



UNIVERSITY OF YORK

SECOND YEAR PROJECT

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# Embedded Systems Project Written Report

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# Chapter 1

## Introduction

### 1.1 Summary of project work

The Second Year Embedded Systems Project was a ten week project, undertaken for the duration of Spring Term 2014-2015. The project was a primarily a group task, completed in groups consisting of four members. However, there was also the capability for individual extensions to the main body of the project, allowing each member to showcase competency and creativity.

The group project involved programming an ARM LPC1768 'MBED' microcontroller, situated on top of a board of peripheral accessories, in order to generate and play audio on a user selectable channel corresponding to data being sent down a Controller Area Network bus (CAN bus). The individual component was not specified, and was instead left up to each individual to decide on an extension project, research, and implement it.

My groups solution was very complete, not only matching the full specification, but also extending the implementation to a high degree, producing a user friendly end product with a high quality audio output. My individual extension provided the device with a more user friendly interface than the rudimentary keypad attached to the MBED board through the implementation of a shell type interface. This interface allows the user to input commands via a computer keyboard in order to change modes, adjust settings, or display useful information.

### 1.2 Experiences as a team

The capability to work successfully as a group was imperative to the triumph of the project. Throughout the ten week period we worked effectively as a team through a number of different means. First of all we held regular group meetings. This allowed us to keep track of each group member's progress and enabled each member to feedback any potential problems they had encountered, as well as ensuring we were meeting the specifications of the project. Secondly, each contribution to the group solution was passed through a code review prior to inclusion. This ensured that each member was only adding high quality contributions, and enabled group members to learn from each other. In addition, each member of the group agreed to use the version control system, git, coupled with github. This enabled a much easier collaboration of code throughout the

project, and made communication between individuals much simpler. Through the combination of these methods, my group was able to remain highly productive throughout the course of the project. Furthermore, the high levels of communication enabled each individual to work primarily on their areas of interest, removing the need to continually worry about the overall progress of the project. Overall I feel we worked very well together as a team, and the project served as a valuable insight into a fluent working environment as a team.

## 1.3 Expectations and actual outcomes

Due to my own personal inexperience programming embedded systems, and unfamiliarity with the LPC1768 board used, it was very difficult to predict the outcome of the project. However, due to the competency and eagerness of my groups members, it was expected from a very early stage that we would rapidly be able to match the specification and extend the project to a high degree. The majority of the project went very fluently, however, certain aspects of the project took much longer than initially expected. Notably the CAN bus in the labs was not working at the beginning of the ten week period, and consequently producing working code for reading the CAN packets took longer than expected. Furthermore, handling the wide range of possible cases for user input, and interaction between the keypad and shell input methods took much longer than expected. The end product that we implemented was capable of matching each point of the specification, and surpassed the specification within the group project, as well as individual extension project. Therefore I feel the groups time management skills worked very well, and the end product lived up to expectations.

## 1.4 What is in the report

This report sets out to provide a description of our team solution to the set assignment, as well as highlighting areas of individual contribution throughout. The report will begin with a technical description of the set problem, including a discussion of requirements and technical challenges that may be faced in the meeting of these requirements. Following a description of the problem, the group solution will be discussed. The discussion will highlight how each section of the requirements has been met by the implemented solution, as well as detailing how the problem has been broken down for each individual member, presenting each members implementation and technical innovation. After a discussion of the group's solution, the appropriate testing strategies and methods that were used throughout the project will be examined in detail, providing feedback on how they have proved useful, and incorporating a discussion on a professional/social/ethical/environmental aspect of the solution. The report will then focus critically on my individual implementation, detailing the technical innovation, implementation, and testing undergone for my contribution. Finally the report will conclude with a reflective summary of work undertaken, consid-

ering which aspects of the project went smoothly, which areas did not go as smoothly, how this might be improved in future, and what lessons can be taken away from the completion of the project.

## Chapter 2

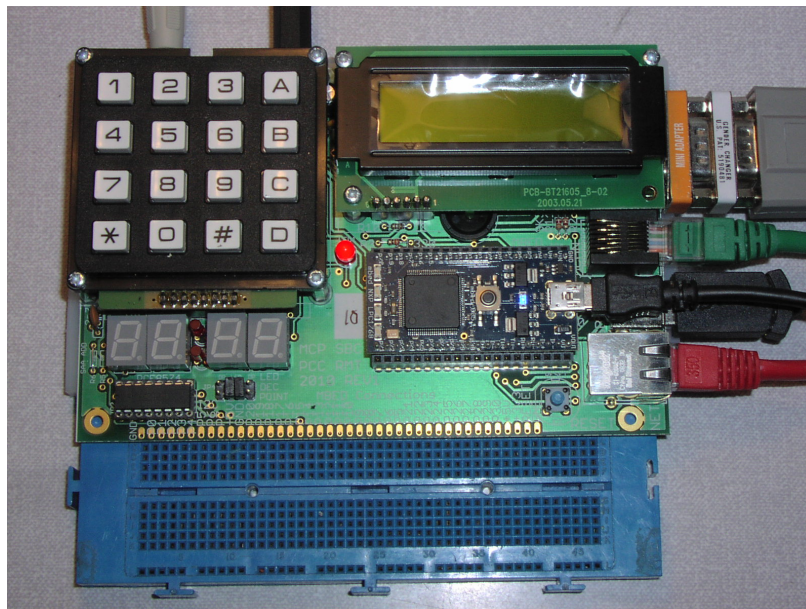
# Technical Description of Problem

### 2.1 Description of Problem and Requirements

The Embedded Systems Project consisted of two main sections: a group solution to a predetermined problem, and an individual extension to the group's work, left up to each person to determine. Both sections of the project involved embedded systems software development in the C programming language.

The target platform of the development is an ARM-based microcontroller, situated on a board of peripheral accessories. The microcontroller consists of an interface board coupled with the ARM cortex-M3 based LPC1768, providing easy interaction via USB cable to transfer binaries, and simplifying the process of serial communication [how-mbed-works].

The MBED board is sat on a board of peripheral accessories, as pictured below.



The board contains multiple accessories that the MBED board can interface with in various ways to fulfil the requirements, and allowing many options for

individual extensions. The accessories on the board include: a 16 key keyboard, a 16 by 2 line LCD, four seven segment displays, a micro SD slot, a USB host connection, CAN bus connector, audio in and out jacks, a TCP/IP connection, as well as off board connections to users hardware.

The group task consisted of multiple different challenges, with the concept that the MBED board would continually receive CAN packets, filter out those that do not match a user selectable id, decode the CAN packets, and play notes corresponding to the frequency, volume, and duration that were specified from the CAN transmissions. In addition the user must be able to view useful information, select the channel id, and adjust the volume.

In addition there was an individual component. This did not have to match any specification, and was instead left up to each person to decide on their own extension to the group project. For my individual extension, I implemented a Linux shell style user interface. This allows user to interact with the device by typing commands into a terminal on their computer, effectively adding an additional element of user control that is more intuitive and responsive than using the 16 digit keypad from the MBED board.

For our group solution, the specification was broken down into three separate areas, allowing us to focus our expertise and interests on what suited us best. The breakdown of the three sections was as follows: The receiving and decoding of CAN packets (CAN bus), generation of audio samples corresponding to frequency, duration and volume (Audio), and the ability for the user to interact with the device in order to adjust settings (User Interface).

## 2.2 Discussion of Technical Aspects and Challenges

As previously mentioned, my group deconstructed the specification into three main areas of technical challenge. The first of these challenging areas regarded the receiving of data from the CAN bus, and the decoding of the packets received to extract their content. As the CAN packets are not arriving at regularly timed intervals, the solution to this problem is required to be interrupt based. However, due to the nature of the CAN packets, a very large number can arrive in a comparatively short space of time. This therefore requires a highly optimised solution, in order to prevent packets either being missed, or race conditions within the interrupt handler from occurring.

The second technical challenge of the project is the generation of audio tones corresponding to frequency, duration and volume levels as specified by the CAN packets. The CAN packets do not contain information detailing what each note should sound like. As a result, all musical notes need to be generated from first principals, for example using a look up table detailing values for a note at each moment in time. In combination, to make the notes sound more realistic, each note must go through at least three stages. The first of these stages defines the

initial playing of a note, plucking a string or pressing a key. This is known as 'attack'. The second stage corresponds to the continual noise made from the note until it is stopped and is known as 'sustain'. The final stage details the note as it dies down and stops and is known as 'release'. This presents additional problems as each note requires multiple states, and needs to be tracked in its progress through each. Furthermore, it may be an additional desire to play more than one note at any one moment in time. This requires synthesis of multiple different notes in order to produce an appropriate output. The mathematics of this can be expensive to compute, and furthermore, an increase in the number of notes can drastically increase the processing time. A delay in the output of the notes can lead to a strange sounding finished product, so the efficiency of any synthesis calculations are paramount to the end product.

The third technical challenge that can be presented is the user's control over the device. The specification determines that the user must be able to control the volume of the output, alter which channel of notes is being played, and view useful information on the MBED board. This requires a level of interaction, most likely via the 16 digit keypad on the device, however this could be via alternate input methods, such as a computer keyboard. The user's interaction with either device once again may not be continual, but may either be polled, at the cost of system resources, or interrupt based. Further challenges are presented as any possible user input must be stored on the device, parsed on command, and then the desired command must be executed without any significant effect on the audio output. Furthermore, the challenge is made increasingly difficult by the required ability to interface with the entire project: the audio synthesis code and the CAN bus code must be fully understood in order to be manipulated through the user's input.



## Chapter 3

# Description and Discussion of Team-based Solution

### 3.1 Description of the Team Solution

The end product of our team solution was a successful working product. Through the incorporation of a Linux style shell into the group solution, we managed to produce a highly configurable single solution that managed to satisfy each section of specification. In addition the group solution contained two custom built speakers, capable of being powered by the 5V voltage rails from the peripherals board. The solution had a strong user interface, allowing the user to type in commands through the computer keyboard to adjust settings and select modes, set an id to filter channels out, and display information, or custom text on the mbed board. In addition it was also possible to adjust volume, channel and display information on the mbed board using the 16 digit keypad. This high level of user interfacing allowed settings to be flexibly turned on and off, and avoided the need to be continually re-installing binaries to the device. By typing in the command "listen", the mbed would then initialise the CAN bus and begin receiving packets. These could be printed out to the screen by issuing a further command, or they could be used to generate audio tones. It is also possible to filter out data according to a preset id by issuing a command, or using the keypad. For each data element received, audio tones can be generated. The solution supports a full synthesis, allowing multiple notes to be played on each channel, and multiple channels to play notes simultaneously. In addition the audio output also implemented an 'attack-sustain-release' model, creating a more realistic sounding solution. The audio code used direct memory access (DMA) to provide a reduced processing cost in outputting the audio samples. The user could also choose to display useful information such as the current song name, the volume, or the channel names on the computer screen or on the MBED board in a variety of ways. For example they could be statically printed on the MBED board, or scrolled across the LCD display, or even printed out to the terminal on the computer.

## 3.2 How the problem was broken down for individual members

The breakdown of our solution into components individual members could work on was a great strength of our team. Each person worked on an aspect of the project that they found interesting, and throughout the project we had regular feedback on all our work in order to make sure we were meeting our specifications and that nobody was out of their depth. Below I have divided up the work that each individual completed during the duration of the project, and why they were working on that aspect of the project.

### Mingzhao Zhao

Each individual was allowed to choose their own area of the project to work on. Mingzhao was not especially confident with the platform, and therefore he decided to target user interaction with the device via the keypad. This provided a possible method of user input, as well as providing a means to optionally filter data, or control the volume output of the device. Following suggestions of other group members he decided to convert the previous keypad polling method incorporated in the mini-projects into an interrupt based system, removing the need for unnecessary CPU cycles to be used polling the device continually.

### Shivam Mistry

Shivam worked very strongly as a group member. To begin with he took on the challenge of constructing code to read the data from the CAN bus continually, as well as implementing the base for filtering out data according to a preset ID. Following the construction of the CAN bus code, he worked on optimising the CAN bus code through the implementation of a queue, as well as decoding the CAN packets to extract their data, and the parsing of text packets to extract only the useful information. Furthermore, on realisation of additional device memory, Shivam wrote a memory allocator allowing the additional memory to be used constructively, further optimising the system.

### Myself (Douglas Parsons)

Following the mini projects, and from reviewing the specification, it was clear that a strong level of user interaction with the device would provide valuable debugging tools, could potentially allow settings to be changed without re-installing binaries on the device, and could be used for a wide range of useful functions, such as changing the volume or displaying song information. From the mini projects it became clear that the 16 digit keypad attached to the mbed would not provide an intuitive user experience. Rather than relying on the keypad as the sole method of user interaction, I instead focused on allowing a further degree of interaction via the computer keypad. This enabled the user to preset an ID to filter out data, adjust the volume of the output, display any data received on the CAN bus, as well as adjust settings within the project without requiring a full

### 3.3. TECHNICAL INNOVATION AND IMPLEMENTATION OF EACH MEMBER

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reinstate. During the implementation of the shell it became clear that this could be a valuable tool for displaying useful information such as the song name, and therefore I additionally worked with the LCD display to enable a much greater degree of control over what was displayed, enabling scrolling text, and writing to each line of the display individually.

#### **Liam Fraser**

Liam has a strong background in music technology, taking the subject at A-level, and working on personal projects involving music. Furthermore his interest from the beginning of the project in audio processing meant that it was an obvious choice for Liam to look into the generation and playback of music. The specification was exceeded with his contributions, not only did his solution generate an audio tone corresponding to the frequency, duration, and volume levels specified in the data stream, but implemented an attack sustain release curve to improve the realism of the output sound, as well as additive synthesis enabling multiple notes to be played simultaneously, and his solution also used DMA and a fixed point library to improve the efficiency of the system.

### **3.3 Technical innovation and implementation of each member**

#### **Mingzhao Zhao**

Mingzhao's work was primarily focused on implementing interaction via the 16 digit keypad on the mbed board. The keypad was set up in the mini-projects to allow user interaction through continually polling the keypad. However, due to the limited speed of the processor it was decided that a better solution would be to use an interrupt based system. However, this caused additional problems with bounce on the switches: multiple interrupts could occur in a very short space of time due to bounces on the switches. Many of these interrupts generated were redundant, or gave nonsensical input values, and furthermore their rapidity caused race conditions to occur within the interrupt handler. Due to the row/column method in which the key pad is scanned, the number of bounces was reduced significantly by filtering out any inputs that did not match one of the keys pressed. The switch bounces were then reduced further by only allowing a single key press every half a second. This method of debounce was implemented using a system timer (SysTick) to count the time between successive key presses. Any key presses that occurred too closely together were disregarded.

#### **Shivam Mistry**

Shivam initially targeted the CAN bus, and was able to rapidly achieve a fully functioning prototype. The original solution processed each packet as it was received. However, as the complexity of songs increased it became clear that this simplistic method was not going to be sufficient when many CAN packets

### 3.3. TECHNICAL INNOVATION AND IMPLEMENTATION OF EACH MEMBER

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require processing in a short space of time. In order to improve the functionality, a queue was implemented. Packets were added to the queue on being received, and processed whenever there was sufficient processor resources available. This removed the requirement of each packet being processed as it was received, and therefore provided a clean, efficient solution. Shivam's contribution also included the reverse engineering and decoding of any CAN packets received through testing their check-sum, and parsing any received text. As the check-sum method was not specified in any documentation, the first challenge was determining what the check-sum corresponded to. Values that did not match the length specified by the check-sum were not processed, and therefore could not have any impact on the system. Furthermore, the text packets sent prior to each song being played required parsing in order to extract any useful information. Therefore, a text parser, extracting the useful information from these packets to the device was implemented using a state based solution.

Furthermore, following an instance where the physical memory (RAM) on the device was fully used up, Shivam discovered that the device contains an additional 32Kb of memory, typically reserved for communicating to a USB or Ethernet device. However, due to the reserved status of this memory, a memory allocator was required for it to be utilised. Therefore, the group solution contains a memory allocator allowing access to a further 32Kb of memory. This allows a much greater amount of information to be stored on the device. In addition, the look-up table used by the memory allocator was stored in the additional memory, making it a self containing allocator.

#### **Myself (Douglas Parsons)**

My personal contribution to the project was primarily targeted at the user interactions with the device. While it was initially set out that Mingzhao was going to work on implementing an interrupt based keypad, I decided that the communication via serial would potentially allow a much greater level of debugging, interaction, and manipulation of settings for the device. From the beginning of the ten week period, I focused on setting up a shell style interface for the device. This would allow the user to communicate with the mbed board by typing in commands on a computer keyboard, and execute the command by pressing the enter key. The input from the keyboard was implemented using interrupts in order to avoid unnecessary computation time from continual polling. Furthermore, the processing of text input required a text-parser to be used. Due to an unknown number of words, and an unknown input length, the parser had to be very carefully adjusted to avoid memory overflow situations. Further difficulty was added to the implementation, as alterations had to be made in many different aspects of the group solution. A detailed understanding of each individuals contributions was required to manipulate their functionality, and continual additions and updates were needed throughout the project as changes were made. In addition to implementing the additional interfacing method of a shell style interface, I focused on customisation of the mini-project LCD screen code in order to allow a greater level of control. I implemented features such as the abil-

### 3.3. TECHNICAL INNOVATION AND IMPLEMENTATION OF EACH MEMBER

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ity to write to each individual line of the LCD display, and the ability to scroll text across the screen. The latter of which was particularly difficult, not only requiring pointer manipulation for efficient text processing, but accessing only the required section of the LCD in order to avoid displaying unwanted characters provided a significant technical challenge. Following the implementation of the shell, and the LCD screen code, I worked alongside Mingzhao on combining his code with the rest of the group solution.

#### **Liam Fraser**

Liam Fraser, following an interest in music technology was eager to work on the audio code for the project. He implemented a simplistic system, allowing musical notes to be generated by scanning, and interpolating over a look up table. He then looked into generating synthesised music, and implemented additional synthesis into the project, allowing multiple notes to be playing simultaneously. However, on testing his synthesis code on the mbed board, it rapidly became apparent that the use of floating point numbers was not sufficiently quick to produce clean sounding audio. Therefore, a fixed point library was implemented, this allowed much quicker calculations to occur compared to those of floating point numbers. Following this optimisation of the synthesis code, the synth code was further optimised through the use of Direct Memory Access (DMA). This allowed the audio output to work independent of the central processing unit (CPU). This therefore speeds up the processing of any audio, as the CPU does not have to be involved for any sound to be output, only for the generation of audio samples [dma-book]. In addition, to create a more realistic sounding output from the device, an attack sustain release state model was incorporated for each note. This gives an initial rise in volume as the note is turned on, and a fading out of the note as it is turned off, producing a volume curve more typical of an actual instrument [asr-book].

## Chapter 4

# Evaluation and Testing of Team-based Solution

### 4.1 Description of the Team's Testing Strategy

Throughout the duration of the project, each section of the project underwent significant reviews, and testing in order to ensure that it was of the highest quality and that it was not laden with any issues causing undesirable behaviour, or significant faults that may have caused the device to crash. Furthermore, once incorporated into the group's main solution, the implemented code underwent a thorough review in order to ensure that the quality of the implemented product was the highest possible, and free from anything that may cause issues in the future. In effect the product underwent many different stages of testing throughout its life-cycle.

#### Individual Testing

Prior to the inclusion within a greater completed solution, each section of the project underwent individual tests. In order to test each section of the project, a debugging library was created. The debugging library was only included in the binaries installed on the device if the `make` command included it. This means, for the purposes of testing it was possible to use `make debug` and have debug messages containing text, or values printed out over serial. However, once sufficient testing was done, no alterations had to be made to the source code to remove these statements, and instead the project could be installed by calling `make`. This enabled statements to be added to the project, that would print out messages over serial.

#### Code Review

Before each contribution was incorporated into the group's solution, it was first checked over by at least two other group members to ensure the quality of the solution was high. These checks often resulted in re-factoring code to achieve a more streamlined end product, examples of which could include the simplification of logic for writing text to the LCD display through pointer arithmetic, or simplifying code within an interrupt handler in order to avoid race conditions.

### Integration Testing

Following the combination of individual components into the group solution, the combined product was then tested thoroughly to ensure no erroneous behaviour could occur. This was primarily done by leaving the boards running for long periods of time within the labs, and listening to make sure nothing unexpected was occurring. In addition, each feature was continually explored in order to make sure everything fully functioned.

## 4.2 Results of Testing Strategy and How Well This Met the Requirements

At many points throughout the project minor issues were discovered, and corrected. Through the continual testing of the full solution by leaving it running for a long period of time, a large number of test cases and situations were explored. Furthermore, a careful eye was kept at all times to ensure that the product's functionality was as desired, and further testing was done to ensure the requirements of the specification were fully met. Through our thorough and rigorous testing, the end product was remarkably stable. We encountered no situations that would cause the product to produce undesirable behaviour, and furthermore the full requirements were met.

## 4.3 A Social/Ethical Aspect of the Group Solution

The group solution created has the potential to solve any issues that may arise when considering the usability of the user interface with respect to a disabled user or users. Interaction with the device via the 16 digit keypad that is on the host board may not provide a very effective method of interaction with the device for many users. However, the shell style interface allows user to interact with the device via a computer. Interaction with a computer, and hence the mbed would typically be achieved through use of a keyboard, however, there are many alternative methods of input that would allow interaction with the mbed board in a method better suited for a disabled user. These input methods could include tools such as an improved computer keyboard, speech recognition, or the tailoring of custom tools to allow a greater level of interaction. Such tools are highlighted in many works, examples of which could include *Computer Access for People with Disabilities: A Human Factors Approach*, or *Universal Access in Human-Computer Interaction* [disabled-book, disabled-book2]. The flexibility of input method provides a wide range of possible tools enabling communication with the device. This therefore avoids significantly the problem of interaction for a handicapped or disabled user.

## Chapter 5

# Description, Discussion, Testing and Evaluation of Individual Component

### 5.1 Description of Individual Component Solution

My individual contribution to the project consisted primarily of a shell style interface for the host board, allowing user interaction via a computer keyboard and monitor, but also consisted of the modification and extension of previously existing LCD screen code, to allow a much greater degree of control over the attached LCD display.

The shell style interface was set up using an interrupt based system from the computer. This enables users to enter commands through any input method for the computer and process them on the device. This method also allows the user to display useful information through the computer monitor.

There were a wide range of possible input commands available through this interface, with many possible options and settings being adjusted on the fly. By typing 'help' and pressing enter, the user could view a list of possible commands, as seen below:

This therefore provides the user with a high amount of control over the devices output though both audio and visual elements, as well as a high level of control over the devices functionality. Furthermore, the interaction with the on board LCD display can be clearly seen through the above commands, hence explicating the necessity for the alterations made to LCD display code to permit a greater degree of control, and enable features such as scrolling text, and writing to only part of the LCD screen.

### 5.2 Discussion of Technical Innovation and Implementation

The implementation of the shell style interface and the improvement of the LCD display code consists of many different technical challenges, and required



## 5.2. DISCUSSION OF TECHNICAL INNOVATION AND IMPLEMENTATION

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List of available commands:

playnote note volume	: plays the selected midi note
noteoff note	: turns off any playing notes
volume vol	: sets the output volume to 'vol'
showvol	: displays the current volume
write text	: writes text to the LCD screen
writeline text linenumber	: writes text to one line of the LCD screen
listen	: listens to music on the CAN bus
stoplisten	: stops listening to music on the CAN bus
setid channel	: Filters out channels that do not match channel number channel. To play all, use setid all
showid	: Shows the id of the current channel
showtrack	: Shows the current track name on the LCD
showchan	: Scrolls the channels on the LCD
showpacket	: Prints CAN packets until a key is pressed
scroll text line	: displays scrolling text on line line of the LCD screen
stopscroll line	: stops scrolling text on the screen. To stop both lines, enter line as 2 or all.
scrollenable line	: enables scrolling text on the screen.
shownotes	: displays all notes currently being played
cowsay text	: displays an ASCII cow, saying text
clear line	: clears any text that is on the lcd line line Note - you may also have to call stopscroll to fully clear

many different technical challenges throughout. First and foremost there was the challenge of setting up a system to enable user input to be recognised. This is achieved using an interrupt based system, such that each new character entered into a screen set up for the board will trigger an interrupt. When the interrupt is triggered, the character that was input is transferred to the host board and stored into memory for processing at a later stage. This incorporated several different technical challenges in the implementation, such as figuring out how to set up the interrupt, and how to allocate memory for storing any characters input. The simplest solution for allocating memory was used: a set input limit is defined, and any characters that are input past this count are not stored in memory. Other technical challenges involved handling special input cases such as backspace to delete a character from memory, but only if there was any input to delete.

When the enter key is pressed (`\r\n` received on the interrupt), processing of the user's input command begins. First the text is split up into tokens for processing. This requires the use of a text parser. The text parser implemented uses a state based system, with different states corresponding to whether it is interpreting a single word, a phrase (group of words encased in quotation marks), or whitespace. This breaks the user's command into it's constituent

components, which can then be individually evaluated. However, it was found that memory allocation problems could occur due to the large range of possible tokens in the input. For example, the user could input 'a a a a a a', and this would be interpreted as 6 individual tokens, requiring the allocation of six blocks of memory. A solution to this problem was found by simply setting a limit on the number of tokens that can be generated by a single command.

Following the dissection of the user's input into components, a string comparison tool (`strcmp`) was used to determine what the user's input was, enabling the corresponding desired behaviour to be executed. In order to prevent race conditions from occurring within in the interrupt handler, all text processing following the enter key being pressed occurs outside of the interrupt handler using a flag based system.

In order to successfully perform the desired functionality, settings are altered within many different areas of the project. The implementation of the shell therefore required a fully detailed understanding of how each individual component of the project functions in order to manipulate and alter existing code. Modifications were made throughout the project, and included; the addition of a settable id within the CAN bus code, the addition of a filter in the CAN bus to ignore unwanted data according to the preset id, the addition of a volume control in the synth code, and a major overhaul of existing LCD code to allow a much greater degree of control over the display.

The overhaul of the LCD display code provided a significant technical challenge. The initial desire was simply to allow scrolling text on the display, however it soon became clear that further alterations were required. Initially the LCD code would write to the LCD display, and clear it. To match what I wished to achieve, it was necessary to first figure out how to write only to a single line of the LCD display, without clearing the other line. This required accessing only certain memory addresses of the LCD display buffer in order to prevent clearing parts of the display. Following the successful implementation of the capability to write to each individual line of the LCD display, the next target was to give the ability to scroll text across the display, in order to effectively increase the number of characters that could be read.

## 5.3 Testing Strategy, and the Results

Due to the nature of the extension project, testing was relatively straightforward. Using the debugging library, it was very easy to check the effects of any command that was entered to ensure correct behaviour. Therefore, any errors or undesirable behaviour was rapidly discovered. Furthermore, the interface became a central aspect of the group solution, and as a result was used by each member of the group on a regular basis to interact with the device. Through each individuals interaction many test cases were encountered, and therefore the device has undergone a continual and thorough testing strategy.

### *5.3. TESTING STRATEGY, AND THE RESULTS*

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The results of the testing strategy were very positive. The shell style interface had a large number of features by the end of the project, and worked very well. Furthermore, my individual contribution provided a very valuable tool throughout the project due to the high level of interaction that it provided.

## Chapter 6

# Summary and Conclusions

### 6.1 Reflective Summary of Team Work

Team work was an essential part of the project, and an area where my group excelled. Each individual was allowed to select their own areas of the project to work on, and furthermore regular meetings and code review sessions both ensured that no individual was overwhelmed, and ensured that contributions to the solution were of the highest quality.

The group solution achieved every point of the specification in an elegant manner, and had a wealth of additional functionality through additions to the project. Examples of these additions could include; the ability to synthesise music and play back multiple notes on each channel and multiple channels simultaneously, an improved user interaction via a shell style interface complete with the ability to adjust settings and change mode of operation without reinstalling the device, or a more realistic sounding audio playback through the use of attack decay sustain release models.

### 6.2 Reflective Summary of Individual Work

My individual extension project was the implementation of a Linux style shell, enabling user interaction with the mbed board using a computer monitor and keyboard via serial communication. The addition of the shell style interface provided a wide range of valuable tools, and a great degree of control over the host board. Examples of the control given includes:

- The ability to play notes
- The ability to change the device volume
- the ability to write custom text to the LCD display
- The ability to change which channel of music is being listened to
- The ability to view useful information, such as the track name, channel, or what notes are currently being played
- The ability to view CAN packets as they are received on the CAN bus

- The ability to scroll text on the LCD display

This enabled a great degree of control over the host board, and provided invaluable tools throughout the course of the project. This extension project was initially very challenging and was an ambitious task to undertake due to the scale of the implementation combined with any desired features. However, the end result was very rewarding and one that I can be proud of.

## 6.3 What went well

My group had a very successful end product, and this was the result of many aspects of the project going very well. From the beginning of the project it was clear that each member of the group was very enthusiastic about producing a high quality end result, this enabled a positive working atmosphere where each group member was free to work on whatever aspect they desired as the project moved on.

Furthermore, we were aware of the limitations of the host mbed board prior to the start of the project, and therefore continually conscious of performance. Each feature implemented into the product was carefully considered, and its implementation was carefully monitored to ensure that it did not take excessive resources. Coupled with careful study of the data sheet for the host board, we were able to extract a great amount from the device, and produce a high quality finished product that was well optimised.

## 6.4 What went poorly

While the vast majority of the project went very smoothly and according to plan, there were two occasions where significant issues were encountered. The first problem we encountered was in the first week of the project. After spending a week attempting to receive data from the CAN bus and failing, we decided to use the online tool-chain to set up a device to send CAN packets, and plugged this into our existing code. This worked perfectly, and led to the discovery that the CAN bus was not working everywhere within the lab. Because of this a lot of time within the first week of the project was spent attempting to correct code that was already working.

The second issue that was faced was the inconsistent use of version control software. The majority of the group (Myself, Shivam and Liam) all used git, and github as a central location allowing us to effectively work as a team on the project. Mingzhao, despite being shown how to use git many times, elected not to use any version control software. This made interaction with his contributions to the project much more difficult, and keeping up to date with his progress a much more difficult task.

## 6.5 What could have been improved

Due to the nature of the project, there is a large amount of extension to the basic functionality that can be added. Our group solution extended the base implementation a long way, however, additional features were nearly implemented that could have made a good improvement to the finished product. There are three examples of features that were not implemented in the final version of our project, but would have contributed to an overall improvement of the project.

The first improvement would be the incorporation of multiple wave tables. Our group solution used sine waves to generate audio samples, however, there is scope for allowing any wave to be used. Through use of the shell it would be possible to alternate between different wave tables without the need to reinstall the binary on the device. This would allow a further degree of control over the device, and could be used to alternate to more pleasurable sounding outputs for certain channels.

The second potential improvement that could have been made ties in to the first, and is the implementation of drum samples to create a more complete sounding audio track. On the CAN bus sixteen channels of audio data is sent corresponding to the different instruments. Channel 11 typically represents a drum track, and for our project this channel is being ignored. This therefore is a potential improvement that could have been made.

The third potential improvement is a greater level of interaction between the shell and the keypad user input methods. As the keypad interaction was only implemented into the group solution near to the end of the project, the interfacing between the two methods is not flawless, and it is possible for minor discontinuities to occur. For example, if the user changes the volume using the keypad the new volume level is displayed on the LCD display. Changing the volume once again via the shell does not update the value displayed on the LCD display. The finished product could therefore be improved by improving the interactions between the two devices.

## 6.6 Lessons Learned

The project has served as a valuable learning experience throughout the duration, and has provided a great lesson to me personally in many different ways. First of all I have developed a much stronger understanding of the technical intricacies of programming in C - while the language itself is very minimal and straightforward to learn, there are many small details that require careful thought and consideration, such as the use of pointer arithmetics. Over ten weeks I have developed a greater knowledge and familiarity with this. Having no prior experience of programming an embedded system, this project has equally been an invaluable learning experience in that regard. Concepts such as interrupts, SysTick, or direct memory access are not entirely unfamiliar, however, the implementation

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desired features using these tools has been a new experience. The project has also greatly developed my understanding of music technology. Through meeting the projects requirements to generate audio samples, and our own desire to make these samples sound more realistic a lot of research has been done into this field. Having no background in music technology it has been fascinating to research and learn about all the different aspects involved in our groups solution, such as sound synthesis, attack decay sustain release curves and equal loudness curves. In addition, I have not worked on a group project before where version control software such as git has been used. Throughout the project I have gained a much better understanding of how a group should function, and I have developed a much better understanding of the communication between group members and how collaboration works.

Overall there is a huge amount that I can take away from the Embedded Systems Project, and the project has provided a valuable opportunity to further develop my knowledge of embedded systems programming, working as a group, and music technology.

## Appendix A

# Specified Documents

**A.1 Meeting minutes**

**A.2 Evidence of Preparation**