto the network.

4.2.1 Messages

The ZeroMQ layer transmits all information as messages, as opposed to the standard networking design or streams. Figure 4.2 shows the difference between these two methodologies.

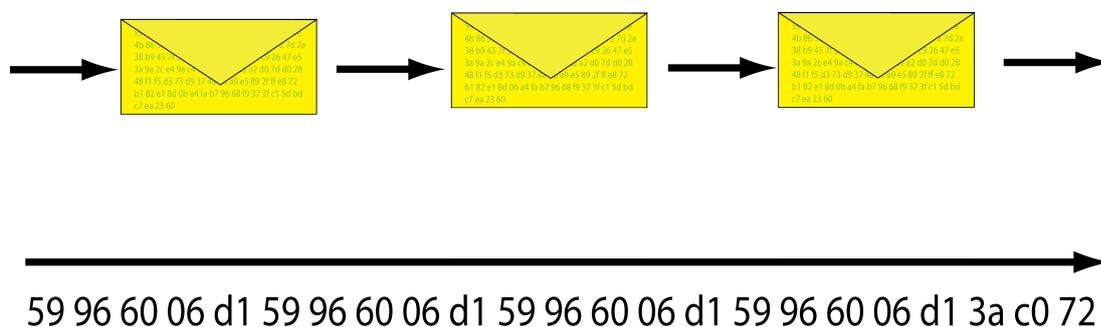


Figure 4.2: Messages Vs Streams of Data -

TCP transmits data as a stream, it is stored and then read from a buffer on the receiving end. This method of transmission makes it hard to synchronize where the data stream has begun. Assumptions must be made as to the position of the currently received byte in the stream. While the nature of TCP does provide some guarantees as to the start of the stream, a careless error in reading the length of the message could result in the program believing the wrong location is the current one. This can cause instability in the program, as the data would be interpreted incorrectly. This can either occur via accidental, or malicious means, such as a buffer overflow attack (14).

A ZeroMQ message differs from a TCP stream as it is a bounded element of data. A message is received in full when it arrives. This allows the entire message to be processed, and removes concern about missing data that may still be on the network. It is important to note that the TCP issues still exist over the ZeroMQ layer, as ZeroMQ runs on-top of the TCP layer. It is still theoretically vulnerable to these issues, but these problems can be prevented by different programming techniques. As these protections exist in this layer, there is no concern with implementing them, and the layer can be used in multiple projects, simplifying development time.

4.2.2 Publish-Subscribe model

The system developed will use a publish subscribe model. Each component will publish data, that any number of subscribers can listen to. This simplifies communication as there are no ACKs or NACKs to worry about. Each publisher can have an infinite number of subscribers listening. This is taken care of by the ZeroMQ layer, so the development of the publisher is unaware of how many subscribers exist. Figure 4.3 shows an illustration of this.

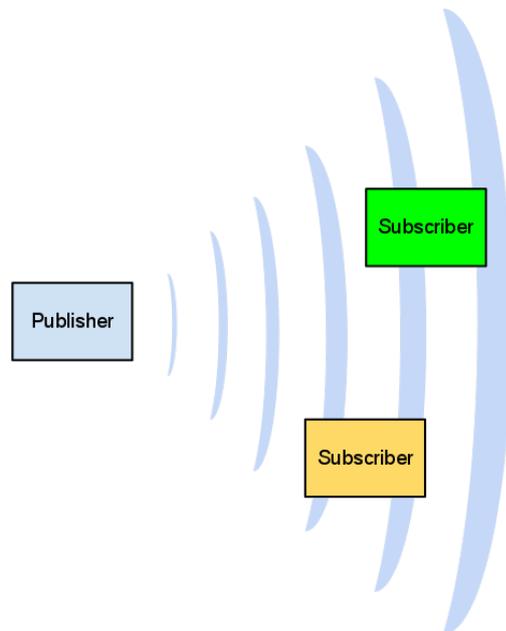


Figure 4.3: Publish Subscribe Model - This diagram shows a publish subscribe model of communication. The publisher is unaware of the subscribers and has no code to deal with them, simplifying transmission

4.2.3 Description of Network Protocol

As the system communicates via messages, no synchronization is needed in order to sync the sender and receiver. The protocol is thus a standard ordering of bytes that can

4. SYSTEM DESIGN

| | | | | | | |
|---------------------------|--------|--------|--------------|-----------------|---------|----------|
| Byte 1 | Byte 2 | Byte 3 | Byte 4 | Byte 5 | | |
| Header | | | | | | |
| Filter | | | Minor Filter | Revision Number | | |
| Byte 6 | Byte 7 | Byte 8 | Byte 9 | Byte 10 | Byte 11 | Byte ... |
| Data Payload | | | | | | |
| Meaning depends on filter | | | | | | |

Table 4.1: Network protocol for the distributed system

be used to identify different messages from each other. Table 4.7 shows the meaning of each byte.

Each message is started with a 5 byte header, followed by a variable length data payload. The formatting of the data inside the payload depends on the individual message being transmitted. The header consists of a 3 byte major filter, a single minor filter, and the revision number of the protocol. As the major filter takes up 3 bytes there are over 16 million possible unique messages, see equation 4.1. This is more than will ever be needed, however it provides a 3 byte way of identifying messages. This is useful for inspecting the bytes, as it is easy to remember 3 unique numbers and differentiate between them.

$$\begin{aligned}
 \text{UniquePossibleMessages} &= \text{Possible values of a byte}^3 & (4.1) \\
 &= 2^8 * 2^8 * 2^8 \\
 &= 16777216
 \end{aligned}$$

After the major filter is a minor filter. The purpose of this filter is to differentiate between subsets of the same component. If a component wishes to perform some form of processing on the data, or to transmit its message in a different format, it can specify a minor filter to use. This differentiates the two different messages, but groups them logically as coming from the same source.

The last component of the header is the revision number. This is used to break compatibility with older programs. Whatever component is receiving the messages will only process messages that have a compatible revision number. When a component has a major change in the structure of it's messages, it will increase the revision number

transmitted. This will cause any other components expecting the older revision to not accept the new version. This helps avoid errors, as the old receiver will not misinterpret the new message, it will ignore it and record an error.

4.3 Error Logging

All components of the system will log any errors or unusual occurrences so they can be examined and the causes investigated. There are many different methods that can be utilized in order to log this data. The simplest is to allow each daemon to create its own file to log to. This method is simple to implement, but can become difficult to manage. Code must be written in each module to record the error messages, which requires time and effort to debug. The files that the system is logging to must also be managed, as there is only finite space available on the device.

As all components of the system will be run on Linux, a much more elegant solution exists to solve this problem. A set of standards was defined for logging data from programs. This method is commonly referred to as "syslog" (15). These logging mechanisms are native to most Linux installations, they exist on the platform the device is running on. There have been implementations of syslog on Linux, Unix and BSD platforms. Syslog separates the logging functionality from the code of the program, which helps simplify development of the program. It has been developed by many contributors over many years (15). This makes it much more robust and scalable than any logging system that could have been developed for this thesis.

The added advantage of using syslog is that it has been developed to also work over a network. A Log device can log messages to a Log collector that is running on a different device. This provides a good synergy with the system design. As the logging of each device can take place on one central device, making it easier to check the log files for any errors.

All the components developed in this project use the `syslog.h` file which is a part of the standard C libraries. There is no special libraries required to utilize the functions required to log to the system logger. By default the log messages are stored in `/var/log/messages`. The resulting log messages contain information about the process that created the message, the time it occurred, and the contents of the message itself.

4. SYSTEM DESIGN

This allows the log files to be filtered for specific circumstances, helping track down errors that may occur in the system.

4.4 GPS Module

4.4.1 Hardware

A vital part of the data logging and user-interface of the software is finding the cars current location. This is done by the use of a off-the self GPS unit. Currently the system is using a Qstar usb equipped GPS receiver. This receiver operates at a rate of 10hz , though it can be set to operate at a slower frequency of 1hz. For the purposes of recording positional data, along with estimating the vehicles current speed, the unit should run as fast as possible. The extra precision is useful for the data-logging aspect, with no negative effects on the user-display aspect.

The GPS device can be enumerated as a standard serial port. This is beneficial as it can be used on any device that has the correct drivers and a available usb port. As it appears as a normal serial port, it can be queried using standard system routines. This allows the program that reads the device to operate any custom knowledge of the device it is connected to, aside from the serial parameters to make the connection.

4.4.2 Drivers

While the Eyebot M6 has hardware usb support, it was not immediately compatible with the GPS sensor. Various versions of usb-serial drivers where tried each with their own problems. The main cause of this difficultly was the out-dated Linux kernel being run in the system. This was kernel version number 2.6.17 and was released in 2006, which is 5 years old as of writing (16). This was a major cause of incompatibilities, as the GPS receiver was manufactured a significant time after this kernel was written. The drivers had no clue as to what the usb product keys were, nor the specific quirks that the devices may have had.

The first driver attempted was the generic usb-serial driver, included as a kernel module in 2.6.17. This drivers success would mean that the sensor and program could be easily installed in just about any machine running Linux. The driver would have matured after the 2.6.17 kernel, and newer kernels would have support by default. This

is beneficial to the system as it would require the least amount of configuration and setup if the GPS program was set to run in a different machine.

Sadly this driver did not perform correctly with the GPS device. While the driver was able to be loaded into the kernel without any errors, it caused problems when trying to associate with the GPS. The device uses extra features, which were unsupported by the generic driver. This caused strange symptoms in the operating system. The main symptom of an incorrect driver was the generation of the `/dev/ttyUSB0` device. This availability of this device implies that a `tty` is available to read/write from. Due to the incompatibility of the driver, this serial port would never report any bytes to be read, which is why it is unsuitable for use with this device. Customizing the generic driver to support this device would be unfeasible because it is unlikely that newer versions of this driver would support the device. This leads to the situation that if the GPS program is ported to a different machine, a custom version of the generic usb serial drivers would have to be ported as well.

As the GPS device did not work with the generic serial drivers, alternative drivers were investigated in order to support this device. Experiments indicated that this device was automatically detected and loaded in a newer kernel. This functioned correctly and was able to communicate with the GPS device at the full rate of 10hz. The driver used by this kernel was called `cdc-acm`. Further investigation showed that this driver could be included as a kernel module for the gumstix platform.

This driver was not immediately compatible with the device. This was because the device was manufactured after the kernel . As such the driver did not recognize the manufacturer ID and product ID of the GPS. The driver was then modified to include this information and re-deployed to the eye-bot. This was successful in creating the virtual serial device inside `/dev`, and also in allowing data to be read from this device.

While the `cdc-acm` driver was able to be loaded and functioned, it still contained errors. If the system was under intense CPU load, the program may not run quick enough to remove all the data from the serial port buffer. This would cause the operating system to throttle the port. Examination of the driver source code reveals that new information is dropped while this driver is throttled. This is acceptable behavior in this instance, however this driver had a race condition. If the TTY was throttled under certain conditions, it would be unable to unthrottle later on. This cause the TTY to drain its buffer and never accept any new data from the GPS even if its buffer

4. SYSTEM DESIGN

was empty. The driver was further modified to include spin-locks, a primitive kernel locking technique, in order to prevent this situation. The driver is now able to run for extended periods of time without locking up, enabling a reliable GPS reporting mechanism to be developed.

4.4.3 Design

Development of the GPS reporting component was done in C. This was chosen as it is a relatively low level language, with wide support. It is simpler to understand than more complicated object oriented style languages. This makes it a good choice for the GPS reporting mechanism, as it only has to do one task. In order to ensure that the code can be easily modified by future programmers, the structure of this program is simple. It runs in only one-thread, aside from the back ground ZeroMQ threads, and thus requires no concurrency management.

4.4.3.1 Initial Design

This first iteration of this code used blocking ports and read a single byte at a time. This was the style used to match existing examples (12). This was a functional design however it did lead to some problems. One problem with this approach was excessive throttling. The process would be woken up every time one character could be read, and would only remove one character from the buffer, even if there were hundreds waiting. This is a bad situation, as the process will continually be awoken to do trivial work. This steals cpu-time from another process, and caused the program to appear sluggish. This design was also in-sufficient as blocked the process while attempting to read from the port. This would cause the program to appear to hang if no data was available. It made it difficult to diagnose errors with this program.

4.4.3.2 Final Design

The design was refined in order to support bulk-reads and non-blocking operation. This fixes the two problems with the first approach. Rather than reading one character at a time, the program now reads as many as possible and stores the information into it's own circular buffer. This allows the serial port to be purged as quickly as possible. It also has the added feature of allowing the program to decide how to discard messages

| | | | | | |
|--------------|--------------|-----------------|-----------|----------|--------------|
| 47 | 50 | 53 | 0 | 0 | 01 |
| Header | | | | | Data Payload |
| Filter | Minor Filter | Revision Number | Fix | | |
| 4E1FE968 | 00000000 | C1FFD54D | 42E7A1F1 | 43B40000 | 41200000 |
| Data Payload | | | | | |
| Time(s) | Time(us) | Latitude | Longitude | Bearing | Speed |

Table 4.2: Network protocol for GPS daemon

in the case that it cannot keep up with the GPS. Figure 4.4 shows the program flow of the final design.

4.4.3.3 Network Protocol

Table 4.2 shows the protocol for the GPS message when transmitted over the network. The protocol uses a binary format instead of an ASCII based one. This reduces the space/data transmitted over the link, which helps reduce cost and improve speed. The motivation for ASCII based protocols is that control characters can be used to help synchronize the data. As this design uses ZeroMQ in order to manage the flow of data, such control characters are unnecessary. All values are transmitted in network order, this is big-endian order so that the most significant byte is transmitted first.

4.5 TBS Module

4.5.1 Hardware

The most important external device used in the user interface and data-logging aspect of the software is that of the battery monitoring module. The car has 45 Lithium Ion batteries installed, and it is useful to monitor the charge, current and voltage of the battery cells at all times. The system that the monitoring software runs on is not a highly reliable embedded system. It requires a few minutes to start up, and consumes too much power to leave running all the time. As such a different device is used to track the health and charge of the batteries. This device is a e-xpert pro battery monitor manufactured by TBS electronics. This is a commercial unit which increases the reliability of the data that it produces. Unlike the eyebot, it is powered as long as

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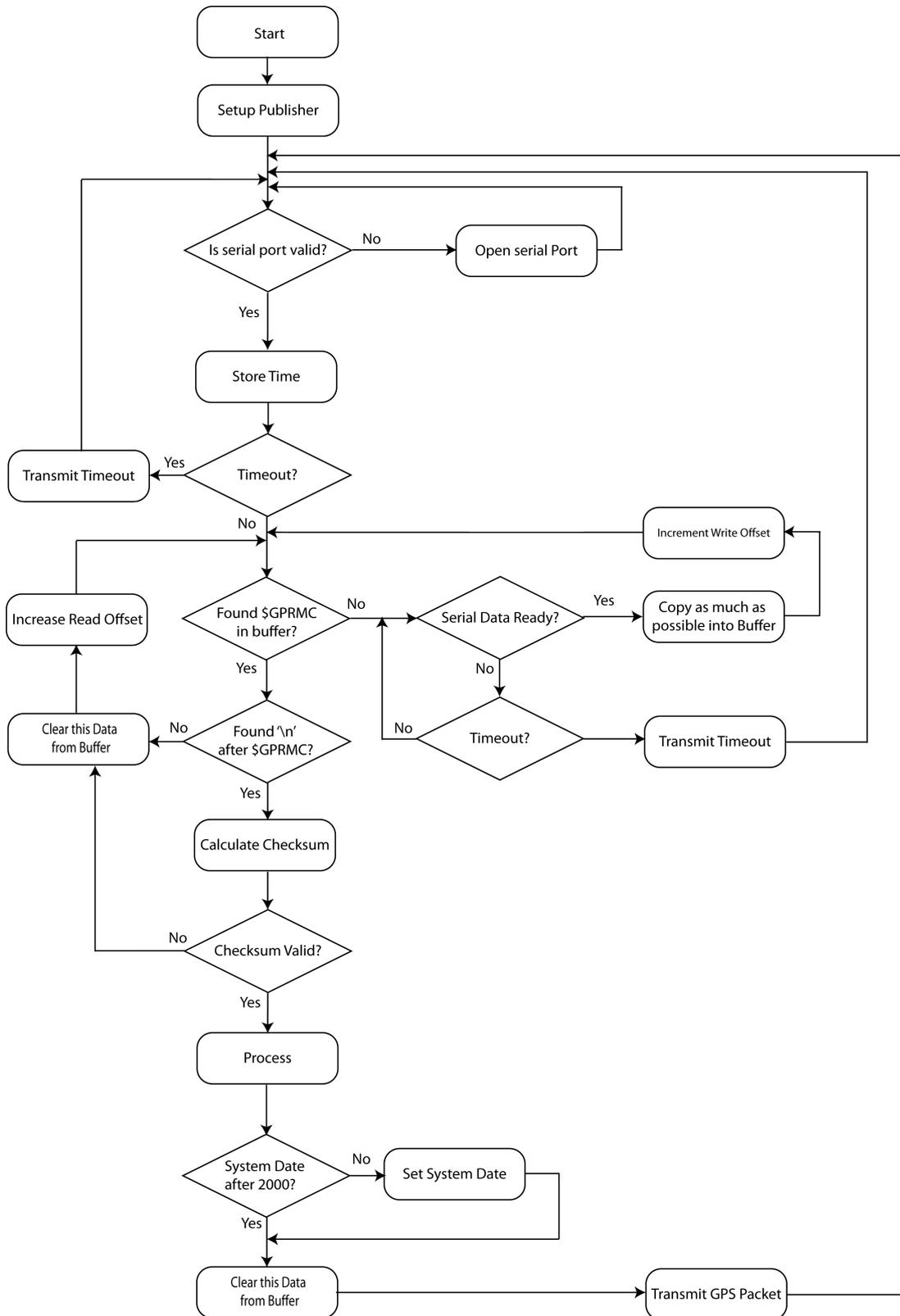


Figure 4.4: Flow chart of the GPS daemon -

| Property | Value |
|--------------|-------|
| Baud Rate | 2400 |
| Data Bits | 8 |
| Stop Bits | 1 |
| Parity | Even |
| Flow Control | None |

Table 4.3: Connection settings for Battery Monitor

the cells in the car remain energized, so it will always log and monitor the health of the batteries.

4.5.2 Expert protocol

The e-xpert device has a set protocol that it uses to communicate with other devices. It uses a RS232 connection over a 9 pin plug. This is a common way of communicating with external modules, and the eyebot has a serial port available to communicate with the e-xpert pro module. The module communicates using asynchronous communication. It automatically sends out updates at a rate of 1hz(17). These updates contain all the information that is recorded by the e-xpert pro module. As the communication is asynchronous, this will happen automatically, even while the eyebot is not connected. This is not a problem as the e-xpert pro does not expect a response. This mode of operation is referred to as broadcast mode in the e-xpert documentation (17).

4.5.2.1 Destination and Start Byte

The message data that the module outputs is transmitted via serial. The first byte in the message is the start byte, in order to identify this start byte as the start byte it must be unique and never occur anywhere inside the payload. This is done by reserving the most significant bit (MSB) to be one only if it is a start or ending byte. The documentation refers to this bit as the IDHT (Identify Header Trailer) bit. This does mean that there are only 7 bits available in each byte for transmitting data, but guarantees that the start and end of messages can be synchronized. As the first bit is a one due to the start byte being the header, the value of this byte is greater than 0x80. The rest of the bits in this first byte are the destination address. While communicating

4. SYSTEM DESIGN

| Property | Value |
|-----------------|-------|
| Battery Voltage | 0x60 |
| Battery Current | 0x61 |
| Amphours | 0x62 |
| Charge | 0x64 |
| Time Remaining | 0x65 |

Table 4.4: Hexadecimal values of different TBS messages

with a PC in broadcast mode, these bits can be ignored (17). The module also will not know where it is sending the byte, it is in broadcast mode, so there is no destination address. Thus the destination address bits will be 0, so the first header byte is always received as 0x80.

4.5.2.2 Source

The next byte transmitted is the source address. This byte is not a IDHT byte, so the MSB will always be 0. The device installed in the car, "e-xpert pro" will always set the source address as being 0. Combining this with the IDHT bit results in the second byte always being hex 0.

4.5.2.3 Device ID

The third byte in the message is the device ID. This is a unique number that identifies the type of equipment being used. This number is set by the manufacturer to distinguish different devices in its product range. For the case of this product, the "e-xpert pro" the device id is 0x22.

4.5.2.4 Message Identifier

The e-xpert pro module transmits a variety of messages, which can be categorized into three groups. These different groups are handshake, commands and data. In broadcast mode, handshake and command messages are not required in order to extract information from the battery monitor. Table 4.4 shows the hexadecimal values for different messages.

4.5.2.5 Data

Following the message identifier is the actual payload of the message. This can take on various forms, but in the most simplistic sense is a number spread across a few bytes. Figure 4.5 shows the data layout for the battery voltage message. For more information about the different values, see "e-xpert pro communications interface specifications" (17). Due to the MSB of each byte being reserved, it is only possible to transmit 7 bits of data inside a byte, any value that requires more than 7 bits to be represented must be transmitted across multiple bytes.

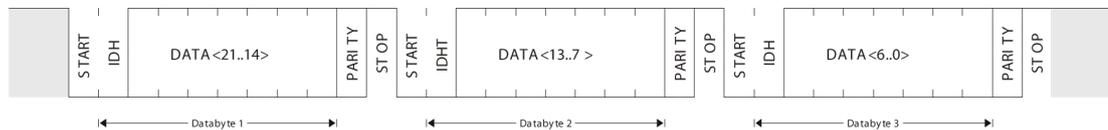


Figure 4.5: Structure of data payload - Note that each byte transmitted only has seven usable bits of data, the 8th bit becomes the lowest bit in the next byte (17)

4.5.2.6 Trailing Byte

The last byte in the message is the "end of transfer" byte (17). The purpose of this byte is to signal that the message has been sent. Like the starting byte, the MSB of this byte is set to one. The rest of the bits in this byte are also set to one, to signify that this is the end byte, rather than the start byte. The value transmitted is 0xFF, and this is the only location in which 0xFF can appear.

4.5.3 Design

Like the GPS module, the battery monitor module was developed using C. This keeps in line with the design principles of making each component as simple as possible. Figure 4.6 shows the program flow of this daemon.

4.5.3.1 Network protocol

Table 4.5 shows the protocol for the battery monitor message when transmitted over the network. As the design uses a binary format file like the GPS module, this format is impossible to read natively, but more efficient on space. There is no need for these

4. SYSTEM DESIGN

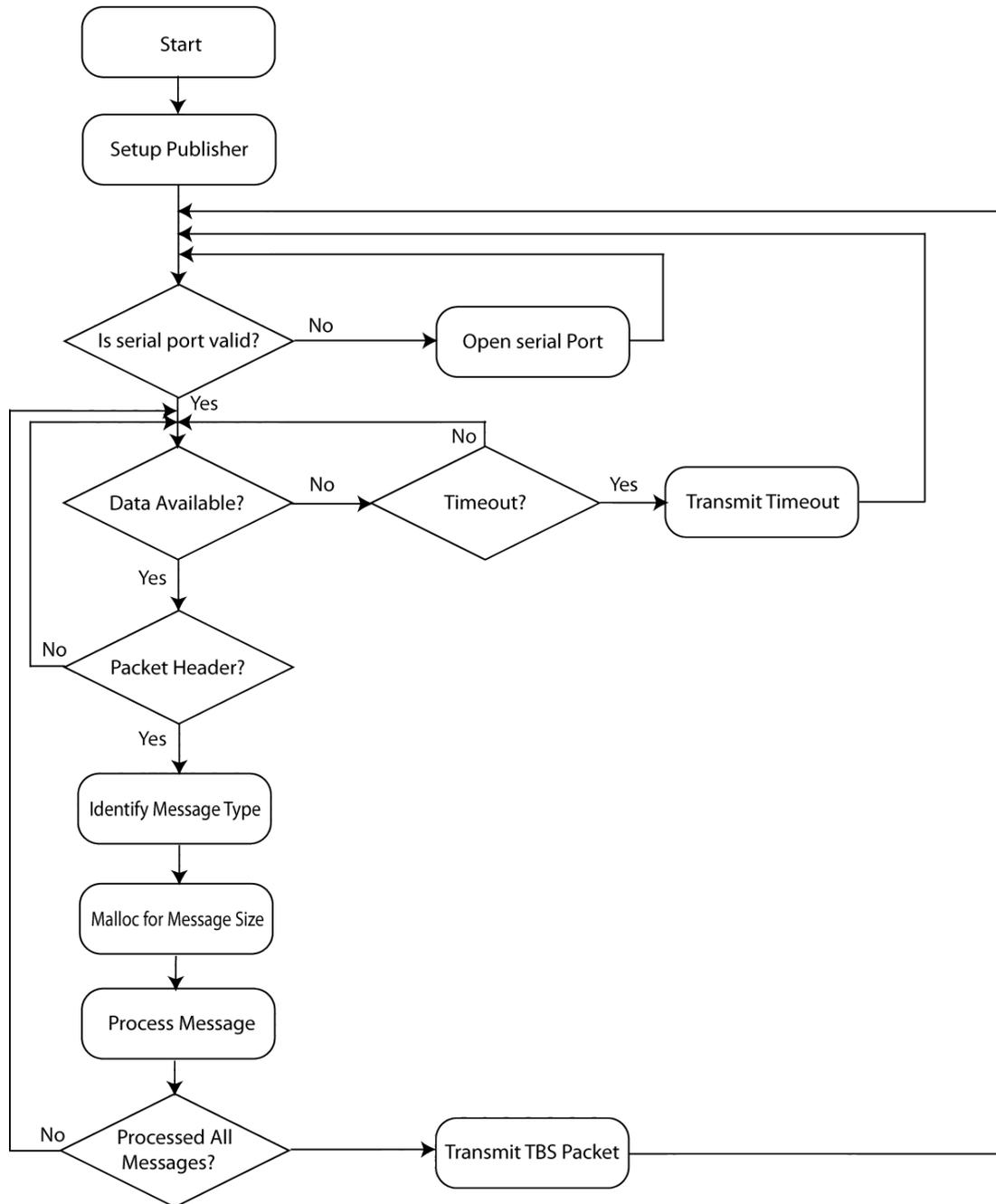


Figure 4.6: Flow chart of the battery monitor daemon -

4.6 Arduino Digital Input Module

| | | | | | | |
|--------------|--------------|-----------------|--------------|----------------|--------------------|----------|
| 54 | 42 | 53 | 0 | 0 | 4e1fe968 | 00000000 |
| Header | | | | Data Payload | | |
| Filter | Minor Filter | Revision Number | | Time(s) | Time remaining (s) | |
| 42b40000 | 43710000 | c150000 | 00000000 | | 00000000 | 00000000 |
| Data Payload | | | | | | |
| Charge(%) | Voltage(V) | Current(A) | AmpHours(Ah) | Temperature(C) | Status | |

Table 4.5: Network protocol for Battery Monitor daemon

values to be read on the network layer anyway. All values are transmitted in big endian network order.

4.6 Arduino Digital Input Module

The car has access to many physical inputs that would be useful to monitor and record. Variables such as the state of the air-conditioning or the radio are useful aspects to monitor. These are currently exposed via bare wires inside the vehicle. As these signals are simple digital logic, they need a way to interface with the controller in order to be used in the system.

Previously the in-built FPGA on the Eye-bot was used to accomplish this end (12). This method requires complex cabling to the inside of the Eye-bot. Use of the FPGA also requires special code to be written to interface with the FPGA, which will be different for different kinds of FPGA devices. This makes maintaining this design difficult, and ties the code in with the specific Eye-bot it was developed for.

Investigation was done into a top16 digital input and output module. This module has 8 digital input lines, and 8 digital output lines. This allows for a total of 8 inputs to be read. While this would be enough to satisfy the input variables, it suffers from some drawbacks. This board was found to use an FTDI chip for usb serial communication. This chip appears as a serial port when the correct drivers are present. Sadly the FTDI drivers for the older Linux kernel were not stable, and it was not possible to use this board in the system.

As the current methods were unsuitable to fulfill this role, a new digital interface system was developed in order to satisfy the requirements needed. This new board

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would have digital inputs, analogue voltage inputs, and be able to read other signals generated by the car.

4.6.1 Speedometer and Tachometer

A desired feature would be to record more complicated signals from the car, such as the current speed. While the GPS can provide speed readings, a more accurate source of speed data is available. This source is the cars built-in speedometer. The speedometer and tachometer use hall effect sensors in order to read the rotational rate of the gearbox and motor respectively.

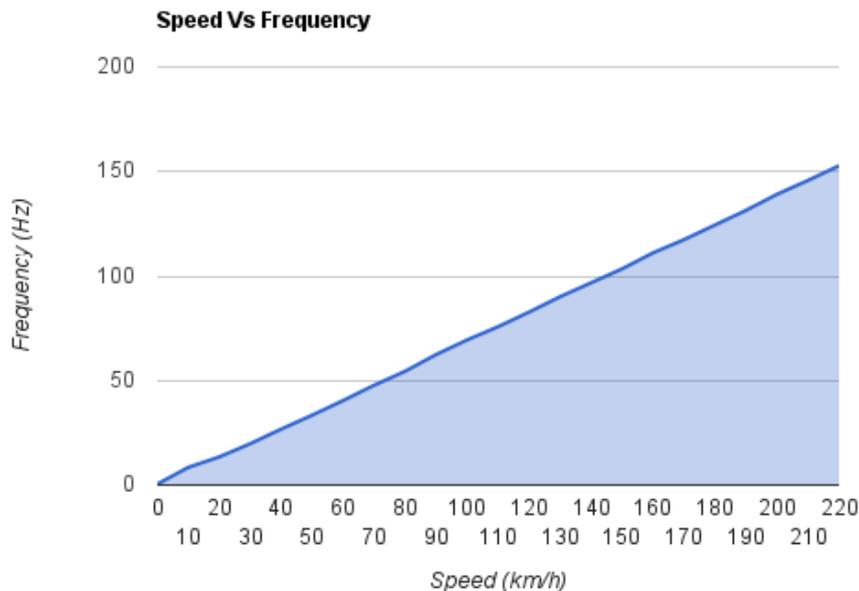


Figure 4.7: Speed (km/h) vs Frequency (Hz) -

Figures 4.7 and 4.8 show the output on the in-built dash in response to various pulse train frequencies. Both these graphs show that the relationship between the frequency and desired variable are highly linear. Thus it is possible to count the amount of pulses that have transpired and perform a calculation in order to determine the cars current speed.

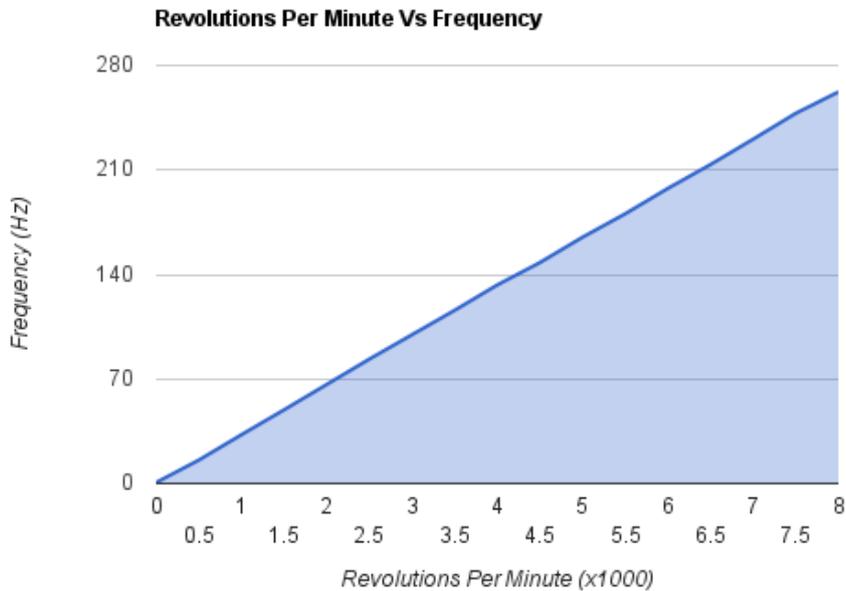


Figure 4.8: RPM vs Frequency (Hz) -

4.6.2 Hardware

The hardware used to accomplish this task is an Arduino Uno compatible board. This board provides 14 Digital IO pins and 6 Analogue Input pins (18). The Atmega chip inside the board also has inbuilt timers, which can be used to implement the frequency component of the requirements. The board is quite small in size, and only needs 5v to run. Figure 4.9 shows the Arduino Uno board.

4.6.3 Drivers

One advantage of the Arduino Uno board over other Arduino boards is that it implements the cdc-acm device drivers that were used in section 4.4.2. The fixes to the drivers implemented previously allow the Arduino Uno to work with the system without any hassle.

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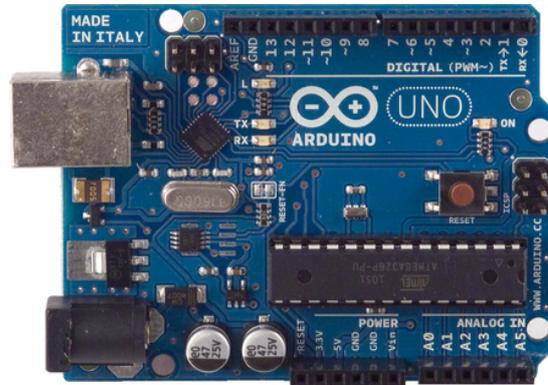


Figure 4.9: Arduino Uno -

| Property | Value |
|--------------|--------|
| Baud Rate | 115200 |
| Data Bits | 8 |
| Stop Bits | 1 |
| Parity | None |
| Flow Control | None |

Table 4.6: Connection settings for Arduino

4.6.4 Design

4.6.4.1 Arduino

The program designed for the Arduino uses the internal interrupts of the Arduino in order to keep track of time and the amount of pulse that have occurred. The Arduino contains an ATmega328 (18). This chip contains internal circuitry that is able to count the number of pulses independently of the current system clock. There are two pins available on the micro-controller to facilitate this functionality, and two frequencies the system is interested in recording.

The main logic of the Arduino program is fired in an interrupt that fires at a frequency of 125Hz. This interrupt checks the overflow of the 8 bit counter, and stores the result so it can be used later on in the calculation. This allows the program to work with larger numbers than a 8 bit byte can contain. Every 125 cycles of this interrupt, or every one second, the system calculates the number of pulses that have occurred

4.7 Accelerometer Module

| | | | | | | | |
|--------------|-------------|------------|------------|-------------|-------------|--------------|---------|
| Byte 1 | Byte 2 | Byte 3 | Byte 4 | Byte 5 | Byte 6 | Byte 7 | |
| Header | Count | 7 Bits DIO | 5 bits DIO | Analog0 MSB | Analog0 LSB | Analog 1 MSB | |
| Byte 8 | Byte 9 | Byte 10 | Byte 11 | Byte 12 | Byte 13 | Byte 14 | Byte 15 |
| Analog 1 LSB | Frequency 0 | | | | Frequency 1 | | |
| Byte 16 | Byte 17 | Byte 18 | Byte 19 | Byte 20 | Byte 21 | Byte 22 | |
| Frequency 1 | Reserved | | | | | | Trailer |

Table 4.7: Network protocol for the distributed system

since the last second, and stores it in a different memory location. The program also sets a flag inside the micro-controller, signaling that the data is ready to be sent via a serial link.

When the serial link is signaled, it will read all the digital inputs and analogue inputs as well as the calculated pulses, and transmit them to the device on the other end. As this is a serial stream, it must have some values that are reserved in order to synchronize the data stream. The same method as used in section 4.5.2.1. This uses the same header byte (0xFF) and allows for 7 bits of data to be transmitted per byte. Rather than sending multiple messages, the Arduino sends everything in one message, that is transmitted at 1Hz.

4.6.4.2 Host side

On the host side, the program functions similarly to that of the GPS program, such as in Figure 4.4. This module of course, will not set the system date, but otherwise they perform similarly, attempting to read as much data as possible into a buffer, and then finding the correct section to synchronize on.

4.7 Accelerometer Module

Acceleration data is an important addition to any telemetry software. The aim behind this module is to provide various acceleration data so it can be analyzed later. Like all the previous components, this module reads information from a hardware device, and transmits it using the network protocol developed earlier.

4. SYSTEM DESIGN

| Property | Value |
|--------------|--------|
| Baud Rate | 115200 |
| Data Bits | 8 |
| Stop Bits | 1 |
| Parity | None |
| Flow Control | None |

Table 4.8: Connection settings for Atomic IMU

4.7.1 Hardware

The hardware used in this module is a Sparkfun 6Dof Atomic IMU (19). This unit contains 3 accelerometers and 3 gyros. It also features a ATmega168 microprocessor that outputs the accelerometer data over a hardware UART. Table 4.8 show the properties of the serial connection to the device.

4.7.2 Drivers

The device used to capture the inertial data outputs the data over a serial link. As such any serial to usb module can be used. The serial connections on the eyebot itself are already used for the battery monitoring hardware. As mentioned earlier, there are issues with the FTDI drivers under this kernel, thus any FTDI branded hardware should be avoided. The other main manufacturer of usb to serial converters is Prolific. During development a Prolific usb to serial converter was used, using the pl-2303 drivers that are bundled with the kernel. This worked successfully and is currently the recommended way of interfacing with the IMU.

The Atomic IMU has different modes of operation. It can output data in an ASCII or binary format. In order to simplify the code that interprets the IMU data, the device is set into the binary format. This outputs bytes that can be directly interpreted by the component software. The device is also set into auto-run mode, so it will output information as soon as it receives power. The IMU synchronizes messages via two ASCII characters. A message starts with the 'A' character and is then followed by the 'Z' character exactly 15 bytes later. As the distance between characters is static, the chance that this exact combination would appear in the data is very low.

| | | | | | | |
|--------------|---------|--------------|-----------------|------|--------------|---------|
| 49 | 4d | 55 | 0 | 0 | 4e1fe968 | 01F5 |
| Header | | | | | Data Payload | |
| Filter | | Minor Filter | Revision Number | | Time(s) | Accel X |
| 01FE | 0314 | 0209 | 01F8 | 01EC | | |
| Data Payload | | | | | | |
| Accel Y | Accel Z | Pitch | Roll | Yaw | | |

Table 4.9: Network protocol for Atomic IMU daemon

4.7.3 Design

The IMU program control loop works exactly like the GPS and Arduino loops. It will attempt to read as much data as possible into a buffer, and then find the control codes in the buffer. It will then process and transmit the data using the protocol mentioned earlier. Table 4.9 shows the ZeroMQ layer message that is transmitted from this component.

4.8 File Logger

The previously mentioned components all generate data at various periodic rates. Data acquisition is useful, but it would be more useful to record this data so it can be analyzed at a later stage. This section outlines the design of a logging mechanism that will record the Battery Monitor and GPS data to a file.

4.8.1 Design

4.8.1.1 Program Flow

The process flow of the logger component is shown in Figure 4.10. This process will log the data for both the GPS and Battery monitor components. It adapts to the speed of the slowest component. This was done to make the processor utilization more efficient. As the system will only write to a file when both values have data, it will automatically match that of the slowest component. Thus the limitation in the resolution that can be logged, is the resolution of the slowest data generating component.

If a component is does not transmit any messages in a reasonable time, the system will log the other values. This has been implemented so the system will not wait forever,

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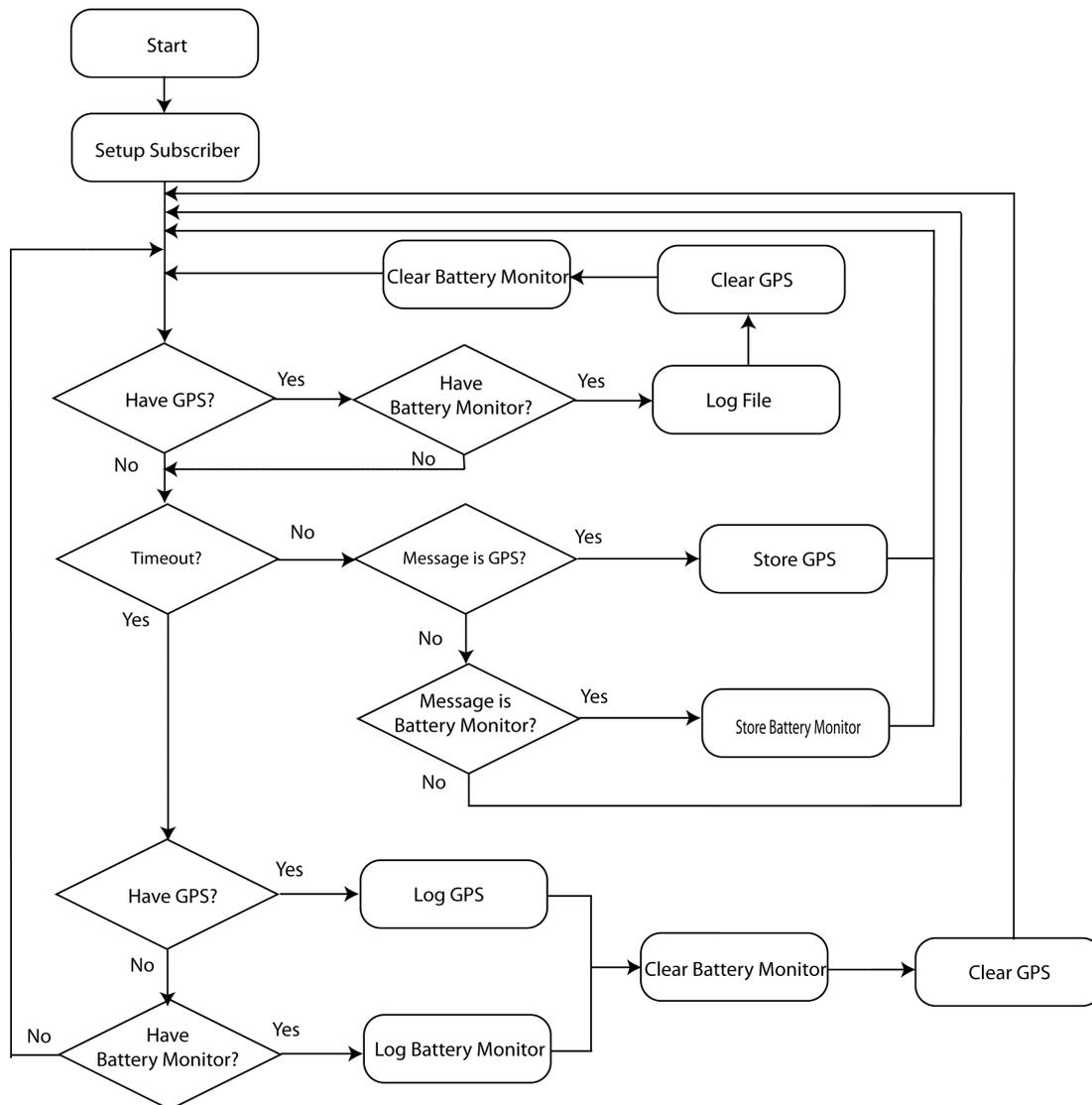


Figure 4.10: Flow chart of the Logger component - This figure shows the process flow of the logger daemon. It will log both the battery monitor and GPS messages together, or individually one component is not transmitting.

for values that will never come. This allows the battery health, or the current location of the car to be recorded in all instances. Ideally this should never occur, but if the vehicle loses GPS signal, for instance when inside a tunnel, it is desirable to still record any changes in the battery status.

4.8.1.2 File storage

A massive file containing all the information logged is troublesome to manage. Each entry in the logger is recorded with a time-stamp. This time-stamp can be used to determine the current system date. A more manage-able solution to storing the data is to provide a unique file for each day. All new entries are appended to the end of this file. This makes it much easier to manage the logged data, and also makes it easier to observe how many days the logger has been active for.

4.8.1.3 File Format

The file format is a simple ASCII based CSV file. Each property of an entry is separated by a comma. A new entry occurs on the next line. This format is simple, human readable and does not require much space to store. Figure 4.11 shows a sample entry of the text file logger.

```
03:44:51PM,-31.980343,115.816620,30.002399,95.800003,138.099991,-137.099991
Time      ,Latitude ,Longitude ,Speed  ,Charge ,Voltage ,Current
```

Figure 4.11: Sample entry in log file - This figure shows a sample entry in the file logger. The file is CSV formatted. The second line shows what each entry in the file means

As seen in figure 4.11 each line in the file contains 78 characters. Each line will also store the newline character as-well. With the information the rate that the logging file consumes storage can be calculated using equation 4.2. In ideal conditions the log file will fill up at a rate of 4760 bytes per minute. This is equivalent to 277 kBytes an hour, or 6.5 megabytes per day. The internal storage of the eyebot is approximately 16 megabytes, but most of this needs to be taken up by the operating system and the code to run the various components. Luckily the eyebot can support usb storage devices. A

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inexpensive 16GB usb drive has enough capacity to last 2520 days, which is more than enough logging capacity for the system.

$$\begin{aligned}\text{Bytes per minute} &= \text{Characters per line} * \text{Frequency} * \text{Seconds per minute} & (4.2) \\ &= 79 * 1 * 60 \\ &= 4740\end{aligned}$$

4.9 Network Logger

Previously developed by other students was a server that provides Internet logging functionality. This server exists on a separate system, and uses TCP/IP to communicate with various clients. The car is equipped with a 3g module that enables it to access this server remotely. This component is concerned with receiving information from the existing components, and logging them to the already existing server so they can be displayed and analyzed via a web-portal. The logger implements the protocol according to Pearce's thesis (20).

4.9.1 Design

An important limitation of any network communication is that the network is unstable. At any time the network connection could disappear, preventing the program from logging data to the server. This would cause the program to hang while it waits for communication to resume. In order to solve this problem non-blocking communication was used. Non-blocking communication is when any data transmission will return instantly from being called. This allows the program to examine what has happened and react accordingly.

If the network is down for an extended period of time, the system will not discard messages generated during this period of inactivity. These unsent messages are stored in memory in a queue. This queue maintains all the unsent messages, until the time in which they are able to be transmitted. Figure 4.12 shows the program flow of the internet based logger.

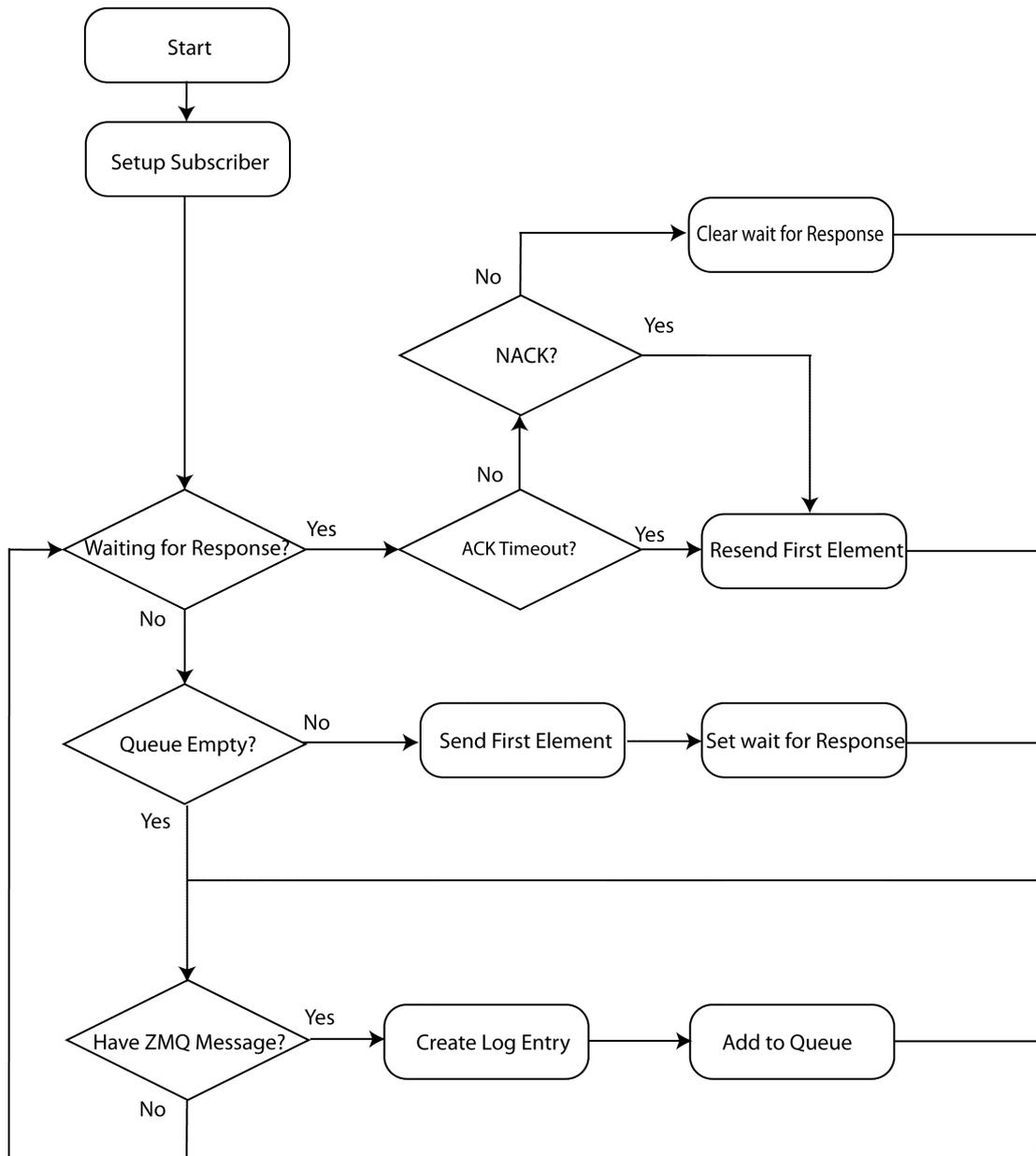


Figure 4.12: Flow chart of the Network Logger component - This figure shows the process flow of the logger daemon. It will log both the battery monitor and GPS messages together. This diagram has simplified the receiving of ZeroMQ messages

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5

Windowing Toolkit

5.1 Motivation

In order to improve stability of the system, a windowing toolkit was developed to display information to the user. Interactions with the user occur in only a few pre-definable ways. The user will either view data that the system has produced, or press buttons on the screen in order to transition the display to another screen. The currently developed software (EyeLin) provided very low level access to complete these actions. This allows for greater flexibility in developing using the software, but makes it more confusing to deal with, and contributes to bugs in the software. In order to alleviate this problem, a high-level abstraction was developed on top of the existing software. This abstraction allows the low level functionality, such as interacting with the touchscreen, to be hidden. This simplifies development when layout the user interface. This also allows for code to be written and debugged once, for example the toolkit completely removes interactions with the touchscreen, allowing buttons to be added in a much simpler fashion.

As other requirements of the system required C++ libraries, the windowing toolkit was implemented using C++. This is an object oriented language that provides a few distinct advantages over the C language that is traditionally used on embedded devices such as this. The first advantage is the use of object orientation. When constructing a user interface, it is much easier to understand the different elements of the interface as unique objects. By thinking of a text display as a single object, it becomes more intuitive to manipulate. The other advantage in the use of C++ is that it allows

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for objects to inherit from other objects. This use of polymorphism allows elements to implement the functionality they require by inheriting from specifications in the toolkit. The toolkit is able to call these new functions due to use of virtual methods.

The toolkit has been written in a way that the programmer utilizing it does not need to understand anything about threads. While the mechanics inside the toolkit do use threads, the interaction with these threads is completely abstracted away. It is not possible to directly manipulate the underlying threads with the toolkit. This removes any problems with synchronization between threads, as they cannot be manipulated. There are three threads running inside the toolkit. One thread is responsible for manipulating the screen, one thread is responsible for responding to events occurring on the touchscreen and the last thread is responsible for reading and processing the network messages.

The final advantage of developing this toolkit, is that it is not limited to use in this project. As the toolkit is written in a generic way, with the exception of being able to receive the messages transmitted over the network, it is able to be deployed on future projects. This allows future projects to have a rich user interface, while keeping the high-level abstraction in place.

5.2 Elements

The windowing toolkit consists of pre-made classes that are either used directly, such as the digit display element, or are inherited from, such as the base or runnable classes. Figure 5.1 shows the classes developed in the toolkit.

5.2.1 UIElement

The UIElement is the most basic class definition in the toolkit. It is an abstract class that can never be instantiated. Its purpose is to define methods for interacting with the screen and other objects. It also provides default functionality for most methods, this allows all the classes that inherit from it to function the same way.

5.2.1.1 addChild()

An important definition of the UIElement class, is that it may contain any number of other UIElement classes inside it. To add another UIElement class the method

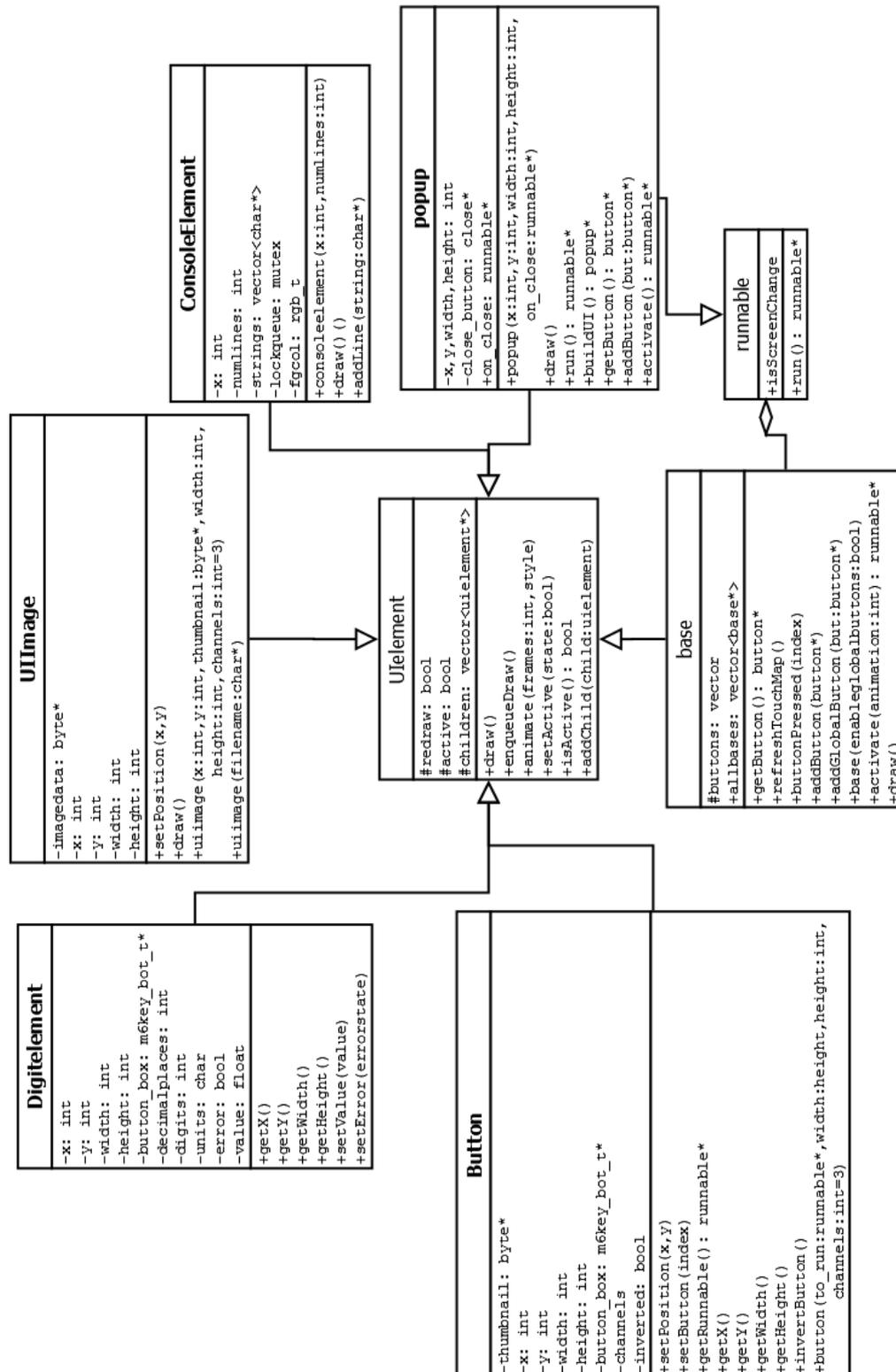


Figure 5.1: UML diagram of the window toolkit -

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`addChild()` is called. This stores the child element inside a C++ vector whose length is only limited by the amount of ram inside the machine. The advantage of this is that actions can be performed on a `UIElement` and all it's children. If a element needs to be drawn, all it's children will be drawn too or if an element is disabled, all it's children will be disabled too.

5.2.1.2 `draw()`

The most important method of the `UIElement` class is the `draw` method. This method definition is not implemented in the `UIElement` class, it is defined a virtual abstract method. All classes that can be instantiated must implement this function call. The purpose of this function call is to allow the user to specify the low level commands that are used to display this element. This can include drawing lines, squares, or setting individual pixels. This method should be implemented by the programmer, but should only ever be called by the mechanics of the toolkit. The developed of the user interface should never directly call this method.

5.2.1.3 `enqueueDraw()`

`enqueueDraw()` is called whenever the system, or the programmer, wants to trigger a refresh of the screen. This will signal the toolkit that a redraw should be prepared. The purpose of this method is two-fold. Firstly it allows the toolkit to perform optimizations of the draw function in order to maximize speed (see 5.5). Secondly it's implementation has $O(1)$ complexity. This means that the call to `enqueueDraw()` completes in constant time. This is used for performance reasons, as whatever thread has called `enqueueDraw()`, will not need to wait for the screen to be redrawn, it will return instantly. The draw will be scheduled to occur some time after `enqueueDraw()` is called. By default this method will also call the `enqueueDraw()` method of all it's children, allowing entire sections of the display to be redrawn using one function call.

5.2.1.4 `animate()`

In order to improve the user experience the ability to transition between two panels was implemented. This transition is triggered via two calls to the `animate` command. The first call signals the screen driver that it wishes to animate from the currently

displayed panel, to some other panel. This backs up the current panel to memory, so it can be drawn at the beginning of the animation later. After the first call, all the drawing functions for the second screen are run. This will draw the new panel to a fake screen, it will not actually be displayed to the user until later. Once the fake screen has been drawn, the final call to animate is called. This triggers the transition with the supplied animation and number of frames.

The extra calls allow any of the existing image functions to still be used. Due to the method in which the screen is backed up, and new images are drawn to a temporary screen, the existing commands to set pixels or draw lines will still function. This allows the animations to exist without requiring complicated re-programming of the entire screen manipulation libraries.

In section 5.5 the drawing commands are stored in queues before they are processed. As such the animate commands must also be stored in that queue, so they are executed at the correct time in relation to the drawing commands. Figure 5.2 shows this.

5.2.1.5 setActive()

A property that is required of any draw-able object inside the toolkit is whether it is current being displayed to the user. This property allows elements to exist in the machines memory, but only be draw if they are current being displayed. To manipulate this property, the method setActive() is called. This method allows the state to be set to either true or false, meaning that the object will be drawn or not drawn respectively. If the active state is false, calls to enqueueDraw() will be processed, but the call to the draw() function will be skipped. Thus individual elements of the display can be hidden at will. This method will also call the setActive() method of all the children of this element. Thus allowing sections of the display to be hidden with one function call.

5.2.1.6 isActive()

This method will return the current state of the element. This is used to check whether the current element is being drawn or not. This method is called internally by the screen drawing mechanics. It can also be used in order to check whether the element is being displayed, and perform different tasks if it is not being displayed.

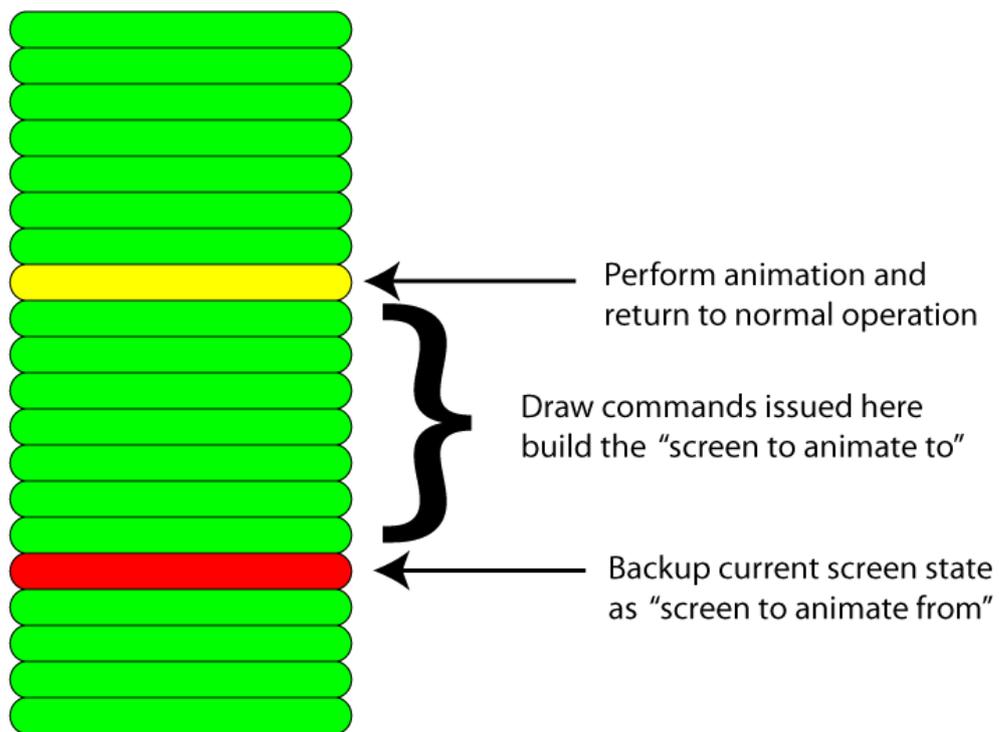


Figure 5.2: Animation Events in screen drawing queue - This figure shows animation signals relative to various draw commands

5.2.2 base

The base element represents the panels or windows that are being displayed to the user. An important property of the base element is that it is defined to occupy the whole screen. This element will draw the entire width of the screen, which will clear any old draws that may still be present. Another extended property of the base element is that it maintains a list of all the other base elements that are present. This is used in order to allow for global navigation buttons. Rather than layout buttons in the same location on every screen, a button can be added as a global button. This will ensure that it appears on all the screens present in the list. This allows the buttons and their location on the screen to be defined once, making the final program more stable and simpler to understand. For further discussion on the button element see 5.2.5. The base class itself is abstract, it cannot be instantiated. There is no way to display a "default" base element. In order to build a panel, the panel must inherit from the base element, and implement at minimum the abstract function `getButton()`.

5.2.2.1 base()

The constructor for this class takes a single argument. This argument is a boolean value indicating whether this panel will display global buttons or not. By default this option is set to true, though it can be easily overridden when a new class is inheriting from this one. This optional argument allows a panel to forgo global buttons. This is used in the case when the developed only wishes to display a simpler panel, or when the current set of global buttons would appear in-appropriately on this panel.

5.2.2.2 draw()

This class implements a rudimentary version of the draw method. This specifies a default display for each full-screen panel the user will view. The reasons for this functionality are two-fold. Firstly, it allows a common backdrop to be defined for each screen. This keeps a sense of constituency while navigating, as the background will always be similar. It is also useful in speeding up development, as having a default state for a panel is useful for prototyping and implementing new panels. The second reason a default is specified is to remove any elements that were present on the previous screen. Even though buttons and UIelements may not be active anymore, pixels may

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still be set corresponding to their images. These pixels may have last been refreshed a long time ago. They will remain in the frame-buffer until they are overwritten by a new set of image data. As the a base panel is defined as occupying the whole screen, it will replace and UIElements that may already exist on the screen, thus removing them from being visible. As the instance of this base class with be enqueued onto the drawing queue first, all it's child elements will still be drawn correctly.

5.2.2.3 `getButton()`

In order to transition to a panel, an action must be undertaken by either the user or the system. The most common way of transitioning would be when the user wants to display a different screen. Typically this would occur by the use of pressing buttons. This is why any base panel must implement the `getButton()` function. This function returns a button object that contains the image data to display for this button, and the action to undertake when the button is pressed. This action will typically be a call to the `activate()` function of the panel, though other actions can be called before the call to `activate()`.

5.2.2.4 `addButton()`

A common element that will be placed on any panel is a button element. This is the basic way in which the user navigates. A button element itself is a child element of the panel it is contained in, it needs to be drawn when the panel is drawn. A button will also have extra functionality than just being drawn, namely, it can be pressed by the user. As the existing `addChild()` function only adds the element to the list of child elements to be drawn, an extra method was developed to add buttons to a panel. This method is the `addButton` method. This method adds the button element to the list of children, but also registers the button element as an interact-able object. Internally this is achieved by adding the button to a list that contains only buttons. This list is ordered in the order that the buttons were added to the panel. Maintain this list is important in order to translate the lower level screen interactions into finding which button was pressed see 5.4.

5.2.2.5 `addGlobalButton()`

Mentioned earlier was the use of global buttons, which are buttons that will appear on every class that inherits from base. In order to distinguish between buttons that are added to every base panel and buttons that are added only to the current base panel, the `addGlobalButton()` function was developed. This method is declared statically and does not need to be called on an instance of a base class, however it does need at least one instance to have been created for its effects to be observable. In its simplest form, this method iterates over the list of base elements, and calls the `addButton()` method on each base using the supplied button argument. This allows the same button to appear on multiple screens, due to the fact that it is the exact same object, it will perform the exact same action and be laid out in the exact same place on each screen.

5.2.2.6 `refreshTouchMap()`

This method is an internal method to the framework, and should not need to be called by the developer. It is responsible for setting up the touch screen in the lower level libraries. It takes the list of buttons that has been built by calling `addButton()` and registers each button and the region the button exists on with the touch drivers. This abstracts any interaction or understanding of how the touch screen mechanics away from the developer. This function will be called whenever `activate` is called, thus setting up the framework to respond to actions on the buttons that exist on the current panel. It will also clear the previously registered buttons, so they cannot be clicked while the system is displaying the new panel.

5.2.2.7 `buttonPressed()`

The `buttonPressed()` method defines what happens when the user presses a button. This method is implemented in the base class definition in a way that it should never need to be overwritten in any classes inheriting from the base class. This method takes the position in the list of buttons that is pressed and performs the actions that occur when the button is pressed. The runnable abstract class allows any action to be coded and run by this method see 5.2.4. This method also performs things like animating the buttons. In order to provide instant feedback to the user pressing a button, the framework will invert the colour of the button. After a short while, the button will

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turn back to its previous state, and the buttons action will be performed. This small animation provides instant feedback that the user has pressed the button, and results in a much more enjoyable user experience. Delaying the action also has another advantage. By waiting a short time between running the action, which is usually the display of a different base panel, the framework is able to remove and duplicate key-presses that may occur. This prevents the user from pressing a button to transition into a panel, and then immediately pressing a button in the new panel which they did not intend to press.

5.2.2.8 `activate()`

The `activate` method is defined in the base class. It can be overwritten in classes that inherit from the base class, though any class implementing different functionality should call the base classes `activate()` method as well. This method's main responsibility is to display or 'activate' the panel that it is called upon, and to translate the touch driver information into button presses. The default functionality of this method, is to call `enqueueDraw()` first. This will display the current panel on the screen. Next it will call `refreshTouchMap()`, to register the active buttons to the framework. Once the panel has been setup, this method will then block and await input from the user via screen events. Thus this method should only ever be called in the thread that is responsible for controlling the button presses. A apparent downside to this is that there is no easy to for the developer to change the active panel inside a different thread, it is certainly possible to change the active panel though it is more difficult than changing in response to user interaction. On the other hand, this limitation is actually advantageous from a user friendliness standpoint. As the screen will only change from different base panels in response to actions performed by the user, it is easier for them to mentally link actions they have performed into re-actions displayed by the device. This specification means that the panels won't transition by themselves, leading to a much simpler and easier to understand user interface.

This method also allows animations to be specified. By supplying an argument defining the type of screen transition to use, `activate` method will perform the actions necessary to animate the transition between the previous panel and this one. These transitions are implemented inside the screen driver, and include sliding the screen in

and out. For performance reasons, the default transition is an in-place swap, which is the most efficient in respect to CPU time.

When this method finishes it returns the next action to run. This could either be a class that runs the next panel, or some other action to be performed when this panel is not longer being displayed.

5.2.3 Popup

No user interface is complete without pop-up windows. These are smaller windows that overlay the existing panel. A pop-up can be positioned anywhere on the screen, and have any width and size, making it a flexible element for displaying information. The pop-up window will prevent any interaction with the panel they are sitting on top of. This is defined as a modal behaviour (21). The reason the pop-ups will only implement modal interfaces is due to the fact that there is no way for the user to manipulate the position of the dialog box. This was done to simplify the user interface, and make it easier to understand. By default a pop-up will include a close button, so any new pop-up will always be able to close and return to the normal operation of the panel. Other buttons must be added by the developer.

5.2.3.1 popup()

The constructor to the pop-up takes arguments in the form of the size and position of the pop-up, and an action to be performed when the pop-up closes. The last argument is a runnable object that will be called when the pop-up is closed. This allows actions to be scheduled in between the pop-up disappearing, and the previous panel taking focus. This flexibility can be used to trigger screen refresh events, or to flush a file to the disk, or even make another panel take focus. The pop-up class is a child of the base class, and the runnable class.

5.2.3.2 buildUI()

Due to the way C++ calls constructors, a method buildUI has been created in order to over-ride the default button layout. Any class that inherits from another class will call the super-classes constructor. This is a problem if the child class does not wish to use the default exit button provided. To overcome this, the elements inside the pop-up are

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laid out when `buildUI()` is called. This method is called after the pop-up has been fully constructed. Due to polymorphism, the method will always call the implementation of the child class. This allows the child class to completely override the default layout.

The method has returns a pointer to the class it was called on. This is done to allow the object to be constructed and the layout generated in one line of code, and still return a pointer to the popup object.

5.2.3.3 `run()`

The pop-up class implements the runnable abstract class by default. This allows the pop-up to be passed as a runnable object. This run action performs the necessary steps in order to activate the pop-up and display it on the screen. The advantage of this is that a pop-up can be passed as an argument to the button class, meaning that when the button is pressed the pop-up will be shown. This results in very simple and easy to read code.

5.2.3.4 `getButton()`

This method exists because the popup inherits from the base class. It allows the popup to specify a button element that should be used to display the popup. This button element will usually contain a runnable class that activates the popup. This method can return null if there is no button for this popup.

5.2.3.5 `activate()`

This method is inherited from the base class. See section 5.2.2.8 for more information.

5.2.4 `runnable`

The runnable class is an abstract class which is used to allow the developer using the toolkit to run actions inside the toolkit. By using polymorphism, the toolkit is able to call methods on classes which were not programmed or compiled with the toolkit. This runnable aspect is used in order to 'run' various aspects of the user interface. For instance, the base class's `activate` function must return a pointer to a runnable class. This is used to define what happens when the panel is no longer active. Runnable classes are also used extensively by the button system. A button must contain a

runnable class. This class will be run when the button is pressed. Thus allowing any code to run whenever a button is pressed by the user.

5.2.4.1 isScreenChange

A property used in the runnable class is whether this action is triggering a screen change or not. This property is set to true by default. If this property is to, the previous base panel that called this action will have its active property set to false. This suppresses the last screen from being changed, so the runnable action does not need to know where it was called from. If this property is set to false, the previous panel will not be flagged as inactive. This is used whenever an action is updating a element on the user interface, and does only wants to trigger a redraw of the element that changed. The previous panel will remain active, and will resume listening to touch events when the runnable action is finished.

5.2.4.2 run()

This is the abstract method that must be implemented in any class inheriting from the runnable class. It is called by the framework in order to run developer specified actions. Any code inside this method is run by the thread that controls the button interactions. This means that whatever is inside this method will block the touchscreen until it has completed, though this method is able to interact with the touch screen and read of events itself. This is a useful property, as while the system is performing some action, the user will be prevented from transitioning the screen, or running another action.

5.2.5 Button

The button class is a fully implemented class in the framework. The developer using the framework does not need to inherit from this class in order to use its functionality, though they are able to if they desire more control over the way buttons behave. This element is a object representation of a button, and contains all the information required to use the button in the framework. It stores information pertaining to the position, size, state, image and action to be performed when this button is pressed. This allows the framework to lay the button out and display it to the user, and perform actions when the button is pressed. The thumbnail is able to exist as a simple RGB based

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image, or an alpha enabled RGBA image see ???. The information stored in this object is also used to correctly set up the touch drivers in order to correctly identify when the button is pressed.

5.2.5.1 `button()`

The constructor of this button requires two parts of information, the action to run when the button is pressed and the image data that will represent this button on the screen. The runnable action must be a class that inherits from the runnable class see 5.2.4. The image data must be an array of bytes formatted as either RGB or RGBA pixels. As the image data is a contiguous array, the function also requires the knowledge of its width and height. In order to differentiate the difference between RGB and RGBA, the constructor also needs to know how many channels are in the image data. 3 defines a RGB image and 4 defines a RGBA image. In order to neaten code, if the channels argument is omitted the system will assume a RGB image is supplied. This will be safe, as if an RGBA image is supplied but the channels are 3, the framework will not read outside the array of the image. It will however display a corrupted looking image, so it is recommended to explicitly pass the number of channels inside the image. Note that the size of the image is the size of the area that responds to the users touch. If the areas were different sizes, image scaling would have to be performed, which will lead to high levels of distortion on the very low resolution images displayed.

5.2.5.2 `setPosition()`

This method allows the developer to move the location of the button. It takes two arguments, the x and y co-ordinates where the top left corner of the button will sit. The co-ordinate system used is that of pixels available on the screen. By default the button will be placed at (0,0) which places the top left corner of the button at the top left corner of the screen.

5.2.5.3 `getX()`

This method returns the current x position of the top left corner of the button. It is mainly used to find out the location of the button on the screen, in order to avoid laying another button over the same space.

5.2.5.4 `getY()`

Performs the same function as `getX()`, except it returns the y co-ordinate in pixels.

5.2.5.5 `getWidth()`

Returns the width of the image in pixels. This is used to find out how wide the image is on the screen.

5.2.5.6 `getHeight()`

Performs the same function as `getWidth()`, except returns the height instead of the width.

5.2.5.7 `invertButton()`

This method inverts all the colours on the button. This is used in the base class when a button is pressed (see 5.2.2.7). This method marks the button as inverted, and the next call to `enqueueDraw()` will draw the button with inverted colours. Calling this function a second time will restore the state to it's original condition.

5.2.5.8 `getRunnable()`

When the button object is created, it requires a runnable object to perform when the button is pressed. This method returns a pointer to that object so that it may be run, or inspected by the framework.

5.2.6 Digitelement

The digit element is a class that is responsible for displaying numbers to the screen. It is fully implemented in the framework, and does not need any methods to be implemented to be use-able. It renders white colour numbers from zero to nine, with a transparent surrounding so it is able to be overlaid on any image. Internally the digitelement is aware of the number that it has currently displaying and the new value it needs to display. It maintains this awareness in order to change only the information that differs from that present on the screen. This is done in order to maximize performance of the system. If a number, say zero, is displayed the system will not draw a zero over the top of it, it will skip to drawing the next digit.

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One caveat of this element is that it records the current background when it is initialized. This snapshot is used to clear out the previous image data if it differs from the desired data. This is done to prevent the digits from being drawn on-top of each other continuously. This does make the digit element currently unsuitable for display over any moving image data, though moving image data is not used extensively in the interface.

The digitelement is highly configurable, allowing the developer to specify the position, size, integer places, decimal places and units to be displayed after the digit element. Common engineering units are defined in the image element, such as km/h, V and A. This allows relevant information to be laid out quickly. The class takes double length floating point values as an input, but will display the number according to the parameters specified during construction. This ensures the element has consistent sizing, as a change in the magnitude of the number will not cause it to shift about on the display. If decimal places is less than 1, the element will round the value to the nearest integer.

Finally the digitelement can also represent an error state. This is typically used when no information has been recieved, so the number to be displayed is undefined. In this situation displaying any number would be incorrect. As such the element will display a horizontal dash. This indicates that an error has been triggered, and there is no valid data to display.

5.2.6.1 `getX()`

This method returns the current x position of the top left corner of the button. It is mainly used to find out the location of the button on the screen.

5.2.6.2 `getY()`

Performs the same function as `getX()`, except it returns the y co-ordinate in pixels.

5.2.6.3 `getWidth()`

Returns the width of the digitelement in pixels. This will be the width of a individual digit element multiplied by the number of digits that are being displayed.

5.2.6.4 `getHeight()`

Returns the height of the digitelement. This is the same as the height of any individual number in the element, as they are all rendered at the same size.

5.2.6.5 `setValue()`

This function is used to set the value to be displayed on the digitelement. The new value will be displayed on the screen after a call to `enqueueDraw()`.

5.2.6.6 `setError()`

This function is used to set or reset the error state. It will cause the digitelement to display a horizontal line instead of numbers.

5.2.7 Console Element

The console element is a generic text element that is used to display full width text to the screen. The main purpose of this element is to provide an easy way to see debugging information on the screen itself, without requiring any remote connections to the controller. This element takes any string and converts it to be correctly displayed on the screen. It is designed to be used with data that is dynamically changing.

The console element maintains an internal queue of the elements it is currently displayed. This allows a buffer to exist that will display the most recently added strings. The older strings will be removed as newer strings are added. To avoid any conflicts with memory, a string is copied into the internal buffer when it is added. This prevents any other section of the program from freeing or overwriting the memory where the string was stored. When a string is no longer being displayed, it is removed from the queue, and the memory used to store it is cleared.

As the queue has the possibility of being accessed from multiple threads, it must have security in place to ensure the queue does not become corrupted. If any strings memory is cleared at the same it is being drawn, the system will have undefined behaviour. In order to prevent this, a mechanism calling locking is used. When a thread needs to manipulate or read the queue, it locks the queue. Any other thread that tries to lock the queue at this point will be forced to wait. When the thread is finally finished with the queue, it will unlock the queue, allowing the other thread to

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perform an operation on it. This will cause the second thread to stop until the first thread is finished. This simple method of synchronization will prevent the queue from becoming corrupt, and ensures the stability of the console element.

The console element is concerned with displaying the newest values first. In order to best illustrate this, the new values appear at the bottom of the screen, and move upwards until they are no longer displayed. This mimics the display of consoles in normal computers.

A problem that can occur with the display of the strings is the string length. The display only has a fixed width, and the desired string may be longer than the screen width. This could cause some of the data to not appear on the screen. In order to alleviate this problem, the string is split into multiple strings, each with a maximum length that is equal to the width of the screen. This allows the string to be rendered on multiple lines. When a string spills over to multiple lines, it means less space for the older lines that are to be rendered. The element takes into account multi-line strings, and may not always display the desired amount of strings if some strings are too long. This is done to enable all of the information of the newer strings to be read.

A problem with multiple-lined strings is that it can be hard to differentiated between the different lines. To solve this the console element uses alternating colours when displaying different lines. This provides strong visual indicators as to which lines are grouped together as one string, making it easy to identify what the element is trying to say.

5.2.7.1 `consolelement()`

The constructor to the `consoleelement` takes two arguments. The first is an offset. This offset specifies how many lines at the top of the screen the element should not print in. This is to prevent the element from drawing text over buttons or other elements that may appear at the top of the screen. The second element is the maximum number of lines that should be drawn. This argument is used to prevent the element from drawing over buttons or other elements at the bottom of the screen.

5.2.7.2 `addLine()`

This method adds a line to the queue. It will lock the queue, add the line, free any lines that are now too old and then finally unlock the queue. Note that this makes it's

own copy of the supplied string, so it's argument may be destroyed after this method is called.

5.2.7.3 draw()

This method is implemented in the console element and does not need to be overridden. It will lock the queue, split any multiple line strings, draw the lines and then unlock the queue. This method is called by the framework, if the developed wants to refresh the console element, `enqueueDraw()` should be called instead.

5.2.8 UIImage

Basic functionality that is useful to have in any graphical display is that of displaying images. This ability is facilitated by the image class. This is a simple class that allows an image to be displayed and placed anywhere on the display. The image class represents an image internally as an uncompressed byte array. This image is sent to the lower layers for display, and can have it's location manipulated by calling functions on the class.

The image class does not need to be extended to be utilized by the developer. It is fully implemented inside the windowing toolkit. Once it has been instantiated it is able to display the image to the screen. The image class can accept either raw uncompressed byte data to display, or it can load up a PNG format image from the devices file-system. This flexibility was introduced in order to allow images not compiled with the executable to be displayed. This functionality is used in depth in the Map display panel of the user inter-face see section 6.4.

Image data that is loaded via a byte array will only be displayed by the image class. The memory used to store the image will not be cleared on destruction of the image object. This is done for stability reasons, as it is impossible to know if any other portion of the program is using this data, or if the data was statically compiled into the executable. If a filename is supplied, the image class will perform all the memory management functions. It will load the PNG image and convert it to the internal structure required by the lower level display drivers. It will also free the converted data when the image class is destroyed. As this is all done internally, the developer does not need to worry about memory management when using the image class. This was done

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to minimize memory leaks, as the class will always free internal data when it will no longer needed to be used.

5.2.8.1 `uiimage()`

Two constructors exist for the image class. The first constructor takes the position and image data as an argument. This constructor will set the internal pointers to the image data towards the supplied arguments. It will set up the image in a non memory managed mode. In this mode the image class will not free the image data when it is destroyed. This mode of operation is suited towards static image data that is compiled into the program. An example of this is images or icons that are used to display navigational or informational aids.

The other constructor for this class takes the filename of an image on the device's filesystem. If the file cannot be found, a substitute error message is used in it's place. This will cause something always to be displayed to the user inter-face on this images location. This mode will convert the supplied file from the PNG format to a contiguous array of bytes. When destroyed, the array of bytes will be cleared automatically.

5.2.8.2 `setPosition()`

This method allows the developer to set the x and y position of the top left corner of the image.

5.3 Subscriber Queue

As the interface will receive many different types of messages that are described in section 4.1, the ability to easily process these messages was added to the framework. Three classes were developed in order to facilitate this functionality. A UML diagram of the classes is shown in figure 5.3. This functionality uses a listener based system, in order to direct each message to the class that needs the information.

5.3.1 Subscriber

The subscriber class is the class that takes care of reading the messages from the network. This class maintains a instance of a ZeroMQ socket, and registers to receive all messages that are sent to that socket. It is able to listen to multiple endpoints, so

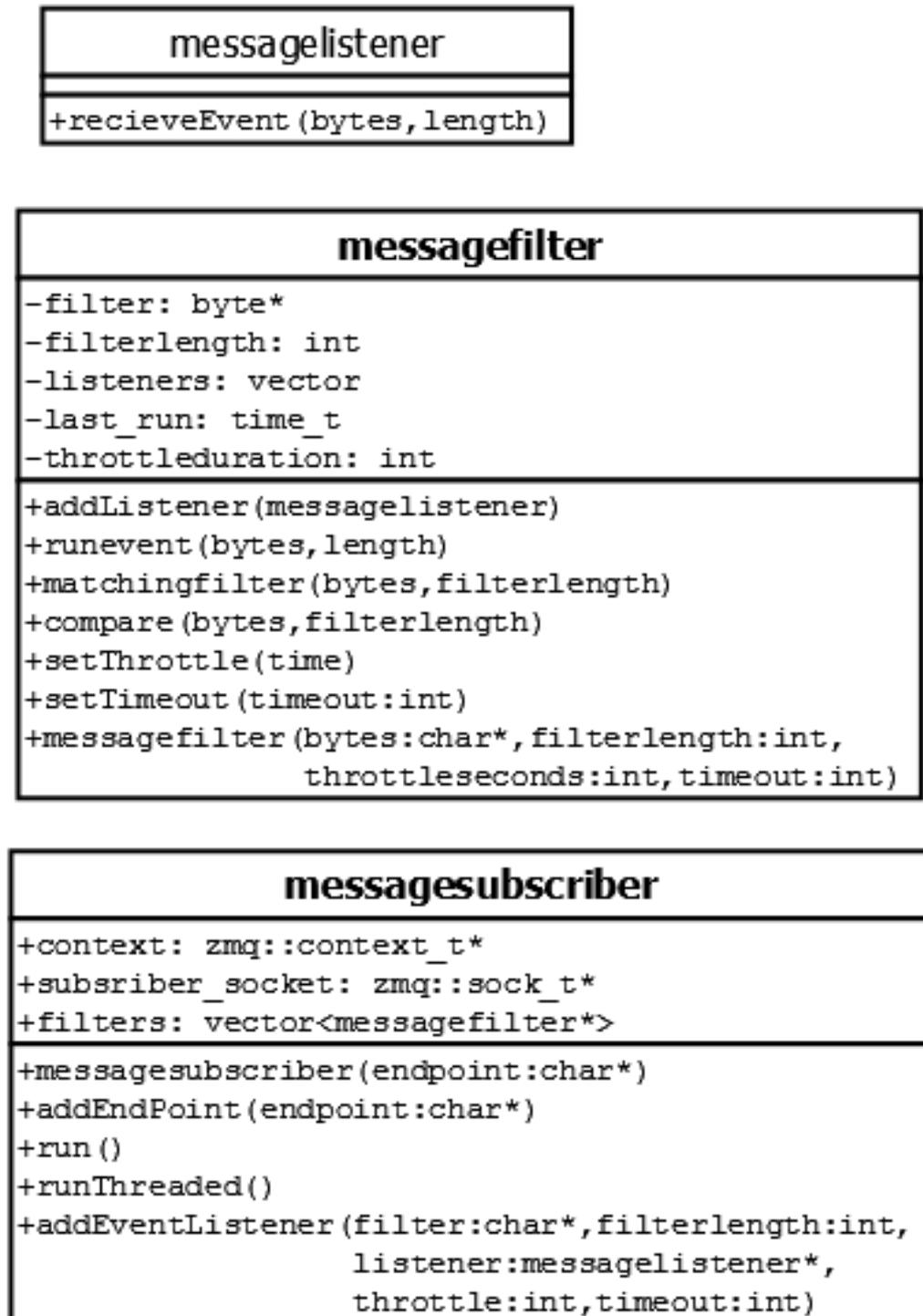


Figure 5.3: UML Diagram of messaging system for the window toolkit - This figure shows the UML diagram of the message subscriber, filter and receiver classes

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it can receive messages from multiple unique devices and deal with them from the one class.

The class can be run directly, or can spawn it's own thread. When the class is run, it will block indefinitely, as to direct messages to their intended destination. Thus it is recommended that the threaded functionality be utilized when this class is instantiated.

An infinite number of listeners can be registered to this class. Each listener will specify a filter that indicates what messages it is interested in. This associates the added listener with the desired filter. If the filter does not currently exist, it will be created by the subscriber class.

When a message is received, all the implemented filters are compared to the message. If a filter matches the received message, the message is forwarded to all the classes that are listening to this filter.

5.3.2 Filter

The filter class is responsible for identifying what messages will pass this filter, and maintaining a list of classes that should receive the message if it passes. Any class implementing the listener interface can be registered to a filter.

A filter also has some other options that are useful to it's operation. It is possible to set a timeout for each filter that is created. If a message that matches the filter is not received in the length it takes the timeout to occur, the listeners of this filter will be notified. This allows the listeners to respond to lapses in communication in whatever way they want.

A filter can also throttle the message rate. It is possible to specify a minimum time between messages, in order to reduce processing time used by the CPU. If the message rate is greater than the throttle rate, messages will be discarded at the filter level. This can be used to help prevent too many messages from appearing at a listener that cannot cope.

5.3.3 Listener

A listener is a abstract class that defines the function that will be called when a valid message arrives. If a class implements the `recieveEvent` method, whenever a message that it is interested in arrives it will call this method. This arguments passed through

are the length of an array of bytes, and a pointer to the start of this array. This allows the class to receive the contents of the message, and use it in whatever way it pleases.

5.4 Button Translation

Discussed in section 5.2.5 is the class that represents buttons on the display. In order to interact with these buttons, and not interfere the operation of the other aspects of the system, a separate thread must be utilized. This thread has the sole responsibility of navigating through the display that is shown to the user, and triggering the actions of the button. The functionality of this thread is implemented in the `activate()` function of the base class. This ensures that any element created that will contain buttons has the ability to trigger them.

The existing libraries for interfacing with the touch screen written by Sommer provided an integer indicating which button had been pressed (22). This method, while usable, is complicated and can cause many problems when determining what action had occurred. In order to simplify this, the `activate()` loop will take this integer value, and determine which button element it corresponded to.

The buttons on any element are stored in a vector that is separated from other elements. This provides a list of the buttons that have been added to the device in order. When `refreshTouchmap()` is called on an element, the loop will setup the touch regions using methods provided by Sommer's library. Sommer's library will associate each button to a bit in a 32 bit register. Each bit corresponds to a section of the screen for an individual button. This allows multiple buttons to be pressed at the same time.

The relationship between the value in the register and the position in the vector is given by equation 5.1. Thus it is possible to convert the value returned from Sommer's library into an index in the vector. Knowing this, the loop will retrieve the runnable action from the button at this vector location. If the runnable action is valid, the result will be returned to the framework. When the framework receives a runnable action, it will run it. As a safe-guard, if a runnable action is invalid for whatever reason, it will perform the action to display a default panel. As all calls to `activate` will return to the highest level of the framework, there is no nesting of panels in the system memory. Hence `activate` will always return to the top level.

$$\text{Button}_i = \log 2(\text{Register}) \quad (5.1)$$

5.5 Screen Drawing Queue

Due to the limited resources of the system, care must be taken when attempting to update the screen. As a windowing system was already being developed, it was desirable to have this system abstract these actions away from the programmer. By using the toolkit the programmer can trigger when an element should be drawn, and specify the drawing code to draw the element. The abstraction means that the developed code will never be called directly by the programmer, it is all taken care of by the underlying mechanisms.

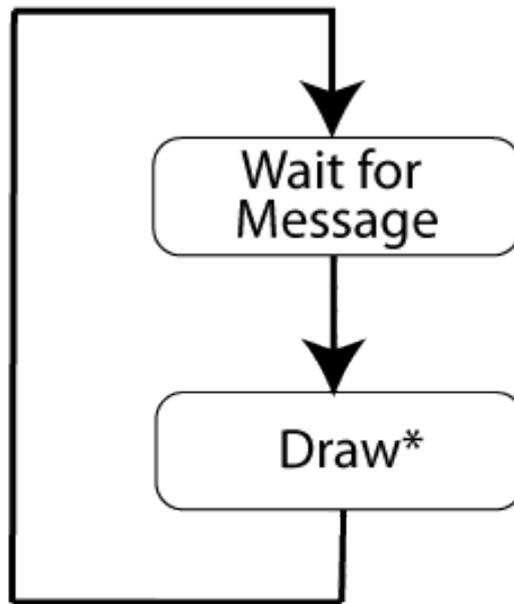
5.5.1 Refresh on Arrival

Whenever a new message is received by the user interface, it would seem appropriate to process that message instantaneously. Figure 5.4 shows the flow of this methodology. A message is received, then the system processes the message, redraws the screen, and then starts over again. While this is a working solution, it does present problems in regards to performance and the overall usability of the system.

The performance penalty in such a design is not immediately obvious. Data that is received should be displayed instantaneously. Inspecting Figure 5.4 further does help highlight the problem that occurs in this situation. While the system is processing or displaying the message, it is unable to process anymore messages. This can be a problem when the source of the messages is generating messages faster than the device can process.

5.5.1.1 Message speed greater than redraw rate

In situations such as the BMS module, the program was able to sufficiently cope with the input. This led to all the messages being instantly removed from the network layer when they arrived. Thus the program was always in the state of "waiting for a message". However another important sensor caused problems with this method. This sensor was the one designed to read the GPS signals. Messages containing GPS



*Possibly expensive time consuming operation

Figure 5.4: Processing message flow chart - This figure shows the naive approach to processing and displaying received message data

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information were generated at a rate of 10 messages per second, or 10hz. This speed led to the situation where when a new message arrived, the process was still in the "Draw" state. This would cause the message to be delayed on the network layer.

The rate of input regarding the GPS module was constant, these messages would continually build up on the network layer. Any new messages that were transmitted would be dropped when they were attempted to be sent. While this is acceptable, eventually space would be cleared for new messages, it would lead to a lot of new messages to be dropped. The other issue that occurred here, was the new messages appeared at the back of the "Queue". Until all the older messages were processed, the new ones would not be seen. This is expected from how ZeroMQ functions (10). However, this meant that there was a significant delay until new data was seen.

The delay that occurred was proportional to the size of the ZeroMQ Message Queue (10). This delay could be up to a couple of seconds, which is unacceptable for live feedback to the driver. Reducing the size of the Message Queue helped alleviate the problem, however the screen would still attempt to redraw as fast as the messages were received. This also led to the interface portion of the system hogging the CPU. Thus an alternate method of dealing with screen updates was developed.

5.5.2 Add to Queue

5.5.3 Redrawing the Screen

The previous section discussed the problems that occurred with allowing the screen to update whenever a message was received. The biggest performance penalty that occurred was not from the actual processing of the data, but from having to display it on the screen. All of the processing is relatively trivial computation wise. It is the transfer of variables into various memory locations so they can be accessed when the screen is displayed. Copying a variable itself is trivial, however processing that variable for display on screen is incredibly intense.

5.5.4 Redraw rate

Inspection of the EyeLin library source code showed that the library was using a simple frame-buffer in order to interact with the screen. This frame-buffer method stored the entire screen state as a 24bit image. By default, whenever one pixel was changed

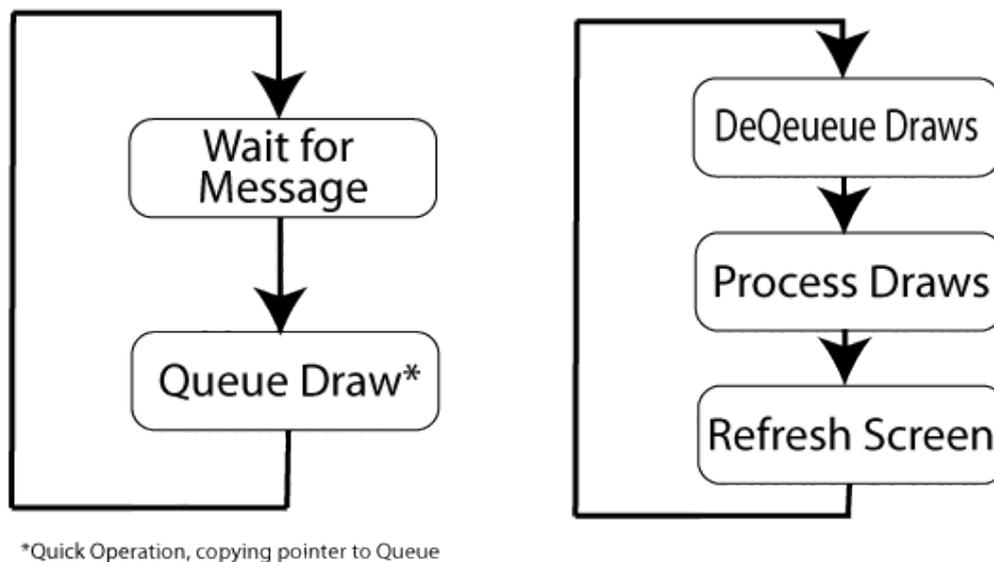


Figure 5.5: Appending to Queue - This figure shows the flow of appending screen refreshes to a queue

in this image, all the data was copied to the frame-buffer again. This was incredibly wasteful, and contributed to the large delays in redrawing the screen. Many items on the screen need to be redrawn together, for instance, a digit display has three or more digits that may change from it's last appearance. By default the library would redraw three times if the number changed by a large amount. This caused a lot of performance issues in previous projects using these libraries see

5.5.5 Batch Redraw

In order to offset this problem the way in which the queue processed draws was modified. The thread that processed the queue would attempting to dequeue as much items as possible and process them as a batch. This gives more performance than attempting to redraw the screen for every change.

5.5.5.1 Maximum batch size

Attempting to remove as many items as possible is a problem in a multi-threaded system. Consider the case where a thread is adding elements, the producer thread,

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at the same time the drawing thread is removing them, the consumer thread. If the producer thread is operating faster than the consumer thread, the consumer thread will always be removing elements from the queue. Thus the consumer thread has a maximum amount of elements it will process at a time. This guarantees that the consumer thread will always refresh the screen.

5.5.5.2 Incomplete batch

Another issue that can occur with processing drawing events in a batch format is that no new draw events may be generated. Consider that the thread is attempting to remove a certain number of redraw events, however there may only be half present inside the queue. If, for whatever reason, no more redraw events are added, the queue will wait forever attempting to remove them. This is undesirable, as some transitions may only trigger a few redraw events and do nothing more. A good example of this is a static page, like the sponsor page. It only has a few elements, the buttons and the sponsor logos, and is not dynamically updated in response to any data. If the thread was waiting for more draw events, they would never be received. The solution to this problem is to continue on with the drawing actions if the queue is ever empty. This prevents the thread from waiting for more events, and helps guarantee the constant refreshing of the screen.

5.6 Alpha Transparency

In modern user interfaces, elements on the screen may be any shape or size. This presents a problem as all image data consists as square objects. A solution to this problem is to create images that contain an alpha channel. This is an extra channel on-top of the RGB channel that represents the transparency of that pixel. This allows a pixel to completely disappear when drawing the image. Only the existing data will be drawn. This is illustrated in figure 5.7.

This alpha channel was integrated as an extra function into the existing libraries. The new function will accept images formatted with alpha channels and blend them with the current displayed data. This is done for each channel, red green and blue, for each pixel according to the formula 5.2.

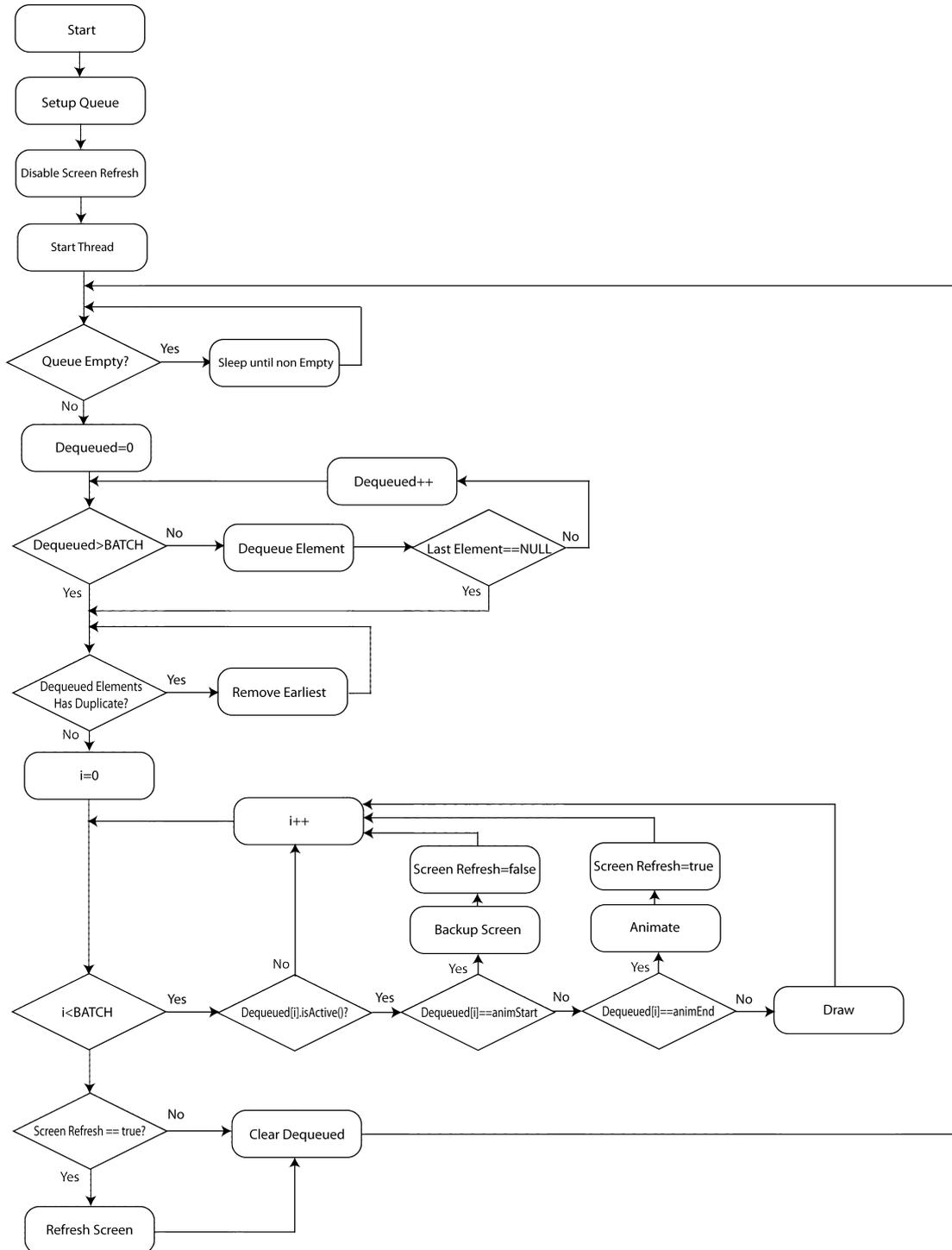
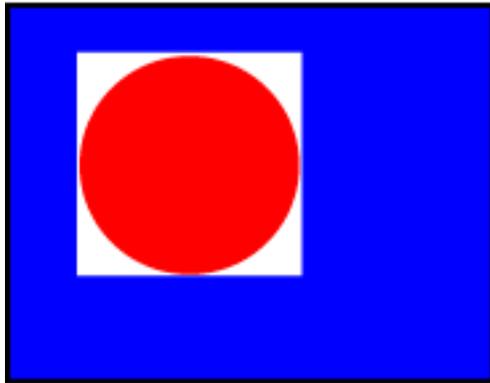
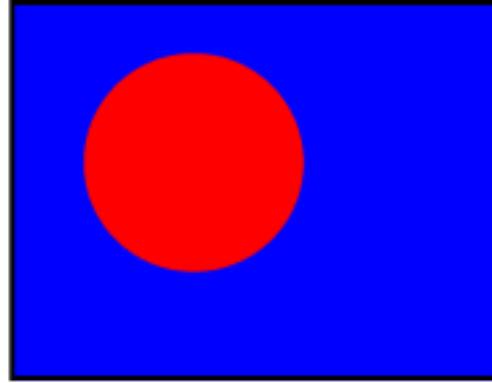


Figure 5.6: Screen drawing flow chart - This figure shows the managing and drawing of elements inside the drawing queue



Without alpha
Blending



With alpha
Blending

Figure 5.7: Example of alpha blending - This figure shows the advantage of using alpha blending to display non-square objects on the screen

$$\text{Drawn Pixel} = \text{New Pixel} * \alpha + (1 - \alpha) * \text{Old Pixel} \quad (5.2)$$

6

Interface

6.1 Layout

An important aspect of user interfaces is that they must be visually impressive. This keeps the user interested in the product, and helps new users want to learn how to operate the device. The work done in the windowing toolkit allowed a much more visually impressive layout to be developed. This was achieved through the use of transparencies in order to overlay different elements on top of each other.

6.1.1 Background

As the device does not have enough power to dynamically render any sort of complex images or motions, a pre-rendered static background was used. This background was designed on another pc, and converted for use on the embedded system. It consists of two main regions. The first area is the main display region. This section is the largest of the space and exists so the current data being displayed can be laid over it. The second region is the navigation bar region. This area is at the bottom of the image, it uses a more uniform texture in order to contrast the main data display area above it. The background itself is rendered in black and white. The black and white styling allows important information to contrast against it easily. This helps highlight the information and user interface actions present to the user, and avoids a simple single-colour background on the user interface.

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6.1.2 Navigation Model

Figure 6.1 shows the basic routes throughout the user interface. This model is a generic tree, that can have as many leafs as possible. When the user wishes to navigate to a new panel, a pointer to that new panel is required. Thus as-long as the panel knows of the panel it wishes to transition to, any panel can be made active from any other panel. This allows the nested elements, such as syslog and status to navigate to any of the higher level panels easily as-well. These routes are not shown on the diagram, as there would be too many pathways to follow. If a panel returns a NULL pointer, the system will navigate to the App Panel to avoid a crash. This also provides handy functionality for traversing back to the top-most panel in the tree, as any leaf panel can request to transition to NULL and the App Panel will be displayed.

6.2 Overview Panel

To facilitate easy navigation a panel was designed that shows all the different panels available. This panel is shown in figure 6.2. It contains 8 different aspects of the program, with room available for 12. This will allow the system to be extended in the future.

6.3 Battery

The battery panel is the main display panel used in the user interface. It is the first panel displayed to the user when the system turns on. It displays five important pieces of information to the user operating the vehicle. This panel listens to both the battery (TBS) and GPS messages. It requires the battery messages to display the battery voltage, current and charge to the user. These are displayed using the digit-elements mentioned in 5.2.6. It also uses a custom charge element class that exists outside of the framework to draw a battery on the center of the screen. This green bar on this battery will decrease in proportion to the charge remaining in the car, providing a quick visual indicator for how much charge is still stored.

This panel also displays the speed in km/h, which is why it has to register to the gps module. The speed is included so the user does not have to interact with the screen

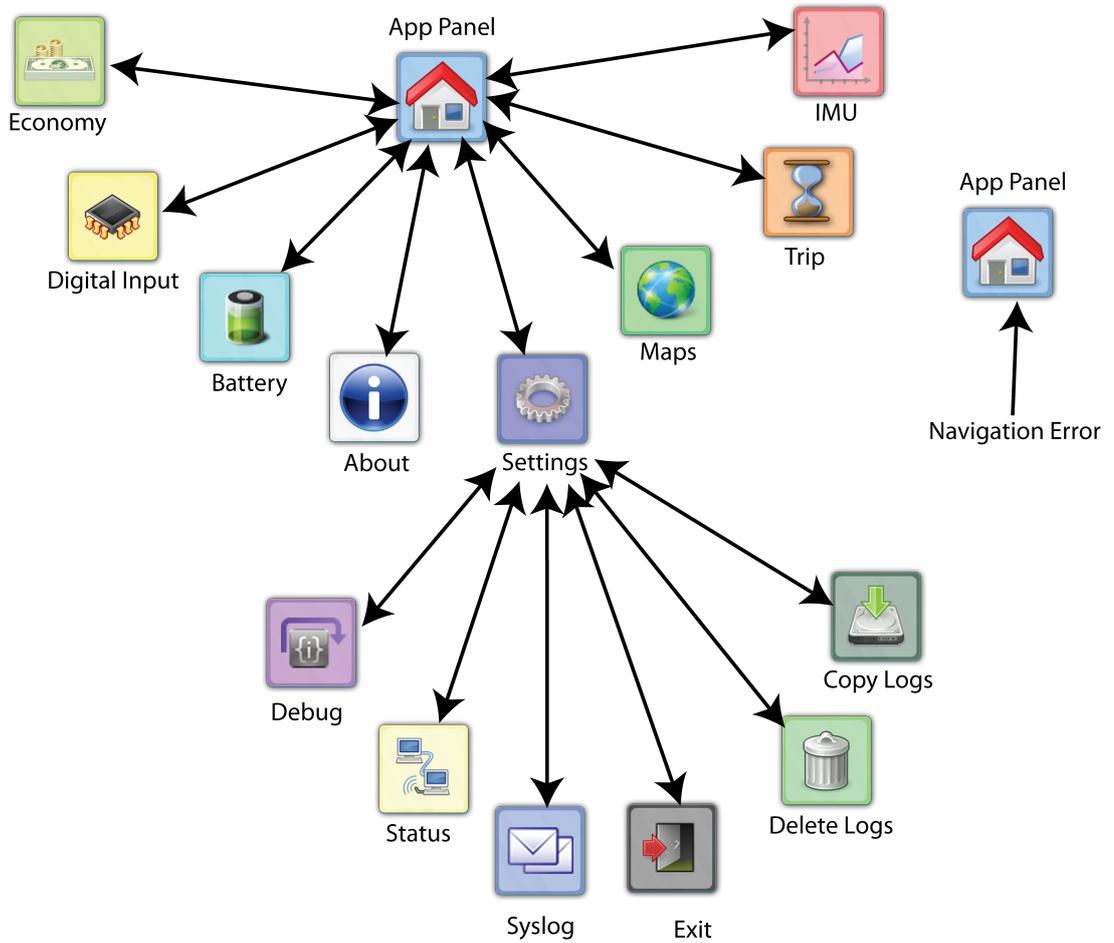


Figure 6.1: Basic Navigation of the interface - The basic navigation routes through the user interface, does not show "quickbar" navigation routes

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Figure 6.2: Panel showing other panels - Shortcuts to different aspects of the program. (Battery, Maps, Trip Meter, Accelerometer, Arduino, Savings, About, Options)

while driving. This panel's main purpose was to provide a quick overview to data points that are immediately of concern to the driver.

Displayed in the top left corner is a rudimentary calculation of how much distance is remaining in the car. Range tests conducted by the REV team indicated that this distance was 80km from a full charge. To provide some security while driving, the interface assumes that the max distance the car will travel on a full charge is 70km. It uses this to calculate the distance remaining according to the formula 6.1

$$\text{Distance Remaining} = \text{Charge} * 0.8 - 10 \quad (6.1)$$

6.4 Maps

A common, yet useful driver aid is displaying the map of the current location. This is what the maps panel does. It listens to the GPS messages to determine the position of the car. A screen-shot of this panel is shown in Figure 6.4. This panel uses the full area to display the current location of the vehicle on the screen. The actual position of the vehicle is centered on the middle of the screen, allowing the driver to view streets and



Figure 6.3: Battery state panel - Screen-shot of the battery state panel, showing the voltage, current, charge, speed (via gps) and distance remaining

landmarks relative to his current position. The panel features several levels of zoom, controlled by the bar on the top right corner on the screen. The plus button will zoom in, and move the slider to the right, while the minus button will zoom out, and move the slider to the left. The system supports various levels of zoom, being able to display a few buildings relative to the car or being able to display the surrounding suburbs.

The controls visible on Figure 6.4 are not always required by the operator. They can obscure parts of the map in which the driver may be interested in. This can be a problem as the driver should not be expected to adjust the position of the car, in order to see a part of the map that is hidden by the UI controls. In order to prevent this problem, the controls can be hidden by tapping any area of the screen that is not occupied by a button. Doing this will hide all the navigation elements and just display the map as shown in 6.5.

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Figure 6.4: Map display panel - Screen-shot of the map display panel, showing the map of the current location and the map controls visible

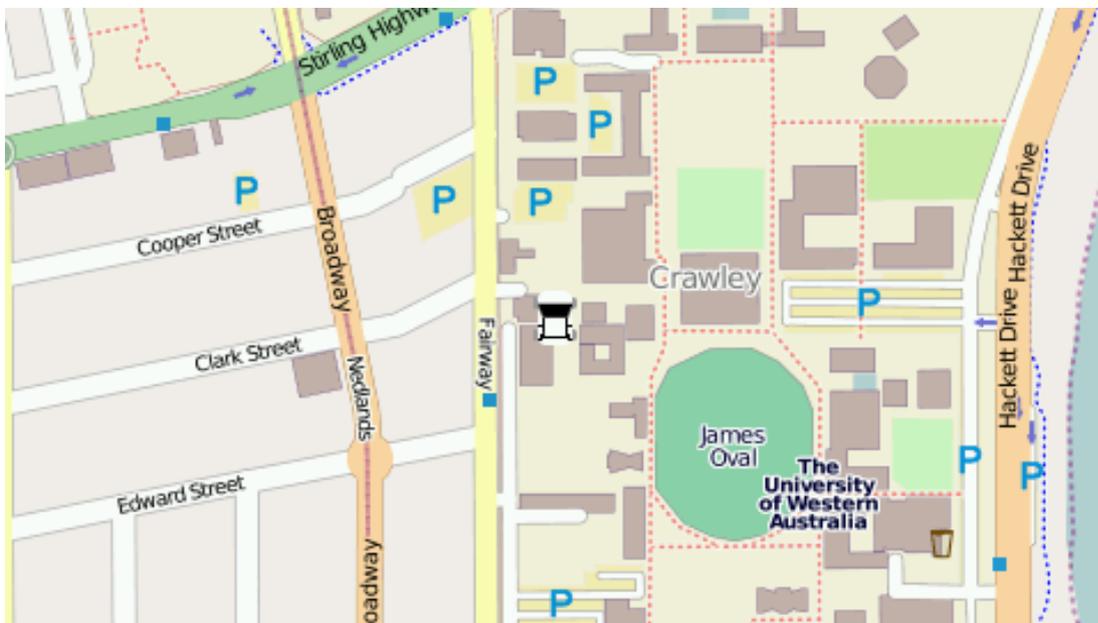


Figure 6.5: Map display panel with hidden controls - Screen-shot of the map display panel, showing the map of the current location and the map controls hidden

6.4.1 Map Data

In order to display the map images, the map data must first be obtained and stored. There are many possible methods for doing this, ranging from creating the maps as needed, or downloading them from external services and storing them in a cache. The relatively low CPU power of the eye-bot m6 makes rendering the maps on-the-fly a undesirable prospect. Open source map data for the entire planet results in a file that is 18GB in size (23). This file is much too large to store locally, and this file is actually storing a compressed version of the data. Even if it were possible for the eye-bot to store this file, via the use of external storage, it would be a large strain on the CPU to convert the street level data into viewable maps. It would also require many other pieces of software to be installed on the device, making it much more complicated to manage.

Another possibility is to use an existing Internet based map server and download the map imagery as needed. This has several downsides. Foremost it requires an Internet connection whenever to display the maps. The system does have a 3G connection installed, but this cannot be considered a dependable communication channel. It is highly likely to drop out, and is limited in coverage to the areas in which it has reception. Even without these issues, most map-servers do not allow you to download maps in bulk, as this violates their usage policies (24). This makes this method undesirable as it is not suit-able for downloading maps in bulk, or as needed. Attempting to pre-download all these maps using a non-3g link would result in a violation of the usage policy.

The method chosen to obtain the map data was to pre-create create the map data using a more powerful machine. A map-server was setup and loaded with all the street data for the Oceania region. For more information on the map-server setup see appendix C. This method overcomes the problems of the previously mentioned methods. All the processing is done on the much faster machine in advance. The area processed in advance is defined by the properties in table 6.1. This area is depicted by the image shown in Figure 6.6. The expanse of these maps covers all of metropolitan Perth. In future more maps can easily be processed, however this will result in more storage space being required. The current settings are a good balance between storage and expanse of data. This is because the map data will be less useful outside of the city, and the

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car is typically not driven any further than the pre-rendered maps. The current space usage of the map data is given in table 6.2. As this is much much larger than the internal 16MB of flash storage the eyebot has, it must be stored on external storage. Luckily, storage is now cheap, and 8GB usb thumb drive has enough performance and space to store and serve the image data.

| Property | Value |
|--------------------|-----------------|
| Minimum Zoom Level | 11 |
| Maximum Zoom Level | 18 |
| Top Left | 115.687,-31.71 |
| Bottom Right | 116.508,-32.253 |

Table 6.1: The properties of the pre-rendered map data

| Property | Value |
|-----------------------|---------------------|
| Zoom Levels | 7 |
| Number of Files | 435,456 |
| Total Size | 580.2 MB |
| File Resolution | 256*256 pixels |
| File Format | Palette PNG |
| Time taken to process | Approximately 1 Day |

Table 6.2: File statistics of map data

6.4.2 Tiling

As mentioned previously, the map data is much larger than the internal storage of the eye-bot. It is also much much larger than the operating systems 64MB of ram. This makes it impossible for the entire map data to be loaded inside any program to be displayed to the user. In order to overcome this limitation, the map panel only loads a small subset of the map data at a time, and displays it using a method called tiling. Rather than have one giant map that displays all of the information, and sliding this around to view the correct part, this method divides the map into many smaller maps. These smaller maps are referred to as tiles. Each tile consists of a 256 pixels wide

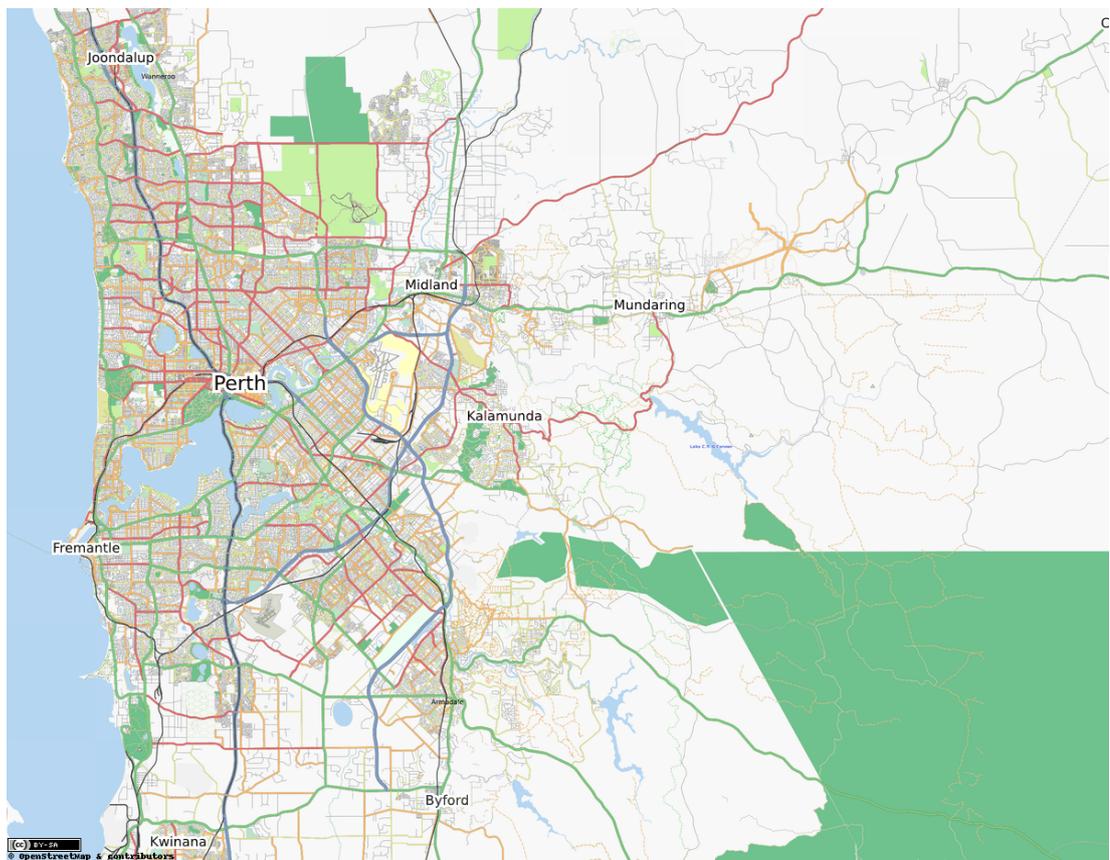


Figure 6.6: Pre-rendered map size - This figure shows the area that has been pre-rendered for use in the map panel display

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by 256 pixels high image. These images are combined in order to display the current location, as seen in figure 6.7. By loading the adjacent tiles in all directions the screen will always have data to display.

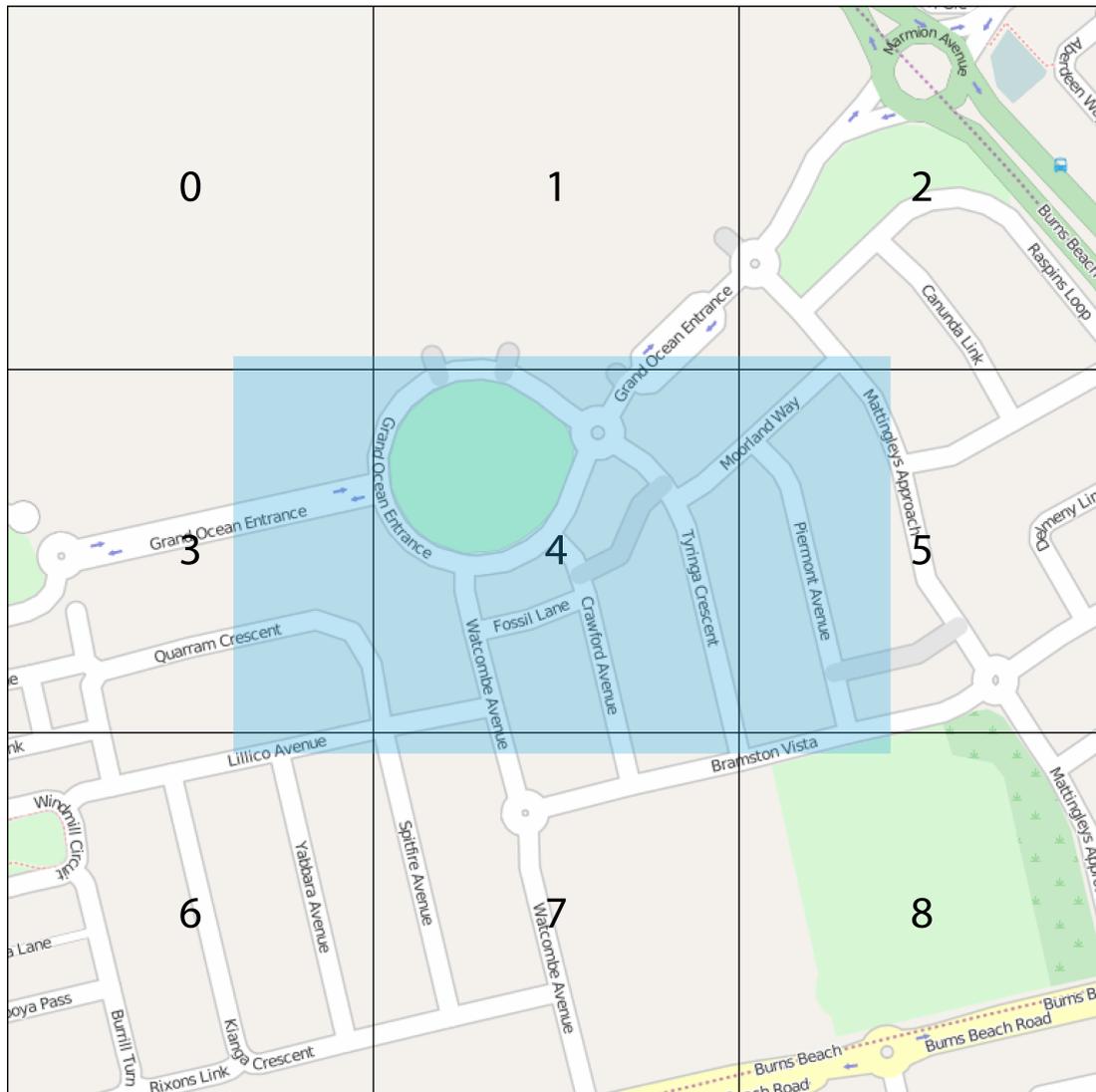


Figure 6.7: Tiling Maps - This figure shows the tiles that are loaded, labeled 0-8, and the area of the screen that is able to view them.

6.4.2.1 Converting GPS Co-ordinates

The GPS outputs the current position in latitude/longitude format. This format must be converted so that the correct tiles may be loaded. To do this the GPS co-ordinates

are converted to grid based co-ordinates using a Mercator projection (25). The equations to convert to this format are given by 6.2 (25). It is possible to convert from a grid co-ordinate back to a GPS co-ordinate using the equations given by 6.4 (25). This of course will only be able to return the top left corner of the tile in GPS co-ordinates, and not the original position.

$$\text{Tile X} = \lfloor \left(\frac{\text{longitude} + 180.0}{360} * 2^{\text{zoom}} \right) \rfloor \quad (6.2)$$

$$\text{Tile Y} = \lfloor \left(1 - \frac{\ln \left(\tan \left(\frac{\pi * \text{latitude}}{180} \right) + \frac{1}{\cos \left(\frac{\text{latitude} * \pi}{180} \right)} \right)}{\pi} \right) * 2^{\text{zoom}-1} \rfloor \quad (6.3)$$

$$\text{Longitude} = \frac{\text{X} * 360}{2^{\text{zoom}}} - 180 \quad (6.4)$$

$$(6.5)$$

$$n = \frac{\pi - 2.0 * \pi * \text{Y}}{2^{\text{zoom}}} \quad (6.6)$$

$$\text{Latitude} = \frac{180 * \tan^{-1}(0.5 * (e^n - e^{-n}))}{\pi} \quad (6.7)$$

With the GPS co-ordinate converted it is possible to locate the tile to display to the user. Rather than utilize lookup files to locate the tile, a specific folder structure is used to instantaneously load the file. This is done by storing the files in the format */zoom/tilex/tiley.png*. This allows the system to directly open the file and display it. Thus even if the entire world was loaded in the maps folder, for many different zoom levels, the display time of the current location would not change.

6.4.3 Palleted File Format

The amount of storage required for all these tiles in an uncompressed format is shown in equation 6.8 using the data obtained in table 6.2. This amounts to approximately 81 gigabytes of information at all the various zoom levels. This size is much too large to store and a small usb drive. It would be possible to store this data on a mechanical disk, but this is much more costly than a cheaper flash based drive, and would require

6. INTERFACE

much more power to run. In order to solve this problem, a compressed file format is used. The PNG file format results in a much more smaller filesize per tile. The average filesize of the final compressed files is approximately 1.3 kB. This is a large contrast to the size of one file in an uncompressed format, being 192 kB. PNG uses various compression techniques to greatly reduce the filesize of the tiles.

$$\begin{aligned} TotalSpaceRequired &= \frac{\text{height} * \text{width} * \text{image} * \text{number of tiles}}{\text{bytes in a megabyte}} & (6.8) \\ &= \frac{256 * 256 * 3 * 435456}{1048676} \\ &= 81648 \text{ MB} \end{aligned}$$

The main technique that is utilized in this system is the use of palettes. Palleting restricts the colour space in the image, in order to save space. The map images do not utilize the full 24bit colour space that the screen is capable of displaying as the maps need to be visually clean, they only use a handful of colours to represent the area. Palleting works by defining the sets of colours that will be used in the image beforehand, or the palette of this image. Consider an image with only two colours. If each colour in the palette is given a value, each pixel in the image can be represented by that value. Hence each pixel can be represented by 1 bit, rather than 3 bytes (24 bits). This is a simple example, but it highlights how palettes can be used to save space. The downside to using this technique, is that it is slightly slower than using raw image data. As the palette is represented in a different format, it must be loaded and converted to the unprocessed data when needed. This takes some time compared to just reading the raw data. This trade-off is worthwhile however, as the space saving more than makes up for the extra CPU time to load the images. The method also has the advantage that the tile images can be easily read or modified by consumer software on other machines, PNG files are very common and can be natively viewed on all full-blown operating systems.

6.4.4 Sliding Maps

The last feature that the map panel implements is centering the vehicles position on the screen. This means that the screen will slide around in response to changes in the vehicles position. It does this by using a modified version of the equations in 6.2.

These modified equation works takes the same inputs, but returns the position of the car inside the grid co-ordinate as a floating point number. This return result has the range $0 \leq result < 1$. A return value of 0 indicates that the top right corner of the image should be placed in the center of the screen. A return value of 1 is never possible, as this would be 0 on a different tile. This allows the tiles to be moved around as the car moves, providing sleek graphical feedback to the operator of the vehicle.

6.5 Trip Meter

A useful driver aid that is common on vehicles is that of a trip meter. Traditionally this component records the distance the car has traveled since the trip meter was set. This functionality is usually a result of the simple systems in place, and is tied to the revolutions of the wheels on the vehicle. As this system has more hardware at it's disposal, the trip meter can implement more functionality than a standard trip meter, making it much more useful in examining the performance of the car. Figure 6.8 shows the trip meter panel being displayed on the screen. An important note of this panel is that all calculations are done whether the panel is being displayed or not.



Figure 6.8: Trip Meter Panel - This figure shows two independent trip meters and the best record speed data

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The first unique point of this trip meter, is that it contains two independent meters. This is useful as it allows the driver to evaluate the statistics of two overlapping trips. One trip meter can be used to record the distance traveled since the car was last charged, while the other can be used to record the distance traveled in the last week or month. This independence allows the operator to decide how best to use the trip meter data, resulting in a high level of flexibility. In figure 6.8 the trip meters are located on the left, sitting above each other.

Each trip meter records the distance traveled, the time elapsed since the meter was started, the time the car has been moving since the meter was started and calculations based on the elapsed and moving time. These statistics are displayed live to the user, but are not logged, as the logging functionality is taken care of by a different component in the system. The trip meter panel also displays the current moving speed in the top right. Below the moving speed are the best run records in seconds. This allows the driver to have quick feedback as to how the car is performing, without having to do lots of processing on logged data.

6.5.1 Distance Driven

The most important part of a trip meter, is the distance that the meter has recorded. This is shown on figure 6.8 at the bottom of each trip meter. The meter stores the distance driven internally as a double length floating point number, but displays it on the screen as a rounded integer. This is done in order improve precision for later calculations as other values will depend on the distance that has been driven. Equation 6.9 shows the the distance is calculated based on the GPS position.

$$\text{Distance} = \text{Distance}_{\text{lastrun}} + \text{Speed}(\text{Time}_{\text{now}} - \text{Time}_{\text{lastrun}}) \quad (6.9)$$

The method for working out is a continuous function that is based on the last known distance the car has traveled. This method was chosen as it does not require any information other than the last time the formula was run, and the last distance calculated. This also makes the trip meter flexible in that the distance calculation does not need to be processed at exact intervals. If messages are dropped for whatever reason, the calculation will still take place, though it will not be as accurate as it could

be. The calculation will be able to cope with fluctuations in the message timing, and can adapt to the speed of the GPS being used.

The downside of this method, is that big changes in time can cause problems with the calculation. If the signal drops out for an extended period of time, such as going through a tunnel, the calculation in 6.9 would have a big margin for error. In order to prevent this, the trip meter will ignore large time differences. If two calculations are over 10 seconds apart, the result will not be trusted, and not be used in the calculation. This prevents GPS signal loss from having an adverse effect on the trip meter calculations, but does impose a limit on the trip meter.

The limitation of this method of calculating the distance driven is that it relies on the GPS messages being sent to it. If the GPS signal is lost, the distance driven will not be increased. This is a limitation imposed by the use of the GPS sensor, and cannot be avoided, as attempting to guess the distance driven while the GPS signal has been lost has a very high probability of being incorrect.

6.5.2 Time Elapsed

Another variable displayed on the trip panel is the time elapsed. This is simply the time elapsed since the trip meter was last reset. This time increments even while the GPS signal has been lost, performing a stop-watch like action on the trip. While it may seem natural to just record the time that the trip meter was started and subtract it from the current system time, this would lead to problems during the system startup. The time needs to increment even while the GPS is connecting, and must be resistant to changes in the systems internal clock. Thus the time is calculated similar to section 6.5.1. The formula used to calculate the elapsed time is given in equation 6.10. The time elapsed is displayed as the highest element of the trip meter in Figure 6.8

$$\text{TimeElapsed} = \text{TimeElapsed}_{\text{lastrun}} + (\text{Time}_{\text{now}} - \text{Time}_{\text{lastrun}}) \quad (6.10)$$

Much like the distance, this method of calculation depends on the last known values. This means it does not matter at the actual time the system trip started once the timer has been running. This makes it resistant to changes in the system time, and thus makes the timer more robust. This timer records the time elapsed on the nanosecond level,

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as it is used elsewhere in calculations. For display, the timer converts these values into the traditional hours, minutes, seconds format that is easy for the operator to read.

6.5.3 Moving Time

An aspect of the cars telemetry that would be interesting to the driver is the cars moving time. This is defined as the time in which the car has spent in motion. The main use of this data point is to contrast it against the elapsed time, to highlight how long the car has spent sitting still in traffic. This variable is also useful to record for future calculations, such as working out the average speed of the trip. This element is calculated according to equation 6.10, except that it will not update if the current speed of the car is 0 km/h. As such this element requires the speed of the car to be processed, so it cannot be calculated when the GPS signal is lost. This fits in with the functionality defined in section 6.5.1, as the trip meter will not update the moving time or distance driven if the GPS signal is lost. The moving time is displayed below the elapsed time and above the distance driven in Figure 6.8

6.5.4 Average Speed

When reviewing the trip meter data, it is useful to know the average speed the car was traveling during the trip. Having this information allows the driver to better understand the characteristics of the drive. This element is also easy to calculate, as the time elapsed and the distance driven are already available. Equation 6.11 shows the formula used to calculate the average speed. The calculated value is displayed to the right of the elapsed time in figure 6.8.

$$\text{AverageSpeed} = \frac{\text{DistanceDriven}}{\text{TimeElapsed}} \quad (6.11)$$

This value is calculated whenever the distance driven or elapsed time values are updated. As this value is using two calculated values, it does not need to worry about discrepancies in time or the loss of the GPS signal.

6.5.5 Average Moving Speed

The average moving speed is like the average speed. The only difference is that it uses the moving time to calculate the speed, rather than the elapsed time. This is done using the same equation 6.11, only substituting "Time Elapsed" for "Moving Time". This value provides the average speed of the car when it was actually being driven, thus ignoring time spent waiting in traffic.

6.5.6 Reset

The final functionality of each independent trip meter is the reset button. This button resets the trip meter it is attached to. The distance driven, moving and elapsed time counters will all display zero, and the average speed calculators will display zero. As each trip meter is independent, one can be reset without affecting the other. To reset the trip meters, the driver just has to press the reset button, located below the average moving time and to the right of the distance driven in Figure 6.8.

6.5.7 Current Speed

The trip meters provide statistics on where the car has been driven, but do not provide much insight into the instantaneous speed of the vehicle. As this variable is already being used in calculations it is trivial to display it to the driver. This is displayed using a simple digit element, and appears in the top right corner of Figure 6.8.

6.5.8 Time Trial Data

A common metric in measuring the performance of cars is to measure how long the car takes to achieve a certain speed. Usually this requires expensive equipment in order to accurately measure the time and speed data. As the information exists inside the trip meter in some form already, it is useful to display a less accurate version of this time trial data. By recording the time it takes to reach 50 or 100 km/h the operator is able to have quick feedback on the performance, without having to setup lots of equipment. The flow chart of this calculation is given by Figure 6.9. The results of this are displayed below the current speed in Figure 6.8

An important condition on this flow chart is that the zero time must be set before any calculations are performed. The zero time is the time at which the car was last

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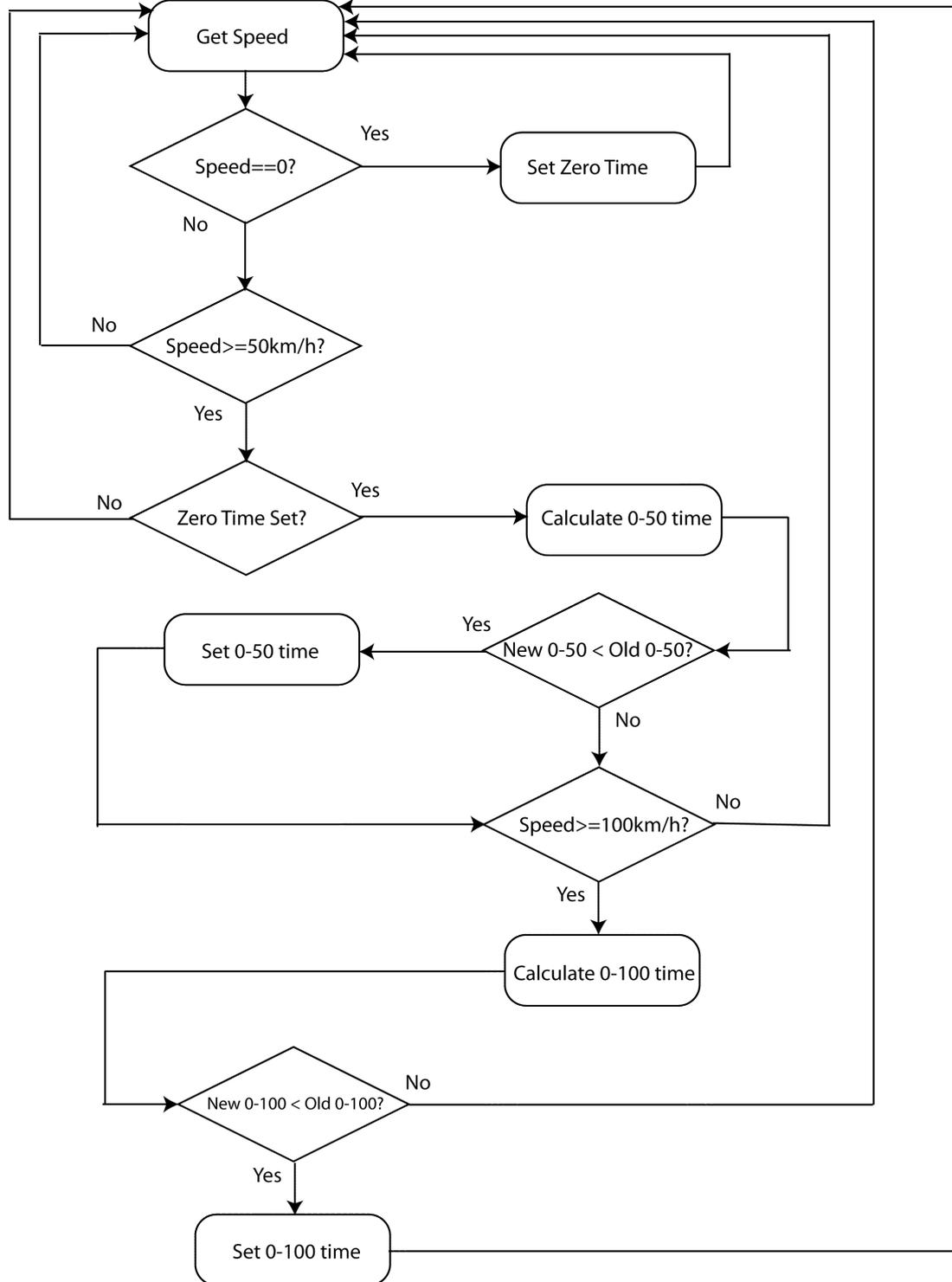


Figure 6.9: Time Trial Data flow chart - The program flow used to calculate the 0-50 km/h and 0-100 km/h time trial data

traveling 0 km/h. This time will be reset whenever the car is stopped, so the calculation requires no input from the user. Also present in the flow diagram is that the system will display the best time recorded. If there is a previous best time, and a new one is achieved, the new one will automatically be displayed. This allows the user to ignore the trip meter panel entirely, and be able to trigger and record some performance data on normal drives.

6.5.9 Persistence

A required feature of this panel, is persistence of the calculated results. If the system is off-line, it should remember the calculated values when it next starts up. It achieves this functionality by storing the values needed in a simple text file, that is present with the program's executable. If this file is not present when the program is run, it will be created with zero values. The system will write data to this file every 10 seconds. The delay is required so that the file-system is not overloaded by requests to continually write the data to the file system, which would result in poor performance of the messaging loop. 10 seconds is an adequate trade-off between loss of data due to a system crash, and the performance cost of saving the data.

Table 6.3 shows the file structure used to store the persistent information. This file format is stored as an ASCII file, so it is easy to modify the values displayed should the need arise. Each property is separated by a newline character. There is only one property stored per line, making the file a simple one-dimensional column. It creates it's own file under the name of *tripsaved.txt* in order to simplify loading and protect it from errors in other files.

Most of these values are directly displayed on the screen, so it is easy to verify if they have been set correctly. Line 1 is the current distance value. This value is used to offset the other trip meters. This value should be 0 under normal operation. Lines 2 and 3 represent how far the each individual trip meter has recorded. Lines 4 and 6 represent the elapsed time of each meter and Lines 5 and 7 represent the moving time. The average speed values are calculated from these values.

The last important aspect of the file is that it is written atomically. All the values are written out to the file together. This is done in an attempt to minimize the affect of power outages on the file. It reduces the chances that half the file has been written when the power was cut, thus helping to protect the file's integrity.

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| Line | Property | Example Value |
|------|------------------------|---------------|
| 1 | Current Distance (km) | 0 |
| 2 | Trip 1 Start (km) | -118.962 |
| 3 | Trip 2 Start (km) | -128.845 |
| 4 | Trip 1 Time (s) | 70430 |
| 5 | Trip 1 Moving Time (s) | 46652 |
| 6 | Trip 2 Time (s) | 70162 |
| 7 | Trip 2 Moving Time (s) | 46384 |

Table 6.3: File Format for persistence of Trip Panel

6.6 Interrial Measurement Unit Display Panel

Developed in section 4.7 was a system that read accelerometer data from a serial connection. This data is displayed on the device via the IMU display panel. This panel is shown in figure 6.10. As the data in 4.7 is not currently calibrated, this panel outputs the raw data for display on the screen. The main purpose of this is to verify that the module is functioning correctly, and to developed a template for future work with displaying and interpreting this data. This panel displays the acceleration on the x, y and z axis and also shows the pitch roll and yaw of the IMU device.

6.7 Digital Inputs

Described in section 4.6 was a hardware system able to interface with digital inputs. The purpose of this panel is to display those inputs to the operator. This display is shown in figure 6.11. It uses digit elements to display the two connected voltages, and the two calculated frequencies. It also uses a boolean triggered display element to display the status of 8 individual digital inputs. This display shows the raw data from the input board, enabling the values being transmitted to be examined and analyzed in real-time.



Figure 6.10: IMU display panel - This figure shows the information output by the IMU daemon



Figure 6.11: Arduino display panel - This figure shows the information output by the Arduino based IO board

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6.8 Economy Panel

Reduced running costs are one of the most cited reasons for the interest in electric vehicles. As such the system tries to quantify the savings that occur by providing a screen which shows an approximation of the running costs of the vehicle. It does this by making some assumptions as to the cost that the petrol version of the car would consume. This is contrasted against the power that the car has consumed over the same duration. Using these values, the cost of running the car on electricity and on petrol can be calculated and the difference can be displayed. Figure 6.12 shows this panel displayed on the device. The values displayed here are persistent through multiple drives, allowing for the differences to be calculated over a long period.



Figure 6.12: Savings Panel - This figure shows the savings panel, it calculates the cost of running the car on electricity and approximates the cost of running the car on petrol

6.8.1 Petrol approximation calculation

The car does not consume any petrol, so it is not able to provide data in relation to the amount of fuel consumed. As such the system attempts to approximate the amount of fuel that would be consumed. It does this by using the cars advertised fuel consumption, at 6.1 L per 100 km (26). It uses the same method to calculate the distance driven as

seen in section 6.5.1. This value is calculated independently of the values calculated in the trip panel, this was done to ensure that each panel cannot affect the other panel. It is not possible to reset the a trip meter and change the economy panel. The last variable required to calculate the cost is the price of the fuel. While this is highly variable, a single value is used to provide an approximation to the cost.

$$Petrol\ Cost = Distance\ Driven * Fuel\ Economy * Price\ per\ Litre \quad (6.12)$$

Equation 6.12 shows the formula used to calculate the petrol cost. The distance driven, and cost per litre of fuel are displayed on the display providing insight into how the calculation is performed. The static price of petrol used works with this display, as the user is able to see the links between the numbers.

This is not an incredibly precise calculation, as the GPS can drop out or be slightly off with the distance traveled. It also will not reflect the real cost, due to a static fuel consumption being assumed. It is also unable to take into account the fluctuation of fuel prices over a long period of time. The calculations purpose is to provide a rough ballpark figure, so the user is able to have some indication of the cost the petrol car might have incurred.

6.8.2 Electricity calculation

Given the voltage and current, the instantaneous power can be calculated according to Joule's Law (27). The formula for calculating the power is given in equation 6.13.

$$P = VI \quad (6.13)$$

The battery monitor module outputs both the current flowing out of, and the voltage level of the battery at a rate of 1hz. With this information it is possible to calculate the power that the vehicle has consumed. By dividing equation 6.13 by the number of seconds in an hour, the power consumed in units of kwh is obtained for the last second. Continually summing this value will lead to the total kwh consumed by the vehicle.

By multiplying the result by the cost in per kwh hour, the total cost can be obtained. Like the petrol calculation, the units of this calculation are displayed on the screen, so the user is able to intuitively understand the calculations being performed. This

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calculation does have some drawbacks, as it does not take into account fluctuations in electricity costs, such as on and off-peak charging. It does also not take into account in-efficiencies in the charging equipment. The power present in the batteries, and consumed by system while running will not be equal to the power that was supplied to charge the batteries. This is acceptable however, as the purpose of the calculation is to provide rough estimates, in order to provide feedback as to how much the car is costing to drive.

6.8.3 Resetting

Over time, the operator may want to reset the settings back to an initial zero state. This could possibly after months of driving. To facilitate this, the panel has a reset button present. This button will reset the distance driven and kwh consumed values. As these values are now both zero, the calculated cost values will also become zero.

6.8.4 Persistence

Like the trip panel, see section 6.5.9. The Economy panel also requires memory if the system goes off-line. It achieves this functionality by storing the values needed in a simple text file, that is present with the program's executable. If this file is not present when the program is run, it will be created with zero values. The system will write data to this file every 10 seconds. The is exactly the same method use to provide memory to the trip panel.

Table 6.4 shows the file structure used to store the information. Like the Trip panel the format used stored is an ASCII file. It creates it's own file under the name of *moneysaved.txt* in order to simplify loading and protect it from errors in other files. This file is completely independent of *tripsaved.txt* so changes in one file will not affect the other.

Most of these values are directly displayed on the screen, so it is easy to verify if they have been set correctly. Lines 1 and 2 are the variable values of distance driven and power consumed. These lines will be updated every 10 seconds as discussed earlier. The other values on lines 3-5 are read from the file. These are the parameters of the car used in the calculation. They will remain static throughout each update of the file.

| Line | Property | Example Value |
|------|-----------------------|---------------|
| 1 | Distance Driven (km) | 145.242 |
| 2 | Power Consumed (kWh) | 44.2259 |
| 3 | Petrol Cost (c/L) | 147 |
| 4 | Power Cost (c/kWh) | 18 |
| 5 | Petrol Economy (km/L) | 0.062 |

Table 6.4: File Format for persistence of Economy Panel

6.9 About

The about panel is a simple panel that only displays one image element. This image element consists of a brief information about the program follow by images of all the sponsor logos. The purpose of this panel is to help provide advertising for the sponsors, and to highlight that the system is a project of the Renewable Energy Vehicle group.

This panel has one image element that takes up the whole screen, and a button that is not visible to the user. This button also takes up the whole screen. The purpose of the button is to provide a trigger point to transition back into the main program. If the user presses anywhere on the screen, the button will be pressed, and the interface will return to the application selection panel.

6.10 Settings

The previous features have all discussed elements of the interface that are useful to any general driver. These are features that are useful while operating the vehicle. There also exists another user that has a different set of requirements to fulfill. This user is the maintainer of the car. This user will need access to various aspects for debugging and development purposes, including the ability to easily examine and transfer the internal logs of the system. In order to help simplify the navigation of the program, these elements are located in the settings screen. A screen-shot of the settings screen is shown in figure 6.14.

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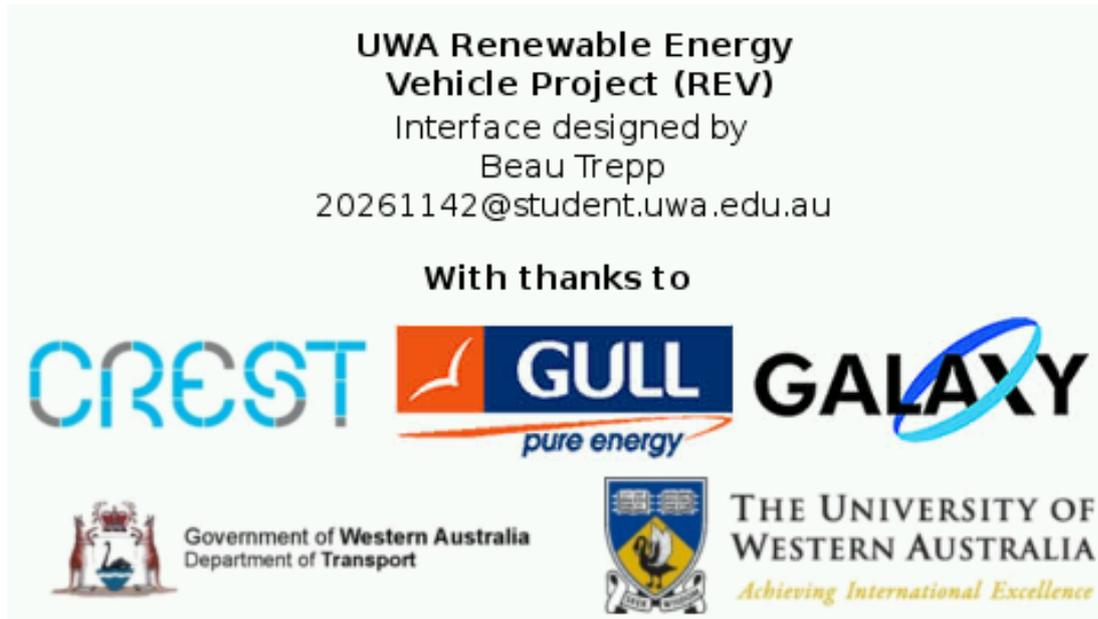


Figure 6.13: About Panel - This figure shows the about panel, which displays the sponsor information of the car.



Figure 6.14: Options Panel - This figure shows the options panel, which displays various utilities that are needed by the maintainer of the vehicle.

6.11 Debug

The top left most button in figure 6.14 will navigate to the debug panel. This panel is shown in figure 6.15. The purpose of this panel is to display the messages that are being received from the daemon programs, see section 4.1. This panel displays the byte level contents of each message to the user as it is received. This is used to help facilitate debugging, as the writer of the daemon is able to see exactly what is being received in the interface.

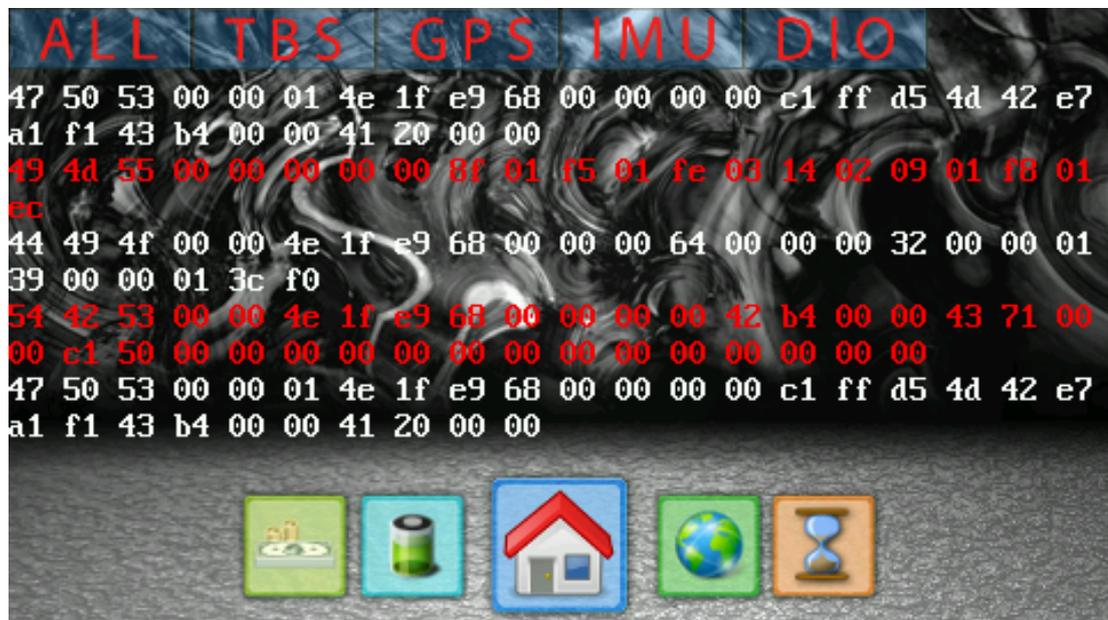


Figure 6.15: Debug Messages Panel - This figure shows the Debug panel, it allows the user to filter which messages are displayed and alternates the colour between each received message

This display panel has various buttons that exist on the top of the screen. These buttons allow known messages to be filtered out, enabling specific debugging to be undertaken. As discussed earlier, the first 3 bytes of a message are used to filter different kinds of messages. When a button is enabled, it will allow those messages to be drawn on the screen. Multiple combinations of messages can be combined to display any combination. The buttons labeled, TBS,GPS,IMU and DIO will filter the ASCII values of the first three bytes of each message. The all button will ignore any filtering, and will allow any message to be displayed, including ones that may not have been

6. INTERFACE

developed or seen before.

This panel uses a `ConsoleElement` to display it's data as seen in section 5.2.7. This allows new messages to be displayed on the bottom of the screen, and travel upwards as they become outdated. It also provides a clear distinction between messages, as seen in figure 6.15. The messages alternate between red and white as they are displayed, making it easy to identify the trailing portions of each message.

6.12 Network Status Display

In order to verify that the system is working correctly, it is helpful to view the messages being sent as in the Debug Panel. This panel can provide too much information, and requires the user to understand hex in order to verify that each message is being received. In order to simplify this, a panel was developed that displays the status of each different type of message. This uses the simple boolean display element previously mentioned in section 6.7. This element will display green whenever messages are currently being received by the system. If no message is received in the previous 10 seconds, the marker will transition to red in order to illustrate this. This allows a quick view as to the health of the system, and highlights components that need to have further inspection.

6.13 System Logs Display

As mentioned in section 4.3, all aspects of this system report errors by logging them to the syslog application. This prints out the warnings and errors created to `/var/log/messages`. This panel loads and displays any information logged into this file. This information may come from any of the daemons mentioned in section 4.1, the interface itself, or even other systems that are running on the Linux installation.

An important aspect of this panel is that it only displays the most recent information that has been logged. This makes it compatible with the `ConsoleElement` described in section 5.2.7. The Console Element will automatically take care of displaying the last pieces of information it has received. This would produce the desired functionality, however further optimization needed to be undertaken.



Figure 6.16: Daemon Status Panel - This figure shows the status of the various daemons, green indicates the daemon is active, red indicates a timeout

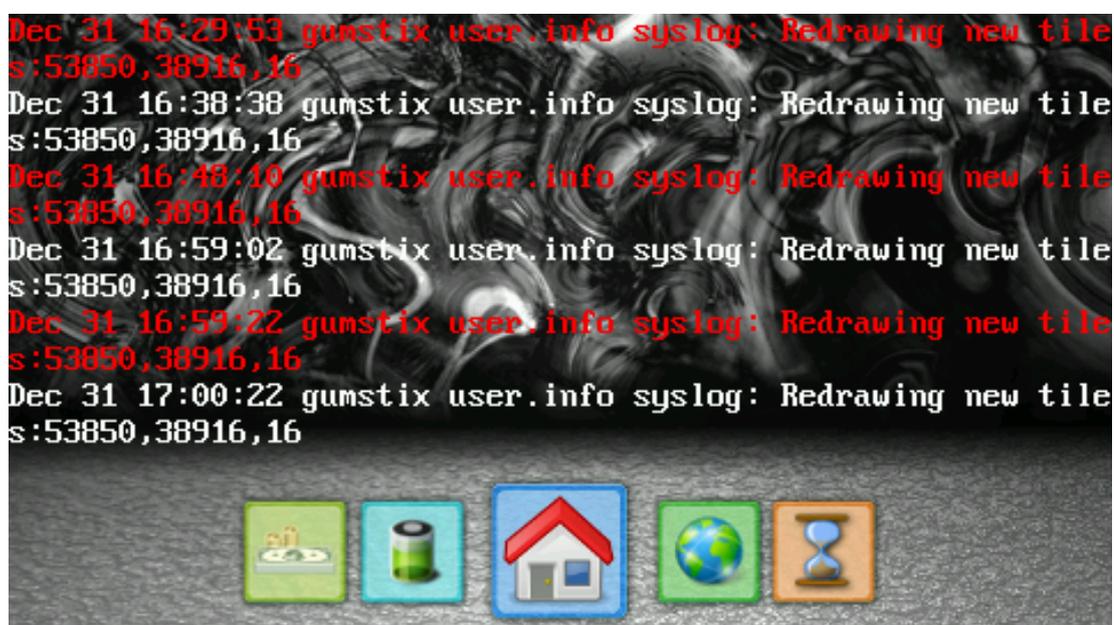


Figure 6.17: Syslog Panel - This figure shows the System Log panel, this displays the most recent entries in `/var/log/messages`

6. INTERFACE

The file */var/log/messages*, is logged to by all applications since the system started. Thus it grows in size the longer the system has been operational. Without optimizing the way this file is read, it would take $O(n)$ time to display the newest entries in the file on the Console Element, where n is the number of entries in the file. This is not acceptable as the time taken to display the logs will increase the longer the application is running. In order to fix this problem, the file is read from the end of the file minus a 2048 byte offset. The maximum width that can be displayed is 60 characters, and the maximum possible lines that can be shown on the screen is 20. This yields the result of 1200 possible characters as seen in equation 6.14. This size is roughly doubled to 2048, in order to ensure more than enough lines are read for each update. This method of reading the last 2048 characters and finding the unique lines inside them is not affected by the file size, so the time taken to update the display is now $O(1)$. The update is not dependent on the number of lines in */var/log/messages*

$$\begin{aligned}\text{Maximum Characters} &= \text{Characters per line} * \text{Number of Lines} && (6.14) \\ &= 20 * 60 \\ &= 1200\end{aligned}$$

As the actual log file may be updated very quickly the screen must not update automatically. This is to stop the screen transitioning while the user may be reading something on it. As such the panel does not support any automatically updating functionality. In order to update the screen, a system like that in section 6.9 is used. An invisible button is created to span the whole display. When pressed, this button will read the */var/log/messages* file and update the screen accordingly. This allows for the maximum utilization of space possible, as no space needs to be created to display a refresh button. The messages will also be updated when this panel becomes the active panel displayed on the screen.

6.14 Copy Log Files

Discussed in section 4.8 is a utility that records the telemetry data locally. In order to make the files created by this logger easier to access, the user interface provides a mechanism for them to be copied onto an external usb drive. Figure 6.18 shows the

display asking for user confirmation to copy the log files. If the user confirms the action, the program will navigate to the directory in which the log files are stored, and copy them byte by byte to the external drive. Once completed the screen will display the figure 6.19.

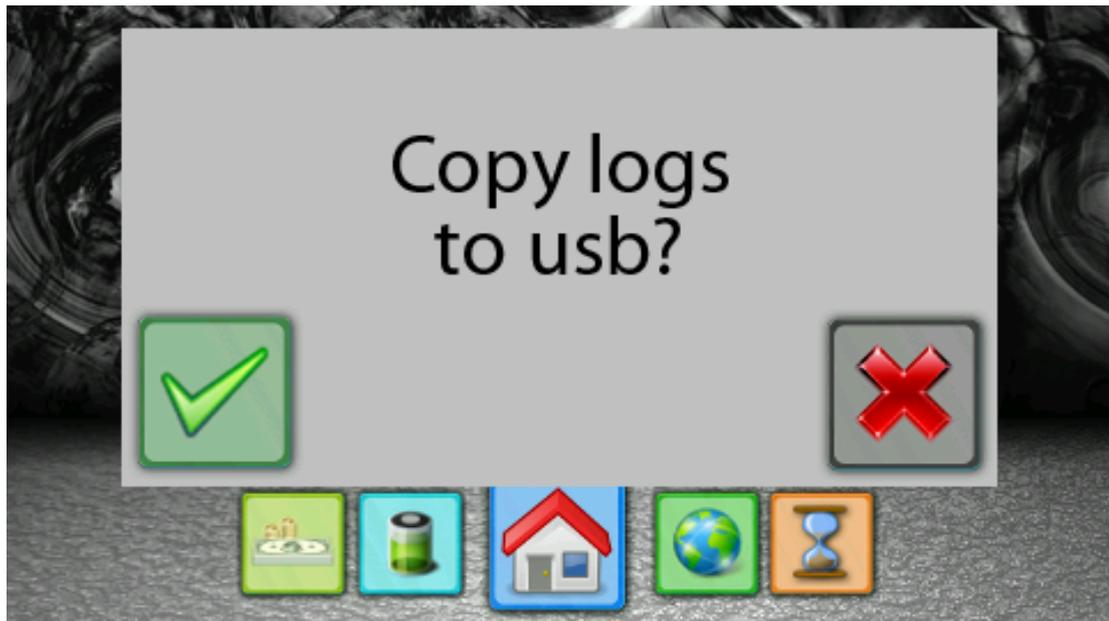


Figure 6.18: Copy Popup - Popup asking the user if they wish to copy log files to the an external drive

If an error occurs, the system will log the results to the in-built system logger, syslog. This will allow the results to be viewable at `/var/log/messages`, and thus can be viewed by the Syslog panel. While copying, the interface will display the progress of the action. It does this by indicating the amount of files to be copied, and the current file it is copying across. This is implemented so the user can be sure the system has not hung or encountered another error.

6.15 Delete Log Files

In order to prevent the storage media from filling up, and to help organize the files when they are copied over the interface provides a mechanism to delete all the log files. Figure 6.20 shows a popup asking the user if they wish to delete the files. This functionality functions much the same way as copy, except that it does not require an



Figure 6.19: Copy Completed Popup - This popup confirms that all the log files have been correctly copied to the usb drive

external drive. It will simply open the folder and delete the files one by one. This action will also display its progress, and will provide the user with a message once the action is complete.

6.16 Exit Program

In order to allow other programs that use the various hardware, such as the screen or the touch driver, to run the current application must be exited. The system facilitates this by placing an exit action on the options panel. When this button is pressed, the popup shown in figure 6.21 will be displayed. This popup confirms that the user wishes to exit the application. If the user agrees, the program will exit and the screen will be set to black. If the user cancels, the system will return to the previously displayed panel, allowing normal operation to resume.

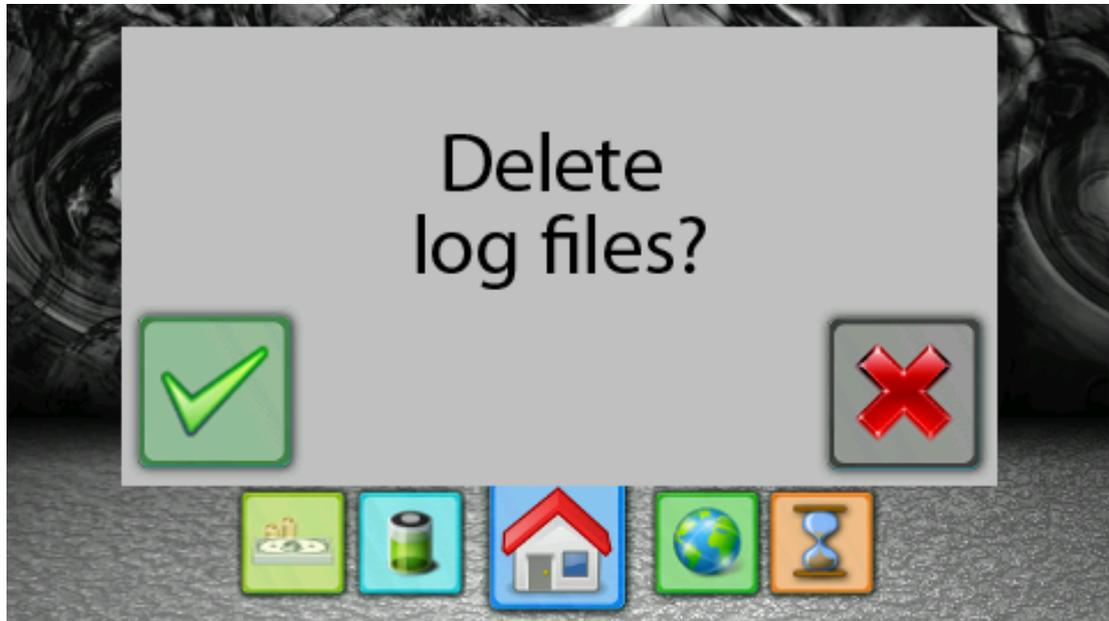


Figure 6.20: Delete Log Files Popup - This asks the user if they want to delete all the log files stored on the system

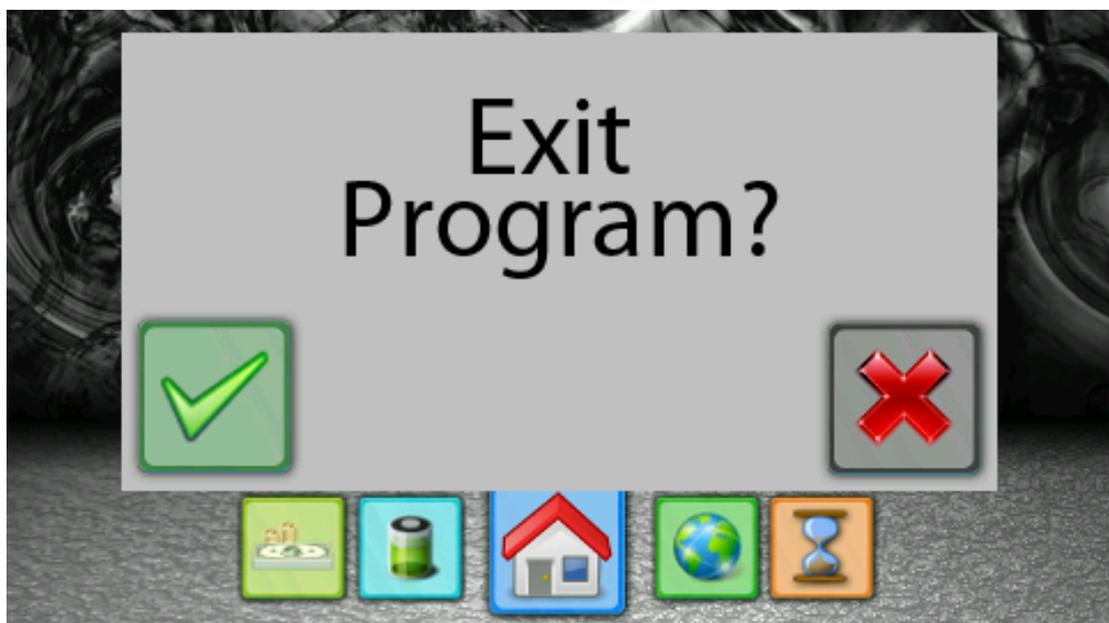


Figure 6.21: Exit Popup - This popup confirms that the user wants to exit the running application

6. INTERFACE

7

Performance

7.1 Limitations

In testing the final system, issues arose which limited the depth in which the systems could be evaluated. As such only partial evaluation has been undertaken. This was done in an effort to provide some indication as to the stability of the system, and this section will provide analysis over what data could be obtained.

7.1.1 Restricted Access to Vehicle

On the 15th of August the vehicle that was the main target for development was involved in a car accident. For safety reasons, the author was not allowed to work on the car in any form after this accident. This severely limited the amount of testing that could take place, as many aspects of the hardware are installed in the car which was no longer accessible.

7.2 Message throughput

Figure 7.1 shows the amount of time it takes to receive varying sized messages. The raw data is available in appendix F. This data was obtained by having the eyebot receive messages while a laptop sent them as fast as possible.

The interesting thing about this graph is that it shows that the time taken to receive the messages does not differ greatly with larger message sizes. This is useful to observe as it means more complicated messages will not slow down the system, in regards to

7. PERFORMANCE

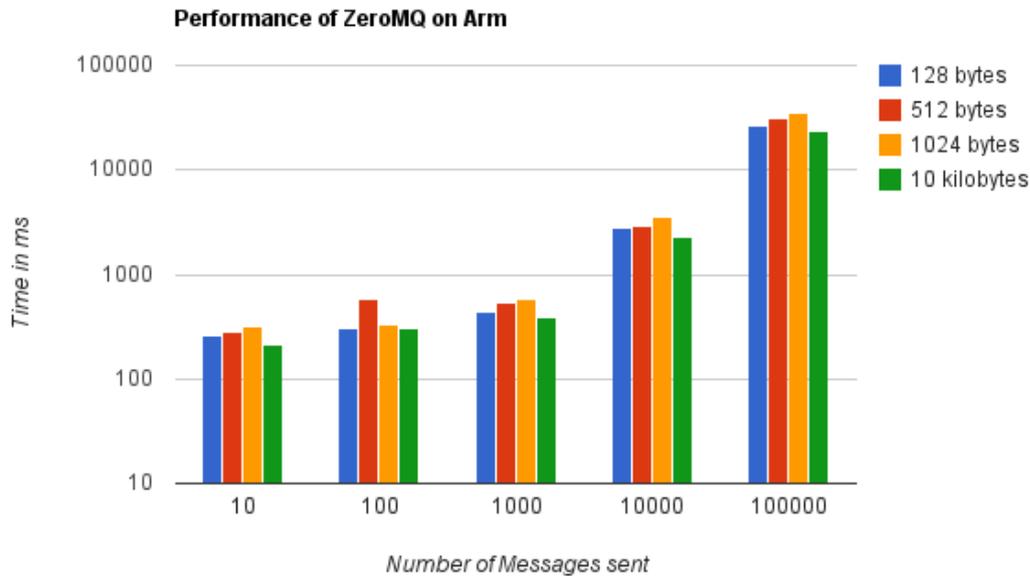


Figure 7.1: Message throughput - Time taken for a varying amount of messages to be received, for varying message sizes

transmission times. More complicated messages do mean there is more data to process, which would adversely affect the system. A peculiar aspect is that of the 10 kilobyte payload size. It appears to take less time than the others. This is most likely due to the processor of the laptop or the eyebot being more busy when the other tests took place. This is very hard to prevent, as it is impossible to control the operating system to prevent this. However the difference is not too great, so the slight change in values is not a large problem.

This graph also shows that the system does not slow down too much when under 1000 messages are being sent. The fact that 10,100 and 1000 are all reasonably similar indicates that the physical transmission and overhead of sending the data has more impact than the amount of messages being sent. This is good as the system currently does not exceed a message rate of 100 messages per second, using packets much smaller than the minimum in the test. As such the current configuration will not be hampered by transmission delays.

It is important to note that this is transmitting the data from a laptop to the eyebot.

On the hardware, the components reside on the same device, as such the transmission statistics would be much more favorable. This of course out-weighed by the fact that the hardware would be doing two things, generating and transmitting messages. The message subsystem was not tested this way as it would be hard to identify what was causing delays when the same device is both transmitting and receiving the messages.

7.3 Inter-message Timings

This section reveals the time in between messages for the various components that transmit them. This was done using an eyebot to run the programs, and the messages were received on another laptop. Errors in the measurement can be contributed to the process switching active on both devices, as well as the fact that the laptop was communicating via a wireless network connection. All tests were conducted for approximately 20 minutes.

7.3.1 Arduino Board

Figure 7.2 shows the time between messages received vs the running time in the program. It is interesting to note that there are occasions when the time between two messages can be as much as 4 seconds. As the graph displays, this phenomenon appears to occur every 7 seconds. This is most likely caused by delays in the operating system on the receiving or sending end, as the process will not switch to the foreground automatically. As the delay is rarely more than 4 seconds, this will not interfere with the timeouts implemented in section 5.3.2

7.3.2 Accelerometer

The accelerometer runs at a much faster rate than the Arduino board. This is reflected in graph 7.3. It can easily be seen that this program sends out messages much more frequently. It still suffers the same problem with longer delays occurring. However each occurrence is still well under any timeout limits.

7.3.3 GPS and Battery Monitor

Due to both being physically installed in the vehicle, it was not possible to evaluate the message timings of these systems. See section 7.1.1

7. PERFORMANCE

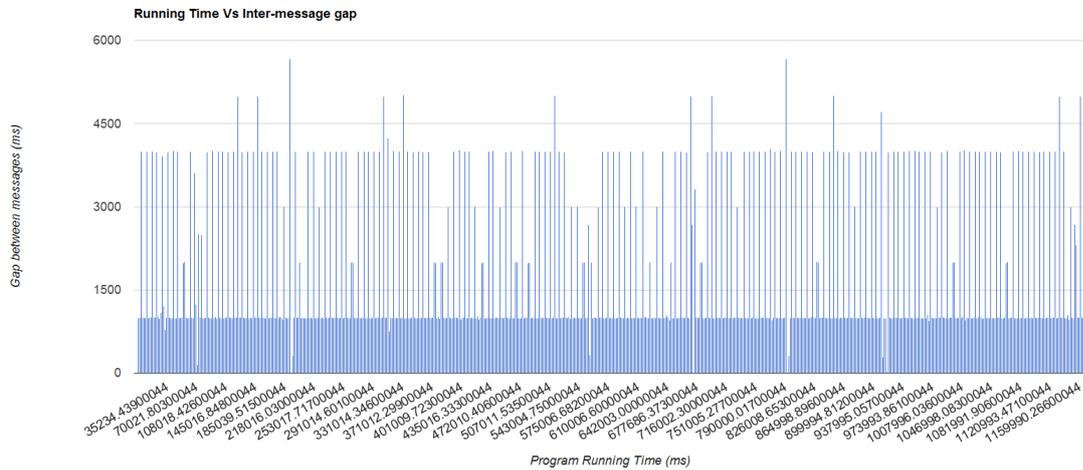


Figure 7.2: Inter message timing for Arduino network messages - The time delay between messages plotted against the time the program has been running for

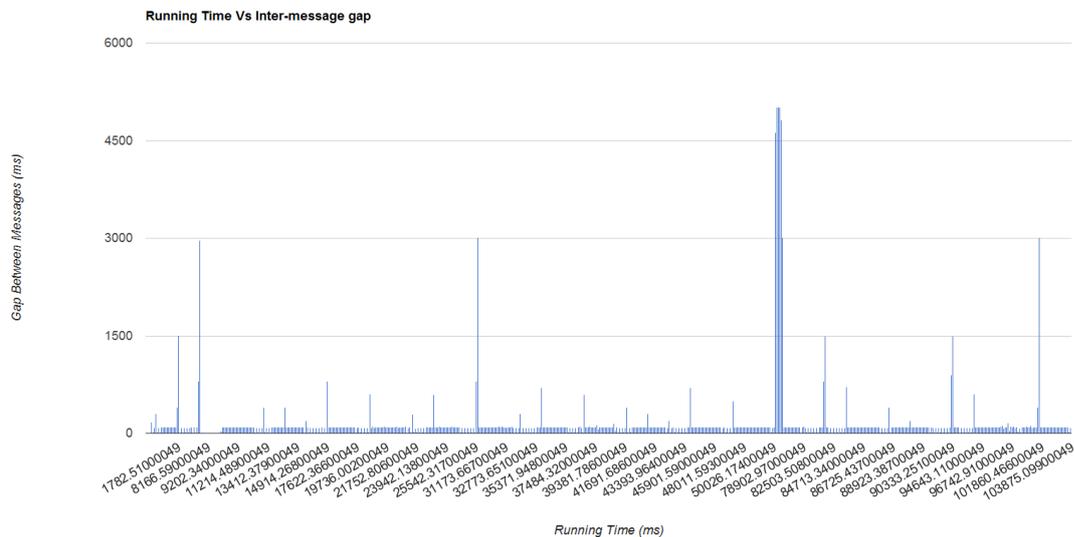


Figure 7.3: Inter message timing for accelerometer network messages - The time delay between messages plotted against the time the program has been running for

7.4 Memory Utilization

This section shows plots of the memory usage of each daemon vs the running time of the program. If a program has a memory leak, it will eventually cause exhaust the systems memory and cause instability. These graphs exist to highlight any issues that may occur with running programs.

7.4.1 Arduino Board

Sadly, as shown in figure 7.4, the Arduino based daemon does have a minor memory leak. After running the program for one hour, the memory usage had increased by 100kb. This memory leak is not too much of a problem. The system will never be on for more than a day at one time. After a day running non-stop, the program will only consume a little over 2mb. This is nothing compared to the 64mb of ram available to the system, so this problem is very minor.

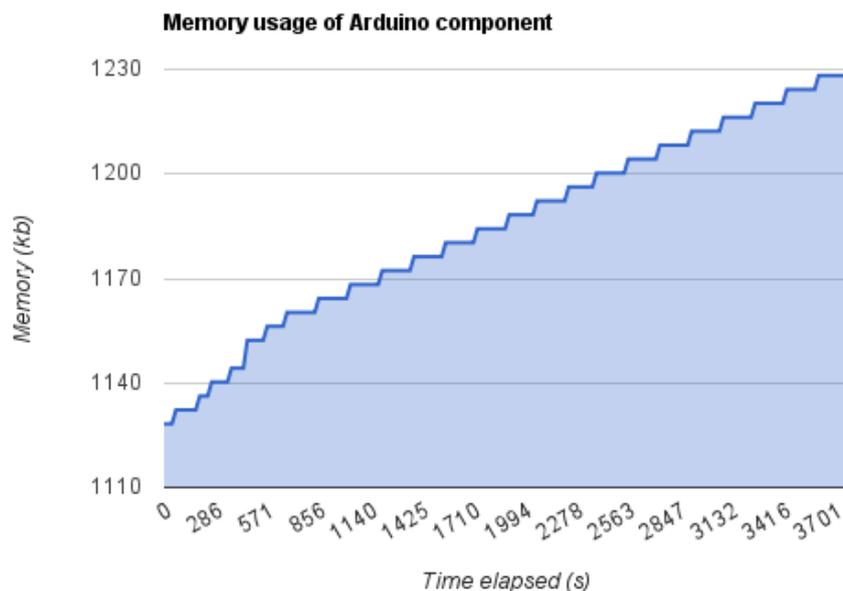


Figure 7.4: Memory usage of the Arduino daemon - Memory usage (in kb) plotted against the time the program has been running for

7. PERFORMANCE

7.4.2 Accelerometer

As shown in figure 7.5 the Accelerometer daemon has a memory leak at the rate of 760kb per hour. This is much worse than the leak in the Arduino board. Extrapolating this usage out to one day yields a memory usage of approximately 18mb. This is still small enough to not cause major problems, though it does warrant an investigation into the cause of the memory leak. As long as the system is not run for over a day without a restart, this leak will not be a problem.

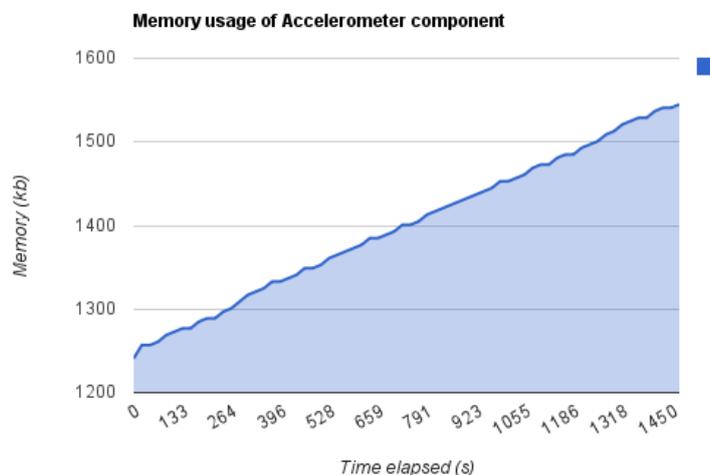


Figure 7.5: Memory usage of the Accelerometer daemon - Memory usage (in kb) plotted against the time the program has been running for

7.4.3 User interface

The user interface was tested with a simulator sending messages from all four components developed in section 4.1. As figure 7.6 shows, the user interface does not have any memory leaks. The interface can run for any amount of time and will not cause system instability. This is a good result as the user interface will always remain responsive.

7.4.4 GPS and Battery Monitor

Due to both being physically installed in the vehicle, it was not possible to evaluate the message timings of these systems. See section 7.1.1. Running these programs without access to the hardware would not yield reliable results.

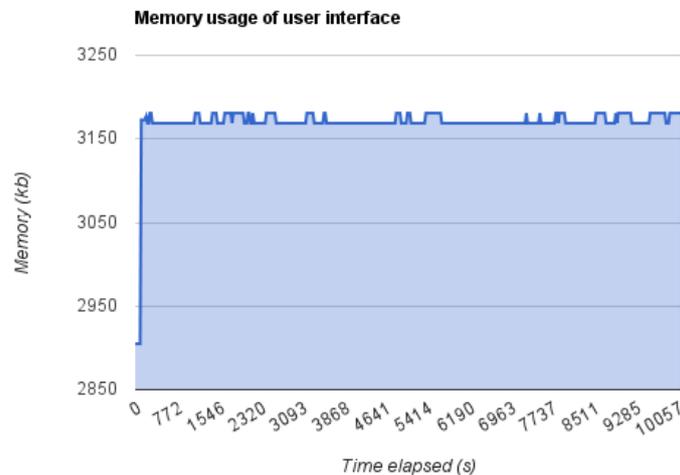


Figure 7.6: Memory usage of the user interface - Memory usage (in kb) plotted against the time the program has been running for

7.5 Logged data

Discussed earlier was logging mechanisms in order to record information about the vehicle. The following shows some of the data obtained through this mechanism. The following sections discuss the results obtained from a single drive. The intent was to undertake much more test drives, but due to the circumstances mentioned in section 7.1.1 this was not possible.

7.5.1 Path recording

The system developed records the GPS location. This will be recorded at a minimum of 1hz, so there will be one entry in the log file for each second. Figure 7.7 shows the path the car undertook on a test drive. This path drove from the 'University of Western Australia' to 'East Fremantle' and back again.

7.5.2 Speed and Current

Other aspects also recorded by the system are the speed and the current. These two variables are showed graphed against time in figure 7.8. This graphs shows a few interesting points that would not be evident without the use of the logging system.

7. PERFORMANCE

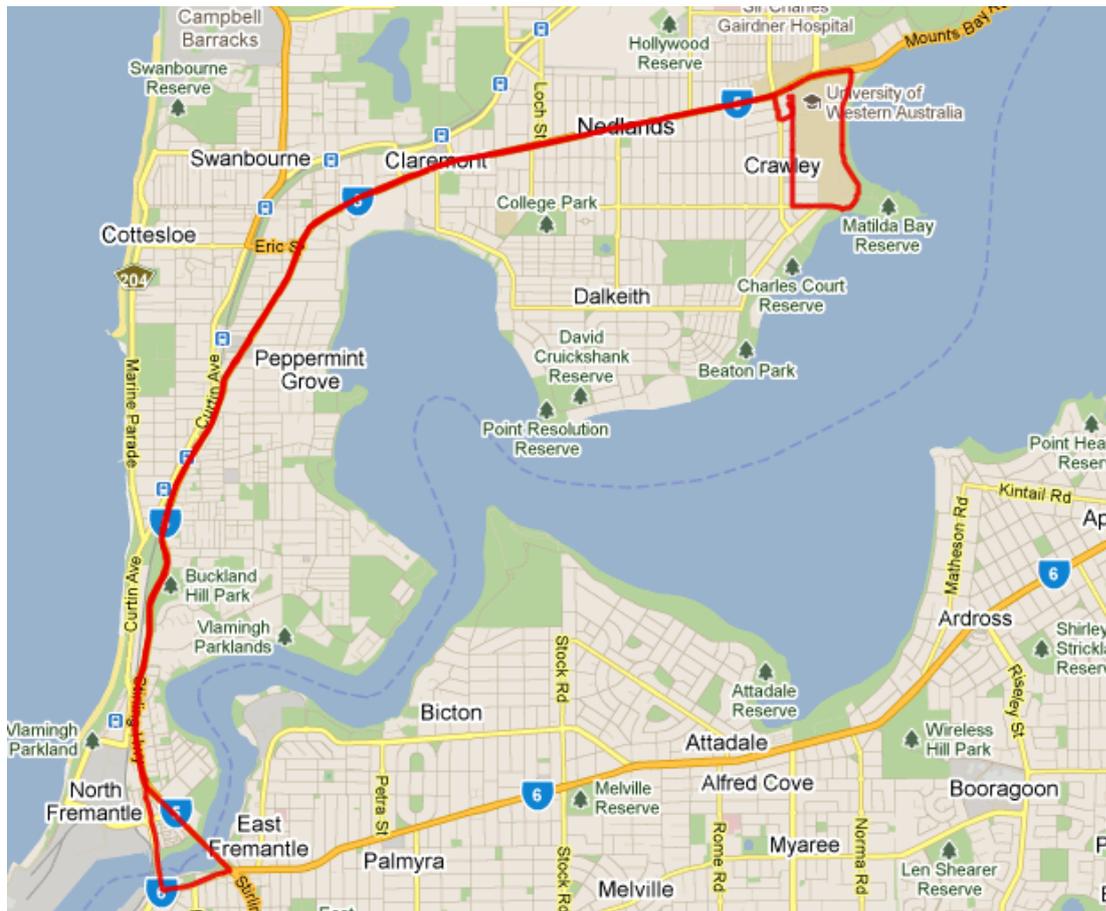


Figure 7.7: Map of test drive - The path taken by the car during a test drive

The main point of this graph is that it shows the highest current consumption during times of acceleration. This is to be expected, however it also highlights that while the car is up to speed, it uses minimal current to maintain that speed. All the energy built up is wiped off by the breaks when the car slows down. This highlights that driving style may have a large impact on the range of the car, and prompts investigation into the use of regenerative braking to capture the lost kinetic energy of the car.

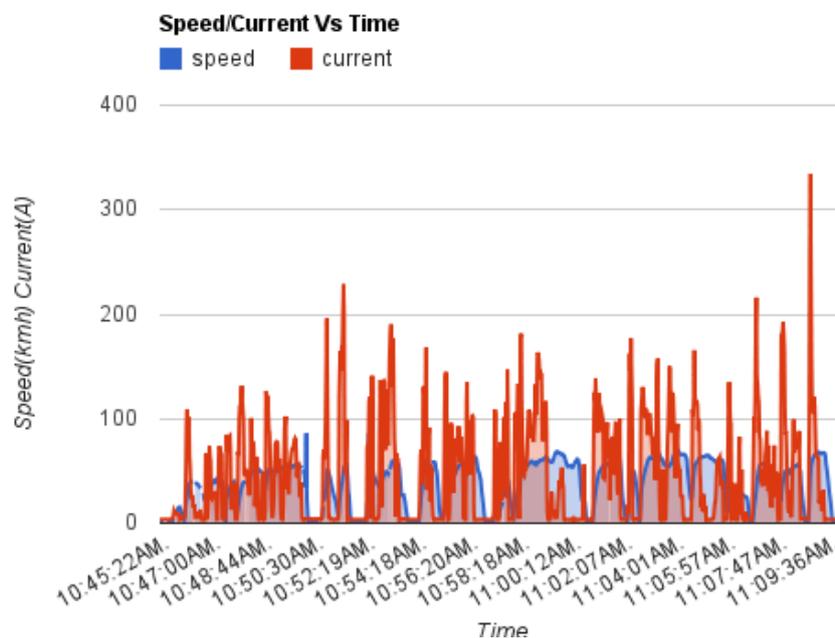


Figure 7.8: Speed & Current vs Time - Instantaneous speed and current plotted against time for a test drive

7.5.3 Charge vs Time

As figure 7.8 showed, the speed kept was reasonably constant. This is important when considering figure 7.9, which shows the charge plotted against time for the same drive. As the charge decreases reasonably linearly, and the speed is constant, the distance traveled will be proportional to the charge depleted. This validates equation 6.1 used to predict the remaining distance.

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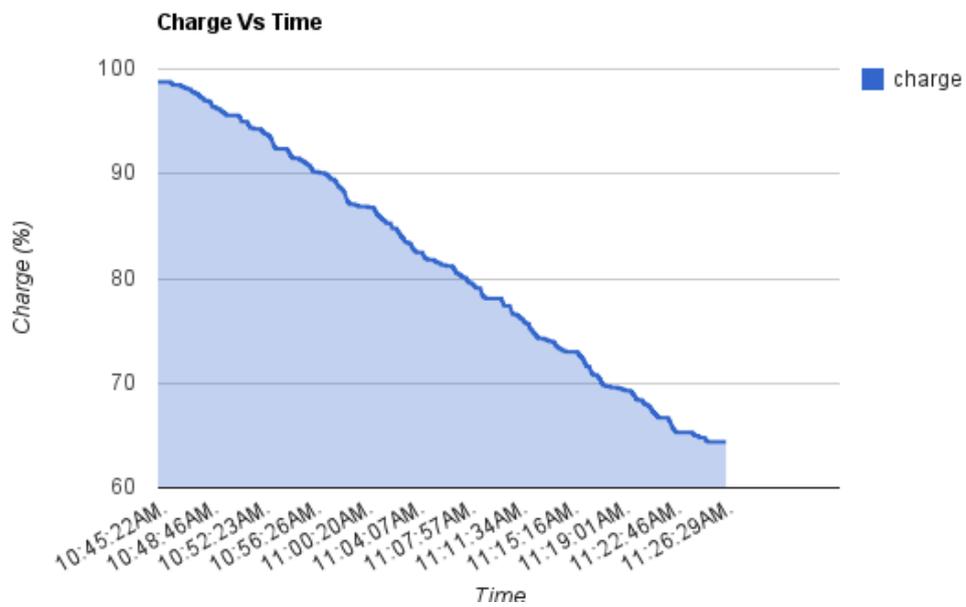


Figure 7.9: Charge vs Time - Instantaneous charge plotted against time for a test drive

8

Conclusions

This project shows that it is possible to use high level programming techniques when developing for embedded devices. The hardware used in this project was powerful enough to separate into multiple components. This is significant as it provides flexibility in the development of embedded devices and highlights how these products are becoming more like traditional computers.

This project also illustrates the viability of using existing networking techniques, such as TCP/IP, in providing communication between different devices. The application of this technology to embedded systems provides increased robustness and decreases development time. This shows that a network of small embedded systems that each contribute a portion of the overall system functionality is a viable solution to the problems of scaling and system cost.

The ability to automatically log all the information recorded by the car is of great help to the goals of the REV team. The group will be able to log much more detailed data, and the system has been constructed in a way to make it easily extend-able. This will ultimately help in the research and development of the vehicle the system is running on.

8.1 Limitations

The system currently has a few limitations. These are caused by various constraints in the hardware and the design of the system.

8. CONCLUSIONS

The system will be unable to support too many more additions with its current processing power. The CPU is not able to run many high frequency data sources at the same time. This will limit the future expansion unless new hardware is acquired.

The system also suffers some issues with the memory utilization of some components. Further investigation will need to take place in order to eliminate the bugs that are causing these issues.

Due to time constraints the Arduino and Accelerometer were not developed fully in regards to the user interface. This is a limitation that can be overcome in the future, when a more specific use of these components is required.

8.2 Advantages

The system is easily expendable, providing a framework for the transmission and display of any data that the group may want to develop in the future. The development of the windowing toolkit makes it much easier to work with the touch interface on the device.

The messaging protocol developed, and the use of a message abstraction, makes it much easier to communicate between different sections. The fact that the complicated components of networking are abstracted from the developer make it easier to conceptualize what is happening. A component in this system only needs to worry about the data being sent, and not a complicated method of ensuring it is received correctly.

Due to its distributed nature, the system is easy and cost-effective to extend. Rather than having to source expensive new hardware to perform all the tasks, cheaper hardware can be used to take the role of some of the tasks. This allows the complete system to adapt to the conditions that it is being used in.

8.3 Applications

The system has applications in the project it was developed for. It provides a clean user interface for the display of data, and logging functionality so it can be analyzed later.

The system is a proof of concept that embedded systems can communicate reliably using network protocols. This concept could be applied to newly developed systems, enabling products that can be purchased in sections, with each section providing different

or improved functionality. This paves the way for embedded systems to be configured via pre-built components, rather than developed using one monolithic structure.

8.4 Future work

The first aspect of future work is the finishing of the Arduino and Accelerometer components. These components are able to be decoded, but do not have very useful user interfaces.

Currently the networking is not encrypted, which does expose the possibility that it can be attacked. This does require access to the network, which is not easily, and understanding of the protocols being communicated. Future work would include the investigation of SSL in order to prevent any third party from viewing the data that is transmitted.

The windowing toolkit could be further developed by providing rendering of the full alphabet at varying sizes. This would simplify the use of the toolkit, as it would be much easier to make text appear. The toolkit could also be further developed into its own standalone package, either with dependencies on the existing libraries or not.

Navigation could be added to the maps portion. A path-finding algorithm could be developed and implemented that would be able to direct the driver towards a specific destination.

Further research could be conducted into sensor fusion. As the system has access to GPS, the speedometer pulse frequency, current, as well as the acceleration the car is undertaking a system could be developed in order to compensate for loss of a sensor. For instance the other sensors could approximate the GPS position when inside a tunnel. This would increase the user experience, as it would appear that the GPS works in all locations.

New hardware should also be investigated for the system. Either in the form of additional devices to offset the load, or replacement of the main component running the system. This would increase the processing power of the system, and allow more complicated functionality to be developed.

8. CONCLUSIONS

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Appendix A

Remotely Accessing Eyebot

A.1 SSH Details

To connect to the eyebot, issue the command from any linux machine that has ssh installed.

```
ssh root@192.168.1.50
```

You will then be prompted for a password. There is no password set by default. Hit enter when prompted for a password. The table A.1 shows the settings to connect.

A.2 Installing programs to Eyebot

Each program is accompanied with a makefile. This makefile will connect to the default IP address of the machine, and install the program in the folder */root/demo/rev2011/*. To install any program just run

```
make install
```

| Property | Value |
|-----------------|--------------|
| SSH Address(IP) | 192.168.1.50 |
| Account name | root |
| Password | empty |

Table A.1: SSH Details

A. REMOTELY ACCESSING EYEBOT

From the source folder of the desired program on the development machine. Press enter when prompted for a password.

Appendix B

Development environment setup

B.1 Buildroot setup

The following section is based upon the legacy buildroot installation guide obtainable from

<http://docwiki.gumstix.org/Buildroot>

This section purpose is to describe the steps needed to be undertaken to build the compiler and libraries required by the eyebot. The online guide requires some tweaks for newer versions of GCC to compile the older versions. This section will detail the changes required for Ubuntu 10.10. Other distributions may require further changes aswell.

B.1.1 Checkout Buildroot source code

1. To perform this section you must have subversion installed on your machine. This is a common version control system, and it's installation is out of the scope of this document.
2. Checkout the 1083 release of buildroot. The eyebot was built with older buildroot libraries, these are version 1083 in the repository. To check out this source use the command (all one line)

```
svn co -r1083 http://svn.gumstix.com/gumstix-buildroot/trunk  
gumstix-buildroot
```

B. DEVELOPMENT ENVIRONMENT SETUP

B.1.2 Setup environment

3. Next you will have to setup the buildroot make environment. Change into the folder buildroot was downloaded too.
4. Remove the existing config (if present) with

```
rm ./config
```

5. Run the autoconfig program

```
make defconfig
```

You will be prompted to select settings about the eyebot. The eyebot contains a 400mhz xscale processor, so select the options according to this. Any other options can be selected with the defaults.

B.1.3 Modify the source

6. Modifying the source files.

The source files will not compile correctly on ubuntu 10.10 without some minor modifications. This has occurred because most systems use gcc4+, while this code was originally compiled on gcc3

- (a) Makeinfo will complain about not being installed to fix this edit the file.

```
toolchain_build_arm_nofpu/binutils-2.17-build/Makefile
```

Change line 258 to

```
MAKEINFO = /usr/bin/makeinfo
```

or whatever the correct path to makeinfo is.

- (b) The older GCC did not require permission settings when opening a file, this must be added in. Edit the file

```
toolchain_build_arm_nofpu/gcc-3.4.5/gcc/collect2.c
```

On line 1537 change it to read

B.2 Compiling ZeroMQ for the arm cpu

```
redir_handle = open (redir, O_WRONLY | O_TRUNC | O_CREAT,0666);
```

- (c) The limits.h file is not included by default when compiling using the newer GCC (caused by changes in libraries) to fix edit.

```
build_arm_nofpu/linux-2.6.17gum/scripts/mod/sumversion.c
```

And insert at the top of the file

```
#include <limits.h>
```

7. Include the e2fs files for the UUID functions. UUID functions are required by the ZeroMQ library. Run

```
make menuconfig
```

And navigate the menus and enable the e2fs library.

B.1.4 Build

8. Compile the environment. Run

```
make
```

This will download and compile the build environment. Note that some packages may no longer be mirrored online. You will need to search the internet and manually download these files to the dl folder that is created. The compile process will fail with the name of the missing packages, so you can hunt them down.

B.2 Compiling ZeroMQ for the arm cpu

This section details the commands used to build zeroMQ libraries to run on the arm board. These commands work with zeroMQ version 2.2 on a ubuntu 10.10 machine.

B.2.1 Setup path variable

1. First you must setup the path variable so the automake process knows the location of the compiler. To do this run this command in the terminal. (all one line)

B. DEVELOPMENT ENVIRONMENT SETUP

```
export PATH=$PATH:%PATHTOBUILDROOT%/gumstix-buildroot/  
build_arm_nofpu/staging_dir/bin/
```

Where %PATHTOBUILDROOT

B.2.2 Run Automake

2. ZeroMQ contains an configure utility that will generate make files for you. Run this utility with this command (all one line)

```
CC=arm-linux-uclibc-gcc CFLAGS=" -pthread -D_REENTRANT  
-march=armv5te -mtune=xscale -DZMQ_FORCE_POLL"  
CXX=arm-linux-uclibc-g++  
CXXFLAGS=" -pthread -D_REENTRANT -march=armv5te -mtune=xscale  
-DZMQ_FORCE_POLL"  
LDFLAGS="-L%X%/gumstix-buildroot/build_arm_nofpu/e2fsprogs-1.38/lib/"  
CPPFLAGS="-I%X%/gumstix-buildroot/build_arm_nofpu/staging_dir/include  
-I%X%/gumstix-buildroot/build_arm_nofpu/e2fsprogs-1.38/lib/uuid/"  
./configure --host=arm-linux  
--prefix=%X%/build_arm_nofpu/root
```

Where %X% is the path to the gumstix buildroot environment setup earlier.

B.2.3 Build

3. To build ZeroMQ run the command

```
make
```

This will build zeroMQ. To obtain the libraries run

```
make install1
```

This will copy the libraries to %X%/build_arm_nofpu/root/%ZEROMQVER%/

Appendix C

Tile server setup

In this project tiles for all of Perth were generated. This was done on a much more powerful machine than the eyebot before hand. This section details how to setup a server to generate these tiles.

C.0.4 Get the planet file

First you will need the raw map data in order to generate the maps. To download the latest version of earth run this command.

```
cd planet
wget http://planet.openstreetmap.org/planet-latest.osm.bz2
```

This file is quite large and will take a while to download. Smaller extract files do exist, so if you are only interested in a subsection, use one of these files instead.

C.0.5 Install a postGIS database

PostGIS is a postgresql extension for GIS functions. To install it in ubuntu run

```
sudo apt-get install postgresql-8.4-postgis postgresql-contrib-8.4
sudo apt-get install postgresql-server-dev-8.4
sudo apt-get install build-essential libxml2-dev libtool
sudo apt-get install libgeos-dev libpq-dev libbz2-dev proj
```

Or use the package manager of your distribution.

C. TILE SERVER SETUP

C.0.6 Install osm2pgsql

Earlier we download a osm file, we need to import that into the GIS database. Luckily scripts exist to do that for us. Run

```
cd ~/bin
svn co http://svn.openstreetmap.org/applications/utils/export/osm2pgsql/
cd osm2pgsql
./autogen.sh
./configure
make
```

C.0.7 Tweak the GIS database

There will be alot of data inserted into this database, so it is best to modify the running parameters for some extra performance. Edit these lines to match in */etc/postgresql/8.4/main/postgresql.conf*

```
shared_buffers = 128MB # 16384 for 8.1 and earlier
checkpoint_segments = 20
maintenance_work_mem = 256MB # 256000 for 8.1 and earlier
autovacuum = off
```

Optionally increase the size of shared memory available

```
sudo sysctl -w kernel.shmmax=268435456
sudo sysctl -p /etc/sysctl.conf
```

Then restart postgresql

C.0.8 Create a database

Create a database called gis. Substitute user-name for the user-name that will be used to generate maps

```
sudo -u postgres -i
createuser username # answer yes for superuser
createdb -E UTF8 -O username gis
createlang plpgsql gis
exit
```

C.0.8.1 Create PostGIS data structures on the database

Run

```
psql -f /usr/share/postgresql/8.4/contrib/postgis-1.5/postgis.sql -d gis
```

C.0.8.2 Change ownership of database

Substitute user-name with the user that will be used to generate maps

```
echo "ALTER TABLE geometry_columns OWNER TO username;  
ALTER TABLE spatial_ref_sys OWNER TO username;" | psql -d gis
```

C.0.8.3 Set the Spatial Reference Identifier

```
psql -f ~/bin/osm2pgsql/900913.sql -d gis
```

C.0.9 Load the planet into the database

Now we have to load the osm file into the GIS database. Run the command

```
cd ~/bin/osm2pgsql  
./osm2pgsql -S default.style --slim -d gis -C 2048  
--number-processes=1 --cache-strategy=dense  
~/planet/planet-100217.osm.bz2
```

Substituting for your planet file. This will take a very long time to complete.

C.0.10 Install mapnik

C.0.10.1 Setup build environment

Run the commands

```
sudo apt-get install libltdl3-dev libpng12-dev libtiff4-dev libicu-dev  
sudo apt-get install libboost-python1.40-dev python-cairo-dev python-nose  
sudo apt-get install libboost1.40-dev libboost-filesystem1.40-dev  
sudo apt-get install libboost-iostreams1.40-dev  
libboost-regex1.40-dev libboost-thread1.40-dev  
sudo apt-get install libboost-program-options1.40-dev libboost-python1.40-dev  
sudo apt-get install libfreetype6-dev libcairo2-dev libcairomm-1.0-dev
```

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```
sudo apt-get install libgeotiff-dev libtiff4 libtiff4-dev libtiffxx0c2
sudo apt-get install libsigc++-dev libsigc++0c2 libsigx-2.0-2 libsigx-2.0-dev
sudo apt-get install libgdal-dev python-gdal
sudo apt-get install imagemagick ttf-dejavu
```

C.0.10.2 Build mapnik from source

```
cd ~/src
svn co http://svn.mapnik.org/tags/release-0.7.1/ mapnik
cd mapnik
python scons/scons.py configure INPUT_PLUGINS=all
OPTIMIZATION=3 SYSTEM_FONTS=/usr/share/fonts/truetype/
python scons/scons.py
sudo python scons/scons.py install
sudo ldconfig
```

C.0.10.3 Install mapnik tools

```
cd ~/bin
svn co http://svn.openstreetmap.org/applications/rendering/mapnik
```

C.0.10.4 Optional: get world boundaries

These mark out ocean areas, which will increase map rendering speed. Run

```
cd ~/bin/mapnik
mkdir world_boundaries
wget http://tile.openstreetmap.org/world_boundaries-spherical.tgz
tar xvzf world_boundaries-spherical.tgz
wget http://tile.openstreetmap.org/processed_p.tar.bz2
tar xvjf processed_p.tar.bz2 -C world_boundaries
wget http://tile.openstreetmap.org/shoreline_300.tar.bz2
tar xjf shoreline_300.tar.bz2 -C world_boundaries
wget http://www.naturalearthdata.com/http://www.naturalearthdata.com/
  download/10m/cultural/10m-populated-places.zip
unzip 10m-populated-places.zip -d world_boundaries
wget http://www.naturalearthdata.com/http://www.naturalearthdata.com/
  download/110m/cultural/110m-admin-0-boundary-lines.zip
unzip 110m-admin-0-boundary-lines.zip -d world_boundaries
```

C.0.11 Generate maps

If all goes well then the server is now setup. The file `~/bin/mapnik/generate_image.py` will allow you to generate images. Other scripts in there will allow the generation of images based on gps co-ordinates, so bulk image generation can be scheduled.

C. TILE SERVER SETUP

Appendix D

Performance Testing Scripts

D.1 Memory Utilization

In section 7.4 the memory usage of various programs was recorded. To do this the following script was used

```
while true
do
date +%s | awk '{ printf "%s ", $0 }' >> output.txt;
ps | grep %EXECUTABLE_NAME% | grep -v grep | head -n1 \
| awk '{print $3}' | awk '{printf "%s", $0}' >> output.txt;
echo '' >> output.txt
sleep 20;
done
```

D. PERFORMANCE TESTING SCRIPTS

Appendix E

Utility Programs

During the development of this system, various utility programs were developed in order to help debug and test the system.

E.1 ZeroMQ Viewer

This component is located in the file

`Utilities/programs/ZeroMQViewer`

This program is a subscriber that will attach to any publisher component. It prints the time-stamp and hexadecimal values of the message whenever a message is received.

E.2 ZeroMQ Emulator

This component is located at

`Utilities/programs/ZeroMQMessageEmulator/`

This component acts as a publisher, it will transmit messages that can be interpreted by subscribers. It loads the information ASCII information from a text file and interprets it as hexadecimal. It supports spaces in-between hexadecimal values and comments so the file should be human readable. Examples are contained in the folder with the binary.

E. UTILITY PROGRAMS

E.3 ZeroMQ Evaluator

This program is contained in

`Utilities/programs/ZeroMQMessageEvaluator/`

This program is a modified version of the Viewer. It will read in the specified number of messages and then stop. It also records the start and end time that this took place. This allows the time it take a certain volume or messages to be transmitted to be recorded and analyzed.

Appendix F

Message Timing Tables

The following section shows the data measured for the time taken to receive varying numbers of messages. This data was obtained by running the Evaluate program on the eyebot, and sending messages from a laptop. This laptop generated messages as fast as it could using the Emulator program. When the Evaluate program received the desired number of messages it would halt and print the timing results. The results are available in system clock ticks, and the system time that elapsed during this period. The results are also available in varying message sizes. These messages were generated randomly using */dev/random* on a linux system, and stored in a file that the Emulator could load and run.

F. MESSAGE TIMING TABLES

| Test Number | 1 | 2 | 3 | 4 | 5 | |
|-------------|---------|----------|----------|----------|----------|----------|
| 1000 | 20000 | 40000 | 20000 | 20000 | 20000 | |
| 10000 | 170000 | 180000 | 120000 | 160000 | 160000 | |
| 100000 | 870000 | 970000 | 1250000 | 1010000 | 1000000 | |
| 1000000 | 9560000 | 10220000 | 10230000 | 11220000 | 9710000 | |
| Test Number | 6 | 7 | 8 | 9 | 10 | Average |
| 1000 | 10000 | 20000 | 30000 | 10000 | 30000 | 22000 |
| 10000 | 140000 | 160000 | 130000 | 120000 | 150000 | 149000 |
| 100000 | 1020000 | 1040000 | 940000 | 890000 | 1050000 | 1004000 |
| 1000000 | 9580000 | 10980000 | 10570000 | 10800000 | 11760000 | 10463000 |

Table F.1: Clock ticks Vs Number of messages for 32byte random data

| Test Number | 1 | 2 | 3 | 4 | 5 | |
|-------------|-----------|-----------|-----------|-----------|-----------|-------------|
| 1000 | 243750 | 212332 | 256312 | 3156460 | 341224 | |
| 10000 | 1419011 | 1349485 | 1436313 | 1534302 | 1349040 | |
| 100000 | 15145656 | 15590986 | 15703572 | 15657899 | 15649278 | |
| 1000000 | 152007642 | 156742950 | 157926991 | 158742238 | 157040941 | |
| Test Number | 6 | 7 | 8 | 9 | 10 | Average |
| 1000 | 356874 | 204477 | 386403 | 233102 | 359293 | 575022.7 |
| 10000 | 1405605 | 1662092 | 1697169 | 1501454 | 1398061 | 1475253.2 |
| 100000 | 15663356 | 15267476 | 15416116 | 15363871 | 15265640 | 15472385 |
| 1000000 | 156889964 | 158464172 | 153960703 | 159458560 | 158363673 | 156959783.4 |

Table F.2: Time (us) Vs Number of messages for 32byte random data

| Test Number | 1 | 2 | 3 | 4 | 5 | |
|-------------|---------|---------|---------|---------|---------|---------|
| 10 | 30000 | 20000 | 20000 | 20000 | 0 | |
| 100 | 70000 | 30000 | 90000 | 60000 | 50000 | |
| 1000 | 80000 | 30000 | 70000 | 40000 | 80000 | |
| 10000 | 150000 | 190000 | 160000 | 210000 | 150000 | |
| 100000 | 1930000 | 2210000 | 1850000 | 1890000 | 2080000 | |
| Test Number | 6 | 7 | 8 | 9 | 10 | Average |
| 10 | 20000 | 30000 | 60000 | 40000 | 30000 | 27000 |
| 100 | 10000 | 40000 | 10000 | 30000 | 10000 | 40000 |
| 1000 | 50000 | 30000 | 50000 | 50000 | 80000 | 56000 |
| 10000 | 280000 | 290000 | 180000 | 220000 | 180000 | 201000 |
| 100000 | 2150000 | 2030000 | 1870000 | 2020000 | 2090000 | 2012000 |

Table F.3: Clock ticks Vs Number of messages for 128byte random data

| Test Number | 1 | 2 | 3 | 4 | 5 | |
|-------------|----------|----------|----------|----------|----------|------------|
| 10 | 323135 | 306990 | 220649 | 220649 | 191386 | |
| 100 | 393113 | 205562 | 315971 | 328754 | 357496 | |
| 1000 | 496815 | 438725 | 389029 | 505927 | 465334 | |
| 10000 | 2740074 | 2723108 | 2601828 | 2576363 | 2711420 | |
| 100000 | 27669065 | 27824854 | 26609896 | 25919529 | 26034126 | |
| Test Number | 6 | 7 | 8 | 9 | 10 | Average |
| 10 | 266575 | 220406 | 317913 | 307281 | 189971 | 256495.5 |
| 100 | 301369 | 291968 | 198676 | 311395 | 331863 | 303616.7 |
| 1000 | 488639 | 5468 | 519439 | 474776 | 523848 | 430800 |
| 10000 | 2732068 | 2710042 | 2631575 | 2639119 | 3595522 | 2766111.9 |
| 100000 | 27232333 | 26982161 | 27233195 | 26655991 | 27697161 | 26985831.1 |

Table F.4: Time (us) Vs Number of messages for 128byte random data

F. MESSAGE TIMING TABLES

| Test Number | 1 | 2 | 3 | 4 | 5 | |
|-------------|---------|---------|---------|---------|---------|----------|
| 10 | 0 | 20000 | 0 | 20000 | 30000 | |
| 100 | 10000 | 50000 | 50000 | 30000 | 10000 | |
| 1000 | 90000 | 70000 | 50000 | 50000 | 80000 | |
| 10000 | 230000 | 170000 | 190000 | 270000 | 350000 | |
| 100000 | 2170000 | 1800000 | 2230000 | 2240000 | 2020000 | |
| Test Number | 6 | 7 | 8 | 9 | 10 | Average |
| 10 | 30000 | 20000 | 20000 | 10000 | 40000 | 19000 |
| 100 | 20000 | 40000 | 90000 | 30000 | 30000 | 36000 |
| 1000 | 10000 | 30000 | 10000 | 40000 | 70000 | 50000 |
| 10000 | 260000 | 260000 | 150000 | 170000 | 3177625 | 522762.5 |
| 100000 | 2180000 | 2040000 | 1980000 | 1940000 | 2260000 | 2086000 |

Table F.5: Clock ticks Vs Number of messages for 512byte random data

| Test Number | 1 | 2 | 3 | 4 | 5 | |
|-------------|----------|----------|----------|----------|----------|------------|
| 10 | 202744 | 299140 | 243188 | 224886 | 310320 | |
| 100 | 3134384 | 336945 | 344085 | 229151 | 226242 | |
| 1000 | 527391 | 546638 | 584975 | 529211 | 548475 | |
| 10000 | 3049670 | 2849869 | 2671973 | 2945053 | 3007291 | |
| 100000 | 30712493 | 31676926 | 30686329 | 30285899 | 31565685 | |
| Test Number | 6 | 7 | 8 | 9 | 10 | Average |
| 10 | 320544 | 306020 | 220204 | 372283 | 325050 | 282437.9 |
| 100 | 203972 | 377633 | 368549 | 319270 | 336170 | 587640.1 |
| 1000 | 477733 | 595697 | 484988 | 587090 | 561919 | 544411.7 |
| 10000 | 2872847 | 2891389 | 2926986 | 3177625 | 2871762 | 2926446.5 |
| 100000 | 30283039 | 31059473 | 31532265 | 32491691 | 31771619 | 31206541.9 |

Table F.6: Time (us) Vs Number of messages for 512byte random data

| Test Number | 1 | 2 | 3 | 4 | 5 | |
|-------------|---------|---------|---------|---------|---------|---------|
| 10 | 30000 | 20000 | 30000 | 20000 | 30000 | |
| 100 | 100000 | 40000 | 40000 | 40000 | 0 | |
| 1000 | 60000 | 30000 | 60000 | 50000 | 90000 | |
| 10000 | 140000 | 200000 | 190000 | 200000 | 260000 | |
| 100000 | 1800000 | 1890000 | 2410000 | 2210000 | 1700000 | |
| Test Number | 6 | 7 | 8 | 9 | 10 | Average |
| 10 | 10000 | 10000 | 30000 | 10000 | 30000 | 22000 |
| 100 | 80000 | 30000 | 10000 | 60000 | 20000 | 42000 |
| 1000 | 60000 | 50000 | 60000 | 0 | 80000 | 54000 |
| 10000 | 330000 | 200000 | 170000 | 280000 | 210000 | 218000 |
| 100000 | 2210000 | 2180000 | 2410000 | 2060000 | 1900000 | 2077000 |

Table F.7: Clock ticks Vs Number of messages for 1024byte random data

| Test Number | 1 | 2 | 3 | 4 | 5 | |
|-------------|----------|----------|----------|----------|----------|-----------|
| 10 | 344441 | 307364 | 330483 | 315630 | 344759 | |
| 100 | 383476 | 351497 | 350538 | 417289 | 339274 | |
| 1000 | 539349 | 601257 | 716008 | 548840 | 711210 | |
| 10000 | 3429580 | 3497672 | 3247387 | 4596539 | 3276066 | |
| 100000 | 36594732 | 35013510 | 34448621 | 34661021 | 35992978 | |
| Test Number | 6 | 7 | 8 | 9 | 10 | Average |
| 10 | 310805 | 231331 | 267536 | 345342 | 335819 | 313351 |
| 100 | 352329 | 366358 | 197007 | 312781 | 215691 | 328624 |
| 1000 | 566045 | 520301 | 500614 | 591720 | 548868 | 584421.2 |
| 10000 | 3489945 | 3114163 | 3573906 | 3328063 | 3611572 | 3516489.3 |
| 100000 | 35032912 | 35081602 | 33674882 | 34417770 | 35152012 | 35007004 |

Table F.8: Time (us) Vs Number of messages for 1024byte random data

F. MESSAGE TIMING TABLES

| Test Number | 1 | 2 | 3 | 4 | 5 | |
|-------------|---------|---------|---------|---------|---------|---------|
| 10 | 30000 | 30000 | 40000 | 40000 | 20000 | |
| 100 | 80000 | 40000 | 70000 | 30000 | 70000 | |
| 1000 | 80000 | 50000 | 20000 | 60000 | 60000 | |
| 10000 | 170000 | 200000 | 230000 | 190000 | 180000 | |
| 100000 | 1730000 | 1580000 | 1580000 | 1570000 | 1490000 | |
| Test Number | 6 | 7 | 8 | 9 | 10 | Average |
| 10 | 40000 | 10000 | 70000 | 30000 | 40000 | 35000 |
| 100 | 50000 | 60000 | 30000 | 20000 | 80000 | 53000 |
| 1000 | 20000 | 60000 | 20000 | 60000 | 30000 | 46000 |
| 10000 | 210000 | 230000 | 190000 | 170000 | 220000 | 199000 |
| 100000 | 1970000 | 1570000 | 2100000 | 2070000 | 1900000 | 1756000 |

Table F.9: Clock ticks Vs Number of messages for 10kilobyte random data

| Test Number | 1 | 2 | 3 | 4 | 5 | |
|-------------|----------|----------|----------|----------|----------|-----------|
| 10 | 377608 | 331011 | 285319 | 186330 | 224346 | |
| 100 | 387303 | 395092 | 349759 | 344359 | 364674 | |
| 1000 | 606900 | 694347 | 651131 | 470944 | 584394 | |
| 10000 | 3034906 | 3020777 | 2916406 | 3016008 | 3014637 | |
| 100000 | 29623959 | 30323297 | 31451455 | 31070588 | 30427494 | |
| Test Number | 6 | 7 | 8 | 9 | 10 | Average |
| 10 | 383401 | 243644 | 345962 | 264199 | 319124 | 296094.4 |
| 100 | 337517 | 395891 | 387481 | 216318 | 401400 | 357979.4 |
| 1000 | 491953 | 581445 | 603782 | 583448 | 704321 | 597266.5 |
| 10000 | 2909019 | 3082147 | 3222074 | 3322947 | 2926152 | 3046507.3 |
| 100000 | 29400026 | 31617928 | 30323380 | 30336067 | 32110036 | 30668423 |

Table F.10: Time (us) Vs Number of messages for 10kilobyte random data

| Message Size | 128 | 512 | 1024 | 10240 |
|--------------|------------|------------|-----------|-------------|
| 10 | 256495.5 | 282437.9 | 313351 | 213073.6 |
| 100 | 303616.7 | 587640.1 | 328624 | 304995.2 |
| 1000 | 430800 | 544411.7 | 584421.2 | 390158.225 |
| 10000 | 2766111.9 | 2926446.5 | 3516489.3 | 2304761.925 |
| 100000 | 26985831.1 | 31206541.9 | 35007004 | 23324844.25 |

Table F.11: Clock ticks Vs Number of messages combined data for varying message sizes

| Message Size | 128 bytes | 512 bytes | 1024 bytes | 10 kilobytes |
|--------------|------------|------------|------------|--------------|
| 10 | 256.4955 | 282.4379 | 313.351 | 213.0736 |
| 100 | 303.6167 | 587.6401 | 328.624 | 304.9952 |
| 1000 | 430.8 | 544.4117 | 584.4212 | 390.158225 |
| 10000 | 2766.1119 | 2926.4465 | 3516.4893 | 2304.761925 |
| 100000 | 26985.8311 | 31206.5419 | 35007.004 | 23324.84425 |

Table F.12: Time(ms) Vs Number of messages combined data for varying message sizes